Hydrochemical Evolution of Ground and Surface Water within the Amansie and Adansi Districts of the Ashanti Region, Ghana

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Abstract

Source–rock deductions of major ions and saturation states of minerals in groundwater were employed to determine the origin of dissolved ions and the thermodynamic controls on the groundwater composition respectively in groundwater within the Amansie and Adansi Districts. The main objective of this study is to characterize groundwater and delineate soil-water-rock interactions responsible for the chemical evolution of groundwater within the districts. Fifty-nine boreholes, twelve wells and two stream samples were collected for quality assessment. Results show that, silicate weathering and ion-exchange reactions are the major processes influencing groundwater chemistry within the Districts. Results also show that groundwater within the districts is strongly to moderately acidic as, 62 % of the groundwaters has pH that range 3.6 - 6.0. Acidity in ground and surface water within the districts is attributable predominantly to natural processes than mining activities; however, the groundwaters still have the potential to neutralize acids due to the presence of silicates/aluminosilicates. The waters are fresh (EC< 500 μS/cm) with conductivity values which ranged 22.8 – 473 μS/cm, and a mean value of 172.9 μS/cm. TDS of the groundwaters ranged 14.9 – 309.8 mg/L with a mean value of 112.6 mg/L. The relative abundance of cations and anions are in the order: $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$ respectively. The states of saturation of the groundwaters with respect to major minerals using hydrogeochemical transport model Phreeqc for Windows suggest that, anhydrite and gypsum are subsaturated and indicates that, groundwater within the districts originates from a formation with insufficient amount of these minerals in solution or short residence time of these minerals with groundwater within the districts. Two principal hydrochemical water types; $Ca-Mg-HCO_3$ and Na–Cl have been delineated, with $Ca-Mg-SO_4$, $Na-Mg-Ca-HCO_3$ and Na- $Cl-SO_4$ as minor water types. Groundwater within the districts principally evolves from fresh $Ca–Mg–HCO_3$ type water into $Na–HCO_3$ type water into $Ca–Mg–Cl$ type water into Na–Cl type water along its flow path due to ion-exchange reactions and therefore, largely characterized by recharge processes through mixing with waters of geochemically different ionic signatures.

Introduction

As water needs for the various water uses such as industrial, agricultural, domestic and recreational use by human population throughout the world is increasingly becoming threatened due to the contamination of surface water bodies through anthropogenic activities; groundwater has become very vital to water budgets throughout the world especially for potable uses. This is because groundwater is well suited to meet the dispersed demand inherent in settlement patterns of rural populations and therefore, plays a very significant role as source of water for supply systems throughout the world especially in Africa (WRC 2011). Ghana, a coastal country in the west coast of Africa is no exception.

Groundwater supply systems development and management as rural water supply is relatively cheaper compared to surface water supply systems (WRC 2011). In view of the problems associated with alternate sources of water and the fact that groundwater is often considered one of the most economically feasible sources of potable water supply, groundwater resources are being increasingly utilized in Ghana in order to meet the upsurge of water supply needs (WRC 2011).

In the past decades, groundwater was considered to be of the best quality due to the purification properties of soil during water-rock-soil interactions. However, the study of hydrogeochemical processes involving water-soil- rock interactions have shown that, source

contamination of groundwater could be due to natural geochemical and biochemical processes besides anthropogenic activities (Tay 2012). Due to the intricacy of the chemical evolution of groundwater along its flow path and the significant water chemistry information in a region, it is difficult for hydrochemists and geochemists to interpret water quality data from a region (Abdullah 2013). However, several data analysis methods such as Piper (1944) trilinear plot, Chadha (1999) plot and Durov (1948) diagram have been proposed to simplify the interpretations of water quality data by graphically classifying groundwater using dissolved ion composition (Abdullah 2013).

Within the framework of quality groundwater supply for sustainable human health, water quality monitoring is key and a very important tool for sustainable development and provides useful information for the management of groundwater (Srinivasamoorthy *et al.* 2009). The quality of groundwater is influenced by physical, chemical and biological constituents and also depends on the composition of recharge water, the interaction between the water and the soil, the soil–gas, the rock with which it comes into contact in the unsaturated zone, and the residence time and reactions that take place within the aquifer (Freeze and Cherry 1979; Hem 1989; Fetter 1990; Appelo and Postma, 1999).

Various factors govern the chemical composition of groundwater and each groundwater system in a region is characterized by a unique chemistry owing to the chemical changes in meteoric water recharging its aquifer system (Hem 1989). According to Hounslow (1995); Andre et al. (2005), the changes in the chemical quality of meteoric water is determined by the geological make-up, composition of infiltrating rainwater, mineralogical constitution of the aquifer, duration of water-soil-rock interaction, dissolution and precipitation of mineral species and anthropogenic influence. Compositional relationships amongst dissolved species in groundwater can show the origin of solutes and the hydrogeochemical processes that produced the observed water chemistry (Jalali 2007; Singh *et al.* 2008). Groundwater quality is indicative of the mineralogical composition of the rocks with which the water is in contact (Hounslow 1995). The composition of groundwater gradually changes as it travels slowly through the subsurface (Hounslow 1995).This reflects the increasing saturation of some ions or the end products of various rock-water interactions (Hounslow 1995). The major ion chemistry of groundwater is a robust tool in the determination of the origin of solutes and for describing water evolution as a result of rock-water-soil interactions leading to the dissolution of minerals, weathering and ion-exchange reactions (Elliot *et al.* 1999; Edmunds and Smedley 2000; Jeelani and Shah 2006).

Like all other rural communities in Ghana, surface and groundwater serves as sources of potable water supply to the Amansie and Adansi Districts in the Ashanti Region of Ghana (Tay *et al.* 2006). However, the districts are located within the Ashanti Gold Belt, where both "large-scale" and "small-scale" and *galamsey* activities using chemicals such as arsenic (As) and mercury (Hg) to recover gold takes place. In view of this, mining activities over the years have impacted on water resources within the district through poor management of effluents and tailings from processing plants, exposure of mined surfaces leading to acid mine drainage, and

from the use of mercury by the "small-scale" alluvial workings (Tay *et al*. 2014). Often, streams or rivers that had served as sources of drinking water to the communities at one time have become contaminated via mining (Tay *et al*.2006). Besides gold mining, other economic activities in these communities are farming and petty trading. Many of the population in these communities use ground and surface waters as sources of water for domestic uses. Notwithstanding, the chemicals used in mining and agricultural activities are likely to infiltrate into groundwater as well as transported into surface water during rainfall (Tay *et al*. 2006). In mining areas, natural geochemical and biochemical processes may take place in outcrops which are exposed resulting in further decreased pH of the water in contact subsequently, increasing the solubility of some toxic metals (Tay *et al*. 2006). The cumulative effect of the decreased pH and increased solubility of toxic metals in these water resources is the rendering of these water sources unusable (Tay *et al*. 2006).

Thus, it is imperative to categorize the different sources of potable water within the Amansie and Adansi districts in order to determine the factors influencing the quality in relation to the hydrochemistry or mining/farming activity. Literature indicates that some studies have previously been conducted on the quality of water within the Ashanti gold belt. These studies include; Sarkodie *et al*.(1997); Amonoo-Niezer & Amenkor (1993); Golow *et al*., (1996); Carboo & Sarfo-Armah (1997); Tay *et al*,(2006). These studies however, failed to employ data analysis methods as proposed by Piper (1944) trilinear plot, Chadha (1999) plot and Durov (1948) diagram etc to simplify the interpretations of water quality data.

The objectives of the this paper is to appraise the hydrochemical processes influencing groundwater and evaluate the evolutionary trend within some selected communities within the Amensie and Adansi Districts of the Ashanti Region using proposed data analysis methods in order to delineate the processes that control groundwater chemistry within the districts.

Materials and methods

Study area

The Amansie and Adansi Districts lies between 6° 00" and 6° 30"N and 1° 15" and 1° 60"W (Figure 1).The area falls within the Ashanti Gold Belt, the most famous of all gold belts in Ghana and extends over 200 km from Akanko, near the coast, through Prestea and Obuasi to Konongo within the central parts of the country (Tay *et al*. 2006).

Climate and Vegetation

According to Dickson and Benneh (1980), the climate is within the wet semi-equatorial climatic zone of Ghana. Two rainy seasons spans the districts, with the major rainy season between May and July, while, the minor rainy season is between September and October. The area is fairly humid with an average monthly relative humidity of 75 - 80 % during the two rainy seasons. According to Dickson and Benneh (2004), annual rainfall ranges between 1250 – 1750 mm with a mean annual temperature of about 25.7° C. The vegetation is principally, a semi-deciduous and degraded forest consisting of limited species of hardwood which are generally harvested as lumber. Larger quantities of the original forest have been depleted resulting in secondary forest in most areas due to the rapid expansion of the cocoa industry in this vegetation belt. The secondary vegetation
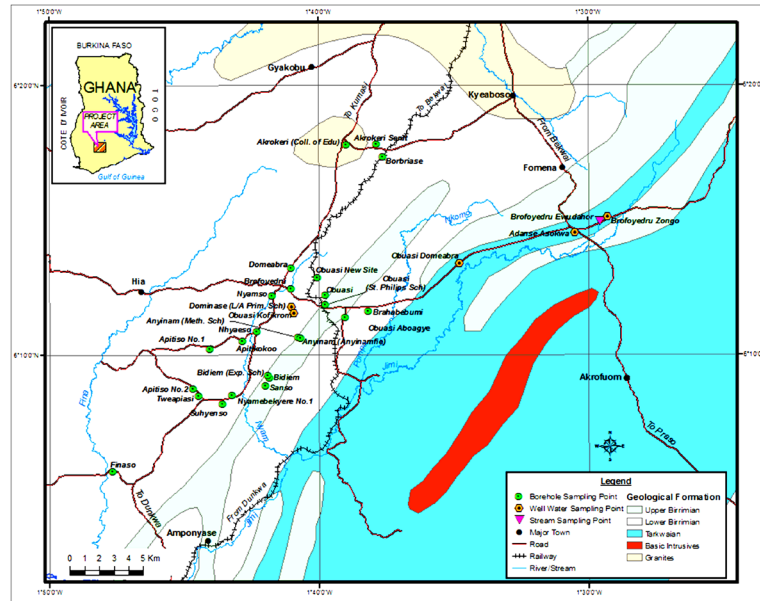
Fig 1: Map of the Amansie and Adansi Districts (insert map of Ghana) with the different geological settings showing sampling communities

is made up of shrubs, soft woody plants and climbers (Dickson and Benneh 2004).

Geology and soil

The ochrosol soils contain greater quantities of nutrients and are generally alkaline. The soil supports numerous tree crops including cocoa. According to Dickson and Benneh (2004), nearly all the cocoa in Ghana is grown in these soils. Dickson and Benneh (2004) reported that, the area is principally characterized by forest ochrosol soils which develop over similar highly weathered parent materials. The Amansie and Adansi Districts are located within the Birimian Supergorup and Tarkwaian System.

Birimian Supergroup

The rocks of the Birimian comprises of the Lower and Upper Birimian Supergroup (Kesse 1985). A major unconformity separates the Birimian Supergroup from the Tarkwaian system. Essentially, the Lower Birimian is pelitic in nature and consists of silts and muds with beds of coarser sediments. According to Kesse (1985), the Upper Birimian is basically

of pyroclastic and volcanic in nature. The rocks consist of bedded group of tuffs, sediments and mafic lavas (greenstones), jointly with minor bands of phyllite that include a zone of manganiferous phyllites containing manganese ore. Kesse (1985) also reported that, batholithic masses of granite and gneiss intrude the sequence. The mostly argillaceous sediments have been metamorphosed to schist, slate and phyllite jointly with some interbedded greywacke.

The Tarkwaian

According to Junner et al. (1942), the Tarkwaian essentially consists largely of fining-upwards broad clastic series of argillaceous and arenaceous sediments. Within the lower members of the system, these sediments are together with two well-defined zones of pebbly beds and conglomerates. The Tarkwaian rocks consist fairly of metamorphosed, shallow-water and sedimentary strata. They are generally quartzite, sandstone, shale and conglomerate resting unconformably on and obtained from the Birimian supergroup rocks. Junner *et al*., (1942) reported that, thick

laccoliths and sills of epidiorite infringe the rocks. Reminiscent of the Birimian rocks, they are folded along axes that trend northeast (Junner *et al.* 1942).

Hydrogeological setting

According to Dappah and Gyau-Boakye (2000), the granite and gneiss derived from the Birimian rocks are considerably critical to the water economy of Ghana. This is due to the fact that, they typically lie beneath extensive and mostly populated areas. Dappah and Gyau-Boakye (2000) also reported that, the granite and gneiss are not intrinsically porous though, secondary porosity has developed due to fracturing and weathering.

The granite and gneiss have principally wear away down low-lying areas where, there is high precipitation; and processes associated with weathering infiltrate deeply along fracture systems. On the other hand, granite occurs in massive poorly combined inselbergs which rise above the surrounding lowlands where, precipitation is fairly low. In certain areas weathered granite or gneiss, form permeable groundwater reservoirs. Favorable sites for groundwater storage may also include major fault zones (Dappah and Gyau-Boakye 2000). Where, fractures are close to the surface substantial water may infiltrate through them (Dappah and Gyau-Boakye 2000).

Sampling and analysis

Water samples were collected from borehole, shallow well and stream sources during the dry and wet seasons in 2012. A total of 59 boreholes, 12 wells and 2 streams were sampled. During sample collection, the design of sampling protocols reported by Claasen (1982) and Barcelona *et al.* (1985) were rigorously followed. Samples were collected using 4-1 acid-washed polypropylene containers. The samples were collected into 250 cm^3 polyethylene bottles without any preservation. All samples were stored on ice in an ice-chest(Appelo and Postma 1999) and transported to the Council for Scientific and Industrial Research -Water Research Institute laboratories in Accra, stored in a refrigerator at a temperature of $< 4^o$C and analyzed within one week. pH,TDS and electrical conductivity were measured in the field using Hach Sens ion 156 Meter.

Appropriate certified and acceptable international procedures outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2011) were used to conduct chemical analyses of the samples. The flame photometric method was used to analyse sodium (Na); calcium (Ca) by EDTA titration; Magnesium (Mg) by calculation after EDTA titration of calcium and total hardness; nitrate-nitrogen was analysed by hydrazine reduction and spectrophotometric determination at 520 nm; chloride (Cl) by argentometric titration. As a basis for scrutinizing analytical results, an ionic balance was calculated for each chemical sample. Result with ionic balance greater that 5% were rejected in accordance with international standards (Appelo and Postma 1999).Charge balances (CB) were calculated using Eqn1:

$$CB = [(\textstyle\sum z\, Mc - \sum z\, Ma) / (\sum z\, Mc + \sum z\, Ma)] * 100 \quad (1)$$

Where z is the ionic charge and M the molality, and the subscripts, a and c refer to anions and cations respectively.

Results and Discussion

The mean hydrochemical data for ground and surface water is shown in Table 1 and the statistical summary of the hydrochemical

TABLE 2:
Statistical summary of hydrochemical parameters within the Amansie and Adansi Districts

Parameter	Min	Max	Mean	SD	WHO (2011) Guideline value
Temperature	25.9	29	27.7	0.7	-
pH	3.6	9.15	6.04	1.16	6.5-8.6
Conductivity	22.8	715	179.8	132.6	-
TDS	14.9	393.3	110.4	81.2	1000
Total alkalinity	2.0	208	44.8	44.1	-
Total Hardness	4.0	216	53.3	47.8	-
Ca^{2+}	0.8	62.5	12.9	12.7	200
Na^+	1.2	40.5	11.1	7	200
K^+	0.1	10.9	1.9	2.1	30
Mg^{2+}	0.5	39.8	5.1	5.5	150
Cl-	1.0	65.5	13.5	10.9	250
HCO_3-	0.0	253	55.6	53.8	-
SO_4^{2-}	0.001	98	9.4	16.3	250
NO3-N	0.00	25.7	5.1	5.4	10
PO_4-P	0.1	3.9	0.9	0.8	-
F-	<0.005	-	-	-	1.5
SiO_2	8.2	64.1	23.7	10.7	-

All concentrations are in mg/L, except, Conductivity (μS/cm), Temperature (oC), pH (pH units

parameters within the districts is shown in Table 2, while, the saturation indices of some minerals in groundwater within the districts is presented in Table 3. The pH of boreholes range 3.6 - 7.3 with a mean value of 5.0. This reflects the strongly acidic to neutral character of the boreholes within the districts. pH of the shallow wells and streams are moderately acidic and range 4.7- 6.6 and 5.4 – 5.8, with mean values of 6.0 and 5.6 respectively. The pH values of the waters were relatively acidic during the dry season, with range 3.5 – 7.3 and mean 5.5 compared to the wet season which range 5.0 – 7.2, with a mean value of 7.1. This could be due to dilution of the waters during the wet season. Groundwaters from boreholes with pH range 3.6 – 7.3 were found to be relatively more acidic compared to wells with pH range 4.7- 6.6 pH units and streams with pH range 5.4 -5.8 pH units. This may be attributed to the influence of aquifer materials

on the chemistry of groundwater within the districts. From the geology of the study area, the occurrence of sulphides and carbonaceous matter within the ore formations suggests that natural geochemical and biochemical oxidation of the sulphide rocks may occur when in contact with oxygen gas containing water, resulting in increased hydrogen ion activity in the waters with which they are in contact. According to Stumm and Morgan(1981), the initial step is the oxidation of pyrite by oxygen in the presence of water and ferrous iron. This reaction produces; Fe^{2+}, SO_4^{2-} and H^+ ions as presented in Eqn 2:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \longrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (2)$$
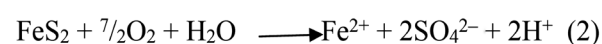
Following reaction Eqn 2, the ferrous ion produced is then oxidized to ferric iron(Fe^{3+}) in a relatively slow reaction which can be catalyzed by bacteria *Thiobacillus Ferooxidans*

as in Eqn 3 (Stumm and Morgan 1981):

$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ \longrightarrow Fe^{3+} + \tfrac{1}{2}H_2O \quad (3)$$
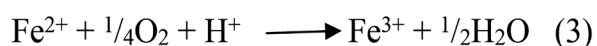
According to Stumm and Morgan (1981), the reaction in Eqn 3 is the major rate-limiting step of acid drainage formation and that, any further progress of this reaction depends on the pH of water. For instance, If pH is higher than 3.0 (consistent with groundwater within the districts with,100 % of boreholes with pH 3.6 - 7, wells with pH 4.7- 6.6 and streams with pH 5.5 – 5.8), then there is precipitation of ferric hydroxide, $Fe(OH)_3$ as described in Eqn 4 (Tay 2015):

$$Fe^{3+} + 3H_2O \longrightarrow Fe(OH)_3 + 3H^+ \quad (4)$$

Eqn 4 suggests that, acid mine drainage reactions in groundwater within the districts principally produces $Fe(OH)_3$ which is perhaps the source of iron in groundwater within the districts (Tay 2015).

Furthermore, this suggests that, the oxidation of arsenopyrite by oxygen goes through similar reactions with the overall reaction equation as in Eqn 5(Tay 2015):

$$4FeAsS + 13O_2 + 6H_2O = 4Fe^{2+} + 4AsO_4^{3-} + 4SO_4^{2-} + 12H^+ \quad (5)$$
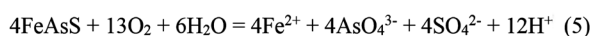
Implying that, likely processes involving acid mine drainage taking place in groundwater within the districts is primarily the result of oxidation of pyrite and/or arsenopyrite by oxygen through proton production to produce largely, $Fe(OH)_3$ (Tay 2015).

Kuyucak et al. (1991) proposed that, the reactions of carbonaceous matter leading to the sources of increased acidification in groundwater can be presented as in Eqns 6, 7 and 8.From the carbonaceous matter reactions in water as proposed by Kuyucak et al. (1991) in Eqns 6, 7 and 8, the hydrogen ion activity
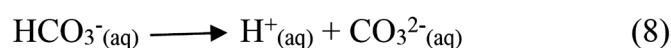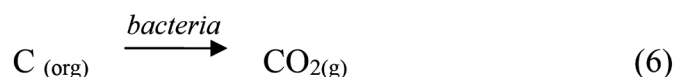
of the waters with which the minerals are in contact is increased. These reactions possibly take place in groundwater within the districts accounting for the increased hydrogen ion activity of groundwaters within the districts.

Another possible source of increased acidity in surface and groundwaters is the reactions which takes place in tailing dumps in abandoned mine areas involving bio-oxidation of sulphur-containing materials and acid mine drainage in exposed workings, as well as in the aquifer (Tay et al. 2006).These reactions result in the release of hydrogen ions into the aqueous environment (Tay et al. 2006).

Additionally, the naturally mild acidic nature of the waters within the districts together with the low SO_4^{2-} concentration and low conductivity in most of the shallow groundwaters within the districts suggests that during rainfall, carbonic acid (H_2CO_3) is produced from atmospheric carbon dioxide (CO_2) resulting in acidity of the waters (Tay 2015). Besides, acidity could also result from soil-generated CO_2 solution as well as dissolved organic acids (e.g humic and fulvic acids) (Langmuir 1997).

Thus, the low pH in ground and surface waters within the districts is therefore, attributable either to mining activity or natural processes especially in areas where no mining operation is on-going.

However, Knutsson (1994) reported that in regions with weathering-resistant soils and rocks where the climate is characteristically humid and the foremost movement of water and the transport of chemical components are downward leading to run-off of base cations, natural acidification is evident. The weather conditions within the Amansie and Adansi Districts where, the climate is quite humid with average monthly relative
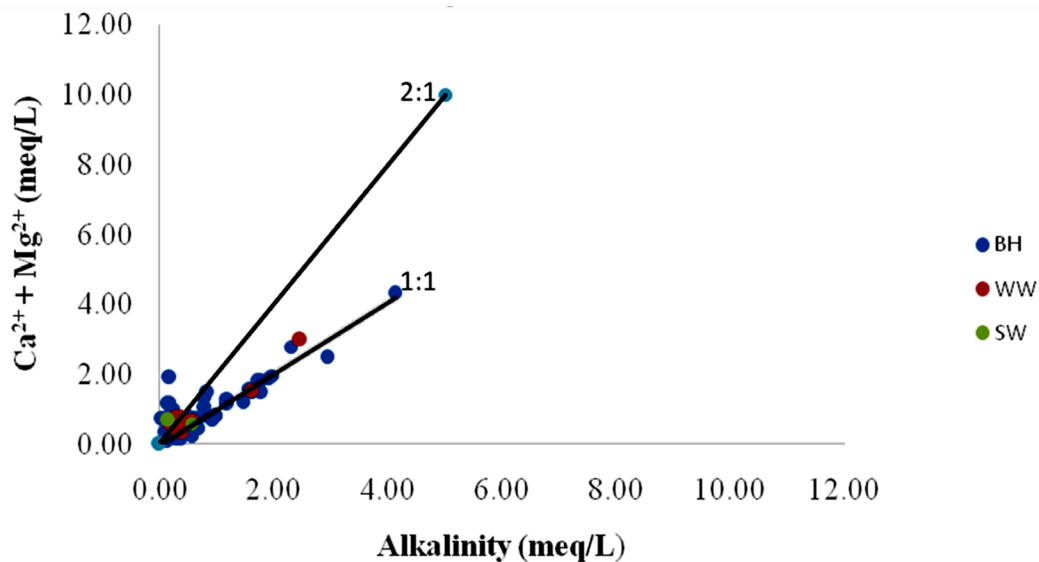
$$C_{(org)} \xrightarrow{\text{bacteria}} CO_{2(g)} \qquad\qquad (6)$$

$$H_2O_{(aq)} + CO_{2(g)} \longrightarrow H^+_{(aq)} + HCO_3^-{}_{(aq)} \quad (7)$$

$$HCO_3^-{}_{(aq)} \longrightarrow H^+_{(aq)} + CO_3^{2-}{}_{(aq)} \qquad\qquad (8)$$

Figure 2: The plot of total hardness vs alkalinity (as CaCO3) for ground and surface waters within the Amansie and Adansi Districts

humidity of 75 - 80 % during the two rainy seasons in consistent with Knutsson (1994). Von Brömssen (1989) and Caritat (1995) also reported that, the acidification status of ground and surface waters can be appraised using the non-marine total hardness-alkalinity plot. In this study, the total hardness values were considered non-marine since chloride which is conservative and is derived solely from marine sources is low in concentration. Figure 2 presents the plot of total hardness vs alkalinity of groundwater within the districts. From Figure 2, majority of the ground and surface waters plotted along the 1:1line. This suggests that, acidification is largely due to natural biogeochemical processes such as the generation of CO_2 in the soil zone via root respiration and organic matter decay (Kortatsi 2004; Tay *et al*. 2014). This was manifested in the brownish colour of the surface waters within the districts throughout the sampling period.

Only a few of the surface and groundwaters plotted along or close to the 2:1 line probably suggestive of sulphide (pyrite and/ or arsenopyrite) oxidation accelerated by mining activities within the districts. Thus,

acidity in groundwater within the districts could be attributed essentially to natural processes than mining activities. This is consistent with the field data for ground and surface water which show that groundwater is more acidic than surface water suggesting that, acidification of groundwater within the districts is fundamentally a function of the mineral composition of the aquifer through which it flows.

Another definition for groundwater acidification (Aci) is the loss of alkalinity and is computed using Eqn 9 (Henriksen and Kirkhusmo 1986; Caritat *et al*. 1998):

$$Aci = 0.93\ (Ca^{2+} + Mg^{2+}) - 14 - Alk + Al \quad (9)$$

where, all concentrations are expressed in meq/L.

Likewise, the acid neutralizing capacity (ANC) of groundwater within the districts can be computed using Eqn10 (Stumm 1992; Caritat 1995):

$$ANC = (Ca^{2+} + Mg^{2+} + Na^+ + K^+) - (SO_4^{2-} + Cl^- + NO_3^-) \quad (10)$$

where, all concentrations are expressed in meq/L. The overall relationships between ANC, net acid neutralizing capacity (NANC) and Aci can be represented pictorially as in Figure 3 (Kortatsi 2004;Kortatsi 2007;

Tay *et al.* 2014). Figure 3 shows that, the groundwaters are low in acid neutralizing capacity with ANC which ranged 0.06 - 4.4 meq/L and a mean value of 1.01 meq/L. This suggests buffering agents other than carbonates (Kortatsi 2004; Kortatsi 2007; Tay *et al.* 2014). In a like manner, the Aci of the groundwaters is also very low, with Aci which ranged -14.98 to -11.31 meq/L, and a mean value of -13.60 meq/L. It is apparent from Figure 3 that, even though the ANC is low it remains positive for all groundwaters while, Aci remains negative. As a result, the NANC is positive for all groundwaters, ranging from 11.37 – 18.62 meq/L, and a mean value of 14.61 meq/L. This is suggestive of the groundwaters still possessing the potential to neutralize acids notwithstanding the moderately low pH (62 % of the groundwaters with pH range 3.6 - 6.0 pH units).The occurrence of silicates/ aluminosilicates and some mafic rocks in the geological matrix within the districts probably, may be responsible for the acid neutralizing potential of groundwater within the districts (Kortatsi 2004; Kortatsi 2007; Tay *et al.* 2014). Characteristic of the ground and surface waters within the districts is low mineralized waters. Low mineralized waters are suggestive of short residence time within the aquifer and/ or contact with relatively insoluble minerals (Hounslow 1995). The electrical conductivity ranged 22.8 – 473 µS/cm, with a mean value of 172.9 µS/cm for groundwater, while, surface water conductivity ranged 105 - 152 µS/cm,

with a mean value of 128.5 µS/cm. Based on the classification by Hounslow (1995), ground and surface waters within the districts can be classified as fresh (EC < 500 µS/cm).

The total dissolved solids (TDS) of the waters are low. TDS ranged 14.9 – 309.8 mg/L and a mean value of 112.6 mg/L. According to Hounslow (1995) typically, the predominant hydrogeochemical process taking place in waters with TDS< 500 mg/L is silicate weathering. This suggests that silicate weathering is the major weathering process taking place within the aquifers with which groundwaters within the districts are in contact (Hounslow 1995, Tay 2012). The alkalinity values of the groundwaters range 2 – 208 mg/L with a mean value of 47mg/L.

Hardness in groundwater within the districts ranged 4 – 216 mg/L, with a mean value of 55.6 mg/L. Hardness values are thus, within the WHO (2011) recommended limit of 500 mg/L. Based on the classification of Sawyer and McCarty (1967), only 77 % of groundwater within the districts can be classified as soft. The chemical constituents in groundwater within the districts generally have low concentrations (Table 2) and are within the WHO (2011) Guideline values. Figure 4 presents the bar chart of mean concentrations of ions present in groundwater within the districts. Consistent with the chemistry of most natural waters, HCO_3^- is the dominant anion, as Cl^- and SO_4^{2-} occur in minor concentrations while,Ca^{2+} is the dominant cation as Na^+ and
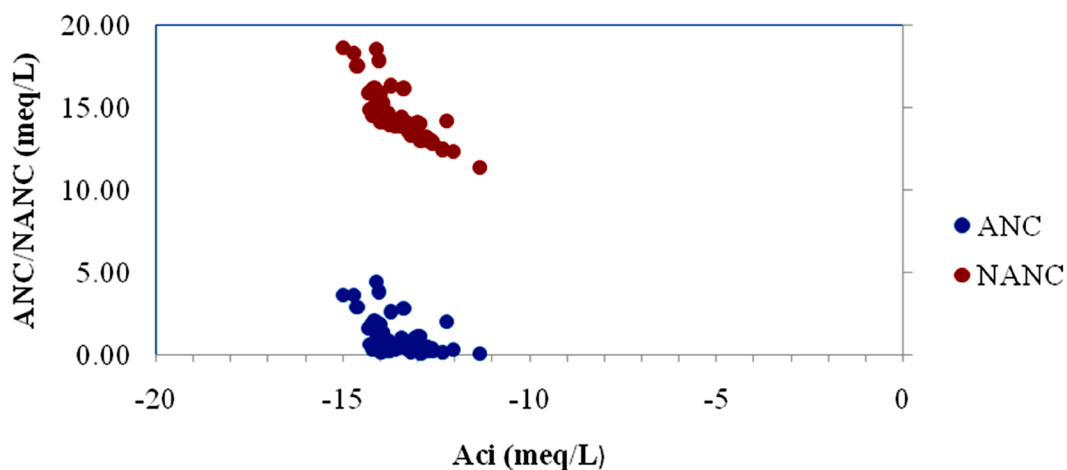

Figure 3: The plot of ANC, NANC against Aci for boreholes within the Amansie and Adansi Districts

Mg^{2+}occur in minor concentrations. Thus, the relative abundance of cations and anions in groundwater within the districts is in the order: $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$ respectively. Based on Chebotarev (1955), groundwater composition within the districts takes place at outcrops producing primarily bicarbonate ions (HCO_3^-).

Sources of major ions
Hounslow (1995), proposed that in any groundwater, if $Na^+/(Na^+ + Cl^-) < 0.5$ and the TDS > 500 mg/L, then there is reverse softening or seawater intrusion, while, $Na^+/(Na^+ + Cl^-)$ ratios > 0.5 suggests sodium source other than halite; perhaps, albite dissolution or ion-exchange reactions and $Na^+/(Na^+ + Cl^-) = 0$ suggests halite dissolution. From the calculated $Na^+/(Na^+ + Cl^-)$ ratios, 76 % of the groundwaters within the districts had $Na^+/(Na^+ + Cl^-)$ ratios > 0.5. However, from Figure 5, majority of the groundwaters plot below the 1:1 line suggestive of reverse-ion exchange reactions. Nevertheless, the TDS values ranged 14.9 – 309.8 mg/L and a mean value of 112.6 mg/L. This suggests that, reverse softening or seawater intrusion is not possible. Thus, sodium sources excluding halite; perhaps, albite dissolution or ion-exchange reactions may partly be responsible for Na^+ in groundwater within the districts.
McLean and Jankowski (2000) proposed that in a plot of $HCO_3^- + SO_4^{2-}$ (meq L^{-1}) vs $Ca^{2+} +$

Mg^{2+} (meq L^{-1}), waters which plot on the 1:1 line show gypsum, anhydrite, calcite and dolomite dissolution as major processes controlling solution composition while, groundwater which plot below the 1:1 dissolution line show ion-exchange, in which case $Ca^{2+} + Mg^{2+}$ are being depleted with respect to $HCO_3^- + SO_4^{2-}$ and groundwater that plot above the 1:1 dissolution line show ion-exchange reactions in which case $HCO_3^- + SO_4^{2-}$ are being depleted with respect to $Ca^{2+} + Mg^{2+}$. Figure 6 shows that majority of the groundwaters plot below the 1:1 line, whilst, a few plot on the 1:1 line. This suggests that gypsum, anhydrite, calcite and dolomite dissolution as well as ion-exchange reactions in which $Ca^{2+} + Mg^{2+}$ are being depleted with respect to $HCO_3^- + SO_4^{2-}$. Additionally, several scientists such as Datta et al. (1996); Rajmohan and Elango (2004); Sandow (2009), Tay *et al*. 2014, 2015) have also employed the scatter plot of ($HCO_3 + SO_4$) vs ($Ca + Mg$) to determine the sources of $Ca^{2+} + Mg^{2+}$ groundwaters either through carbonate or silicate weathering reactions. These studies showed that groundwater plotting above the 1:1 line indicate carbonate weathering dominance while, waters plotting below the 1:1 line shows silicate weathering dominance. From the scatter plot of ($HCO_3 + SO_4$) vs ($Ca + Mg$) majority of the groundwaters plot below the 1:1 line, while, a few groundwaters plot above the 1:1 line. This suggests that, silicate weathering is one of the principal
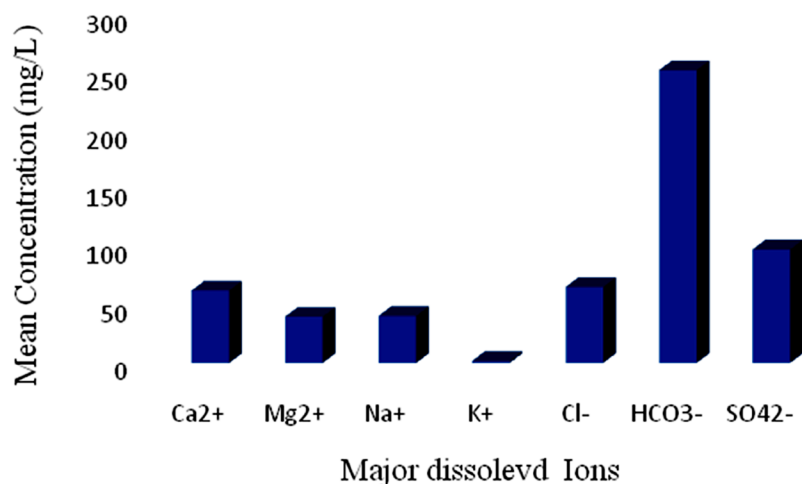
Figure 4: Bar chart of mean concentration of major dissolved ions in groundwater within the districts
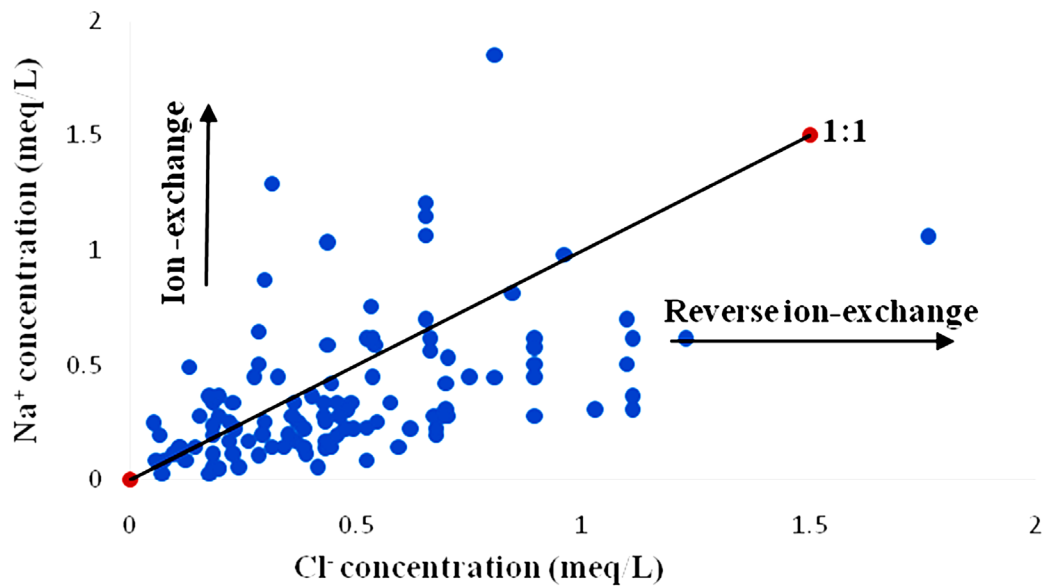
Figure 5: A plot of Na+ vs Cl-

hydrogeochemical processes in groundwater within the districts.

Furthermore, the calculated $Mg^{2+}/(Ca^{2+} + Mg^{2+})$ equivalent ratios show that, 80% of the groundwaters were < 0.5, suggesting limestone-dolomite dissolution while, the calculated $Ca^{2+}/(Ca^{2+} + SO_4^{2-})$ equivalent ratios show that, 85 % of the groundwaters were > 0.5, suggesting calcium sources excluding gypsum- carbonates, calcite/dolomite or silicates. Thus anhydrite, calcite, dolomite dissolution, ion-exchange reactions as well as silicate weathering may have contributed appreciably to the concentrations of Ca^{2+} and Mg^{2+} in groundwater within the districts.

According to Jankowski et al. (1998) in a scatter plot of Na-Cl(meq L^{-1}) vs Ca+Mg– HCO_3+ SO_4 (meq L^{-1}), waters undergoing ion-exchange would typically plot along a line whose slope is -1, while, waters plotting close to the zero value on the x-axis are not influenced by ion-exchange. Figure 7 presents a scatter plot of Na-Cl (meq L^{-1}) vs Ca+Mg– HCO_3+SO_4 (meq L^{-1}) for groundwater within the districts. Figure 7 show that, the groundwaters plot away from the zero value on the x-axis along a line with slope -1.12. This slope is close to the predictable (-1), if cation exchange is the dominant process through which Na^+ enters the groundwater system.
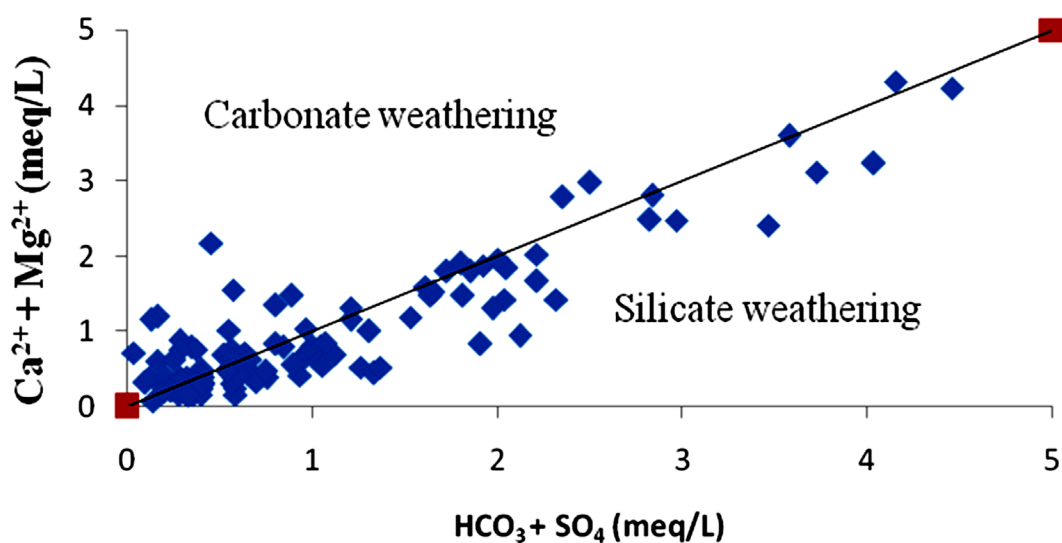
Figure 6: Plot of $HCO_3 + SO_4$ (meq L^{-1}) vs Ca + Mg (meq L^{-1}) for groundwater within the districts

Thus, cation-exchange reaction is one of the hydrogeochemical processes responsible for Na^+ concentrations in groundwater within the Amansie and Adansi districts.

To appreciate and interpret complex groundwater data in relation to ion-exchange reactions between groundwater and its host environment during residence time, Schoeller (1965, 1977) put forward two Chloro-Alkaline Indices, CAI_1 and CAI_2 as depicted in Eqns 11 and 12:

K^+ from groundwater within the districts with Mg^{2+} and Ca^{2+} in the rocks. Consistent with the Na^+/ (Na^+ + Cl^-) ratios for this study (where, 76 % of the groundwaters within the districts had Na^+/ (Na^+ + Cl^-) ratios> 0.5), the computed Chloro-Alkaline Indices also show that ion-exchange reactions is one of the hydrogeochemical processes taking place in groundwater within the districts in which case, Na^+ and K^+ are being exchanged with Ca^{2+} and Mg^{2+} in the rocks. Based on Ashwani
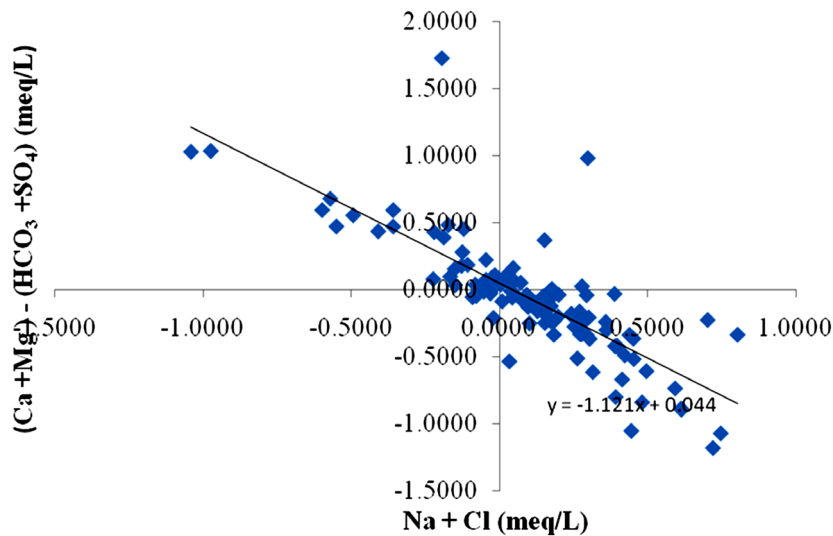
Figure 7: Plot of Na-Cl(meq L^{-1}) vs Ca +Mg- HCO_3+SO_4 (meq L^{-1}) for groundwater within the districts

where, a positive Chloro-Alkaline index signifies an exchange of Na^+ and K^+ from the groundwater with Mg^{2+} and Ca^{2+} in the rocks and a negative Chloro-Alkaline index signifies an exchange of Mg^{2+} and Ca^{2+} from the groundwater with Na^+ and K^+ in the rocks (Nagaraju *et al*. 2006; Zhu *et al.* 2007; Tay *et al.* 2014; Ashwani *et al*. 2014 and Tay 2015). The Chloro-Alkaline Indices as suggested by Schoeller (1965, 1977) were computed for this study. Results from this study show that, CAI_1 indices ranged between 1.26 - 9.5 with

et al.(2014), $Na^+ + K^+$ are exchanged for the alkaline earths (Ca^{2+} + Mg^{2+}> HCO_3^-) and thus, groundwater within the districts may be regarded as base- exchange hardened water.

Hounslow (1995), proposed that for groundwater with ($Na^+ + K^+ - Cl^-$)/ ($Na^+ + K^+ - Cl^- + Ca^{2+}$) ratios >0.2 and < 0.8, the weathering of plagioclase ($Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8$) is possible. The calculated $Na^+ + K^+ - Cl^-$)/ ($Na^+ + K^+ - Cl^- + Ca^{2+}$ ratios for this study show that, 83 % of groundwater had ($Na^+ + K^+-Cl^-$)/ ($Na^+ + K^+ - Cl^- + Ca^{2+}$) ratios fall within 0.2

$$CAI_1 = [Cl^- - (Na^+ + K^+)]/Cl^- \qquad (11)$$

$$CAI_2 = [Cl^- - (Na^+ + K^+)]/ (SO_4^{2-} + HCO_3^- + CO_3^- + NO_3^-) \qquad (12)$$

a mean value of 3.04, while, CAI_2 indices ranged -7.25 to 10.8 with a mean value of 0.6. The results therefore show that, majority of the computed CAI_1 and CAI_2 indices are positive suggesting an exchange of Na^+ and

< ($Na^+ + K^+ Cl^-$)/ ($Na^+ + K^+ Cl^- + Ca^{2+}$) > 0.8. This is consistent with Hounslow 1995 and suggests that, the weathering of plagioclase ($Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8$) is possible. According to Kortatsi 2004; Tay et al. 2014;

Tay 2015, the incongruent dissolution of plagioclase with CO_2 charged water to produce Na^+ and Ca^{2+} can be depicted as in reaction Eqn 13:

$$1.45Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8 + 2CO_2 + 6.6H_2O = Al_2Si_2O_5(OH)_4 + 0.9Na^+ + 0.55Ca^{2+} + 2HCO_3^- + 1.8H_4SiO_4 \quad (13)$$
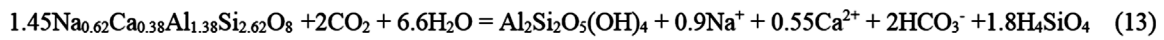
The theoretical H_4SiO_4/Na^+ and H_4SiO_4/HCO_3^- molar ratios for the weathering of plagioclase in Eqn 13 are 2.0 and 0.9 respectively (Kortatsi 2004; Tay *et al.* 2014, Tay 2015). However, the molar ratios for H_4SiO_4/Na^+ and H_4SiO_4/HCO_3^- for groundwater within the districts ranged 0.9 - 14.5 and 0.04 - 4.15 with mean values of 4.7 and 0.97 respectively. Consequently, the computed molar ratios for H_4SiO_4/Na^+ and H_4SiO_4/HCO_3^- for groundwater within the districts show that albeit, plagioclase weathering to produce Kaolinite may not implicitly explain the excess of Na^+ over Cl^-, plagioclase weathering indisputably contributes to the concentration of Na^+, H_4SiO_4 and HCO_3^- in groundwater within the districts. Likewise, the incongruent dissolution of albite to produce kaolinite, morntmorillonite and/or gibbsite may be represented in Eqns 14, 15 and 16 respectively (Kortatsi 2004; Tay *et al.* 2014, Tay 2015):

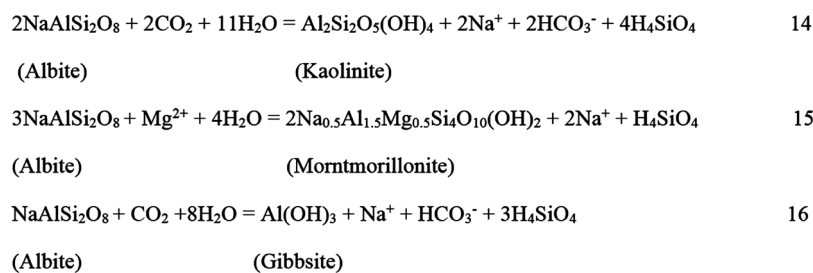In much the same way, the theoretical H_4SiO_4/Na^+ molar ratios for the dissolution of albite to produce kaolinite, morntmorillonite and gibbsite as shown in Eqns 14, 15 and 16 are 2.0, 0.5 and 3.0 respectively (Kortatsi 2004; Tay *et al.* 2014, Tay 2015). Hydrochemical data from this study show that, H_4SiO_4/Na^+ molar ratios for groundwater within the districts ranged 0.9 - 14.5, and a mean value of 4.7. Thus, this study does not clearly show that, albite weathering to produce clay minerals (kaolinite, montmorillonite and gibbsite) may have occurred in groundwater

within the districts.

However, Brady (1974); Brady and Walther (1989) and Appelo and Postma (1999) postulated that, the kind of weathering product is dependent on hydrological conditions as well as the rate of mineral weathering. According to Brady (1974); Brady and Walther (1989) and Appelo and Postma (1999), the weathering of primary silicate minerals to montmorillonite is largely favoured in very dry climate where, the rate of flushing of soil is comparatively slow. Based on Brady (1974); Brady and Walther (1989) and Appelo and Postma (1999), weathering from plagioclase (albite/anorthite) to montmorillonite within the Amansie and Adansi districts is not probable owing to the mean annual rainfall of 1250–1750 mm. Additionally, Brady (1992); Langmuir (1997); Appelo and Postma (1999), postulated that, the weathering of primary silicate minerals to produce morntmorillonite is most often favoured by comparatively very dry climate where, the soils are alkaline in pH and fairly poorly drained.Consistent with Brady (1992); Langmuir (1997); Appelo and Postma (1999), the soil types found in the Amansie and Adansi districts contain greater quantities of nutrients and are generally alkaline (Dickson and Benneh 2004). Thus, kaolinite, gibbsite or iron oxides are the most probable secondary weathering products from the dissolution of albite or anorthite.

The stability of albite and its secondary weathering products gibbsite, kaolinite, and Na- morntmorillonite with respect to groundwater within the districts is presented in Figure 8, while, Figure 9 presents the stability of anorthite and its secondary weathering

$$2NaAlSi_2O_8 + 2CO_2 + 11H_2O = Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4 \qquad 14$$

(Albite)   (Kaolinite)

$$3NaAlSi_2O_8 + Mg^{2+} + 4H_2O = 2Na_{0.5}Al_{1.5}Mg_{0.5}Si_4O_{10}(OH)_2 + 2Na^+ + H_4SiO_4 \qquad 15$$

(Albite)   (Morntmorillonite)

$$NaAlSi_2O_8 + CO_2 + 8H_2O = Al(OH)_3 + Na^+ + HCO_3^- + 3H_4SiO_4 \qquad 16$$

(Albite)   (Gibbsite)

products; gibbsite, kaolinite and Ca-montmorillonite with respect to groundwater within the districts. According to Appelo and Postma (1999) in drawing Figures 8 and 9 it was assumed that, all aluminum is retained in the weathering products. An assumption was also made for end-member compositions using equilibrium relationships of Tardy (1971) for standard temperature (25°C) and pressure (1 atmosphere) which approximately reflects conditions in the groundwater. Phreeqc for windows Version 2.8.01 was used for the computation of constituents' activities (Appelo and Postma 1999). A typical anorthite weathering processes maybe represented as in Eqn 17 (Kortatsi 2004, Tay *et al*. 2014; Tay 2015):

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^- \quad (17)$$
(Anorthite)   (Kaolinite)
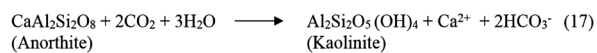
According to Davis (1964), groundwater is invariably highly undersaturated with respect to amorphous silica and generally, quartz and amorphous silica do not exert any appreciable influence on the level of silica in groundwater. (Hounslow 1995), also postulated that silica concentrations in natural waters are generally low. Consistent with Davis (1964) and Hounslow (1995), majority of the groundwaters plot in the kaolinite- stability fields in Figures 8 and 9. This suggests that, kaolinite is the most stable secondary silicate mineral phase for the groundwater system within the districts. Thus, silicate weathering contributes to the Na^+ and Ca^{2+} content in groundwater within the districts.

Hounslow (1995), also postulated that, silicate or carbonate weathering dominance can be deduced from HCO_3^-/SiO_2 molar ratio. If, the molar ratio of $HCO_3^-/SiO_2 < 10$, it implies $HCO_3 \gg SiO_2$ and show carbonate weathering dominance (Hounslow 1995). On the other hand, a ratio of $HCO_3^-/SiO_2 < 5$, implies $SiO_2 \ll HCO_3$ and show silicate weathering dominance (Hounslow 1995). The hydrochemical results from this study show that, 81% of groundwater had $HCO_3^- / SiO_2 < 5$, suggesting that, silicate (mainly plagioclase) weathering is probable. This is in consonance with the TDS results from this study (100 % of the groundwaters

had TDS < 500 mg/L) as well as the stability of anorthite and albite and their possible weathering products in Figures 8 and 9.

Saturation indices
The saturation states of dissociated minerals can be determined in order to investigate the thermodynamic controls as well as calculate the level to which any groundwater has equilibrated with the various mineral phases (Deutsch 1997). Langmuir (1997), Appelo and Postma (1999), proposed that the saturation index (SI) of a given mineral can be defined as in Eqn 18:

$$SI = Log_{10}(IAP/K_{sp}) \quad (18)$$

where, IAP is the ion activity product of the dissociated mineral species in solution, and Ksp is the equilibrium solubility product at a given temperature. An SI > 0 signifies supersaturation, SI < 0 signifies subsaturation and SI = 0 signifies equilibrium conditions of the minerals in solution

An assessment was done on the states of saturation of groundwaters with respect to the major minerals using hydrogeochemical transport model Phreeqc for Windows (Parkhust and Appelo 1999). Using the hydrochemical data and measured field temperatures and pHs for groundwater within the districts saturation indices were computed and presented in Table 3.From Table 3, the saturation indices of anhydrite and gypsum were all negative. According to Garrels and Mackenzie (1971); Stumm and Morgan (1981), this suggests subsaturation of these minerals in groundwater within the districts. Thus, groundwater within the districts may have originated from a formation with deficient amount of anhydrite and gypsum in solution or short residence time of these minerals in groundwater within the districts (Garrels and Mackenzie 1971; Stumm and Morgan 1981). Conversely, the saturation indices for calcite and dolomite for majority of the groundwaters were positive, suggesting that these minerals originates from a formation with adequate amount of calcite and dolomite and would continue to precipitate in solution until the equilibrium conditions are altered.

Figure 8: The stability of albite and its possible weathering products gibbsite, kaolinite, and Na-montmorillonite with respect to groundwater within the district. (After Tardy, 1971)

The calculated saturated indices for calcite were plotted against dolomite and presented in Figure 10. According to Nilsen and Grammeltvedt (1993), this plot essentially gives vital information on the two major minerals that are responsible for the total volume of alkalinity for the neutralization of acidity generated from mining activities. Representing the different kinds of non-equilibrium conditions with respect to both carbonate species are the four quadrants of the plotting field outside the equilibrium area lettered A to D in Figure 10. From Figure 10, majority of the groundwaters plot in Quadrant A. This suggests that the groundwaters are supersaturated with respect to both calcite and dolomite and reflects groundwater discharging from an aquifer containing more than enough calcite and/or dolomite with sufficient residence time to reach equilibrium. No groundwater plot in Quadrant B. A few of the groundwaters plot in Quadrant C suggesting subsaturation with respect to both calcite and dolomite and represents waters that have come from an environment where calcite and dolomite are depleted or where Ca^{2+} and Mg^{2+} exist in other forms. According to Langmuir (1997), water that has not reached equilibrium with the carbonates owing to short residence times would also plot in this field. Table 3 also show that groundwater within the districts is generally subsaturated with respect to anhydrite, melantherite and gypsum. This explains the generally low sulphate and
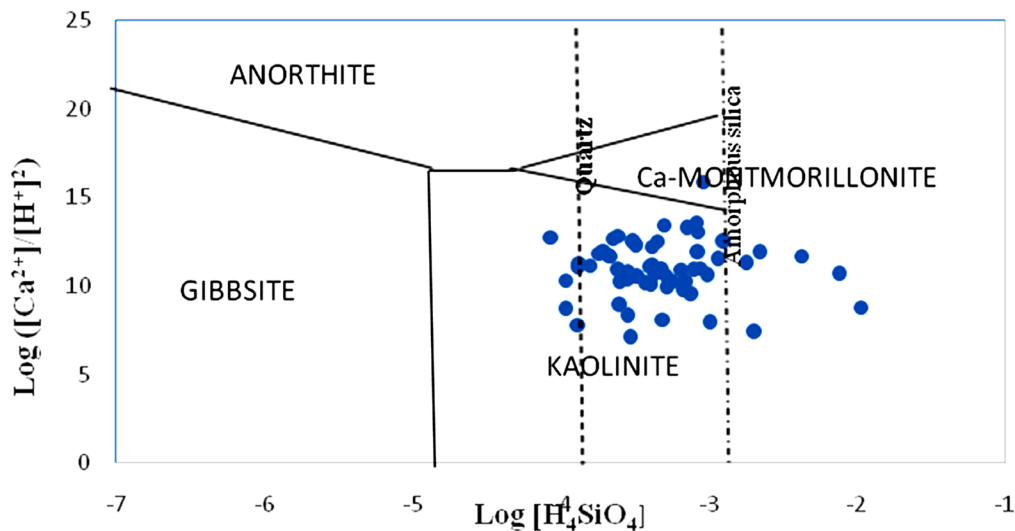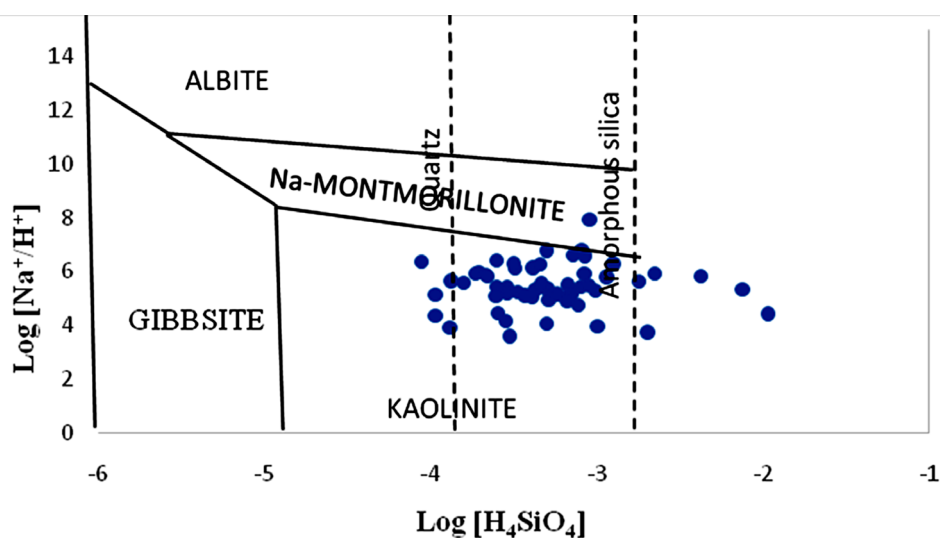

Figure 9: The stability of anorthite and its possible weathering products gibbsite, kaolinite, and Ca-montmorillonite with respect to groundwater within the district (After Tardy, 1971)

calcium ion concentrations in groundwater within the districts, while, groundwater within the districts is generally supersaturated with respect to goethite, hemathite, siderate and amorphous silica. This suggests that these minerals are being precipitated in groundwater within the districts.

Hydrochemical facies

Figure 11 presents the Piper Trilinear Plot (Piper 1944) of major ions in groundwater within the districts. Two principal hydrochemical type waters have been delineated. The Ca-Mg-HCO_3 type water occupying the section of the diamond shape designated by III, where, the chemical properties of the water are dominated by alkaline earths and weak acids (Karanth 1994). According to Plummer *et al.*(1990); Edmunds and Smedley (2000); Adams *et al.*(2001), the Ca-Mg-HCO_3 type water is rich in Ca^{2+} + Mg^{2+} and HCO_3^- and most often, it is considered as recharge area waters at their early phase of geochemical evolution and are rapidly circulating groundwaters which have not experienced pronounced water–rock interaction. The Na-Cl type water occupies the diamond shape designated by V. This type water is rich in Na^+ + K^+ and Cl^- + SO_4^{2-} (Karanth 1994). Owing to the low TDS (< 500 mg/L) of the groundwaters within the districts, the Na-Cl characteristics may be due to the influence of local rain. This illustrates the importance of

local recharge conditions within the districts. Other minor type waters that are of importance in clearly understanding the chemistry of groundwater within the districts can be characterized as mixed waters. This include; The Ca-Mg-SO_4 type water (designated as I) in the diamond shape with source aquifers containing gypsum ($CaSO_4.2H_2O$) or anhydrite ($CaSO_4$) that may have undergone dissolution and therefore, characterized by permanent hardness (Karanth 1994). The Na-Cl-SO_4 type water which occupies the section of the diamond shape designated as II. In this type water, no particular cation predominates while; SO_4^{2-} is the main anion. The Na-Mg-Ca-HCO_3 type water which occupies the section of the diamond shape designated as IV, reminiscent of aggressive recharging water reacting with silicate rocks mainly containing plagioclase. In this type water, no particular cation predominates while HCO_3^- is the main anion.

Groundwater chemistry evolution within the districts

The groundwater chemistry evolution within the districts was investigated using the thermodynamic controls (i.e groundwater equilibration with the various mineral phases) and the geochemical classification as proposed by Chadha (1999).

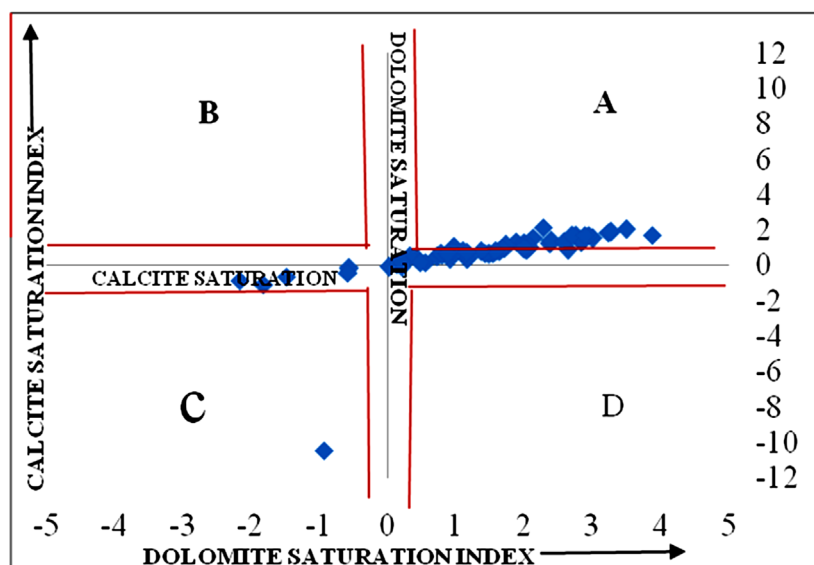From Table 3, groundwater within the

Figure 10: A plot of calcite against dolomite saturation indices for groundwater within the Amansie and Adansi districts

Amansie and Adansi Districts is principally supersaturated with respect to calcite, dolomite, goethite, hemathite, siderate, ferric hydroxide [Fe(OH)$_3$] and amorphous silica and principally subsaturated with respect to anhydrite, melantherite and gypsum. This suggests that; anhydrite, gypsum and melantherite, if present in the groundwater within the districts, will generally dissolve, while, calcite, dolomite, goethite, hemathite, siderate, ferric hydroxide [Fe(OH)$_3$] and amorphous silica will continuously precipitate until equilibrium conditions are achieved. Chadha (1999), proposed a scatter plot of (Ca^{2+} + Mg^{2+}) - (Na$^+$ + K$^+$) vs. (HCO$_3^-$) - (SO$_4^{2-}$ + Cl$^-$) for the geochemical classification of groundwater along its flow path.

From the Chadha plot in Figure 12, stream water is chemically the least evolved of the waters investigated since both streams are principally Ca–Mg–HCO$_3$ type waters which are rich in Ca^{2+} + Mg^{2+} and HCO$_3^-$and most often considered as recharge area waters at their early phase of geochemical evolution and are rapidly circulating groundwaters which have not experienced pronounced water–rock interaction (Plummer et al.1990; Edmunds and Smedley 2000; Adams et al.2001; Tay 2015). The surface waters thus, could be serving potentially as recharge reservoirs to groundwater within the districts. Groundwaters within the districts evolve from fresh waters (largely Ca–Mg–HCO$_3$ typewaters with a few Na–HCO$_3$type waters) into permanent hard-Ca–Mg–Cl type waters and limited recharging local rain- Na–Cl/ Na-SO$_4$ type waters along the groundwater flow path. This could be due largely to ion-exchange reactions along the flow paths and is consistent with the ion-exchange reactions investigations as presented Figure 7 and the Chloro-Alkaline Indices interpretations as discussed. The shallow well waters which are also principally fresh waters also evolve from Ca-Mg-HCO$_3$ (with a few Na–HCO$_3$ type waters) into permanent hard-Ca–Mg–Cl type waters and limited recharging local rain- Na–Cl/ Na-SO$_4$ type waters along the groundwater flow path.

Owing to chemical interactions with aquifer materials and possible mixing with older mineralized water along flow paths, it is expected that naturally, the TDS of groundwater will increase with depth and residence times (Helstrup et al.2007, Tay 2015). Figure 13 shows the relationship between Na$^+$ and Cl$^-$ contents in groundwater within the districts. The groundwaters align well with the conservative mixing line. Additionally, Figure 13 shows that, majority of the groundwaters (boreholes and shallow wells) plot above the mixing line, depicting a surplus of Na$^+$. Figure 14 also shows some extent of deficiency
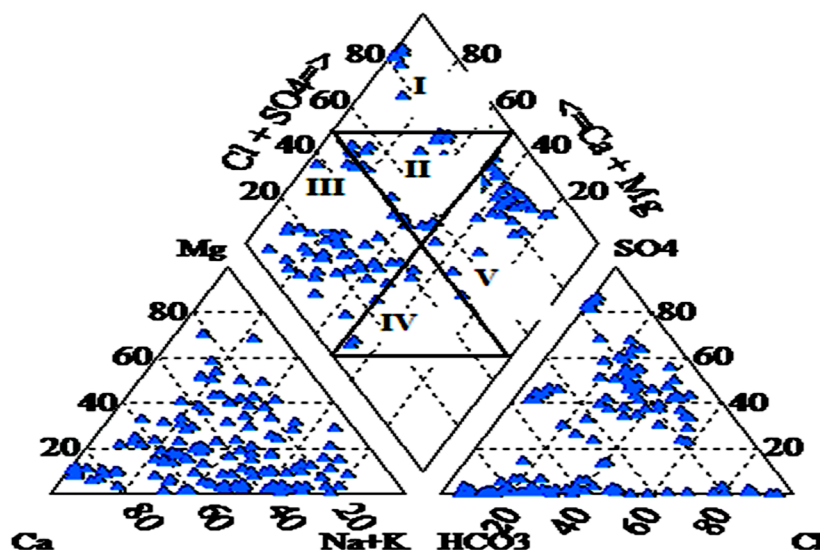
Figure 11: Piper plot showing the chemical types of water sources within the Amansie and Adansi Districts
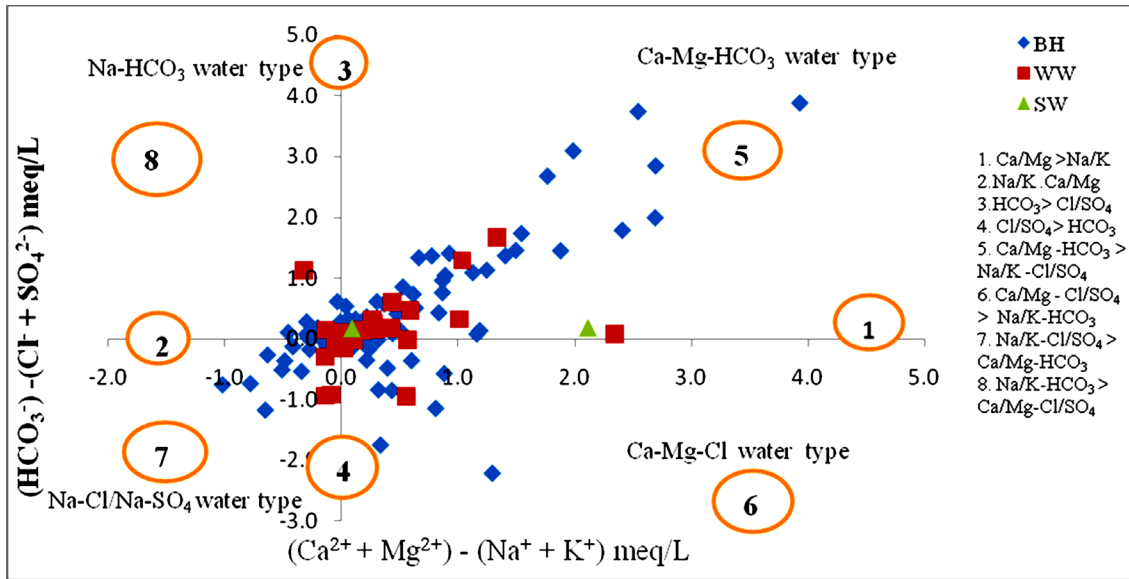
Figure 12: Scatter plot of $(Ca^{2+} + Mg^{2+}) - (Na^+ + K+)$ vs. $(HCO_3-) - (SO_4^{2-} + Cl^-)$ for geochemical classification of surface and groundwater within the Amansie and Adansi Districts (after Chadha 1999)
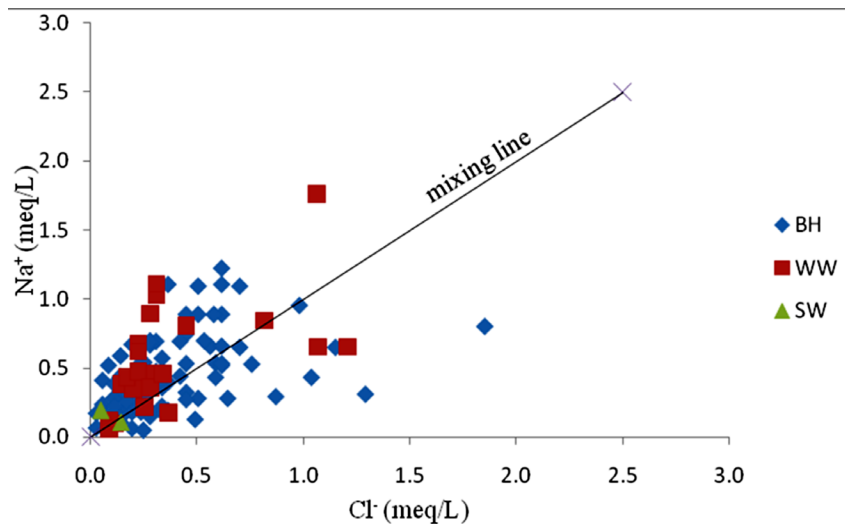
Figure 13: Relationship between Cl- and Na+ contents in groundwater within the Amansie and Adansi Districts

of Ca^{2+} in groundwater within the districts as most of the groundwaters plot below the 1:1 line. According to Appelo and Postma (1999), an excess of Na^+ is an indication of fresh water recharging, while an excess of Ca^{2+} denotes saline-water intrusion. Based on Appelo and Postma (1999), groundwater within the districts is largely characterized by recharge processes (mixing with waters of geochemically different ionic signatures than processes involving saline-water intrusion (mixing of fresh and old waters).The effects of ion-exchange in groundwater within the districts signify evolution (changes) in the water chemistry as groundwater travels along the flow path.

Figures 13 and 14 shows the effects of limited mixing with local rain (as only a few of the groundwaters plot along or close to the mixing line) and limited dissolved carbonate equilibria (as only a few of the groundwaters plot along or close to the 1:1 line). Thus, mixing of local rain and dissolved carbonate equilibria are not essential controls on the hydrochemical evolution of groundwater within the Amansie and Adansi Districts.

Based on Figures 12, 13 and 14 groundwater within the districts principally evolves from
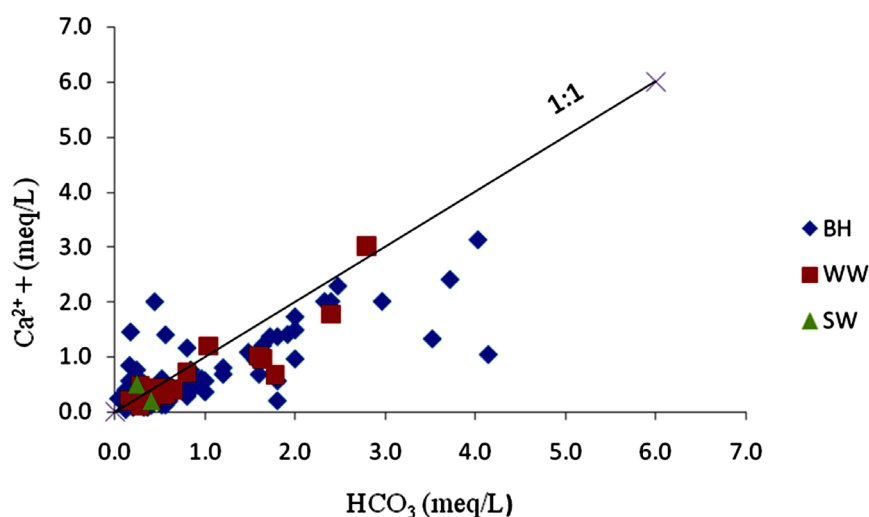
Figure 14: Relationship between HCO$_3$-and Ca^{2+} contents in groundwater within the Amansie and Adansi Districts

fresh Ca–Mg–HCO$_3$ type water into Na–HCO$_3$ type water into Ca–Mg–Cl type water into Na–Cl type water along its flow path due to ion-exchange reactions and is largely characterized by recharge processes through mixing with waters of geochemically different ionic signatures.

Conclusion

The hydrochemical data from the Amansie and Adansi Districts show that, silicate weathering and ion-exchange reactions are the major processes influencing groundwater chemistry within the districts. Results show that groundwater within the districts is strongly to moderately acidic as, 62 % of the groundwaters had pH that range 3.6 - 6.0. Acidity in ground and surface water within the districts is attributable predominantly to natural processes than mining activities; however, the groundwaters still have the potential to neutralize acids due to the presence of silicates/aluminosilicates. The waters are fresh (EC< 500 μS/cm) with conductivity values which ranged 22.8 – 473 μS/cm, and a mean value of 172.9 μS/cm. TDS of the groundwaters range 14.9 – 309.8 mg/L with a mean value of 112.6 mg/L. The relative abundance of cations and anions are in the order: Ca^{2+} > Na$^+$ > Mg^{2+} > K$^+$ and HCO$_3^-$ > Cl$^-$ > SO$_4^{2-}$ respectively. The states of saturation of the groundwaters with respect to major minerals using hydrogeochemical transport model Phreeqc for Windows suggest that, anhydrite and gypsum are subsaturated and indicates that, groundwater within the districts originates from a formation with insufficient amount of anhydrite and gypsum in solution or short residence time of these minerals with groundwater within the districts.Two principal hydrochemical type waters; Ca-Mg-HCO$_3$ and Na–Cl have been delineated, with Ca-Mg-SO$_4$, Na-Mg-Ca-HCO$_3$ and Na- Cl-SO$_4$ type waters as minor water types. Thus, groundwater within the districts principally evolves from fresh Ca– Mg–HCO$_3$ type water into Na–HCO$_3$ type water into Ca– Mg–Cl type water into Na–Cl type water along its flow path principally due to ion-exchange reactions and therefore, is largely characterized by recharge processes through mixing with waters of geochemically different ionic signatures than processes involving saline-water intrusion.

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TABLE 1
Mean hydrochemical data for ground and surface water within the Amansie and Adansi Districts

Sample Source	BH ID	PH	Eh	EC	TDS	ALK	TotH	Ca²⁺	Mg²⁺	Na+	K⁺	Cl⁻	HCO₃⁻	NO₃-N	PO₄-P	SO₄²⁻	SiO2	F⁻	E Bal	CBE %
Obuasi	BH1	5.5	0.05	112	73.6	30	24	8.8	0.5	5.8	3.1	9.9	36.6	0.043	0.594	0.087	11.4	<0.005	-0.07	-4.1
Obuasi New Site	BH2	5.6	0.07	239	156.5	40	68	23.2	2.4	15	4.1	41	48.8	0.46	0.293	0.087	20.0	<0.005	0.16	3.8
Obuasi Abuagye	BH3	5.5	0.05	174	113.9	32	36	8.8	3.4	12	3.5	27	39	0.82	0.333	0.077	20.0	<0.005	-0.07	-2.5
Brofoyedru	BH4	6.3	0.06	434	284.3	116	164	40.1	9.5	6.5	3.6	18	142	0.13	1.023	1.278	14.6	<0.005	0.30	4.9
Brofoyedru Enudaho	BH5	5.4	0.06	78	51.2	30	26	4	3.9	5.3	3	7.9	36.6	1.14	0.498	0.389	16.8	<0.005	-0.02	-1.2
Domeabra	BH6	5.0	0.1	169	110.6	10	14	2.4	1.9	15	5.4	25	12.2	8.66	0.421	0.111	20.0	<0.005	0.03	1.3
Domeabra	BH7	5.8	0.08	188	123.3	50	40	11.2	2.9	17	0.6	16	61	0.49	0.4	0.267	14.6	<0.005	1.0	3.3
Domeabra	BH8	4.4	0.12	372	243.7	8	60	16.8	4.4	7.2	3.2	46	9.8	0.72	0.362	0.357	10.3	<0.005	0.13	4.1
Domeabra	BH9	4.2	0.08	186	121.6	4	16	4	1.5	12	5.1	21	4.9	15.4	0.478	<0.001	16.8	<0.005	0.06	2.9
Obuasi (St Philips Sch.)	BH10	5.4	0.12	81	52.9	34	22	8	0.5	9.5	2.6	2	41.5	15.7	1.937	0.029	28.6	<0.005	-0.07	-3.7
Obuasi (St Philips Sch.)	BH11	5.4	0.14	69	45.3	10	12	1.6	1.9	9.2	4.4	13	12.2	16.1	0.193	0.066	15.7	<0.005	-0.08	-4.8
Brahabebumi	BH12	4.4	0.16	23	15.3	6	4	0.8	0.5	1.6	0.4	1	7.3	1.23	0.21	<0.001	10.3	<0.005	-0.03	-7.9
Brahabebumi	BH13	3.9	0.12	290	190.0	2	36	4.8	5.8	6.8	4.2	31	0.0	7.3	0.183	0.01	15.7	<0.005	0.09	4.4
Anyinam (Anyinamfie)	BH14	4.0	0.18	254	166.4	8	40	11.2	2.9	7.5	3.1	16	21.8	6.5	0.159	8.9	11.4	<0.005	0.11	4.7
Anyinam (Anyinamfie)	BH15	5.0	0.13	101	66.1	20	58	2.4	4.6	4.5	3.1	13	24.4	0.31	0.073	<0.001	31.8	<0.005	0.00	0.2
Anyinam Meth. Sch.	BH16	5.3	0.1	92	60.3	28	26	4	3.9	9.8	0.7	12	34.2	0.21	0.208	0.029	25.4	<0.005	0.06	3.5
Anyinam Meth. Sch.	BH17	5.6	0.1	90	59.0	42	40	10.4	3.4	9.9	0.2	8.9	51.2	0.335	1.742	0.121	22.2	<0.005	0.14	5.8
Bidiem	BH18	6.0	0.07	23	14.9	9	182	27.3	6.7	8.3	2.3	12	110	0.013	1.475	0.098	41.5	<0.005	0.19	4.3
Bidiem	BH19	5.0	0.1	59	38.6	14	8	2.4	0.5	9.8	0.4	9.9	17.1	4.32	0.117	0.09	20.0	<0.005	-0.03	-2.7
Bidiem (Exptal. Sch)	BH20	6.4	0.13	382	250.2	186	156	48.1	8.7	26	0.8	22	227	<0.001	0.518	0.149	13.5	<0.005	-0.09	-1.1
Bidiem (Exptal. Sch)	BH21	7.3	0.1	387	253.5	176	180	26.5	28	21	0.6	22	215	0.165	0.483	2.525	27.5	<0.005	0.31	3.6
Nsiaeso	BH22	6.1	0.11	281	184.1	100	92	19.2	11	22	0.7	35	122	0.12	0.583	2.412	22.2	<0.005	-0.22	-3.7
Nsiaeso	BH23	5.6	0.17	160	104.6	42	94	15.2	8.8	6.5	0.6	23	51.2	4.8	0.123	2.457	9.2	<0.005	0.17	5.0
Nsiaeso	BH24	5.9	0.09	151	98.7	74	60	21.6	1.4	12	0.4	3	90.3	0.12	0.197	2.43	20.0	<0.005	0.11	3.2
Nsiaeso	BH25	6.1	0.14	236	154.6	90	90	4	19	12	1.2	22	110	1	0.284	2.341	20.0	<0.005	-0.13	-2.8
Apitikrokro	BH26	5.2	0.11	59	38.4	26	22	2.4	3.9	6.7	1.7	7	31.7	0.155	0.169	2.425	12.5	<0.005	0.01	0.4
Apitikrokro	BH27	5.1	0.15	80	52.3	26	38	6.4	5.3	5.2	0.9	12	31.7	0.22	0.17	2.451	13.5	<0.005	0.09	5.0
Apitiso No. 1	BH28	5.3	0.17	110	72.2	24	34	5.6	4.9	4.2	2.5	12	29.3	0.24	0.135	2.299	17.8	<0.005	0.06	3.4
Apitiso No. 1	BH29	5.6	0.09	94	61.7	50	40	7.2	5.3	11	0.3	12	61	0.118	0.533	2.1	16.8	<0.005	0.09	-3.4
Apitiso No. 1	BH30	5.3	0.12	70	45.9	26	22	6.4	1.5	7.2	0.5	5	31.7	0.45	0.564	2.206	15.7	<0.005	0.06	3.7
Apitiso No. 1	BH31	5.5	0.13	146	95.4	46	36	11.2	1.9	15	0.4	20	56.1	0.35	0.678	2.25	30.8	<0.005	-0.15	-5.0
Apitiso No. 2	BH32	5.9	0.19	200	131.0	90	74	11.2	11	16	0.5	15	110	<0.001	0.276	0.422	11.4	<0.005	-0.04	-1.0
Apitiso No. 2	BH33	6.2	0.1	24	15.9	86	90	27.3	5.3	15	0.5	22	105	0.057	0.397	0.37	17.8	<0.005	0.13	2.7
Sanso	BH34	5.9	0.1	184	120.8	60	58	16	4.4	12	0.5	16	73.2	0.08	2.273	0.43	25.4	<0.005	0.05	1.5
Sanso	BH35	6.2	0.16	199	130.6	80	80	13.6	11	16	0.5	19	97.6	0.01	1.844	0.615	28.6	<0.005	0.17	3.8
Sanso	BH36	5.9	0.13	181	118.6	60	66	13.6	7.8	10	0.5	15	73.2	0.15	2.012	0.511	35.1	<0.005	0.14	4.2
Sanso	BH37	5.1	0.07	69	45.2	20	16	2.4	2.4	8.5	0.5	8.9	24.4	0.82	1.853	0.591	14.6	<0.005	0.02	1.7
Nyamebekyere No. 1	BH38	4.9	0.08	59	38.5	18	8	1.6	1	8.4	0.1	6	22	2.56	2.044	0.038	30.8	<0.005	-0.04	-3.8
Nyamebekyere No. 1	BH39	6.4	0.15	344	225.3	148	124	40.1	5.8	16	0.5	9.9	181	0.02	2.317	0.036	45.8	<0.005	-0.06	-0.9
Suhyensu	BH40	5.3	0.2	76	49.6	28	12	2.4	1.5	13e	0.1	8.9	34.2	3.01	2.516	<0.001	26.5	<0.005	-0.09	-5.5
Suhyensu	BH41	6.5	0.18	32	21.2	82	106	24	3.4	11	2.5	7.9	100	0.08	2.913	0.068	25.4	<0.005	0.17	4.3
Suhyensu	BH42	4.1	0.16	78	51.4	6	20	2.4	3.4	3.5	0.5	9.9	10.3	5.1	3.59	0.04	15.7	<0.005	0.03	3.0
Suhyensu	BH43	6.7	0.25	473	309.8	202	162	62.5	1.4	15	0.8	9.9	246	0.52	0.568	0.114	20.0	<0.005	-0.40	-4.8
Tweapiasi	BH44	3.7	0.18	454	297.4	6	58	8	9.2	19	0.8	66	0.0	4.1	0.484	0.15	28.6	<0.005	-0.06	-1.5
Tweapiasi	BH45	5.3	0.2	59	38.5	18	14	4	1.6	5	0.3	6	22	0.85	0.504	0.076	22.2	<0.005	0.01	1.0
Tweapiasi	BH46	5.5	0.15	79	51.6	20	22	7.2	1	3.3	0.2	5	24.4	0.8	0.677	0.127	22.2	<0.005	0.03	2.9
Tweapiasi	BH47	5.4	0.17	105	68.8	40	42	5.6	6.8	4.5	0.5	9.9	48.8	0.83	0.482	0.126	44.7	<0.005	-0.05	-2.2
Finosu	BH48	5.1	0.21	47	30.8	16	20	2.4	3.4	1.7	0.2	3	19.5	2.5	0.525	0.054	28.6	<0.005	0.03	3.6
Finosu	BH49	5.2	0.22	48	31.5	20	12	3.2	1	4.2	0.3	2	24.4	0.73	0.585	0.131	29.7	<0.005	-0.04	-4.3
Nyamsu	BH50	6.8	0.09	452	296.1	208	216	20.8	40	6.8	3.3	8.9	253	0.05	0.719	0.206	21.1	<0.005	0.29	3.2
Nyamsu	BH51	6.3	0.09	256	167.7	96	94	28.1	5.8	6	3	6	117	0.04	0.749	0.284	18.9	<0.005	0.12	2.9

TABLE 1 cont.

Sample Source	BH ID	PH	Eh	EC	TDS	ALK	TotH	Ca^{2+}	Mg^{2+}	$Na+$	K^+	Cl^-	HCO_3^-	NO_3-N	PO_4-P	SO_4^{2-}	$SiO2$	F^-	E Bal	CBE %
Akrokeri Coll. of Educ.	BH52	5.8	0.07	149	97.6	40	52	8	7.8	4.2	1	6.9	48.8	0.05	0.678	8.01	10.3	<0.005	0.09	3.6
Akrokeri Coll. of Educ.	BH53	4.5	0.17	64	42.1	10	20	3	2.9	1.5	0.5	6.9	12.2	0.92	0.599	0.542	28.6	<0.005	0.04	5.1
Akrokeri senit	BH54	5.8	0.08	140	91.7	32	32	8	2.9	2.5	0.5	5	39	0.35	0.822	1.316	21.1	<0.005	-0.06	-3.4
Akrokeri senit	BH55	3.6	0.05	364	238.4	12	54	15.2	3.2	3	0.5	17	0.0	0.8	0.746	15	64.1	<0.005	0.11	4.1
Borbriase	BH56	4.8	0.12	351	229.9	12	44	12.8	2.9	10	0.5	37	14.6	0.065	0.782	2.183	15.7	<0.005	0.00	0.2
Borbriase	BH57	5.1	0.05	50	32.6	16	4	1.6	1	4	0.1	1	19.5	0.53	0.749	0.318	34.0	<0.005	-0.02	-3.5
Bobriase	BH58	6.6	0.05	383	250.9	100	98	29.7	5.8	12	0.8	22	122	0.6	0.832	0.353	16.8	<0.005	-0.12	-2.3
Bobriase	BH59	5.5	0.07	166	108.4	30	32	6.4	3.9	10	0.8	21	36.6	0.85	0.708	0.325	27.5	<0.005	-0.11	-4.8
Dominase L/A Primary	WW1	6.6	-	426	279.0	124	200	45.7	8.5	6.3	0.6	16	151	0.22	0.802	1.14	23.2	<0.005	0.32	5.1
Dominase L/A Primary	WW2	5.4	-	146	95.7	18	38	8.8	3.9	4	0.8	18	22	0.94	0.894	0.554	26.5	<0.005	0.06	3.4
Obuasi Kofikrom	WW3	5.6	-	329	215.5	14	38	9.6	3.4	15	9.6	43	17.1	3.5	0.78	0.365	21.1	<0.005	0.11	3.4
Obuasi Kofikrom	WW4	4.7	-	263	172.3	8	30	4	4.9	15	1.6	38	9.8	3.62	0.994	0.377	26.5	<0.005	0.01	0.2
Obuasi Domeabra	WW5	5.3	-	59	38.9	14	20	4.8	1.9	2.2	0.5	4	17.1	3.68	0.632	0.38	37.2	<0.005	0.04	4.6
Obuasi Domeabra	WW6	5.4	-	61	40.0	20	20	4.8	1.9	2.8	0.5	3	24.4	3.75	0.781	0.328	50.1	<0.005	-0.02	-2.0
Obuasi Domeabra	WW7	5.2	-	52	34.2	20	16	4	1.5	8.2	0.8	9.9	24.4	3.5	0.796	0.421	37.2	<0.005	-0.04	-3.1
Obuasi Domeabra	WW8	6.2	-	226	148.0	82	76	19.2	6.8	11	1	12	100	0.16	0.553	0.655	13.5	<0.005	0.01	0.2
Asokwa Adanse	WW9	5.7	-	82	53.7	20	20	6.4	1	5	0.6	8.9	24.4	0.55	0.627	0.362	37.2	<0.005	-0.03	-2.5
Asokwa Adanse	WW10	6.3	-	105	68.6	28	42	8.4	2.9	1.3	0.4	3	34.2	0.45	0.76	0.435	8.2	<0.005	0.06	4.6
Brofoyedru Zongo	WW11	6.2	-	72	47.2	20	20	4	2.4	2.5	0.4	5	24.4	0.53	0.674	0.404	12.5	<0.005	-0.04	-3.4
Brofoyedru Zongo	WW12	5.1	-	47	30.7	12	12	10	1.5	4.5	0.2	18	16.6	0.057	3.85	0.719	23.2	<0.005	0.04	2.4
Brofoyedru Ewudahor	Str. 1	5.4	-	152	99.8	28	28	9	1.9	12	0.8	24	34.2	0.056	3	0.674	45.8	<0.005	-0.10	-4.4
Brofoyedru Ewudahor	Str. 2	5.8	-	105	68.8	7.5	22	10	2.2	1.2	0.5	8.8	26.8	0.61	0.4	0.693	23.2	<0.005	0.03	2.3

All values in mg/L, except EC (μS/cm), pH (pH units), Eh (V), E Bal = Electrical balance, CBE = Charge balance error (in percentage)

TABLE 3
Saturation indices for some minerals in groundwater within the Amansie and Adansi Districts

Sample source	T^oC	pH	$Anh_{(SI)}$	$Cal_{(SI)}$	$Dol_{(SI)}$	$Fe(OH)_{3 (SI)}$	$Geo_{(SI)}$	$Mel_{(SI)}$	$Gyp_{(SI)}$	$Hem_{(SI)}$	$Sid_{(SI)}$	SiO_2 (a) $_{(SI)}$	$CO2(g)$
Obuasi	28.5	5.5	-2.6	1.0	1.0	1.8	7.7	-7.4	-2.3	17.6	0.8	-0.8	-0.7
Obuasi New Site	27.3	5.6	-2.5	1.4	1.9	0.9	6.8	-8.3	-2.2	15.7	0.1	-0.1	-0.5
Obuasi Abuagye	28.3	5.5	-2.7	1.0	1.7	2.3	8.2	-7.0	-2.5	18.6	1.4	-1.4	-0.6
Brofoyedru	28.3	6.3	-1.3	1.8	3.2	0.4	6.3	-7.6	-1.1	14.8	0.1	-0.4	-0.1
Brofoyedru Enudaho	28.2	5.4	-2.3	0.7	1.6	1.1	7.0	-7.4	-2.1	16.2	0.1	-0.1	-0.7
Domeabra	27.6	5.0	-3.0	0.0	0.1	1.7	7.6	-7.3	-2.7	17.5	0.3	-0.8	-1.2
Domeabra	27.5	5.8	-2.2	1.2	2.0	1.4	7.3	-7.3	-2.0	16.7	0.7	-0.7	-0.2
Domeabra	27.6	4.4	-1.9	0.6	0.8	1.5	7.4	-7.0	-1.7	17.0	0.1	-0.1	-1.2
Domeabra	27.4	4.2	-4.8	-0.2	-0.6	1.8	7.7	-9.2	-4.6	17.6	0.1	-0.1	1.5
Obuasi (St Philips Sch.)	28.0	5.4	-3.1	1.0	1.0	2.3	8.2	-7.3	-2.9	18.6	1.4	-1.4	-0.6
Obuasi (St Philips Sch.)	27.9	5.4	-3.3	-0.1	0.0	2.6	8.5	-6.6	-3.1	19.2	1.2	-1.2	-1.1
Brahabebumi	27.5	4.4	-5.1	-10.4	-0.9	2.9	8.8	-8.1	-4.9	19.7	1.2	-1.2	-1.4
Brahabebumi	27.8	3.9	-3.8	-0.4	-0.6	2.7	8.6	-7.4	-3.6	19.3	0.6	-0.6	-1.9
Anyinam (Anyinamfie)	28.1	4.0	-0.6	0.4	0.4	2.5	8.4	-4.7	-0.4	18.9	1.0	-1.0	-1.2
Anyinam (Anyinamfie)	29.3	5.0	-5.0	0.3	1.2	2.5	8.4	-8.6	-4.8	19.1	1.4	-1.4	-0.8
Anyinam Meth. Sch.	28.5	5.3	-3.4	0.7	1.5	1.8	7.6	-7.9	-3.2	17.6	0.8	-0.8	-0.7
Anyinam Meth. Sch.	28.9	5.6	-2.5	1.2	2.0	1.6	7.5	-7.5	-2.3	17.3	0.8	-0.8	-0.5
Bidiem	28.8	6.0	-2.3	-0.9	-2.2	-2.8	3.1	-6.9	-2.1	8.4	-0.8	-0.8	0.5
Bidiem	29.1	5.0	-2.2	2.0	3.5	2.0	7.9	-7.0	-2.0	18.0	2.0	-2.0	0.2
Bidiem (Experimental Sch)	28.6	6.4	-1.2	1.5	3.0	1.7	7.6	-6.0	-1.0	17.4	1.4	-1.4	-0.1
Bidiem (Experimental Sch)	28.9	8.0	-1.2	1.2	2.4	2.1	8.0	-5.7	-1.0	18.3	1.3	-1.3	-0.5
Nsiaeso	28.0	6.1	-1.0	1.6	2.1	1.9	7.8	-5.9	-0.8	17.8	1.4	-1.4	-0.3

TABLE 3 Cont.

Sample source	T^{o}C	pH	Anh$_{(SI)}$	Cal$_{(SI)}$	Dol$_{(SI)}$	Fe(OH)$_{3\,(SI)}$	Geo$_{(SI)}$	Mel$_{(SI)}$	Gyp$_{(SI)}$	Hem$_{(SI)}$	Sid$_{(SI)}$	SiO$_2$ (a)$_{(SI)}$	CO2(g)
Nsiaeso	29.2	5.6	-1.9	0.9	2.6	1.8	7.7	-5.9	-1.7	17.8	1.4	-1.4	-0.2
Nsiaeso	28.8	5.9	-1.7	0.4	1.2	1.1	7.0	-6.6	-1.5	12.8	0.1	-0.1	-0.7
Nsiaeso	28.7	6.1	-1.3	0.8	1.6	1.7	7.5	-6.1	-1.1	17.3	0.7	-0.7	-0.7
Apitikrokro	27.9	5.2	-1.4	0.7	1.4	1.9	7.8	-5.8	-1.2	17.7	0.9	0.9	-0.8
Apitikrokro	27.8	5.1	-1.4	1.0	2.1	1.8	7.7	-6.0	-1.2	17.5	1.1	-1.1	-0.5
Apitiso No. 1	27.3	5.3	-1.3	0.8	1.1	1.9	7.8	-5.8	-1.1	17.8	0.9	-0.9	-0.7
Apitiso No. 1	27.4	5.6	-1.2	1.2	1.7	1.8	7.7	-6.0	-1.0	17.6	1.1	-1.1	-0.5
Apitiso No. 1	27.2	5.3	-2.1	1.3	2.8	1.6	7.5	-6.9	-1.9	17.2	1.2	-1.2	-0.2
Apitiso No. 1	27.5	5.5	-1.9	1.7	2.8	1.6	7.4	-7.0	-1.7	17.1	1.1	-1.1	-0.2
Apitiso No. 2	27.4	5.9	-1.9	1.4	2.4	1.6	7.5	-6.9	-1.7	17.3	1.0	-1.0	-0.4
Apitiso No. 2	27.5	6.2	-1.9	1.4	2.9	0.9	6.8	-7.5	-1.7	15.8	0.4	-0.4	-0.2
Sanso	28.6	5.9	-1.9	1.3	2.6	1.6	7.5	-6.8	-1.7	17.3	1.0	-1.0	-0.4
Sanso	28.6	5.9	-2.2	0.4	0.9	1.5	7.3	-6.9	-2.0	17.0	0.3	-0.3	-0.8
Sanso	28.7	5.9	-2.7	0.5	0.3	-2.6	3.3	8.9	-2.5	8.9	-1.0	-1.0	0.6
Sanso	28.8	5.1	-5.0	0.5	0.9	2.0	7.9	-9.1	-4.8	17.9	1.0	-1.0	-0.7
Nyamebekyere No. 1	27.6	4.9	-2.6	1.7	2.7	0.8	6.7	-8.7	-2.4	15.6	0.2	0.2	-0.3
Nyamebekyere No. 1	27.9	6.4	-3.3	-0.1	0.2	2.3	8.1	-7.2	-3.1	18.5	0.6	-0.6	-1.4
Suhyensu	27.3	5.3	-2.3	2.2	2.3	0.2	6.1	-8.9	-2.1	14.3	0.2	0.2	0.2
Suhyensu	27.7	6.5	-2.6	0.2	0.6	2.0	7.9	-6.9	-2.4	18.0	0.4	0.4	-1.4
Suhyensu	27.8	4.1	-2.8	-0.6	-1.5	-0.7	5.2	-7.2	-2.6	12.7	-0.4	-0.4	-0.4
Suhyensu	27.9	6.7	-2.4	0.8	1.0	2.1	8.0	-6.9	-2.2	18.2	1.0	-1.0	-0.8
Tweapiasi	28.3	3.7	-2.7	0.9	2.0	1.5	7.4	-7.5	-2.5	17.0	1.3	1.3	-0.5
Tweapiasi	28.2	5.3	-3.2	-1.1	-1.8	-0.6	5.3	-6.9	-3.0	12.9	-0.2	-0.2	-0.4
Tweapiasi	28.3	5.5	-2.7	0.5	0.7	2.1	8.0	-6.8	-2.5	18.4	1.0	-1.0	-0.8
Tweapiasi	28.2	5.4	-2.5	1.7	3.9	0.7	6.6	-8.1	-2.3	15.5	0.7	-0.7	-0.2
Finosu	28.7	5.1	-2.0	1.7	3.0	1.1	7.0	-7.6	-1.8	16.2	0.7	-0.7	-0.2
Finosu	28.9	5.2	-0.9	0.9	2.0	2.5	8.4	-4.7	-0.7	19.0	1.7	1.7	-0.6
Nyamsu	28.3	6.8	-2.1	0.2	0.5	2.9	8.8	-5.4	-1.9	19.8	1.5	1.5	-1.1
Nyamsu	28.6	6.3	-1.5	1.0	1.7	1.3	7.1	-6.7	-1.3	16.5	0.3	-0.3	-0.7
Akrokeri College of Educ.	27.3	5.8	-0.3	0.7	0.8	1.3	7.1	-5.7	-0.1	16.5	-0.2	-0.2	-1.1
Akrokeri College of Educ.	27.4	4.5	-1.2	0.7	0.9	1.5	7.4	-6.3	-0.9	16.8	0.2	-0.2	-1.1
Akrokeri zenit	27.1	5.8	-2.5	0.1	0.2	2.9	8.8	-5.5	-2.3	19.8	1.7	-1.7	-1.0
Akrokeri zenit	27.4	3.6	-1.9	1.7	2.9	0.9	6.7	-7.7	-1.7	15.6	0.5	-0.5	-0.2
Borbriase	26.4	4.8	-2.2	0.8	1.6	2.7	8.6	-5.9	-2.0	19.2	1.7	-1.7	-0.7
Borbriase	26.4	5.1	-1.3	1.9	3.3	1.1	7.0	-7.0	-1.1	16.1	0.8	-0.8	-0.1
Bobriase	26.7	6.6	-1.8	0.8	1.4	1.8	7.7	-6.5	-1.6	17.6	0.7	-0.7	-0.9
Bobriase	26.8	5.5	-0.3	0.8	1.2	1.8	7.7	-4.9	-0.1	17.4	0.8	-0.8	-0.7

SI-saturation index, Anh-anhydrite, Cal-calcite, Dol-dolomite, Fe (OH)$_3$-amorphous ferric hydroxide, Geo-geothite, Mel- melantherite, Gyp-gypsum, Hem-hemathite,

Sid-siderite, SiO$_2$- amorphous silica