


Hydrochemical characteristics of groundwater and surface water for domestic and irrigation purposes in Veua catchment, Northern Ghana

Kouakou Valentin Koffi^{1,3}  · Emmanuel Obuobie² · Andre Banning³ · Stefan Wohnlich³

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Abstract The Veua catchment, mainly underlain by crystalline basement rocks, is located in Northern Ghana. Hydrogeochemical studies were carried out in this area with the objective of identifying the geochemical processes influencing water quality and suitability of surface and groundwater for agricultural and domestic uses. Sixty-one groundwater and four surface water samples were collected from boreholes, dams and rivers and analysed for Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , Cl^- , and SO_4^{2-} , Fe_{tot} , PO_4^{3-} , Mn_{tot} , NH_4^+ , NO_3^- , NO_2^- . In addition, pH, total dissolved solids, electrical conductivity, total hardness, turbidity, colour, salinity and dissolved oxygen were analysed. Chloro-alkaline indices 1 and 2, and characterization of weathering processes suggest that the chemistry of groundwater is dominated by the interaction between water and rocks. Cation exchange and silicate weathering are the dominant processes controlling the chemical composition of the groundwater in the area studied. Mineral saturation indices indicate the presence of at least three groups of groundwater in the Veua catchment with respect to residence time. The meteoric genesis index suggests that 86% of the water samples belong to the shallow meteoric water percolation type. The findings further suggest that the groundwater and surface water in the basin studied are mainly Ca–Mg– HCO_3 water type, regardless of the

geology. Compared to the water quality guidelines of WHO, the study results on sodium absorption ratio, sodium percentage, magnesium hazard, permeability index and residual sodium carbonate indicate that groundwater and surface water in the Veua catchment are generally suitable for drinking and irrigation purposes.

Keywords Veua catchment in Northern Ghana · Crystalline basement rock · Groundwater quality · Hydrogeochemistry · Silicate weathering

Introduction

Water is the basis of human life and all economic developments. Like most of Africa's semiarid regions, Northern Ghana is characterized by a prolonged dry season (7 months of very little rainfall) leading to the drying up of many rivers and streams and a high variability of rainfall in space and time. Therefore, surface water is unreliable and insufficient to meet the increasing water demands for domestic and agricultural uses. An alternative solution to this issue is to build dams for surface water storage. The challenge here is that large plots of land are immersed resulting in reduction of the area that is available for agricultural use. Also, with high rate of evapotranspiration in the area, a large amount of the stored water would be lost by evaporation, calling for re-thinking of water storage in large surface dams. This makes the availability of surface water a big challenge in arid areas and mostly in developing countries where storage infrastructures are insufficient because of lack of finance and good water management policies. In addition, in areas with scattered settlements, like rural areas in Northern Ghana, groundwater is the most appropriate source of water supply

✉ Kouakou Valentin Koffi
valenkof@yahoo.fr

¹ WASCAL GRP Climate Change and Water Resources, University of Abomey-Calavi, P.O. Box 526, Cotonou, Benin

² Council for Scientific and Industrial Research, Water Research Institute, P.O. Box AH 38, Achimota, Accra, Ghana

³ Hydrogeology Department, Ruhr Universität Bochum, Universitätsstr. 150, 44801 Bochum, Germany

because, compared to surface water, it can be accessed at the vicinity and it is less exposed to pollution and evaporation. It also has a relatively constant temperature, and its response to demand over time varies only slightly (Tsur and Graham-Tomasi 1991; Zektser and Everett 2004).

In the Veia catchment (study area), some small dams were built for irrigation and cattle breeding. The biggest among them is the Veia Dam constructed for the irrigation of 1400 hectares of land in the catchment and water supply of 4.5 million litres per day to the capital city of the Upper East Region of Ghana—Bolgatanga and its environs, which are outside of the Veia catchment. Generally, demand on water resource in the Veia catchment outstrips supply for two main reasons. Firstly, there is increasing demand for domestic water supply due to population growth in the basin areas as well as in Bolgatanga and its environs and the size of the Veia Dam is not sufficient to meet the water demand, leading to shortage of water for domestic supply and irrigation. Secondly, due to an annual siltation rate of $1000 \text{ m}^3/\text{km}^2/\text{year}$ in the Veia Dam reservoir, its storage has been drastically reduced (Adongo et al. 2014). Climate change may worsen the situation as research findings suggest an increase in temperature and a decrease in rainfall in the area (Asante and Amuakwa-Mensah 2014) leading to less inflow to the dam and exacerbation of evaporation. The aforementioned challenges with surface water make groundwater the most preferred alternative source of water to compliment surface water sources for meeting the water demand in the area. But the use of groundwater in the study area is negated by the poor quality of the resource in some locations in Bongo and Bolgatanga where groundwaters with high fluoride concentrations have been found. High fluoride concentrations above WHO limit of 1.5 mg/L are related to health implications of mottled teeth, dental and skeletal fluorosis. This high content of fluoride has been found to be associated with microcline-rich granitoids (Smedley et al. 1995; Apambire et al. 1997; Firempong et al. 2013). Furthermore, in the rural areas, groundwater and surface water are used in domestic water supply without any proper treatment. Therefore, a study of water quality in the Veia area is of crucial importance. Some studies related to groundwater quality have been carried out in the Northern Ghana (e.g. Smedley et al. 1995; Anku et al. 2009; Loh et al. 2012; Tay 2012). However, Loh et al. (2012) focused on water quality of groundwater at the bigger scale in the crystalline basement aquifer of Northern Ghana, which encompasses the Veia catchment and did not take into account the quality of water for domestic use. Apambire et al. (1997), on the other hand, focused mostly on the genesis of elevated fluoride concentrations in groundwater.

To address this information gap, this study aimed at determining the hydrogeochemical characteristics of

groundwater and surface water for domestic and irrigation purposes in the area using highly representative datasets from the area. Specifically, the study focused on determining (1) the processes influencing groundwater quality, (2) the water type and the influence of geological formations on the water resources and finally (3) the usability of both groundwater and surface water for irrigation and domestic water supply.

As aquifer material and groundwater quality are often closely related, knowing the geological characteristics of a study area is a prerequisite for a meaningful groundwater chemistry investigation. Studies done to date have suggested the land area of Ghana is underlain by three major geological terrains. The first terrain is comprised of Paleoproterozoic rocks (quartzites, phyllites, grits, conglomerates, schists, tuffs, graywackes, metamorphosed lavas and pyroclastic rocks) predominant in the south-western and north-western part of the country, whereas gneisses and supracrustal rocks of mostly Neoproterozoic age are found in the south-east and east of the country. The second geological terrain consists of flat-lying shelf/marine sediments of very late Precambrian to Palaeozoic age, which are found in the central and north-eastern part of the country, while the third sequence, the mostly Cenozoic sediments, occupies a small strip along the coast (Schlüter and Trauth 2008). In Veia catchment, bedrock is mainly comprised of granites, hornblende–biotite–granodiorites (hornblende B granodiorite), biotite gneisses, basaltic and andesitic volcanics and intrusives and migmatites. Basically, granite contains at least 10% and up to 40% free quartz, together with feldspar and mica. Both alkali (K and Na rich, orthoclase, microcline) and plagioclase (Na and Ca rich, albite, oligoclase, andesine, etc.) feldspars are present in most granites (US Bureau of Mines 1996). Pelig-Ba (2012) conducted a physical analysis of granite, hornblende–granodiorite and biotite–granodiorite samples taken from the study area and found that the granites and hornblende–granodiorites were composed of K-feldspar, hornblende and quartz while the biotite–granodiorites were composed of biotite, hornblende and quartz. In addition, the granites and biotite–granodiorites were coarse-grained while the hornblende–granodiorites were medium-size grains. Based on chemical analysis of these samples, the same authors found that silica (SiO_2) with a weight per cent ranging from 46.37 to 62.98 is the major geochemical component and it is followed by Al_2O_3 with weight per cent ranging from 12.05 to 14.37. The coarse-grained granite of the study area comprise mainly of Bongo granite suite that was described by Murray (1960) as a pink rock composed of well-developed euhedral to subhedral microcline phenocrysts up to 1 cm in length, euhedral amphibole crystals, granular interstitial quartz, plagioclase, minor biotite, and trace accessory fluorite.

Materials and methods

Study area

Location

The study was conducted in the Veia catchment, which is a sub-catchment of the White Volta Basin in Ghana and located between latitudes 10.43°N and 11°N, and longitudes 0.45°W and 1°W. Administratively, the Veia catchment is located in the Upper East Region (north-eastern Ghana), where the population was estimated to be 1046,545 in 2010, with a growth rate of about 1.2% and population density of 118 persons per km² (Ghana Statistical Service 2012). The total drainage area of the Veia catchment is approximately 305 km². The mean slope and the mean altitude are 0.2% and 196.5 m a.s.l., respectively. Van der Sommen and Geirnaert (1988) noted that about 75% of the annual rainfall in the catchment occurs between July and September. The rainy season starts in May and ends in October. The region has a seasonal wet–dry tropical climate (Aw in the Köppen system), and it is characterized by high temperatures with a long-term mean annual rainfall of about 990 mm. The soil types in the basin are haplic lixisols, ferric lixisols, eutric leptosols, lithic leptosols, gleyic lixisols, eutric fluvisols, eutric fluvisol and haplic luvisols with three main land use classes which are semi-natural (grass, shrubs, trees or a mixture), artificial (e.g. bare lands, laterite and tarred roads, buildings, hamlets and rocks) and cropland (all crop types).

Geology and hydrogeology

Groundwater in recent years has become a premium source of potable water supply for most communities in Ghana especially in the Upper East Region, where the economy of the region depends heavily on groundwater (Obuobie 2008). The depth to groundwater table in the region including the study catchment varies from ground level in the rainy season to about 15 m below ground level in the dry season. The Bolgatanga area is underlain by basaltic and andesitic Upper Birimian basement rocks of Precambrian age. The area is also underlain by a range of other rock types including hornblende- and biotite-granodiorites, tonalites, adamellites, biotite gneisses and migmatites (Fig. 1). The Birimian forms a folded, steeply dipping, complex group of volcanic rocks that have been metamorphosed to greenschist grade with a steep or vertical cleavage. Groundwater storage in these rocks is generally poor although at shallow depths, it is locally increased by weathering (Smedley et al. 1995). According to Oberthür

et al. (1998), Attoh et al. (2006) and Hirdes et al. (2007), the rocks in the area were formed in the Paleoproterozoic era between 2195 and 2072 Ma.

Methods

A total of 65 samples (61 groundwater samples and four surface water samples) were collected in different locations using pre-cleaned sterilized poly propylene plastic bottles with necessary precautions. In the field, the samples were stored in a cooler containing ice blocks in order to keep the temperature of the samples low and constant. At the laboratory, the samples were stored at 4 °C in a refrigerator for about a week before they were analysed. Two of the surface water samples were collected from Gurugu Dam and Veia Dam. The Veia Dam is the largest dam in the catchment and used for both irrigation and drinking purposes. The two other surface water samples were taken from rivers (Naaba Kolga and Gurugu rivers). The groundwater samples were collected from boreholes and hand-dug wells equipped with pumps. These wells are the main sources of water supply for the inhabitants. The sampling was carried out at the end of the rainy season (from 25 September to 5 October 2015). The wells used in this study were selected in such a way that they represented the different geological formations, soils and land use types in the study area. Parameters such as pH, electrical conductivity (EC), temperature, salinity, dissolved oxygen (DO) and total dissolved solids (TDS) were measured in situ, whereas hydrochemical parameters such as calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), bicarbonate (HCO₃⁻), chloride (Cl⁻), sulphate (SO₄²⁻), total iron (Fe), phosphate (PO₄³⁻), ammonium (NH₄⁺), nitrate (NO₃⁻), nitrite (NO₂⁻), manganese (Mn_{tot}), turbidity, colour, the total hardness (as CaCO₃) and total dissolved solids (TSS) were analysed at the laboratory of Water Research Institute in Accra (cf. methodology in Table 1).

The results from the chemical analysis of water samples carried out in the laboratory were assessed using different methods to determine the water types and quality in the study area as well as the processes influencing the water chemistry. The assessment included determining: the ion balance; sodium adsorption ratio (SAR); total hardness; calcite, dolomite, anhydrite and aragonite saturation indices; and the use of a Piper diagram for inferring hydrogeochemical facies. This was carried out using the computer program Diagrammes—version 6.5 (Simler 2015). Table 2 gives an overview of the methods used to analyse the data.

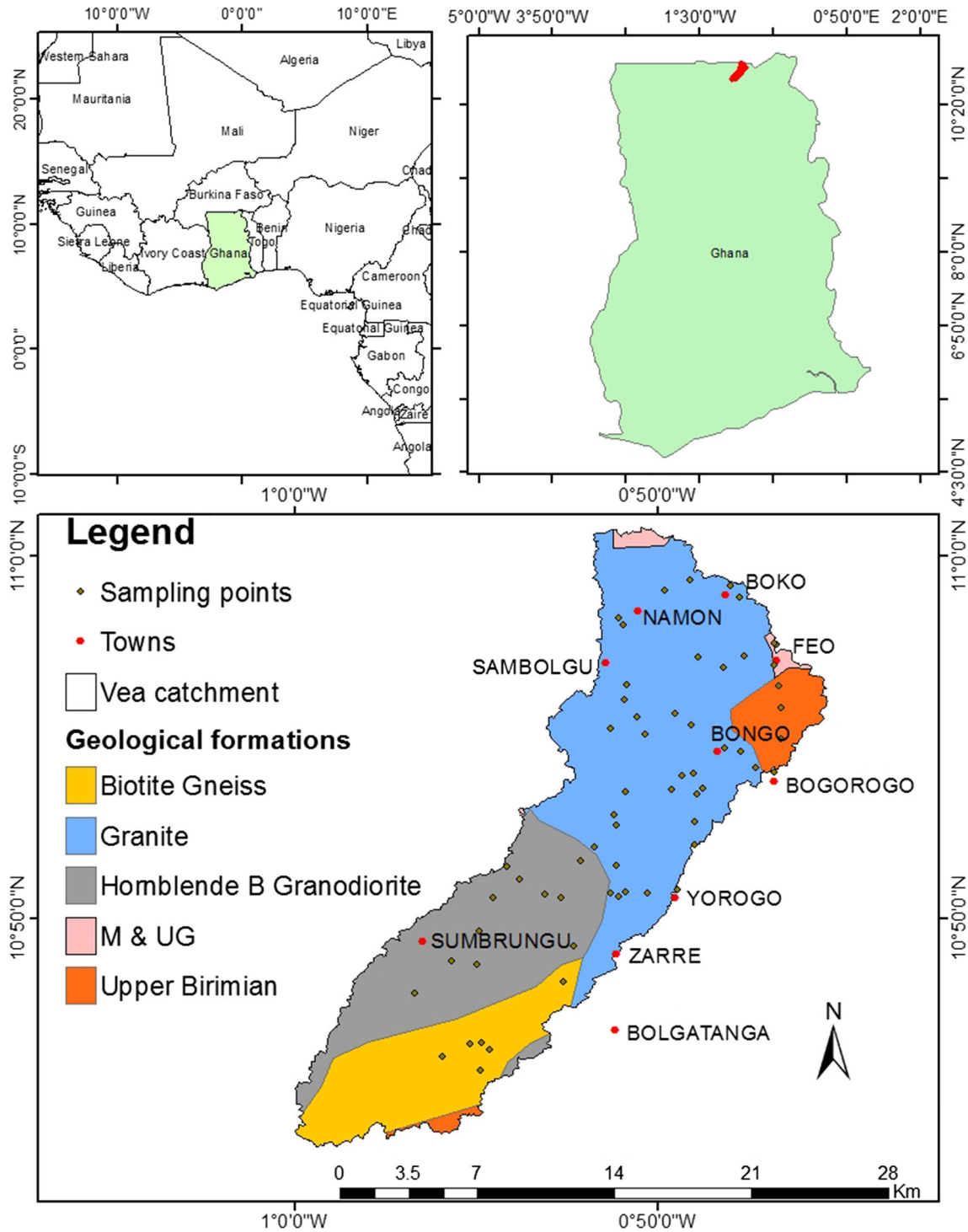


Fig. 1 Location of Ghana in western Africa (*upper left map*), location of the Veia catchment in Ghana (*upper right map*), geological units (Source GLOWA Volta Project) and water sampling points in the study area (*lower map*). *M&UG* migmatite and undifferentiated granite

Results and discussions

The ion balances of the samples range from 0 to 5%, thus the laboratory analysis results of all the samples are acceptable. The range of all the parameters for

groundwater samples is summarized in Table 3, while the distribution of these samples based on the geological setting of the area where the sampled boreholes are located is provided by Table 4.

General Hydrogeochemistry

Chloro-alkaline indices

Along its path and its residence in the aquifer, groundwater interacts with rock which affects its quality (Zaidi et al. 2015). Versluys (1916), (1931) and Schoeller (1965) proposed ion exchange indices to better describe and understand these interactions. In this study, we used the chloro-

alkaline indices (CAI-I and CAI-II) proposed by (Schoeller 1965) and depicted in Eq. (1) and Eq. (2):

$$CAI - I = \frac{Cl - (Na + K)}{Cl} \tag{1}$$

$$CAI - II = \frac{Cl - (Na + K)}{SO_4 + HCO_3 + CO_3 + NO_3} \tag{2}$$

In the above equations, all the ion concentrations are expressed in meq/L.

A positive CAI implies that Na⁺ and K⁺ ions of the water are replaced by Ca²⁺ and Mg²⁺ by contact with aquifer rocks or sediments, indicating reverse ion exchange. A negative CAI means that Ca²⁺ and Mg²⁺ of the water are exchanged against K⁺ and Na⁺ of surrounding formations (ion exchange). If CAI is equal to zero, it means there is equilibrium between the chemical composition of the water and that of the aquifer rocks, i.e. there is no exchange between water and rocks.

In this study, the chloro-alkaline indices were analysed only for groundwater samples. The CAI-I ranged from -10.99 to 0.545, whereas CAI-II ranged from -0.49 to 0.25. For both indices, 93.4% of the samples are negative and only 6.6% are positive (Fig. 2). Thus, for the vast majority of the groundwater samples taken, the Ca²⁺ and Mg²⁺ of the water are replaced by Na⁺ and K⁺ of the rocks. Hence, cation exchange is the main ion exchange process and can also be one of the mechanisms controlling the chemical composition of the groundwater in the studied area. This result is similar to the findings of other works in Ghana such as Yidana and Yidana (2010) and Kaka et al. (2011), who analysed 161 groundwater samples from the Voltaian sedimentary formation and 33 water samples (25 groundwater, 3 streams and 5 from the Volta Lake) from Many Krobo area mainly underlain by rocks of the Voltaian Supergroup, respectively.

Table 1 Instruments and methods used for analysis

Parameter	Instruments and method used
pH	PELI 1520
Electrical conductivity	PELI 1520
Temperature	PELI 1520
Salinity	PELI 1520
Dissolved oxygen	YSI ProODO®
Turbidity	Nephelometric method
Colour (apparent)	Visual comparison method
Total suspended solids	Gravimetric method
Total dissolved solids	Gravimetric method
Ammonia–nitrogen	Direct nesslerization method
Nitrate–nitrogen	Hydrazine reduction method
Phosphate–phosphorous	Stannous chloride method
Nitrite–nitrogen	Diazotization method
Sulphate	Turbidimetric method
Total hardness	EDTA titrimetric method
Calcium	EDTA titrimetric method
Magnesium	Calculation method
Chloride	Argentometric method
Alkalinity	Strong acid titration method
Total iron	Atomic absorption spectrophotometer
Manganese	Atomic absorption spectrophotometer

Table 2 Methods used to analyse the data

Methods	References
Box plot	Helsel and Hirsch (1992), Williamson et al. (1989)
Stability diagrams	Pitkänen et al. (2004), Singaraja et al. (2014)
Saturation index	Lloyd and Heathcote (1985)
Chloro-alkaline indices	Versluys (1916, 1931), Schoeller (1965)
Weathering and ion exchange plots	Cerling et al. (1989), Fisher and Mullican (1997), Datta and Tyagi (1996)
Piper diagram	Piper (1944), Saka et al. (2013)
Gibbs diagram	Gibbs (1970), Kumar et al. (2014)
Sodium percentage and Wilcox diagrams	Wilcox and et al. (1948), Wilcox (1955)
Sodium adsorption ratio	Cobbina et al. (2012), Tomar et al. (2012)
Residual sodium carbonate	Aghazadeh et al. (2010), Yidana (2010)
Magnesium hazard	Szabolcs and Darab (1964), (Singh et al. 2011)
Permeability index	Doneen (1964), Ishaku et al. (2011)

Table 3 Statistics of physico-chemical and hydrochemical parameters of groundwater sampled in Veua catchment, North-east Ghana

Parameter	Unit	Min	Max	Mean	σ	Acceptable limits (GSA/WHO)
$n = 61$						
Electrical conductivity (EC)	$\mu\text{S/cm}$	81.0	1291	26	187	–
Total dissolved solids (TDS)	mg/L	53.0	839	276	122	1000
pH	–	6.60	8.50	7.31	0.31	6.5–8.5
Dissolved oxygen (DO)	mg/L	2.32	6.32	4.55	0.92	–
Temperature	$^{\circ}\text{C}$	28.9	32.4	31.1	0.69	–
Salinity	ppt	0.03	0.61	0.15	0.09	–
Total alkalinity (TA)	mg/L	48.2	312	126	46.8	–
Total hardness (TH)	mg/L	50.8	272	115	47.3	500
Colour	Hz	2.50	20.0	4.55	2.83	–
Turbidity	NTU	<1.00	13.0	1.20	1.96	–
Total suspended solids (TSS)	mg/L	<1.00	28.0	1.96	4.90	–
Ca ²⁺	mg/L	12.3	76.2	24.8	11.4	–
Na ⁺	mg/L	7.50	52.0	20.1	8.93	–
Mg ²⁺	mg/L	2.50	37.9	12.8	6.66	–
Mn _{tot}	mg/L	<0.005	0.06	0.01	0.01	0.40
K ⁺	mg/L	1.10	43.5	3.99	5.34	–
NH ₄ ⁺	mg/L	<0.001	2.58	0.15	0.35	–
Fe _{tot}	mg/L	<0.01	1.28	0.17	0.26	0.30
HCO ₃ [–]	mg/L	58.8	381	157	56.7	–
Cl [–]	mg/L	2.00	93.3	14.4	15.0	250
SO ₄ ^{2–}	mg/L	<1.00	93.8	7.32	14.8	250
PO ₄ ^{3–}	mg/L	0.01	0.47	0.12	0.09	–
NO ₃ -N	mg/L	<0.001	0.07	0.02	0.02	50.0
NO ₂ -N	mg/L	<0.001	0.01	0.01	0.01	3.00

Table 4 Geological units, number of samples and predominant hydrochemical facies in the Veua catchment

Geological units	Number of groundwater samples	Facies
Granite	37	Ca–Mg–HCO ₃
Hornblende–biotite–granodiorite	11	Ca–Mg–HCO ₃ /Ca–Mg–Cl–SO ₄
Biotite gneiss	6	Ca–Mg–HCO ₃
Upper Birimian	4	Ca–Mg–HCO ₃
Migmatite and undifferentiated granite	3	Ca–Mg–HCO ₃

Among the four sampled waters having positive chloro-alkaline indices, three are from an area underlain by granite and only one from an area underlain by hornblende-granodiorite. Within the University of Lagos in Nigeria, Oduoya et al. (2013) observed that reverse ion exchange was the dominant process in the groundwater (52%), whereas normal ion exchange was noticed in 48% of the water samples. In their study, CAI values ranged between –0.86 and 5.5. In India, in an area characterized by crystalline rocks like this work, Jagadeshan et al. (2015) obtain results similar to this current research. In fact, they found that CAI-I and CAI-II vary with respect to time, but reverse ion

exchange was the dominant process in the groundwater, even though normal ion exchange was also identified in very few sampled wells.

Weathering process

The chemical composition of groundwater is mainly determined by the composition of the rock it is abstracted from, but other geochemical processes also play a key role in determining the amount of the chemical constituents in the groundwater (Razowska-Jaworek 2014). Weathering of rocks has been found to be one of the processes controlling

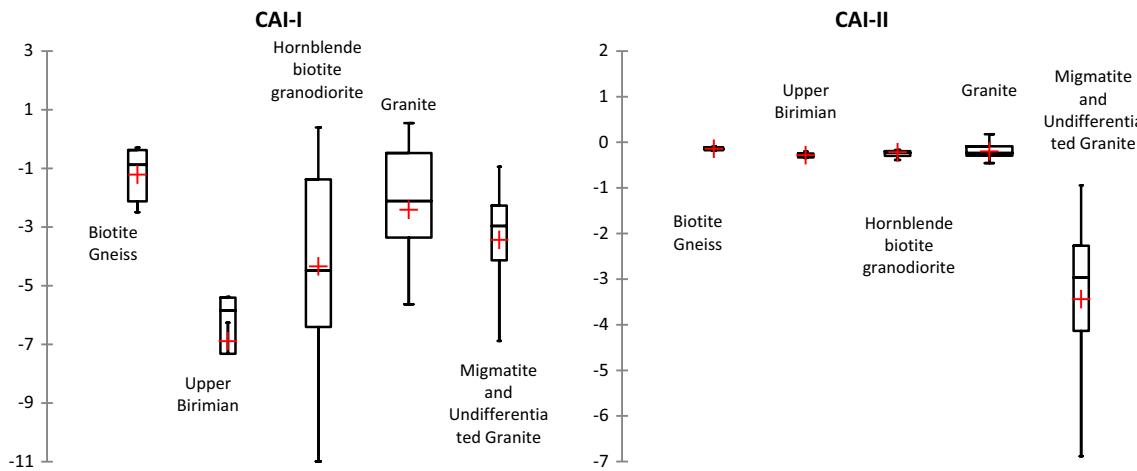


Fig. 2 Box plots of the chloro-alkaline indices of groundwater samples from different lithologies (Fig. 1) in the study area. The red crosses indicate average values; black horizontal line indicates median values

the geochemical cycling of elements (Berg 1932). Middelburg et al. (1988) stated that the rate and nature of chemical weathering which vary widely are controlled by many variables, including parent-rock type, topography, climate and biological activity. In order to comprehend the weathering process taking place in the study area, different methods were used: a plot of $Ca^{2+} + Mg^{2+}$ versus $SO_4^{2-} + HCO_3^-$; the use of stability field diagrams of the partial system $MgO-Na_2O-Al_2O_3-SiO_2-H_2O$; determining the relationship between $Ca^{2+} + Mg^{2+}-SO_4^{2-} + HCO_3^-$ and Na^+-Cl^- ; the use of a plot of sodium versus chloride; the use of the relationship between $Ca^{2+} + Mg^{2+}-SO_4^{2-} + HCO_3^-$ and Na^+-Cl^- ; and Ca^{2+}/Mg^{2+} ratio rock dissolution.

The plot of $Ca^{2+} + Mg^{2+}$ versus $SO_4^{2-} + HCO_3^-$ will be close to the $y = x$ line if the dissolution of calcite, dolomite and gypsum are the dominant reactions in a system. Ion exchange tends to shift the points to the right due to an excess of $SO_4^{2-} + HCO_3^-$ over $Ca^{2+} + Mg^{2+}$, whilst reverse ion exchange shifts the points to the left (Cerling et al. 1989; Fisher and Mullican 1997). In this scatter plot, the points above the equiline result from carbonate weathering [Eq. (3)], whereas those below the equiline depict a silicate weathering [Eq. (4)]. Those along the equiline represent water whose chemistry results from both carbonate and silicate weathering (Datta and Tyagi 1996). In this study, Fig. 3 shows that most of the groundwater samples in this study plot below and along the $y = x$ line due to excess of bicarbonate as only six (five of them are from granite rock aquifers) representing 10% were found to be above the equiline. Thus, compared to reverse ion exchange, ion exchange is the dominant process in the study area. It also indicates that silicate weathering is the main source of sodium and bicarbonate and it exerts major control on groundwater in this area (Rajmohan and Elango

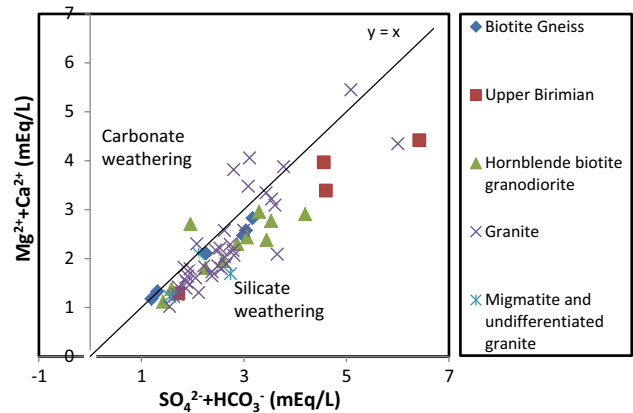


Fig. 3 Relation between $Ca + Mg$ and $SO_4 + HCO_3$

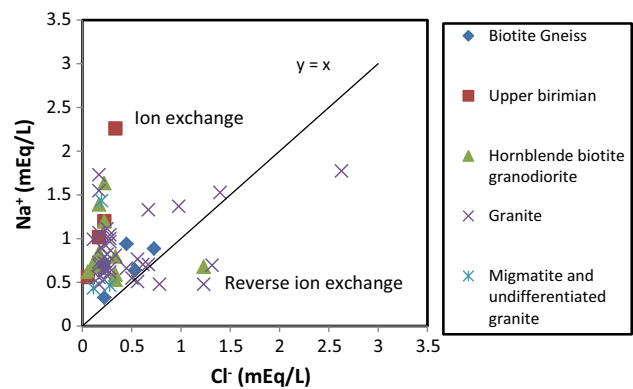


Fig. 4 Plot of sodium versus chloride

2004; Lakshmanan et al. 2003). This result is in agreement with the findings of Loh et al. (2012) for the entire basement aquifer of Northern Ghana, and Tay (2012) whose study area, the Savelugu–Nanton District, is situated at about 140 km from the current study area. It is also supported by the plot of Na^+ versus Cl^- (Fig. 4) showing that most of the

Fig. 5 Stability field diagrams of the partial system $\text{MgO}-\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ of the chemical composition of groundwater samples

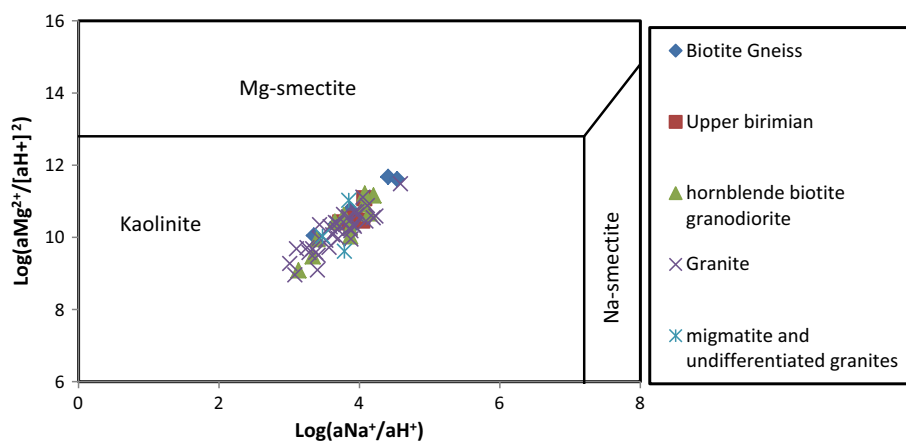
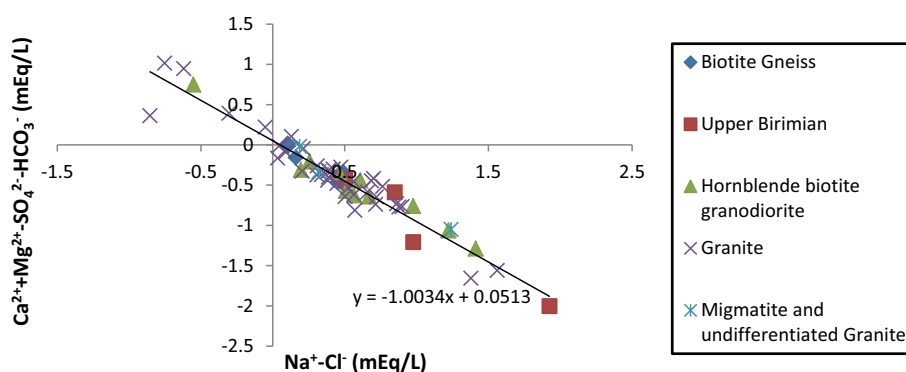
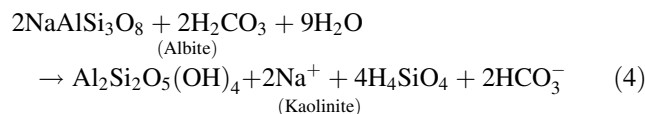
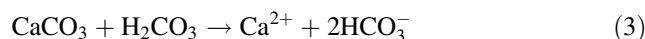


Fig. 6 Relation between $\text{Ca}^{2+} + \text{Mg}^{2+} - \text{SO}_4^{2-} - \text{HCO}_3^-$ and $\text{Na}^+ - \text{Cl}^-$



groundwater samples fall above the 1:1 trend line. In fact, Meybeck (1987) stated that Na^+/Cl^- ratio greater than one is due to Na released from a silicate weathering reaction whereas a ratio approximately equal to one denotes a release of sodium from halite dissolution. According to Stallard and Edmond (1983), the excess of Na^+ can be attributed to silicate weathering from feldspars or due to anthropogenic activities like the seepage of waste water. Rogers (1989) found that if silicate weathering is a probable source of sodium, HCO_3^- would be the most abundant anion as it is in this study. The result is consistent with the TDS values as they are all lower than 500 mg/L except for one sample. In fact, Hounslow (1995) stressed that the weathering process taking place in waters with $\text{TDS} < 500 \text{ mg/L}$ is silicate weathering. Figure 5 also shows that all the groundwater samples are in equilibrium with kaolinite supporting this aforementioned idea as silicate weathering produces kaolinite [Eq. (4)]. This result, in agreement with the work of Tay (2012), is in contrast with findings of Loh et al. (2012) who stressed that their sampled waters were in equilibrium with smectite. Like this work, their study areas are located in Northern Ghana. In India, precisely in the Kancheepuram District, characterized by both alluvium and weathered crystalline charnockite aquifer, Lakshmanan et al. (2003) observed that carbonate

weathering was the dominant process by using the scatter plot $\text{Ca}^{2+} + \text{Mg}^{2+}$ versus $\text{SO}_4^{2-} + \text{HCO}_3^-$.



The plot of $\text{Na}^+ - \text{Cl}^-$ versus $\text{Ca}^{2+} + \text{Mg}^{2+} - \text{SO}_4^{2-} - \text{HCO}_3^-$ (Fig. 6) shows that all groundwater samples define a straight line ($R^2 = 0.9207$) with a slope of -1.003 . The trend line of the scatter plot nearly passes through the origin ($y = -0.0513$), revealing that essentially all Na^+ , Ca^{2+} and Mg^{2+} participate in the ion exchange reaction. It also implies that ion exchange is a significant process controlling the water composition. In fact, $\text{Na}^+ - \text{Cl}^-$ refers to the amount of Na gained or lost relative to that provided by halite dissolution, whereas $\text{Ca}^{2+} + \text{Mg}^{2+} - \text{SO}_4^{2-} - \text{HCO}_3^-$ accounts for the amount of Ca^{2+} and Mg^{2+} gained or lost relative to that provided by gypsum, calcite and dolomite dissolution (Fisher and Mullican 1997). Thus, silicate weathering and ion exchange are probably the processes explaining the deficit of calcium (Ca^{2+}) plus magnesium (Mg^{2+}) compared with bicarbonate (HCO_3^-)

and they are responsible for the groundwater chemistry of the study area. A similar result was found by Anku et al. (2009) as well as Yidana and Yidana (2010). Using a plot of HCO_3^- against $(\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+})-\text{Cl}^-$, Yidana and Yidana (2010) also suggested that silicate mineral weathering does take place in their study area. In the Ga West Municipal area in Ghana underlain by the Cape Coast granite complex and rocks of the Togo formation, using the scatter plot Na^+-Cl^- versus $(\text{Ca}^{2+} + \text{Mg}^{2+}-\text{SO}_4^{2-}-\text{HCO}_3^-)$, Saka et al. (2013) obtain similar result like in this work and concluded that concentrations in groundwater are derived from interaction with aquifer materials.

The Gibbs diagram (Gibbs 1970) has been widely used to find which factor among rain, rock–water interaction and evaporation dominantly influences the water composition. The Gibbs diagram for cations and anions (Fig. 7) shows that all the samples plot in the rock–water interaction dominance field in this area (Gibbs 1970), confirming that the chemistry of groundwater in the study area is dominated by the interaction between water and aquifer material. This result corroborates the cation exchange and silicate weathering found as dominant processes controlling the chemical composition of the groundwater. In Ghana, using the Gibbs diagram, Banoeng-Yakubo et al. (2009); Yidana (2009); Ganyaglo et al. (2011); Kaka et al. (2011); Yidana et al. (2012); Salifu et al. (2013) and Boateng et al. (2016) concluded that rock–water interactions are the most important processes that control the hydrochemistry of groundwater in different areas underlain by various geological formation such as the Birimian Supergroup, the Voltaian Supergroup, the Togo, the Cape Coast granite complex, the Lower Birimian and the Buem. Therefore, results of these works are all in agreement with

this present study. In Nigeria, a similar result was obtained by Talabi and Tijani (2013) and Okiongbo and Douglas (2015) who concluded that the waters of their study areas located in the Precambrian Basement Complex of southwestern Nigeria and Yenagoa city in the Niger Delta alluvial plain in Southern Nigeria, respectively, have their chemistry controlled by the weathered materials derived from the underlying bedrocks. In India, studies in a similar geological environment suggest similar results (Lakshmanan et al. 2003; Rajmohan and Elango 2004).

Saturation index

The saturation index (SI) defines the saturation state of minerals in the water. It can provide significant information on the various hydrogeochemical processes controlling the groundwater chemistry (Belkhir et al. 2010; Kumar et al. 2015). Deutsch and Siegel (1997) stated that it is possible to predict the minerals that are responsible for controlling water quality from groundwater data without collecting the samples of the solid phase and analysing the mineralogy. When the $\text{SI} < 0$, the minerals will be dissolved and the water is said to be undersaturated with respect to the mineral. It may describe a short residence time or a lack of the considered mineral in the aquifer from which the water is discharging (Kortatsi 2006). On the other hand, when groundwater is supersaturated with respect to a mineral, the $\text{SI} > 0$, which means that the mineral will be precipitated. When SI is just equal to 0, it indicates that the water is saturated with respect to the mineral. However, due to uncertainty related to the minerals concentration, water with SI values comprised between -0.5 and 0.5 could be considered as saturated with respect to the mineral in question (Plummer et al. 1976). In this study, SI of calcite,

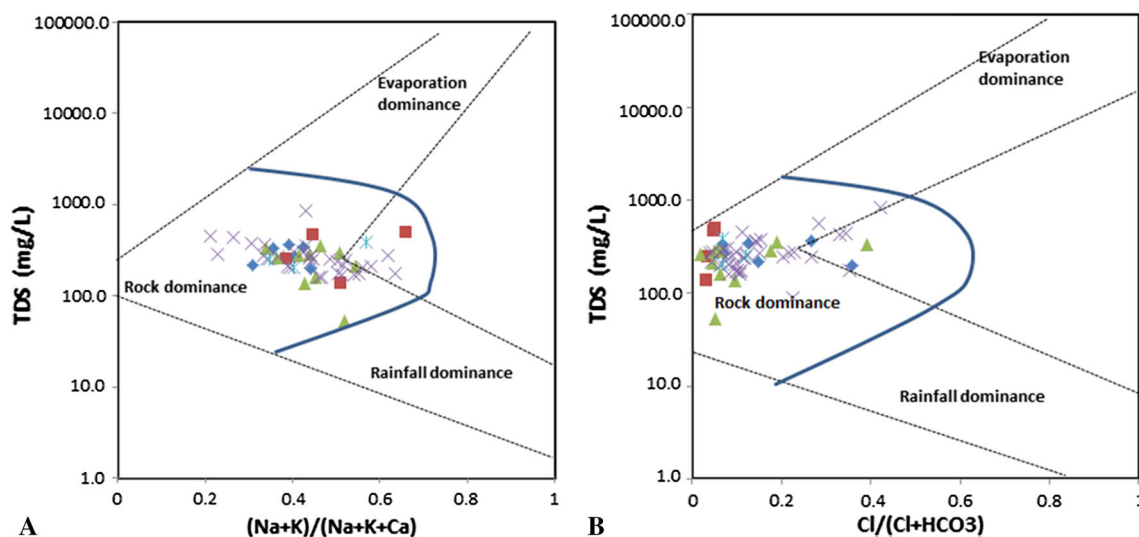


Fig. 7 Gibbs diagrams for cations (a) and anions (b) indicating rock–water interaction

Table 5 Summary of mineral saturation indices of groundwater in Veia catchment, North-east Ghana

Dolomite	-3.66	1.66	-1.31	88.5	11.5
Calcite	-1.42	1.07	-0.45	91.8	8.2
Aragonite	-1.56	0.92	-0.59	96.7	3.3
Anhydrite	-4.24	-1.66	-3.32	100	0
Gypsum	-4.04	-1.47	-3.13	100	0

dolomite, gypsum, anhydrite and aragonite were calculated with Diagrammes software for groundwater samples using Eq. (5) Lloyd and Heathcote (1985):

$$SI = \log \left(\frac{IAP}{K_s(T)} \right) \quad (5)$$

where IAP is the ion activity product of the solution and $K_s(T)$ is the equilibrium constant of the reaction considered at temperature T .

The SI was determined in order to estimate the extent to which the groundwater has equilibrated with these minerals and also to investigate the thermodynamic controls on the composition of the water. It can help in determining the rocks in contact with the water during its movement. Table 5 summarizing the saturation indices analysis shows that the groundwater samples analysed in this study are undersaturated with respect to gypsum and anhydrite. For aragonite, dolomite and calcite, only a few samples show oversaturation. Concerning aragonite, three samples show a clear saturation and about 41% have an index greater than -0.5 , thus around saturation. This suggests that the analysed groundwater generally has a low residence time in aquifers in the study area. The SI of dolomite and calcite differ from the findings of Yidana et al. (2008); Banoeng-Yakubo et al. (2009) and Nartey et al. (2012), while SI of Gypsum is in agreement with those obtained by Banoeng-Yakubo et al. (2009). Nartey et al. (2012) suggested that the majority of their samples from East Gonja in Northern Ghana were saturated with respect to dolomite and calcite; using an inverse modelling approach, Yidana et al. (2008) showed that

groundwater from the Afram Plains area was supersaturated with respect to calcite, aragonite and dolomite. The findings of Fianko et al. (2010) in the Accra Plains mostly underlain by Dahomeyan formation are similar to the results of this work, as all their samples were undersaturated with respect to gypsum and anhydrite; the majority of them were undersaturated with respect to dolomite, calcite and aragonite. In the Ankobra Basin mainly consisting of lower Proterozoic rocks divided into Birimian and Tarkwaian systems, Kortatsi (2007) found that all the groundwater samples were undersaturated with respect to all the carbonate minerals considered in this current study. The results of this work and previous works regarding gypsum corroborate findings of Kesse (1985), who highlighted the scarcity of gypsum deposits in Ghana. The plotting of the dolomite saturation index against calcite saturation index (Fig. 8) shows three groups of groundwaters in the study area with regard to their flow rate and the residence time. Groundwater of group A, which contains water saturated and oversaturated with respect to dolomite and calcite, has higher residence times with low flow velocity that characterizes aquifers with a low permeability, whereas group C has the lowest residence time with the highest flow velocity characterizing mostly unconfined aquifers. Group B is an intermediary group between the two aforementioned groups. The Ca^{2+}/Mg^{2+} plotted in Fig. 9 shows that many of the groundwater samples had more dissolved calcite than dolomite.

The meteoric genesis index (MGI) [Eq. (6)] that helps in determining whether groundwater source is of deep meteoric water aquifers ($MGI < 1$) or shallow meteoric water percolation type ($MGI > 1$) (Soltan 1998) was also calculated. Values of the MGI were only able to be calculated for 48 of the 61 samples because SO_4^{2-} concentration should not be equal to zeros (0). MGI of 10 samples was found to be lower than 1, meaning 16% of the 61 samples belong to deep meteoric water aquifers whereas only 84% are from shallow meteoric water aquifers.

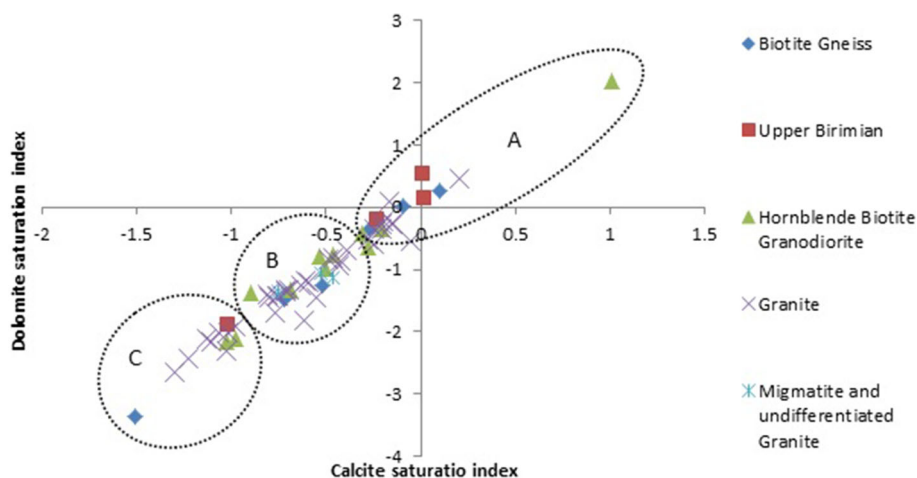
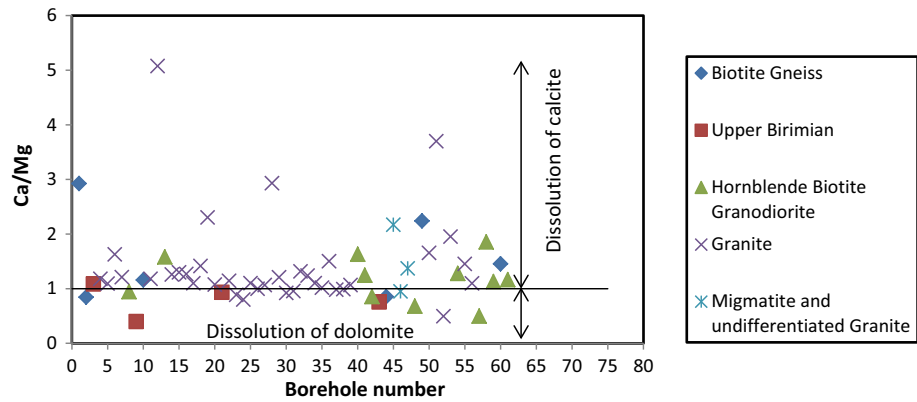
Fig. 8 DSI/CSI of groundwater in Veia catchment, North-east Ghana

Fig. 9 Ca/Mg ratio rock dissolution of groundwater in the Veia catchment, North-east Ghana



$$MGI = \frac{K^+ + Na^+ - Cl^-}{SO_4^{2-}} \quad (6)$$

where elements are expressed in meq/L.

Drinking water quality

Assessment of the quality of water for drinking was based on the water quality guidelines of the World Health Organization—(WHO 2011) and the Ghana Water Standards—GWS (Ghana Standards Authority 2013). The GWS was developed from the WHO guidelines. Only results with regard to TDS, turbidity, pH, total hardness and major ions are discussed in detail in this study. For the estimation of the means and standard deviations, parameter with values below detection limit was replaced by the detection limit value times 0.55 as suggested by Sanford et al. (1993).

Total dissolved solids (TDS) and turbidity

TDS is an indicator of the mineralization of water. About 95% of it is represented by major ions in natural water (Clark 2015). According to WHO (2011), the palatability of water with a TDS level of less than 600 mg/L is considered to be good and becomes significantly and increasingly unpalatable when TDS is greater than 1000 mg/L. Because of excessive scaling in water pipes, heaters, boilers and household appliances, high levels of TDS may also be objectionable to consumers. However, no health-based guideline value regarding TDS has been proposed in the WHO guidelines. The study results show that TDS in the groundwater samples varied from 53 to 839 mg/L, with average of 276 mg/L. This means that all the sampled groundwater are fresh (TDS < 1000) according to the TDS classification by Freeze and Cherry (1979). Based on the aforementioned guideline value, 60 out of 61 samples (98%) met the drinking water quality standard with regards to TDS. The variations in the TDS values may be due to

differences in the solubility of minerals (WHO 2011). As a low-TDS depicts either slow decomposition of rocks or short residence time of the groundwater, this result corroborates the short residence time, mostly characterizing the shallow aquifer as earlier suggested by the saturation index study. The TDS contents are in agreement with those obtained by Anku et al. (2009) and Nartey et al. (2012) in areas underlain by the crystalline basement rock and Voltaian rocks (sandstone, shale, mudstone, sand), respectively, in Northern Ghana. These results are very low compared to TDS values between 62 and 11,900 mg/L found in the Savelugu–Nanton District area, in Northern Ghana, with average and median values of 942 and 405, respectively (Tay 2012).

Turbidity values ranged from 0 to 13 NTU, with two samples exceeding 5 NTU. This may make the water unsuitable for potable use even though there is no health-based guideline value for turbidity in the WHO guidelines. Also 19 out of 61 samples (31%) may be difficult to disinfect in case of need of disinfection. In fact, the WHO guidelines suggest that, ideally, water should have turbidity lower than 0.1 NTU for an effective disinfection.

Total hardness

Total hardness accounts mainly for the magnesium and calcium contents naturally found in water. No health-based guideline value is proposed for hardness in drinking water by WHO (2011). However, as hardness has an impact on water supply distribution systems, it is important to know the values. Usually, water with hardness above 200 mg/L tends to cause scale deposition in the treatment works, distribution system and pipe work and tanks within buildings, depending on the interaction of other factors, such as pH and alkalinity. Water with a hardness of less than 100 mg/L (soft water) may have more corrosive effects for water pipes (Sawyer and McCarty 1967; WHO 2011).

In this study, total hardness as calcium carbonate ranged from 50.8 to 272 mg/L, with mean value of 115 mg/L. The

classification of groundwater based on total hardness shown in Table 6 indicates that the groundwater in the Vea area is mostly moderately hard, with about 60.6% of the samples falling in that category. About 19.7% of the samples can be described as soft water, while the other 19.7% can be described as hard water. Globally, total alkalinity is higher than total hardness, suggesting that hardness of water is derived mainly from carbonate sources as stressed by Cobbina et al. (2012) who obtain total hardness ranging from 54.0 to 642 mg/L with a mean value of 178 in Sawla-Tuna-Kalba District in Northern Ghana. This result is similar to the findings of Anku et al. (2009) who obtain hardness ranging from 20.43 to 495.11 mg/L with 52% of the samples falling in the moderately hard class. In an area underlain by crystalline Basement Complex rocks in Nigeria, thus similar to this work, Ifabiya (2008) obtained a mean value of total hardness of 236.04 mg/L, while Alagbe (2002) reports very low hardness ranging from 0.4 to 42.2 mg/L with an average value of 5.7 mg/L. In the crystalline basement aquifer of Côte d'Ivoire, Lasm et al. (2011) obtained total hardness ranging from 20 to 500 mg/L with a mean value of 116 mg/L. In Kara region located in Northern Togo underlain by crystalline basement rock, Zoulgami et al. (2015) obtained total hardness ranging from 10 to 340 mg/L with a mean value of 147 mg/L, which is greater than the one of this study. Regarding the surface water, all the samples analysed fall in the soft water class, with an average hardness of 38.8 mg/L. Thus, 19.7% of the groundwater and all of the surface water appear to potentially have corrosive effect on the pipes or distribution system.

Major ions

The range of the major ions concentrations in groundwater samples is reported in Table 3. The mean concentration values of the cations are in the order $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$, whereas that for anions is $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^-$. This result is similar to the findings of Anku et al. (2009); Yidana and Yidana (2010) and Boateng et al. (2016); thus, it may suggest that this water type is one of the predominant water types in the crystalline basement aquifer in Ghana and especially in Northern Ghana in general. Tay (2012) obtained similar results in Savelugu–Nanton District in Northern Ghana and stressed that the high bicarbonate contents support the idea of

occurrence of silicate weathering process in the area. HCO_3^- is found to be the dominant ion in the majority of works done up to now in the different geological formations in Ghana (Anku et al. 2009; Yidana and Yidana 2010; Fianko et al. 2010; Ganyaglo et al. 2011; Boateng et al. 2016). However, the order of classification of cations with respect to their contents varies from an area to another (e.g. Apambire et al. 1997). The hydrochemical water type of groundwater and surface water samples is represented in the Piper diagram (Fig. 10). The diagram shows that bicarbonate is the dominant anion. For the cations, there is no dominant element for all the samples except one in which calcium is dominant. Except one sample with Ca–Mg–Cl– SO_4 water type, the chemical composition of water (groundwater and surface) in the study area is mainly Ca–Mg– HCO_3 water type, regardless of the geology. Chloride concentrations show an outlier (93.3 mg/L) for borehole “Bongo 3” situated in Bongo town which may come from anthropogenic sources. However, this value is below the standard limit which is 250 mg/L.

All the parameters analysed are within the range of the GSA/WHO water quality guidelines and therefore can be said to be suitable for drinking. This can be explained by the fact that in the area and elsewhere in Ghana, groundwater accessed via boreholes are first analysed for drinking water quality before they are equipped with pumps for use. For that matter, only boreholes with good quality water are in use.

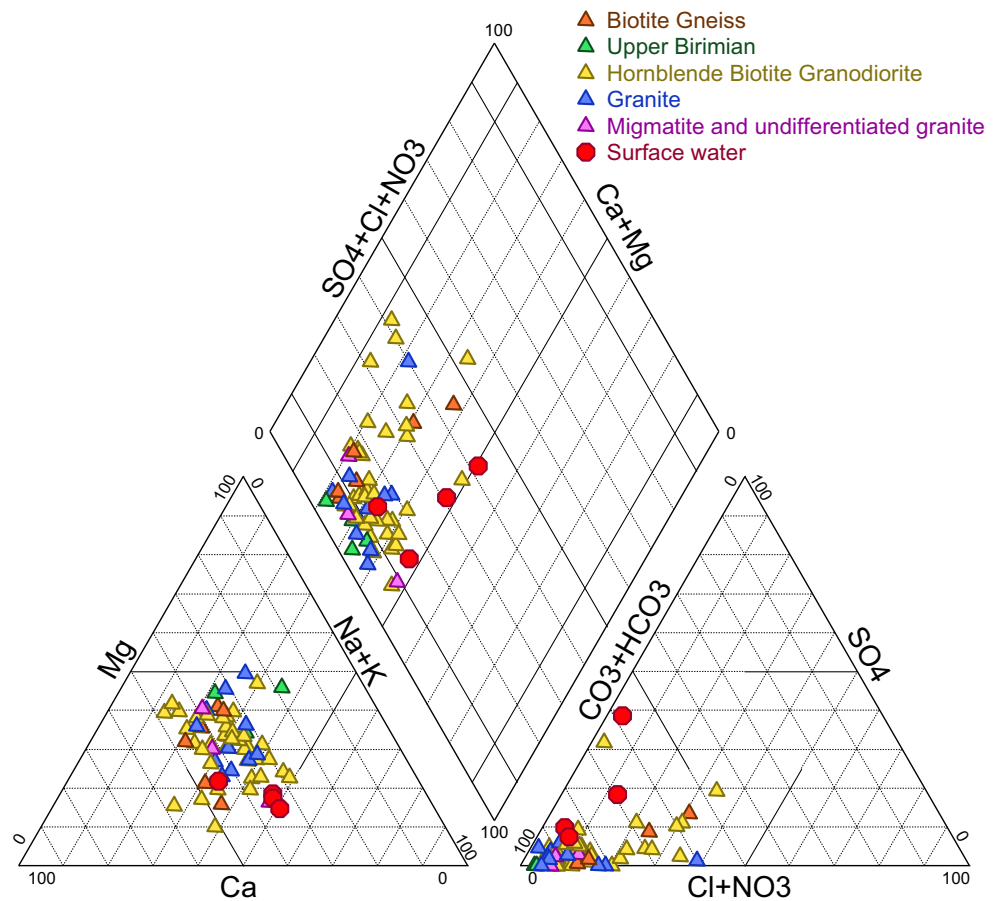
Usability of the water for irrigation

Irrigation water can induce some hydrochemical changes by the presence of high concentrations of a particular salt or due to the presence of toxic constituents in groundwater (Alam 2014). These changes can lead to adverse impacts on plants and crop growth. Sodium is well known as one of the groundwater constituents that impair the groundwater quality for irrigation purposes. Karanth (1987) found that the Na percentage exceeding more than 50% of the total cations present in groundwater leads to reverse ion exchange reactions, causing deflocculation and reducing the fertility and permeability of the soils. But this reverse ion exchange issue is reduced if the amount of calcium plus magnesium is higher than the sodium. Therefore, the concentration of constituents in irrigation water can have a harmful effect on soil, plant growth and yield (Rusan et al. 2007).

Table 6 Total hardness as CaCO_3 for groundwater in the Vea area, North-east Ghana

Total hardness as CaCO_3 (mg/L)	Water class	Number of samples in each class
0–75	Soft	12 (19.7%)
75–150	Moderately hard	37 (60.6%)
150–300	Hard	12 (19.7%)

Fig. 10 Piper diagram of groundwater samples (*triangle*) and surface water samples from Vea catchment (North-east Ghana)



Sodium percentage, sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) are widely used to determine the suitability of water for irrigation purposes. In this study, the sodium absorption ratio (SAR), sodium percentage, the residual sodium carbonate (RSC), magnesium hazard (MH) and the permeability index were calculated to determine the usability of the water for irrigation.

Sodium adsorption ratio (SAR)

The SAR as described in Eq. (7) is used to determine whether the sodium content in the irrigation water will trigger reverse ion exchange or not. The higher the SAR, the less suitable the water for irrigation. In fact, irrigation water with excess sodium can significantly reduce crop productivity by affecting soil structure, soil aeration, flow rate, permeability, infiltration, etc. (Cobbina et al. 2012).

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \tag{7}$$

where elements are expressed in meq/L.

The plot of conductivity versus SAR in the Wilcox Log diagram shows one group with respect to the SAR and

three groups to the conductivity (Fig. 11). In this study, all the samples have low SAR values, ranging from 0.346 to 1.693 meq/L, and therefore are suitable for irrigation. In regard to EC, with the exception of two samples that belong to Class C3, all the samples belong to Class C1 and C2, meaning that the electrical conductivity in the study area is lower than 750 μ S/cm and the salinity ranges from low to medium salinity. Based on EC and SAR, three classes of irrigation water were found. Namely, C1–S1, C2–S1 and C3–S1 where the majority of samples belong to the second class (C2–S1). The results show an increase of electrical conductivity in surface water as you move from upstream to downstream, which implies there is a successive mineralization of surface water along the flow path.

All the samples are classified as “excellent” as the SAR values are less than 10 meq/L. In fact, water with SAR value up to 10 meq/L, from 10 to 18 meq/L, from 18 to 26 meq/L and greater than 26 meq/L is classified as excellent, good, fair and poor, respectively (Raju 2006; Sadashivaiah et al. 2008). The result is in agreement with findings of Salifu et al. (2015). Analysis based on groundwater and surface water samples from the Birimian and Cape Coast granitoid complex formations in the Densu River Basin of Ghana shows that samples from Birimian

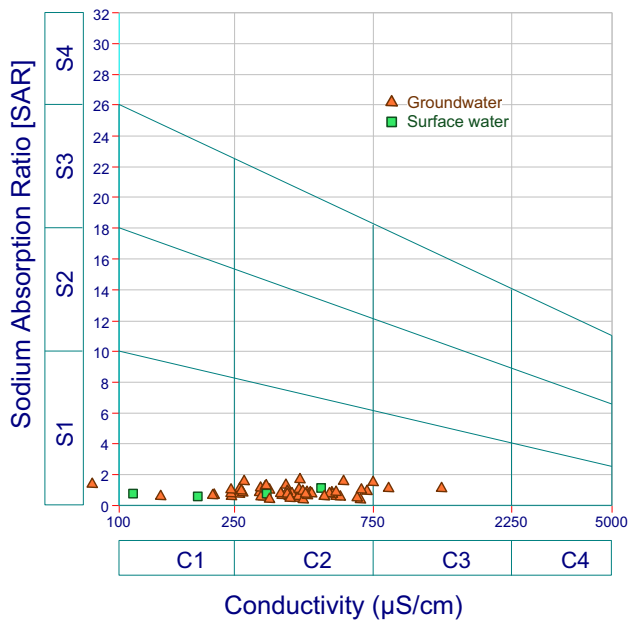


Fig. 11 Wilcox Log diagram of groundwater in the Veia area, North-east Ghana

and surface water are similar to samples of this current work as all of them plot in the excellent water category. However, the SAR values, ranging from 2.62 to 6.7 meq/L, are higher than those found in this current work, whose SAR values range from 0.346 to 1.693 meq/L. Regarding the samples from the Cape Coast granitoid, only 73% fall in the excellent category while 20 and 7% fall in the good and doubtful category, respectively (Gibrilla et al. 2010). Regarding the Birimian formation, findings of Yidana et al. (2012) corroborate results of Gibrilla et al. (2010) and those of this current work. Although results of this current work are globally similar to the findings of Ganyaglo et al. (2011), whose study area is underlain by four main geological formations (the Upper Voltaian, the Togo, the Cape Coast granite complex and Lower Birimian), some differences should be highlighted. Two of their samples fell in classes C3–S2 and C3–S2; C1–S1 and C3–S1 irrigation water classes were well represented while they are negligible in this current study. Using the Wilcox Log diagram, Yidana (2009) found that more than 90% of their surface water from different basins plots within the low sodicity and low to medium salinity fields. Similarly, the four surface water samples of this current work fall within this two classes.

Sodium percentage

Sodium content is also expressed in terms of percentage sodium calculated using Eq. (8).

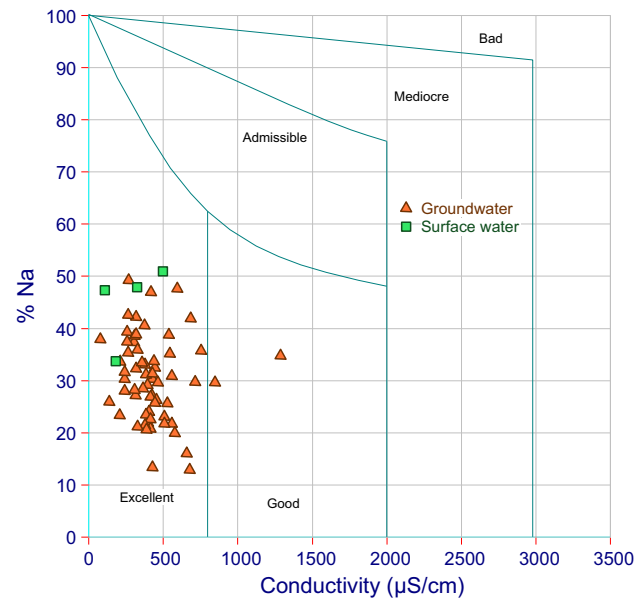


Fig. 12 Rating of groundwater samples based on electrical conductivity and per cent sodium in Veia area, North-east Ghana

$$\text{Na}\% = \frac{(\text{Na} + \text{K}) \times 100}{\text{Ca} + \text{Mg} + \text{Na} + \text{K}} \text{ (meq/L)} \quad (8)$$

The percentage of sodium in water in the study area ranges from 12.8 to 49.0%, with an average of 30.3% for groundwater and from 33.6 to 50.7%, with an average of 44.8% for surface water. The plot of sodium percentage with respect to EC in the Wilcox diagram (Fig. 12) has revealed that out of 61 samples, 59 fall under excellent irrigation water quality class and the remaining two samples fall in the good irrigation water class. Based only on the sodium percentage (Wilcox 1955), 82% of the samples are classified in the good water category, while 6.6 and 11.4% fall in the excellent and permissible category, respectively. Using the same classification, Ma (2016) found that 40% of the samples belong to the excellent category, with 31, 25 and 4% belonging to the good, permissible and doubtful categories, respectively. Using the Wilcox diagram (Wilcox 1955) for irrigation water classification, he observed that about 62.5% of the groundwater samples plotted in the excellent to good irrigation water category, with 31.25% of the groundwater samples falling in the good to permissible water classes and 3% of the samples were classified as unsuitable for irrigation. Classification of water samples from Densu River Basin of Ghana suggested that 100% of the surface water and 83% of the Birimian were excellent to good while 16% of the Birimian samples fell in the permissible to doubtful group. Regarding the Cape Coast granitoid, it showed a wide variation in the Wilcox diagram as 53% of the samples fell in the excellent to good field, while 33% plotted in the field

permissible to doubtful and 13% were doubtful to unsuitable (Gibrilla et al. 2010). His results deviate from the findings of this current work. The work done by Edjah et al. (2015) in the Ellembele District in Ghana mainly underlain by Birimian rocks showed that 38.46% of the hand-dug wells and 60% of the boreholes fell in the field of excellent to good while the permissible to doubtful category was represented by 30.77% of the hand-dug wells and 34.44% of the boreholes. 30.77% of the hand-dug wells and 5.56% of the boreholes plotted on the boundary between excellent to good and permissible to doubtful.

Residual sodium carbonate (RSC)

The RSC index determines the hazardous effect of carbonate and bicarbonate on the quality of water for agricultural purpose (Aghazadeh et al. 2010). RSC is the difference between the bicarbonate ions and those of calcium and magnesium, and it is expressed in meq/L as shown by Eq. (9). When the RSC value is lower than 1.25 meq/L, the water is considered to be of good quality, while if the RSC value exceeds 2.5 meq/L, the water is considered harmful. When RSC is between 1.25 and 2.5 meq/L, the water is termed marginal and it could be used with precautions such as good irrigation management techniques and soil salinity monitored by laboratory analysis (Richards 1954).

$$RSC = (HCO_3^- + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \text{ (meq/L)} \quad (9)$$

The use of RSC requires the content of HCO_3^- , CO_3 , Ca and Mg. In this study, the content of CO_3^{2-} was not analysed but because the pH of the samples ranges from 6.83 to 8.5, CO_3 content is negligible compared with HCO_3^- (Chapman 1996), so $HCO_3^- + CO_3^{2-} = HCO_3^-$. The values of RSC of all the samples analysed in this study ranged from -1.84 to 1.83 meq/L and only two of them have values higher than 1.25 meq/L. Thus, they are suitable for irrigation. Anku et al. (2009), whose study area encompasses this study area, found that 68% of their samples had RSC values below 1.25 meq/L; 27% in the marginal range of 1.25–2.5 meq/L; and the remaining 5% was not suitable for irrigation. Analysis of water from some Voltaian and Birimian aquifers in Northern Ghana revealed that 34% of the samples have RSC values higher than 2.50 meq/L suggesting that they are not suitable for irrigation, while 42% were excellent as their RSC values were lower than 1.25 meq/L. 24% of the samples were classified in the intermediate group (Yidana et al. 2012). Based on the RSC, Kaka et al. (2011) found that 44% of the samples were doubtful, while 32% having RSC values above 2.50 mg/L were not suitable for irrigation and only 24% were good as their RSC values were less than 1.25 meq/L. As for Salifu et al. (2015), they concluded that 56% of the

samples were safe for irrigation, while 34.78% were marginal, and the remaining 8.7% were unsuitable for irrigation purpose. Thus, regarding the RSC these aforementioned works show quite different results compared with the current study.

Magnesium hazard

Generally, Ca^{2+} and Mg^{2+} maintain a state of equilibrium in most waters, although in soil systems, Ca^{2+} and Mg^{2+} do not behave equally and Mg^{2+} deteriorates soil structure particularly when waters are sodium dominated and highly saline (Ravikumar et al. 2011). According to Batayneh et al. (2012), water with calcium and magnesium concentration of higher than 100 mg/L and 50 mg/L, respectively, is not suitable for irrigation purposes. In the study area, the calcium contents range from 12.3 to 76.2 mg/L, whereas magnesium contents range from 2.5 to 37.9 mg/L. Thus, considering this criterion, all the samples from the study area are suitable for irrigation. The residual Mg/Ca ratio (Nazzal et al. 2014) and the method established by Szabolcs and Darab (1964) can be used to estimate the magnesium hazard (MH) for irrigation. In this study, we used the latter which is depicted in Eq. 10:

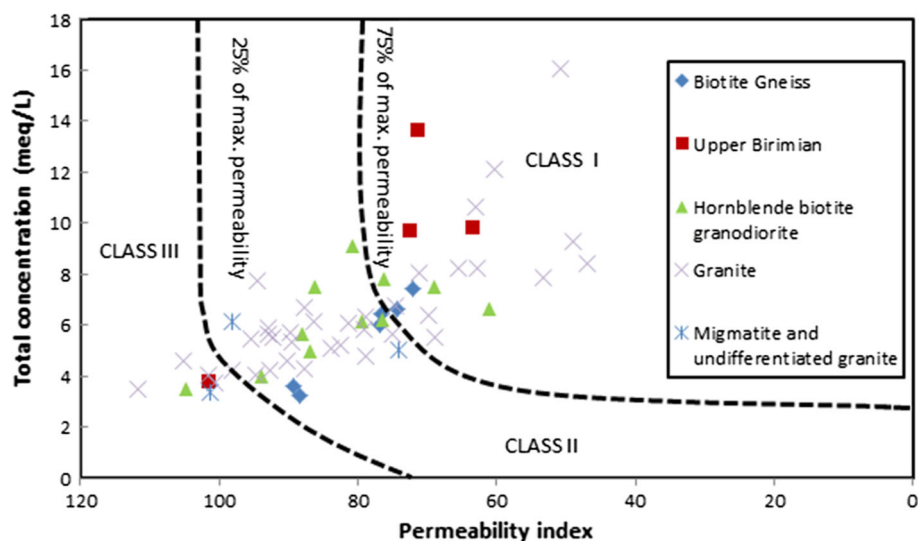
$$MH = \frac{Mg}{Mg + Ca} \times 100 \text{ (meq/L)} \quad (10)$$

According to this indicator, water with a MH value greater than 50% is not suitable for irrigation (Raihan and Alam 2008). The MH values obtained in this study ranges from 16.46 to 71.45% and 17 out of the 61 groundwater samples analysed (representing 27.9%) have MH greater than 50%, which makes them inappropriate for irrigation. Salifu et al. (2015) found in Upper West Region of Ghana that the MH of all the samples analysed in their study were well below 50%. In the Manya Krobo area, Kaka et al. (2011) reported that the MH values of 56% of the samples were below 50%, while 44% of the samples was found to be unsuitable with MH above 50%.

Permeability index (PI)

Because the permeability of soil is influenced by sodium, calcium, and magnesium and bicarbonate contents in soil as well as by long-term use of irrigation water, Doneen (1964) established a permeability index, used as an irrigation water quality indicator, following formula of Eq. 11. In this study, the suitability of groundwater for irrigation based on PI indicator was determined. This criterion categorized water in three classes. Class I and Class II are categorized as good for irrigation, while Class III water is unsuitable for irrigation.

Fig. 13 USSL Classification of irrigation water in Veia (North-east Ghana), based on permeability index



$$PI = \frac{Na + \sqrt{HCO_3}}{Ca + Mg + Na} \text{ (meq/L)} \quad (11)$$

In the study area, 7 out of the 61 samples (11.5%) fall in Class III and the remaining 88.5% fall in Class I and II (Fig. 13). It means that based on this indicator, 11.5% of the samples are not suitable for irrigation, whereas the remaining 88.5% are suitable. Based on Doneen's chart and the USSL diagram, Salifu et al. (2015) found PI varying from 65.09 to 99.39 and 96.65% of the samples fell in Class I while 4.35% was categorized in Class II.

Kaka et al. (2011) mentioned that PI of samples collected from the Manya Krobo area during the post-monsoon season of September 2009 ranged from 17.15 to 77.14%. Additionally, they suggested that all the samples fell under Classes I and II of Doneen's chart. As for Salifu et al. (2015), they found all their samples are Class I samples except for one which is Class II, representing 96.65 and 4.35%, respectively. Results of this current work slightly deviate from those of Kaka et al. (2011) and Salifu et al. (2015) but are close to those of Gibrilla et al. (2010) regarding samples from the Cape Coast granitoid formation. In fact, Gibrilla et al. (2010) mentioned that 87.5% of the Cape Coast granitoid belongs to Class I while the remaining 12.5% belong to Class II group; all the samples from Birimian formation and surface water fell in Class I.

Conclusions

The aim of this work was to identify the geochemical processes influencing water quality and the suitability of surface and groundwater for agricultural and domestic uses in the area. The results show that cation exchange and silicate weathering are the dominant processes controlling

the chemical composition of the groundwater in the studied area. The meteoric genesis index shows that the majority of samples belong to shallow meteoric water percolation. All the groundwaters were found to be fresh, based on the TDS values. The results obtained from the 65 water samples also show that water type in the study area is mainly Ca–Mg–HCO₃. According to the observations and calculations conducted in this study, groundwater in the area is in large parts suitable for irrigation and agricultural purposes, regardless of aquifer lithology. No pollution due to anthropogenic activities was detected. Surface water is also found to be suitable for irrigation. This is the first study to really address the hydrogeochemical processes influencing this area's water quality. Further studies covering heavy metals, other inorganic and organic trace substances as well as microbiological parameters are required to fully characterize groundwater hydrogeochemistry and usability, ideally also taking seasonal effects into account.

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