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The Hydrochemistry of Groundwater in Some Communities in the Ayensu River Basin in the Central Region of Ghana

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Abstract

Hydrochemical analysis of groundwater samples in some communities in the Ayensu river basin of the central Region of Ghana was used to establish the hydrochemistry of the study area. The methodology consisted of physicochemical sampling and laboratory analysis of groundwater resources in the Basin and basic statistical analysis of the laboratory results. Generally, the groundwater is weakly acidic with a mean pH value of 6.32, had high electrical conductivity and TDS values in the range, 256.4 µS cm^{-1} to 2313.3 µS cm^{-1} and 101.7 mg/L to 1247.0 mg/L respectively. The groundwater in the area is undersaturated with respect to carbonate phases and is fresh except for one borehole at Gyangyanadze which has TDS value of 1247.0 mg/L considered as saline water. The dominant water types in the study area are Na- Cl, Ca- Mg - Cl and Ca - Mg - SO_4. The groundwater is to a large extent potable. However, approximately 13% of the groundwater samples had chloride concentrations slightly exceeding the respective WHO maximum acceptable limits for drinking water. Approximately 43%, 16% and 10% respectively of the water samples had Al^{3+}, Fe^{2+} and Cd^{2+} concentrations above the respective WHO maximum acceptable limit for drinking water. Silicate mineral weathering is probably the main process through which major ions enter the groundwater.

Keywords: Groundwater quality hydrochemistry silicate weathering Central Region Ghana

1. Introduction

The rapid growth of population coupled to steady increase in water requirements for agricultural and industrial development have imposed severe stress on the available freshwater resources in terms of both the quantity and quality, requiring consistent and careful assessment and management of water resources for their sustainable development (Mook, 2000). Realizing that most surface water resources are polluted, the government of Ghana has shifted attention from developing surface water resources to groundwater resource development and to supply communities in rural areas because of the anticipated high cost of treating polluted surface water resources. Consequently, groundwater has become the principal and sometimes the only source of rural water supply for domestic, drinking, agricultural and industrial use in most of the rural communities (Kortatsi, 2007). The chemical composition of ground water is controlled by many factors, including composition of precipitation, mineralogy of aquifers, climate, topography, anthropogenic activities. These factors combine to create diverse water compositions that vary temporally and spatially. Additionally, these factors may lead to contamination of ground water with diverse constituents, resulting in severe environmental and socio-economic problems (Kumar and Riyazuddin, 2008). Groundwater is generally less susceptible to contamination and pollution when compared to surface water bodies (Zaman, 2002). Also the natural impurities in rainwater, which replenishes groundwater systems, get removed while infiltrating through soil strata (Veslind, 1993). Reliable data on water quality is of importance for proper management, protection and development of ground and surface water resources for the future (WRC, 2008). A comprehensive assessment of the physical and chemical quality of the groundwater in these communities is therefore required so as to understand its chemical characteristics. The main objective is to determine the hydrochemistry in the area and the possible sources of the various ions in groundwater.

2.0 The study area

The study area is a rural community located in the Central Region of Ghana (Fig. 1). The area lies between latitudes 5^{O} 20'N - 5^{o} 45'N and longitudes 0^{o} 300'W - 0^{o} 450'W. The Ayensu River takes its source from the Bunsu Hills, an extension of Atiwa Range, in the Eastern region of Ghana from where it flows generally southward to the sea. The basin has a varied climatic and vegetation characteristics. The upper reaches of the Ayensu basin fall within the moist (humid) semi-deciduous rainforest zone with a two peak rainfall regime of an average annual rainfall ranging from 1,370 to 1,650 mm. The central and southern coastal areas, however fall within the dry marginal Forest- Savannah Transition zone with an average annual rainfall of some 1,145 to 1,650 mm and the Sub-humid Coastal Savannah Zone with an annual average rainfall ranging from 750 to 1,150 mm, respectively. Most of the forest was opened up for cocoa cultivation which is currently replaced by intensive bush fallow food crop cultivation (cocoyam, plantains, cassava, maize, vegetables) and oil palm plantation development. The original forest cover is almost completely eliminated. The present cover consists of small areas of secondary forest with low bush fallow re-growth in the forest areas and grasses in the coastal zone (WRMS, 2008).

3.0 Hydrogeology of the area

The Ayensu Basin is basically underlain by two main rock types namely Granites and Upper Birimian rocks. The basement rocks consist of the granitoids which largely underlie the northern portion and south eastern corner of the basin. Generally, these rocks are well foliated, often migmatic, potash rich granitoids which come in the form of muscovite biotite granite and granodiorite, porphyroplastic biotite gneiss, aplites and pegmatites. They are often characterized by the presence of many enclaves of schist and gneisses. The upper Birimian are volcanic rocks covering a relatively small portion to the south west of the basin. Generally, these deposits consist of mafic volcanic flows or subvolcanic dikes with pyroclastics, interbedded clastic and chemical metasediments; generally metamorphosed to greenschist and amphibolite facies, and moderately deformed. The Ayensu basin rocks are relatively more deformed to allow mobility of fluid that aids in weathering. The area is very hot and humid and the presence vegetation cover also contributes to the decay process of the rocks. Hence these factors lend themselves to giving the basin a relatively higher rate of weatherability than similar basement and sedimentary rocks found in other places in the country (WRCS, 2008).

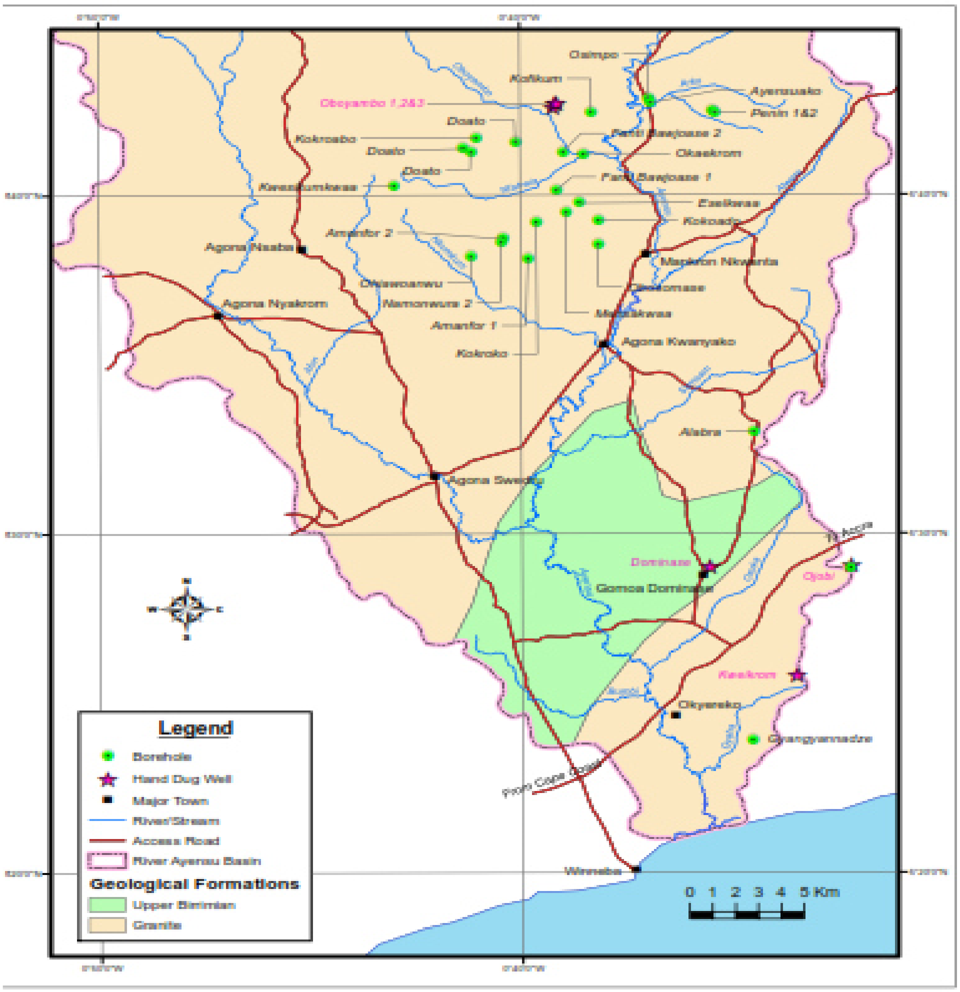

Figure 1 : Map of the study area.

4.0 Methodology

Groundwater samples were collected from 24 boreholes fitted with pumps and 7 shallow hand dug wells. The water samples were collected in 500 cm^3 acid-washed high-density polyethylene sampling bottles after filtering through 0.45µm filters on acetate cellulose with a hand operated vacuum pump. At each sampling point, two samples were collected for major ions and trace metals analysis. Water samples for metal analysis were acidified with 1% HNO_3 to keep metals in solution. The water samples were analyzed in the field for temperature, pH, electrical conductivity (EC), total dissolved solids (TDS) and salinity using pH/conductivity meter (CyberScan PC6000) with a glass electrode (APHA, 1995). Alkalinity titrations were carried out at the sampling sites using HACH Digital Titrator Model 16900. All samples were transported to the laboratory in ice-filled coolers, and kept refrigerated at approximately 4°C until analyzed. Concentrations of Na^+ and K^+ were determined using flame photometer, Ca^{2+} and Mg^{2+} by EDTA titration and the trace metals (Fe, Mn, Al, Zn, Cu, Cr, Cd) were determined using atomic absorption spectrometer. The anions (Cl^-, SO_4^{2-}, NO_3^- and PO_4^{3-}) were analysed using Dionex ICX- 90 Ion Chromatography system. The ionic balance was determined for the results of the major cations and anions and the results are presented in Appendix A table 2.

5 Results and Discussion

5.1 Summary statistics

A statistical summary of hydrochemical parameters and saturation indices for carbonate, iron bearing minerals, gypsum, albite, anhydrite, amorphous silicate and quartz measured in the groundwater samples are presented in Tables 1 and 2 respectively. The actual results are presented in appendices 1, 2 and 3.

Table 1.0: Statistical summary of the parameters determined in the 31 groundwaters sampled in some communities in the Ayensu River Basin.

	Minimum	Maximum	Mean	Median	STD	WHO guideline limit
Temp.	22.5	30.4	26.11	26.3	1.99	
pH	4.77	8.10	6.32	6.14	0.73	6.5 – 8.5
EC	256.4	2313.3	987.86	960.1	481.66	
TDS	101.7	1247.0	466.03	402.5	263.17	
Alk.	1.2	33.4	11.46	7.3	8.02	
Ca^{2+}	8.75	112.0	39.97	38.0	19.83	
Mg^{2+}	5.3	74.73	29.26	31.3	16.18	
Na^+	21.0	510.5	97.70	76.4	91.75	200.0
K^+	2.0	60.5	10.32	8.3	10.1	
HCO_3^-	1.46	40.75	13.98	8.91	9.79	
Cl^-	53.25	613.91	190.91	168.7	112.65	250.0
SO_4^{2-}	42.0	416.97	118.93	104.0	67.63	250.0
NO_3^-	0.031	1.20	0.18	0.141	0.205	50.0
PO_4^{3-}	0.00	17.748	1.84	0.272	3.69	
Zn	0.002	0.704	0.120	0.064	0.147	3.000
Cu	<0.003	0.353	0.090	0.021	0.138	2.000
Fe	<0.006	1.465	0.436	0.226	0.496	0.300
Cr	<0.001	0.009	0.006	0.006	0.002	0.050
Cd	<0.002	0.073	0.050	0.062	0.032	0.003
Mn	<0.002	0.391	0.068	0.027	0.109	0.500
Al	<0.030	0.438	0.287	0.301	0.079	0.200
Salinity	0.096	1.33	0.475	0.403	0.283	

Temp. in °C, pH in pH-units, EC in µS cm^{-1}, TDS to SiO_2 in mgL^{-1}

The groundwater in some of the communities in the Ayensu River Basin shows a wide range of physicochemical parameters and elemental concentrations characteristics (Table 1.0). The temperature of the water samples ranged between 22.2 °C and 30.4°C and a pH range 4.77 – 8.10 with the mean and median values of 6.32 and 6.14, respectively. The results indicate that the groundwater is slightly acidic but fall within the range 4.5- 9.0 for natural water (Langmuir, 1997; Kortatsi, 2007). The electrical conductivity values are in the range 256.4 – 2313.0 µS cm^{-1} with mean and median values of 987.86 µS cm^{-1} and 960.1 µS cm^{-1} respectively. About 97% of the water samples were fresh since the TDS did not exceed 1,000 mg/L recommended for domestic water (Kattan 1995; WHO 1996). The TDS values range between 101.7 mg/L and 1247.0 mg/L with a mean of 466.03 mg/L and median value of 402.5mg/L. An exception was recorded in the borehole at Gyangyanadze. The TDS value for the borehole was 1247.0 mg/L. Gyangyanadze is near the coast and there is a possibility of direct seawater intrusion or sea aerosol sprays getting into the groundwater. In most of water samples (>75%) Na^+ shows a clear dominance but in few cases either Ca^{2+} or Mg^{2+} appear to be the dominant cation. Na^+ ranges from 21.0mg/L to 510.5 mg/L with a mean of 97.97. The dominant anion in the samples is Cl^- followed by SO_4^{2-}, HCO_3^- and then NO_3^-. Cl^- varies from 53.25mg/L to 613.91mg/L with a mean of 190.91mg/L. Approximately 13 % of the water samples exceeded the permissible levels of 250mg/L for Cl^- ion (WHO, 2004).

The trace metal loading of the groundwater is not high. Only aluminium, iron, and cadmium showed concentrations significantly above their detection limits in most of the water samples. Some of the water samples had the Al^{3+} ion concentrations below detection limit but approximately 39% of the samples had Al^{3+} concentrations above the WHO maximum acceptable limit of 0.200 mg/l for drinking water. Nearly 16% of the groundwater samples have their Fe^{2+} concentrations exceeding the WHO maximum acceptable limit of 0.300 mg/L and approximately 10% of the water samples had their Cd^{2+} exceeding WHO limit. This could pose serious health problems for the communities concerned.

Table 2.0: Statistical summary of saturation indices for carbonate, iron bearing minerals, gypsum, albite, anhydrite, amorphous silicate and quartz.

Parameter	Min.	Max.	Mean	Median	Std.
pH	4.77	8.10	6.32	6.13	0.745
Si_ Albite	-2.4	2.53	1.03	1.44	1.34
Si_ Anhydrite	-3.11	-1.36	-2.02	-2.05	0.35
Si_ Calcite	-263.08	-0.29	-129.76	-127.82	129.303
Si_ Dolomite	-525.47	-0.39	-259.33	-255.28	258.57
Si_ $Fe(OH)_3$(a)	-0.97	0.17	-0.32	-0.28	0.24
Si_ Goethite	4.7	8.72	7.36	7.72	1.12
Si_ Gypsum	-2.9	-1.13	-1.8	-1.83	0.35
Si_ Halite	-7.45	-5.32	-6.48	-6.42	0.45
Si_ Hematite	11.4	19.47	16.75	17.46	2.23
Si_ SiO_2(a)	-0.97	-0.06	-0.30	-0.28	0.17
Si_ Quartz	0.27	1.19	0.93	0.95	0.17
H_4SiO_4/Na^+	0.02	1.37	0.41	0.33	0.28
H_4SiO_4/HCO_3^-	0.00	364	14.8	0.96	65.0
Fe^{2+}/SO_4^{2-}(Molar ratio)	0.00	0.197	0.013	0.006	0.030

5.2 Saturation Indices

The saturation state of the groundwater was assessed with respect to the major carbonate minerals in order to investigate the thermodynamic controls on the composition of the groundwater and the approximate degree to which the groundwater has equilibrated with the various carbonate mineral phases. The quality of groundwater also depends on the mineralogy, reactivity of drift materials and the degree of equilibrium that has been attained between water and rock (Robins, 2002). The saturation indices were determined using the hydrogeochemical equilibrium model, Phreeqc for Windows (Parkhurst and Apello, 1999). The saturation index (SI) of groundwater samples with respect to mineral precipitation is expressed by:

$SI = \log_{10}(IAP/K\text{sp})$

where IAP is the ion activity of the solution and K_{sp} is equilibrium constant which is the solubility product at a given temperature. The thermodynamic data used in this computation were those contained in the default database of the Phreeqc for Windows. Supersaturation ($SI > 0$) indicates that precipitation is thermodynamically favorable in spite of the fact that slow rates of reaction can inhibit precipitation. Undersaturation ($SI <0$) on the other hand signifies that dissolution is favored. The summary statistics of saturation indices some of the common mineral phases is presented in Table 2.

A plot of computed saturation indices for calcite and dolomite (the commonest carbonate phases) for the groundwater samples is shown in Fig. 2.0. In the diagram, calcite saturation is indicated on the ordinate and dolomite on the abscissa. A central band, of 0.4 units wide along each axis, represents essential equilibrium with respect to either mineral to account for the possible errors that may occur in the measurement of pH, Mg^{2+} and Ca^{2+}.

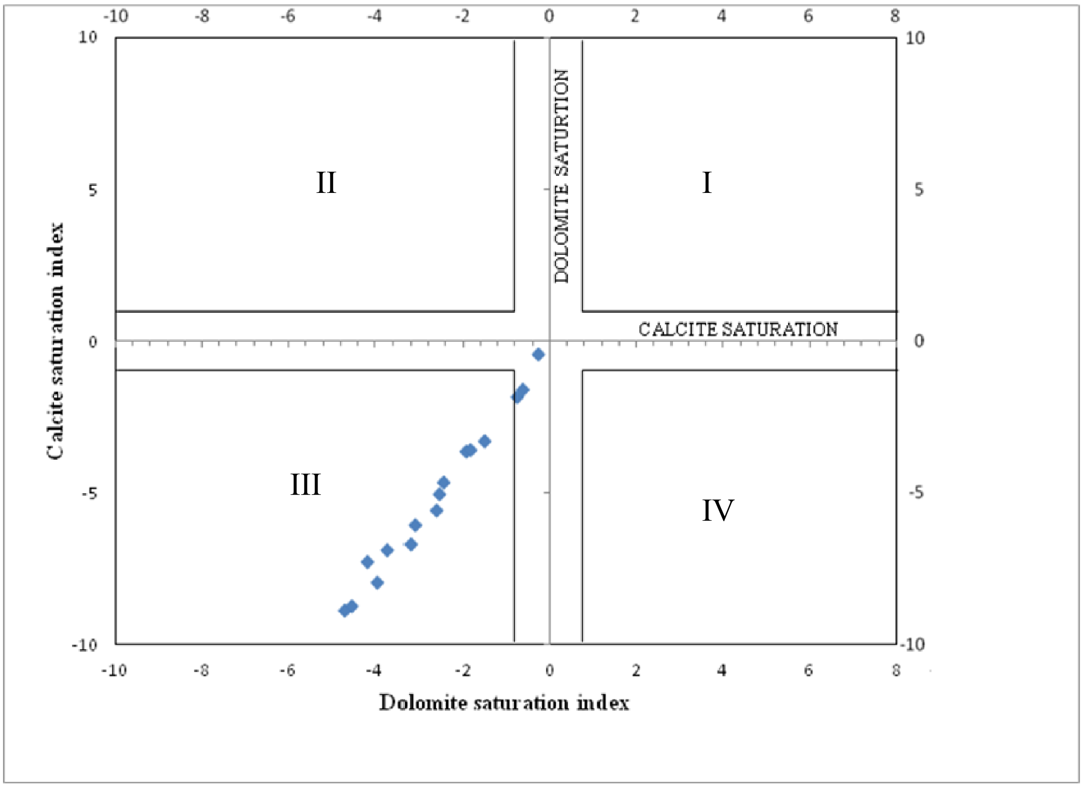

Figure 2.0: Plot of calcite versus dolomite saturation indices

The four quadrants of the plotting field, I- IV, outside the equilibrium area, represent different kinds of equilibrium conditions with respect to calcite and dolomite. Quadrant I represents super-saturation with respect to both carbonates. This condition represents water brought to equilibrium with respect to these carbonates and subsequently transported into a different environment where a higher pH or an apparent condition caused by the failure of the measured pH to accurately represent the actual equilibrium pH of the water in the aquifer (Langmuir, 1971; Kortatsi, 2007). Quadrant II, represent super-saturation with respect to calcite but undersaturation with respect to dolomite. Water undergoing incongruent dissolution of dolomite or precipitation of calcite would plot in the quadrant. Quadrant III, represent undersaturation with respect to both calcite and dolomite. A sample plotting in this quadrant represents water that has come from an environment where carbonates are impoverished. Water that has not reached equilibrium with the carbonates due to the short residence time would plot in this quadrant (Langmuir, 1971; Kortatsi 2007). Quadrant IV represents super-saturation with respect to dolomite and undersaturation with respect to calcite.

All the groundwater samples plotted in quadrant III, indicating that the groundwater is undersaturated with respect to the major carbonate species. Thus, either the groundwater originates from an environment where calcite and dolomite are impoverished or the residence time is short and has inadequate time for the mineral phases to react to equilibrium.

The stability diagram of albite and its possible weathering products gibbsite, kaolinite and Na-montmorillonite (Tardy, 1971) for the groundwaters in the communities sampled is shown in Fig. 3.0.

Thermodynamic plotting of $[Na^+]/[H^+]$, for groundwater from study area are plotted on the stability diagram as a function of $[H_2SiO_4]$. Most of the samples cluster in the Na- montmorillonite stability field and a few plot in the kaolinite stability field, indicating Na–Montmorillonite is the end product of the silicate weathering. This is consistent with the relatively low rainfall and poorly drained soils in the lower Ayensu basin

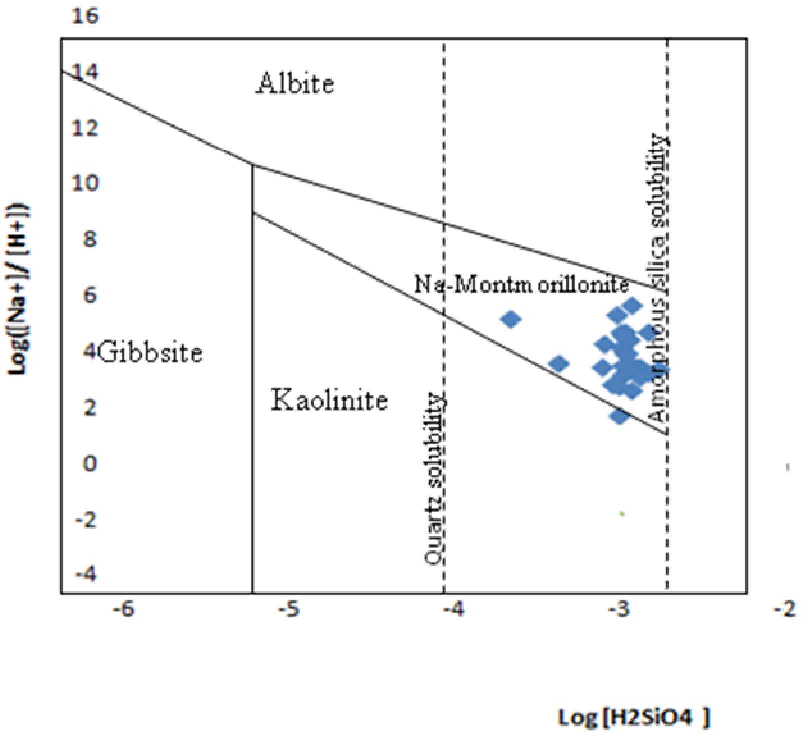

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Figure 3.0: The stability of albite and its possible weathering products gibbsite. kaolinite and Na-montmorillonite with respect to the groundwaters in some communities in the Ayensu Basin (modified after Tardy1971)

5.3 Pearson Correlation

Correlation coefficient is commonly used to establish the relation between independent and dependent variables (Nair *et al*., 2005). Strong (r = 0.8 to 1.0), moderate (r = 0.6 to 0.8) and low (r = 0.5 to 0.6) correlation between selected variables was found out.

The correlation matrix of 13 parameters, for the 31water samples in the study area is indicated in Table 3.0. There is a good correlation between the conductivity (EC) and, Na^+, Cl^-, Mg^{2+}, SO_4^{2-} and TDS. Identically, a good correlation exists between TDS and Na^+, Cl^-, Mg^{2+} and SO_4^{2-}. This high positive correlation implies that TDS or salinity is derived from these ions. Good, medium and low correlation between chemical parameters indicates that electrical conductivity and total dissolved solids is the most appropriate variable in explaining the variation in hardness, sodium, magnesium, sulphate, chloride and bicarbonate (Pattanaik, 2007). The major exchangeable ions, EC and Na (0.7), Na and Cl (0.9), TDS and Na (0.7), Mg and Cl (0.7), Na and SO_4^{2-} (0.8) were found to be correlated positively indicating the origin of major cations to be dissolution/precipitation processes (Khatiwada *et al*., 2002). Cl and Na possess a very good positive correlation (0.9) between each other indicating that are coming from the same source. The dissolution of halite in water release equal concentrations of Na and Cl into the solution (Belkhiri *et al*., 2010).

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Table 3.0: Pearson Correlation Matrix for the water samples

	pH	EC	TDS	ALK	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}	PO_4^{2-}
pH	1												
EC	0.6	1											
TDS	0.7	1	1										
ALK	0.6	0.5	0.56	1									
Ca^{2+}	0.4	0.2	0.22	0.6	1								
Mg^{2+}	0.3	0.6	0.61	0.3	-0.2	1							
Na^{+}	0.5	0.7	0.73	0.2	-0.2	0.6	1						
K^{+}	0.0	0.4	0.33	0.3	0.1	0.1	0.0	1					
Cl^{-}	0.5	0.7	0.79	0.4	0.0	0.7	0.9	0.1	1				
SO_4^{2-}	0.5	0.7	0.72	0.2	-0.1	0.6	0.8	0.1	0.6	1			
HCO_3^{-}	0.6	0.5	0.56	1.0	0.6	0.3	0.2	0.3	0.4	0.18	1		
NO_3^{-}	0.3	0.4	0.4	0.2	-0.1	0.4	0.5	0.0	0.5	0.2	0.21	1	
PO_4^{3-}	0.1	0	-0.3	0.0	-0.1	-0.1	-0.2	0.2	0.3	-0.22	0.01	-0.06	1

5.4 Hydrochemical facies

The chemical composition of the water samples from the study area is shown on the Piper diagram in Fig. 4.0. In the cation plot field (the triangle on the left) some samples plot towards the Na+K corner indicating sodium type or p vaters but some of the samples plotted towards the middle triangle indicating no dominant cati LEGEND ater sample plotted in the Ca water type. In the anion plot field (triangle on the right) the samples mostly plotted towards the Cl^- corner indicating chloride type water, while a few plotted towards the sulphate corner. Most of the boreholes and hand dug wells waters cluster towards Na - Cl section. A few show Ca - Mg - SO_4 and Ca - Mg - Cl water types. The ionic dominance pattern of the groundwater samples were Na > Ca > Mg > K and Cl^- >SO_4^{2-} > HCO_3^- > NO_3^-.

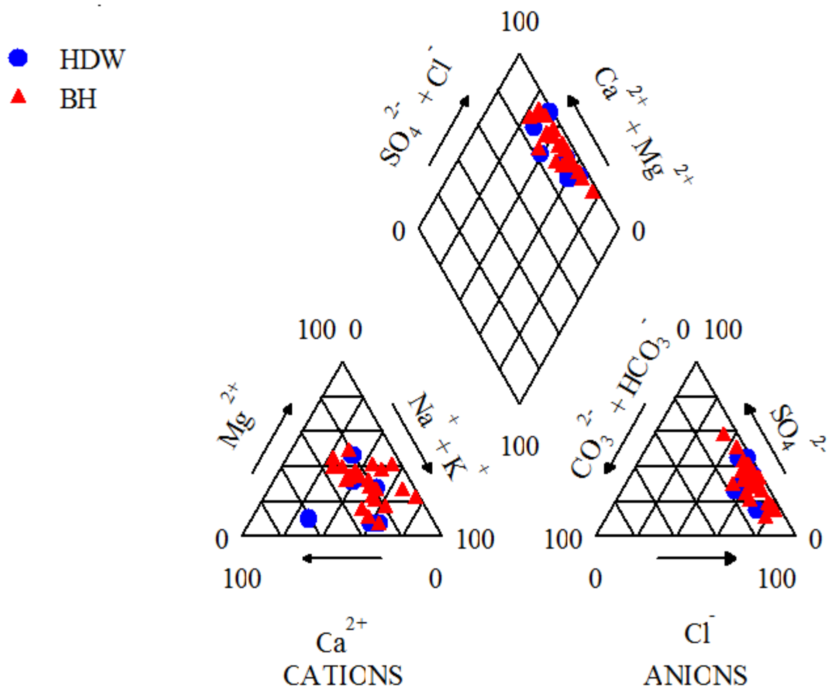

Figure 4.0: Piper diagram for the water samples

5.5 Sources of major ions

Relationships between major cations and anions have been employed to deduce the probable sources of these ions in groundwater (Jalali, 2007; Kortatsi, 2006). The Na–Cl relationships have often been used to identify the mechanisms for acquiring salinity and saline intrusions (Jalali, 2007; Dixon & Chiswell, 1992). From figure 4.0, it is realized that approximately 32% of the water samples have Na^+/ ($Na^+ + Cl^-$) ratio within the range 0.5 ± 0.1 or plot along or close to 1:1 line in the graph of [Na^+] versus [Cl^-]. This suggests that either sea aerosols or halite dissolution is responsible for Na^+ in the groundwater. Since halite is not known to be associated with the rocks in the Ayensu Basin, it implies that sea aerosols is partially the likely source of sodium in the groundwater (Kortatsi, 2007). The other possibility is the dissolution of soluble salts in the soil horizons. Salts could have been formed as a result of aerosol deposition or ancient seawater flooding in the area. Most of the water samples (68%) fall below and away from the 1:1 line indicating that reverse ion exchange is also occurring in the Basin. One sample however, fell above the 1:1 line of the [Na^+] versus [Cl^-] graph (i.e. the milliequivalent concentration of most Na^+ is greater than that of Cl^-) which reflects a release of Na from other sources such as silicate weathering or cation exchange but are not major processes influencing chemical evolution in the river basin. This is mainly ascribed to Na^+ released from feldspar through hydrolysation and acid attack during the groundwater flow and ion- exchange of Ca^{2+} in water for Na^+ in soil (Deng *et al*, 2007).

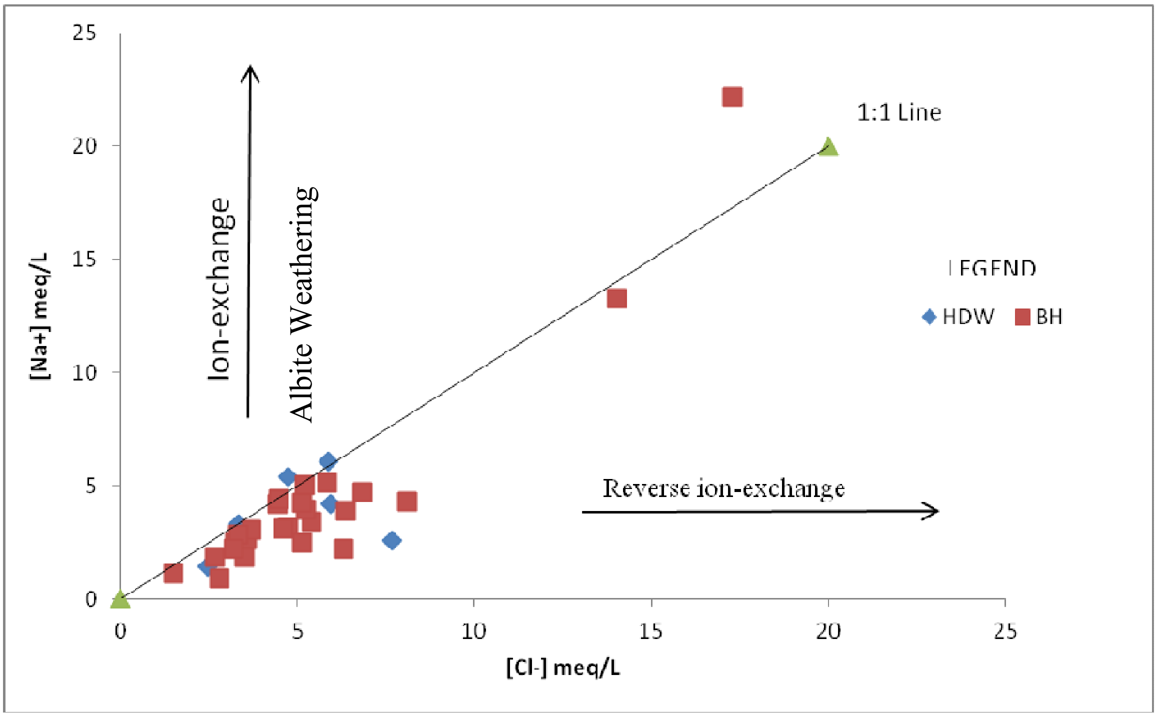

Figure 4.0: [Na^+] versus [Cl^-] of Ground waters in the Ayensu River Basin

Fig. 5.0 shows the relationship between [$Ca^{2+} + Mg^{2+}$] (meq/L) versus [$HCO_3^- + SO_4^{2-}$] (meq/L) for the groundwater in some communities in the Ayensu river basin. A 1:1 relationship would indicate gypsum, anhydrite, calcite and dolomite dissolution as the predominant processes controlling solution composition while groundwater falling below the 1:1 dissolution line signifies ion exchange, in which case $Ca^{2+} + Mg^{2+}$ are being depleted with respect to $SO_4^{2-} + HCO_3^-$ (Kortatsi, 2007; McLean & Jankowski, 2000). If reverse ion exchange is the process, it will shift the points to the left due to a large excess of $Ca^{2+} + Mg^{2+}$ over $SO_4^{2-} + HCO_3^-$. A few groundwater samples fall on the 1:1dissolution line. However, the saturation indexes indicate that the groundwater in the study area is undersaturated with respect to the common carbonates (calcite. aragonite and dolomite) suggesting that the carbonates dissolution is not a major process in the study area. Most of the water samples clustered above 1:1 line toward reverse ion exchange process indicating portion of the $HCO_3^- + SO_4^{2-}$ must be balanced by Na and K by calcium and magnesium in clay material (Srinivasamoorthy, 2012). The $Mg^{2+}/Mg^{2+} + Ca^{2+}$ equivalent ratio for over 50% of the water samples is greater than 0.5 and the HCO_3^-/SiO_2 for almost all the water samples were very low, varying between 0.02 and 1.3 suggesting silicate weathering is likely (Hounslow, 1995; Kortatsi, 2007). Thus, silicate weathering may have contributed significantly to the concentration of the Ca^{2+} and Mg^{2+}.

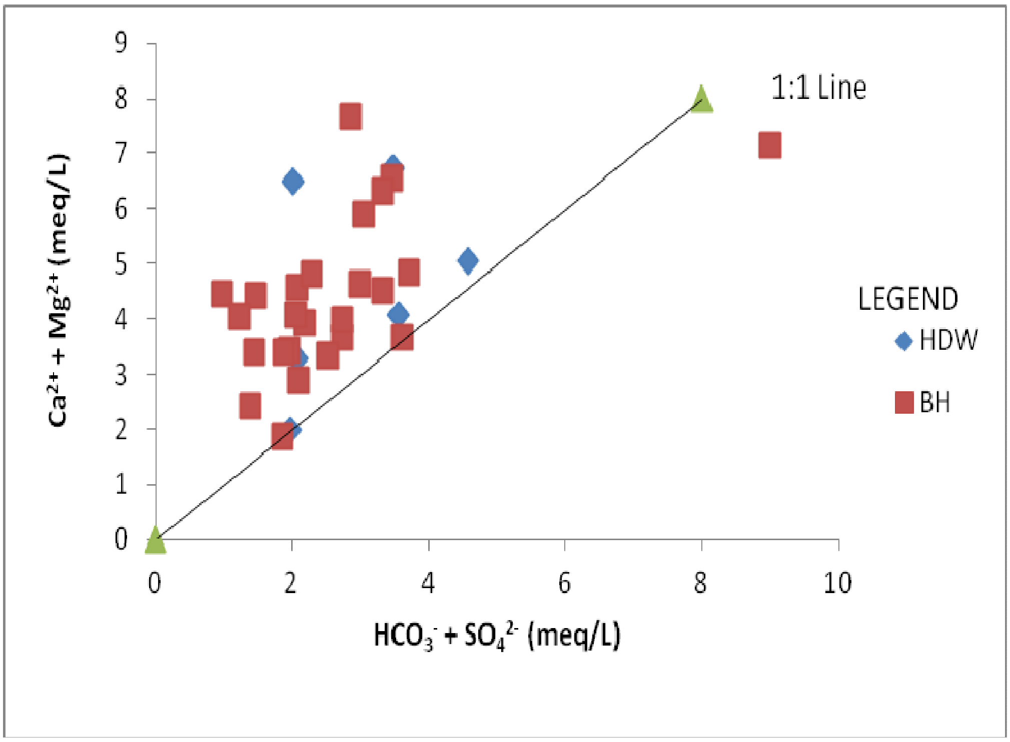

Figure 5.0: Relationship between [Ca^{2+} + Mg^{2+}] versus [HCO_3^- + SO_4^{2-}] of the groundwaters

Fig. 6.0 is a plot of [Ca^{2+} + Mg^{2+} - (SO_4^{2-} + HCO_3^-)] (meq/L) versus [Na^+ - Cl^-] (meq/L) for groundwater samples in the study area. The plot in Fig. 6.0, shows a negative linear trend with a slope of less than unity (-0.73) with a few plotting close to the zero value on the x-axis. According to Jankowski *et al* (1998), waters undergoing ion exchange would 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. Thus, ion exchange process is not a major process controlling the groundwater chemistry in the area. The other possible processes like silicate weathering and halite dissolution may also be taking place.

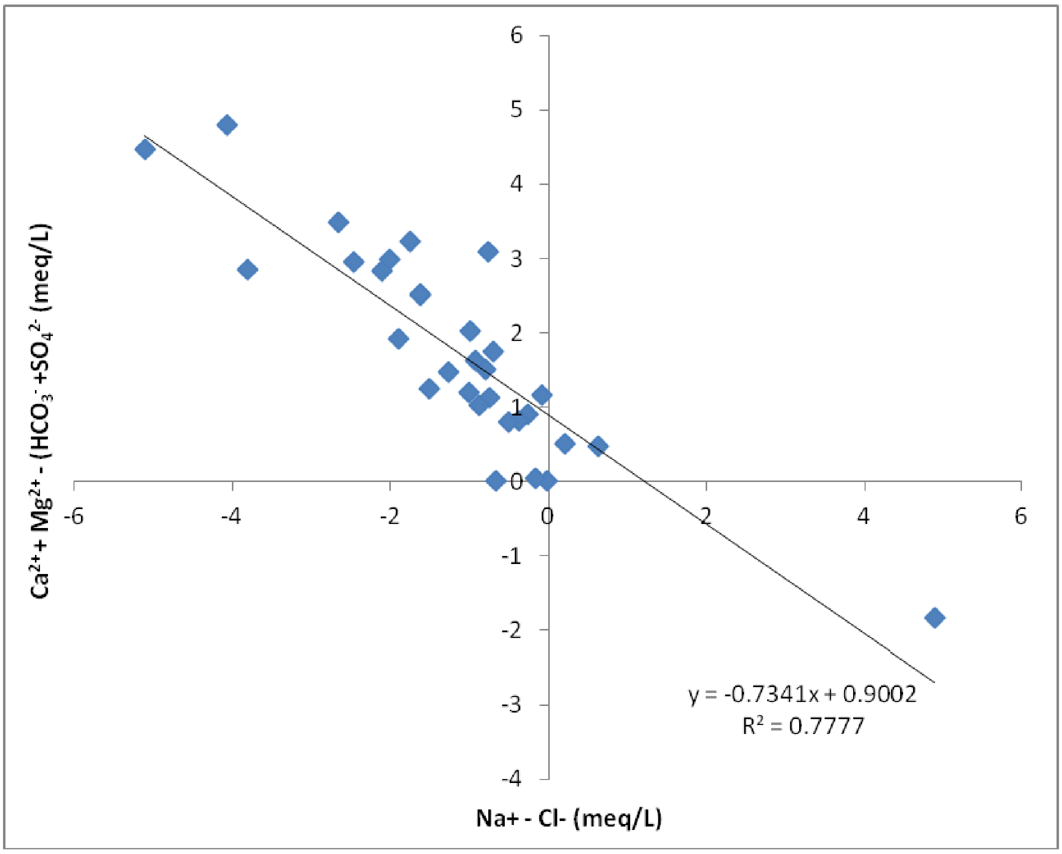

Figure 6.0: Relationship between (Ca^{2+} + Mg^{2+}) – (HCO_3^- + SO_4^{2-}) versus Na- Cl for the groundwater samples.

Gibb's diagrams that represent the ratios of $Na^+/(Na^+ + Ca^{2+})$ and $Cl^-/(Cl^- + HCO_3^-)$ as a function of TDS are widely employed to understand the functional sources of dissolved chemical constituents, such as precipitation-dominance, rock-dominance and evaporation dominance (Gibbs, 1970). Gibbs (1970) has pointed out that the rate of evaporation, chemical compositions of rocks and chemical composition of rainwater generally control the chemistry of water. In order to evaluate the sources of various ions in the waters from Ayensu river basin, the chemical data for waters from the study area were plotted in Gibbs diagram (Figs.44.0 - 47.0). The data points on the Gibbs diagram, suggests that groundwater chemistry is controlled mainly by rock weathering and also to a very small extent evaporation in the study area period. The evaporation process greatly increases the concentrations of ions formed by chemical weathering of the rock, leading to higher salinity.

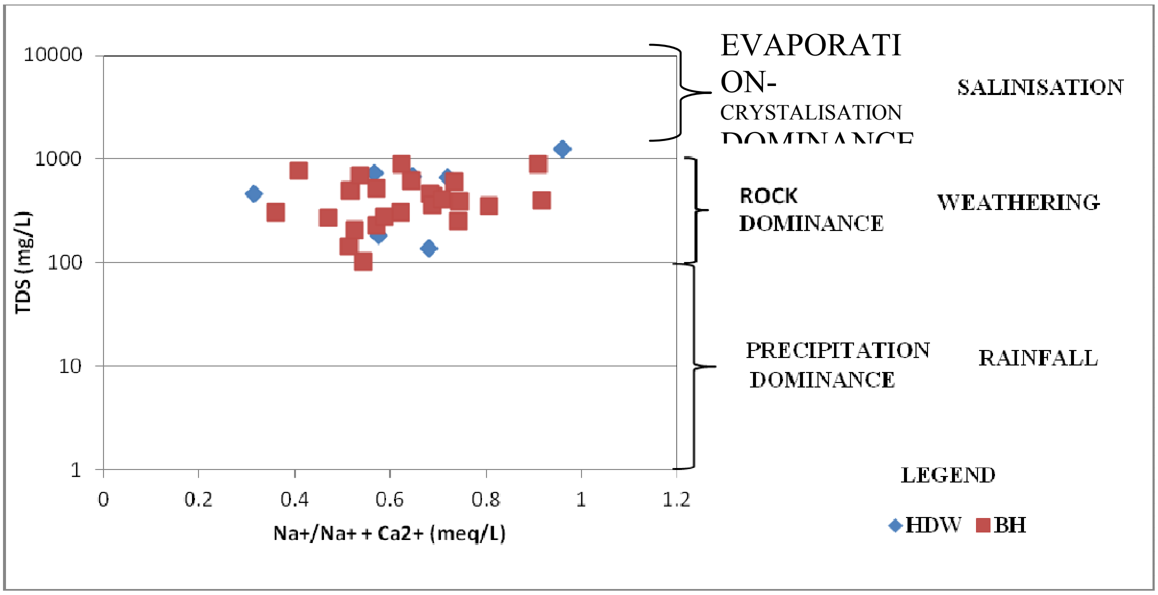

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Figure 7: Gibb's Diagram: Na^+ / Na^+ +Ca^{2+} as function of TDS showing some hydrochemical processes influencing groundwater chemical evolution

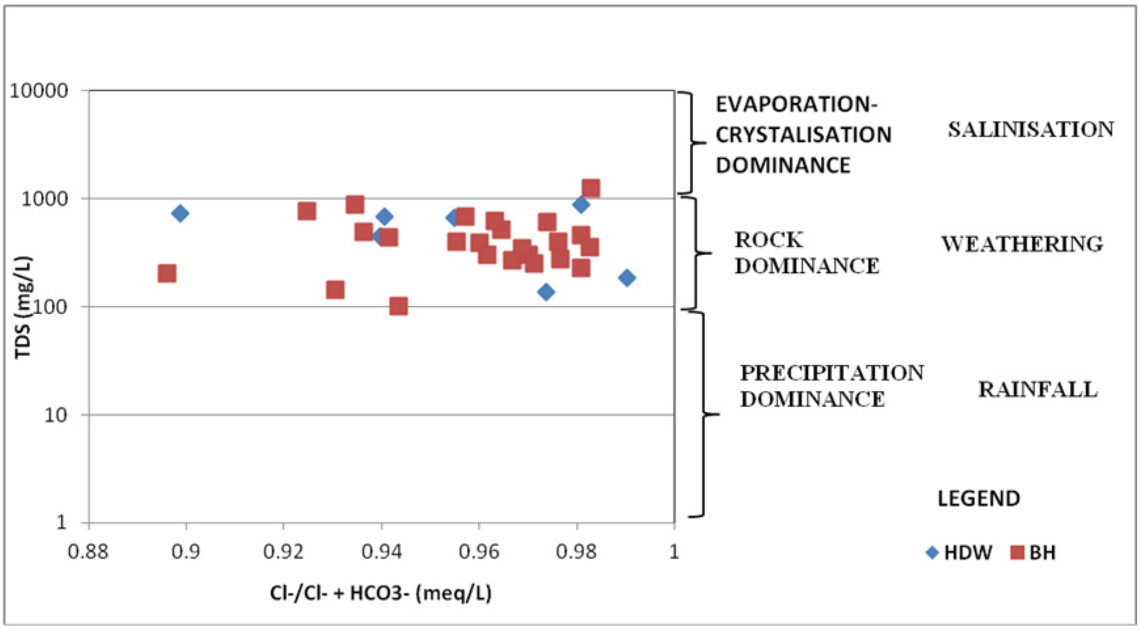

Fig. 8.0: Cl^- /Cl^- + HCO_3^- as function of TDS showing some hydrochemical processes influencing groundwater chemical evolution.

6.0 Conclusions

The study assessed the groundwater quality in some communities in the Ayensu river basin in the central region of Ghana. Analysis of the hydrochemical survey data from groundwater in the study area revealed that the waters are slightly acidic with mean pH value of 6.32. Except for one borehole at Gyangyanadze, all the groundwaters are fresh based on the TDS classification (TDS is in the range 101.7 mg/L to 1247.0 mg/L). The groundwater in the area is undersaturated with respect to carbonate species namely calcite, dolomite and ankerite. In most of water samples (>75%) Na^+ shows a clear dominance but in few cases either Ca^{2+} or Mg^{2+} appear to be the dominant cation. The dominant anion in the samples is Cl^- followed by SO_4^{2-}, HCO_3^- and then NO_3^-. Approximately 13 % of the water samples exceeded the permissible levels of 250mg/L for Cl^- ion in portable water. The trace metal loading of the groundwater is not high. However aluminium, iron, and cadmium showed concentrations significantly above their detection limits in some of the water samples. Three major water types have been identified, which are Na—Cl, Ca—Mg—Cl and Ca—Mg—SO4. The data points on the Gibbs diagram suggests that, groundwater chemistry is controlled by rock weathering and to a less extent by evaporation. Thus chemical breakdown of minerals in the various aquifers is the main process influencing the hydrochemistry of groundwater in the communities sampled in the Ayensu river basin.

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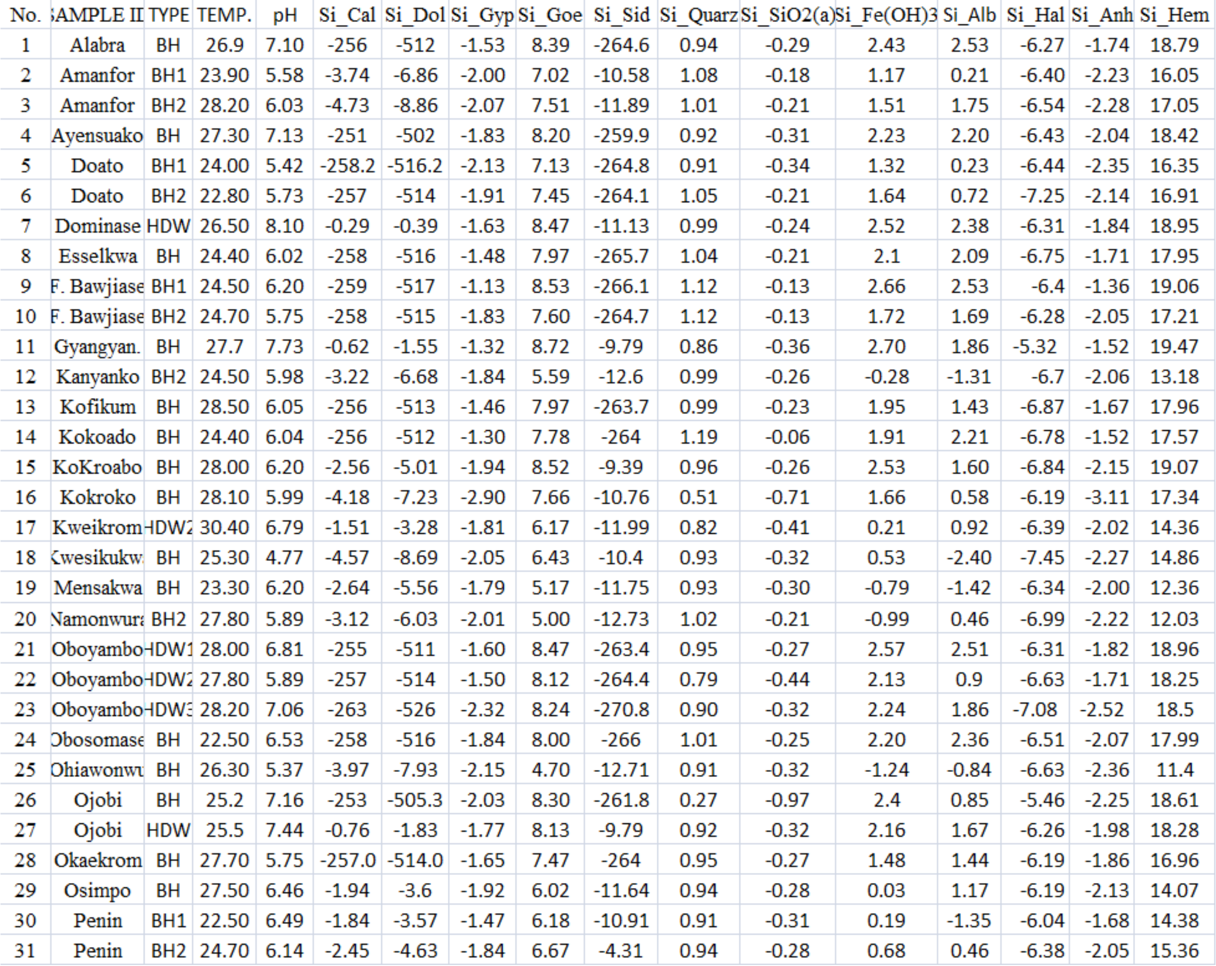
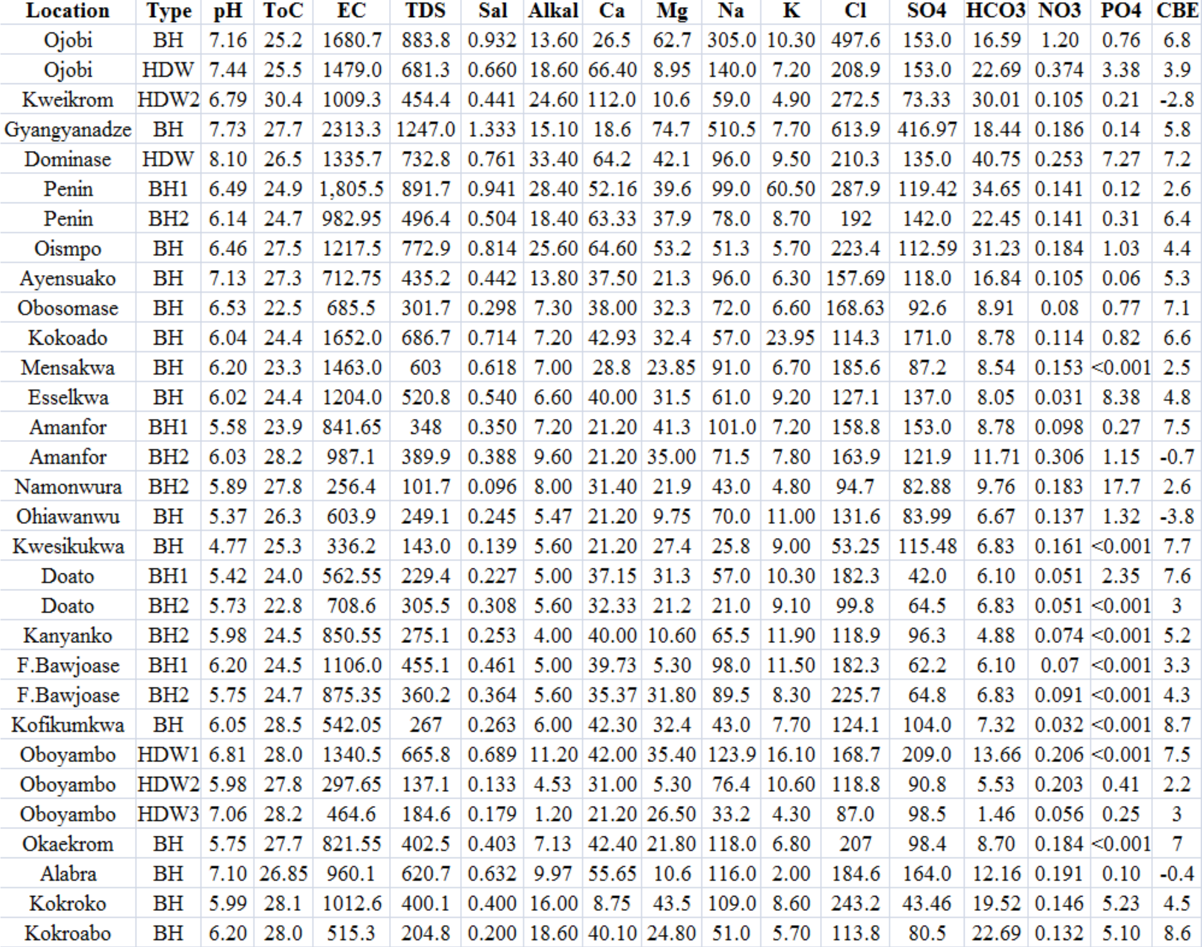
Appendix 1.0 Saturation indices for carbonate, iron bearing mineral gypsum, albite, anhydrite, amorphous silicate and quart.



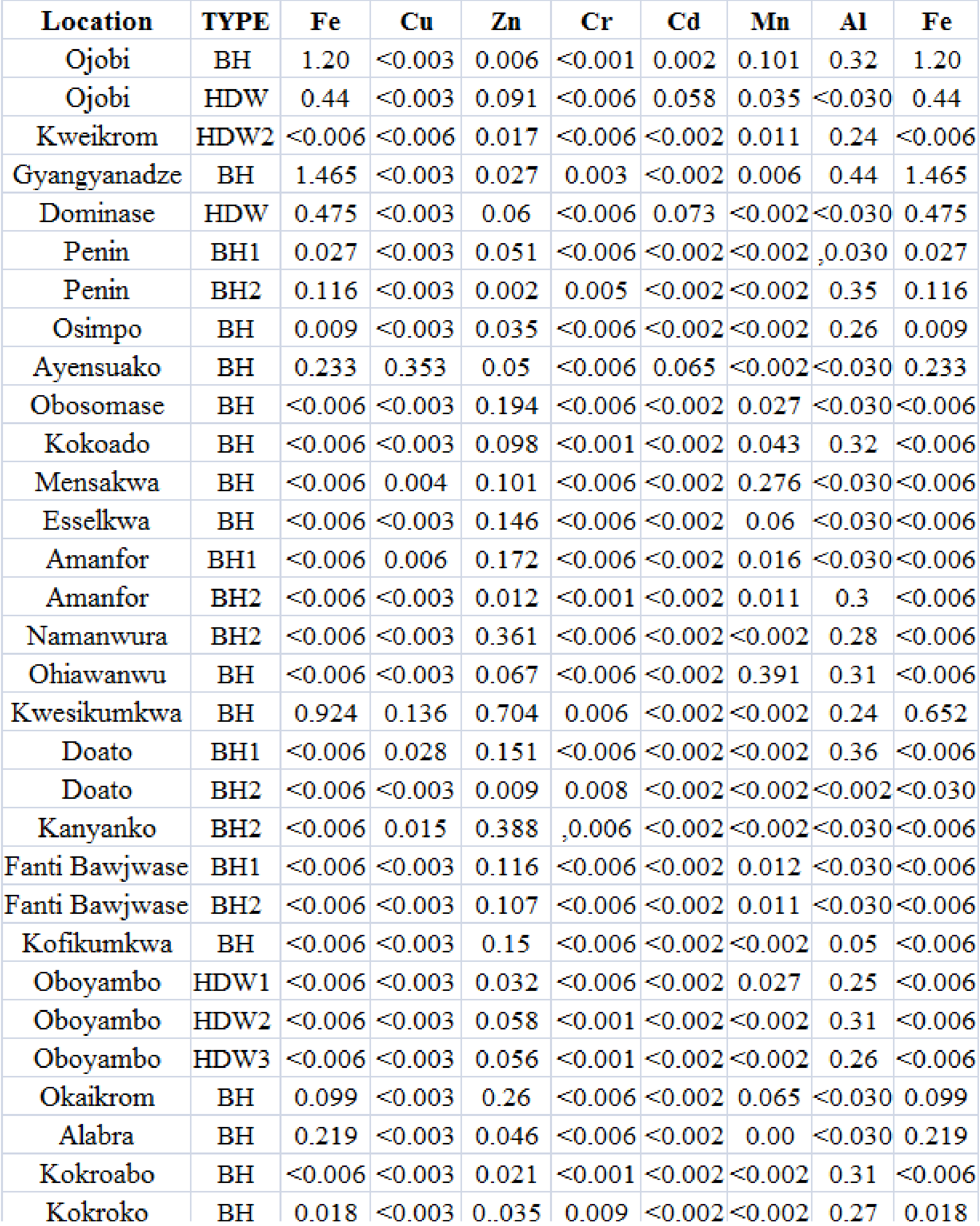
No.	;AMPLE II	TYPE	TEMP.	pH	Si_Cal	Si_Dol	Si_Gyp	Si_Goe	Si_Sid	Si_Quarz	Si_SiO2(a)	Si_Fe(OH)3	Si_Alb	Si_Hal	Si_Anh	Si_Hem
1	Alabra	BH	26.9	7.10	-256	-512	-1.53	8.39	-264.6	0.94	-0.29	2.43	2.53	-6.27	-1.74	18.79
2	Amanfor	BH1	23.90	5.58	-3.74	-6.86	-2.00	7.02	-10.58	1.08	-0.18	1.17	0.21	-6.40	-2.23	16.05
3	Amanfor	BH2	28.20	6.03	-4.73	-8.86	-2.07	7.51	-11.89	1.01	-0.21	1.51	1.75	-6.54	-2.28	17.05
4	Ayensuako	BH	27.30	7.13	-251	-502	-1.83	8.20	-259.9	0.92	-0.31	2.23	2.20	-6.43	-2.04	18.42
5	Doato	BH1	24.00	5.42	-258.2	-516.2	-2.13	7.13	-264.8	0.91	-0.34	1.32	0.23	-6.44	-2.35	16.35
6	Doato	BH2	22.80	5.73	-257	-514	-1.91	7.45	-264.1	1.05	-0.21	1.64	0.72	-7.25	-2.14	16.91
7	Dominase	HDW	26.50	8.10	-0.29	-0.39	-1.63	8.47	-11.13	0.99	-0.24	2.52	2.38	-6.31	-1.84	18.95
8	Esselkwa	BH	24.40	6.02	-258	-516	-1.48	7.97	-265.7	1.04	-0.21	2.1	2.09	-6.75	-1.71	17.95
9	F. Bawjiase	BH1	24.50	6.20	-259	-517	-1.13	8.53	-266.1	1.12	-0.13	2.66	2.53	-6.4	-1.36	19.06
10	F. Bawjiase	BH2	24.70	5.75	-258	-515	-1.83	7.60	-264.7	1.12	-0.13	1.72	1.69	-6.28	-2.05	17.21
11	Gyangyan.	BH	27.7	7.73	-0.62	-1.55	-1.32	8.72	-9.79	0.86	-0.36	2.70	1.86	-5.32	-1.52	19.47
12	Kanyanko	BH2	24.50	5.98	-3.22	-6.68	-1.84	5.59	-12.6	0.99	-0.26	-0.28	-1.31	-6.7	-2.06	13.18
13	Kofikum	BH	28.50	6.05	-256	-513	-1.46	7.97	-263.7	0.99	-0.23	1.95	1.43	-6.87	-1.67	17.96
14	Kokoado	BH	24.40	6.04	-256	-512	-1.30	7.78	-264	1.19	-0.06	1.91	2.21	-6.78	-1.52	17.57
15	KoKroabo	BH	28.00	6.20	-2.56	-5.01	-1.94	8.52	-9.39	0.96	-0.26	2.53	1.60	-6.84	-2.15	19.07
16	Kokroko	BH	28.10	5.99	-4.18	-7.23	-2.90	7.66	-10.76	0.51	-0.71	1.66	0.58	-6.19	-3.11	17.34
17	Kweikrom	HDW2	30.40	6.79	-1.51	-3.28	-1.81	6.17	-11.99	0.82	-0.41	0.21	0.92	-6.39	-2.02	14.36
18	Kwesikukw	BH	25.30	4.77	-4.57	-8.69	-2.05	6.43	-10.4	0.93	-0.32	0.53	-2.40	-7.45	-2.27	14.86
19	Mensakwa	BH	23.30	6.20	-2.64	-5.56	-1.79	5.17	-11.75	0.93	-0.30	-0.79	-1.42	-6.34	-2.00	12.36
20	Namonwura	BH2	27.80	5.89	-3.12	-6.03	-2.01	5.00	-12.73	1.02	-0.21	-0.99	0.46	-6.99	-2.22	12.03
21	Oboyambo	HDW1	28.00	6.81	-255	-511	-1.60	8.47	-263.4	0.95	-0.27	2.57	2.51	-6.31	-1.82	18.96
22	Oboyambo	HDW2	27.80	5.89	-257	-514	-1.50	8.12	-264.4	0.79	-0.44	2.13	0.9	-6.63	-1.71	18.25
23	Oboyambo	HDW3	28.20	7.06	-263	-526	-2.32	8.24	-270.8	0.90	-0.32	2.24	1.86	-7.08	-2.52	18.5
24	Obosomase	BH	22.50	6.53	-258	-516	-1.84	8.00	-266	1.01	-0.25	2.20	2.36	-6.51	-2.07	17.99
25	Ohiawonwu	BH	26.30	5.37	-3.97	-7.93	-2.15	4.70	-12.71	0.91	-0.32	-1.24	-0.84	-6.63	-2.36	11.4
26	Ojobi	BH	25.2	7.16	-253	-505.3	-2.03	8.30	-261.8	0.27	-0.97	2.4	0.85	-5.46	-2.25	18.61
27	Ojobi	HDW	25.5	7.44	-0.76	-1.83	-1.77	8.13	-9.79	0.92	-0.32	2.16	1.67	-6.26	-1.98	18.28
28	Okaekrom	BH	27.70	5.75	-257.0	-514.0	-1.65	7.47	-264	0.95	-0.27	1.48	1.44	-6.19	-1.86	16.96
29	Osimpo	BH	27.50	6.46	-1.94	-3.6	-1.92	6.02	-11.64	0.94	-0.28	0.03	1.17	-6.19	-2.13	14.07
30	Penin	BH1	22.50	6.49	-1.84	-3.57	-1.47	6.18	-10.91	0.91	-0.31	0.19	-1.35	-6.04	-1.68	14.38
31	Penin	BH2	24.70	6.14	-2.45	-4.63	-1.84	6.67	-4.31	0.94	-0.28	0.68	0.46	-6.38	-2.05	15.36

Appendix 2.0: Physico-chemical parameters, major and minor constituents and charge balance error in percentage (CBE%) for groundwater sampled in 31 communities.



Location	Type	pH	ToC	EC	TDS	Sal	Alkal	Ca	Mg	Na	K	Cl	SO4	HCO3	NO3	PO4	CBE
Ojobi	BH	7.16	25.2	1680.7	883.8	0.932	13.60	26.5	62.7	305.0	10.30	497.6	153.0	16.59	1.20	0.76	6.8
Ojobi	HDW	7.44	25.5	1479.0	681.3	0.660	18.60	66.40	8.95	140.0	7.20	208.9	153.0	22.69	0.374	3.38	3.9
Kweikrom	HDW2	6.79	30.4	1009.3	454.4	0.441	24.60	112.0	10.6	59.0	4.90	272.5	73.33	30.01	0.105	0.21	-2.8
Gyangyanadze	BH	7.73	27.7	2313.3	1247.0	1.333	15.10	18.6	74.7	510.5	7.70	613.9	416.97	18.44	0.186	0.14	5.8
Dominase	HDW	8.10	26.5	1335.7	732.8	0.761	33.40	64.2	42.1	96.0	9.50	210.3	135.0	40.75	0.253	7.27	7.2
Penin	BH1	6.49	24.9	1,805.5	891.7	0.941	28.40	52.16	39.6	99.0	60.50	287.9	119.42	34.65	0.141	0.12	2.6
Penin	BH2	6.14	24.7	982.95	496.4	0.504	18.40	63.33	37.9	78.0	8.70	192	142.0	22.45	0.141	0.31	6.4
Oismpo	BH	6.46	27.5	1217.5	772.9	0.814	25.60	64.60	53.2	51.3	5.70	223.4	112.59	31.23	0.184	1.03	4.4
Ayensuako	BH	7.13	27.3	712.75	435.2	0.442	13.80	37.50	21.3	96.0	6.30	157.69	118.0	16.84	0.105	0.06	5.3
Obosomase	BH	6.53	22.5	685.5	301.7	0.298	7.30	38.00	32.3	72.0	6.60	168.63	92.6	8.91	0.08	0.77	7.1
Kokoado	BH	6.04	24.4	1652.0	686.7	0.714	7.20	42.93	32.4	57.0	23.95	114.3	171.0	8.78	0.114	0.82	6.6
Mensakwa	BH	6.20	23.3	1463.0	603	0.618	7.00	28.8	23.85	91.0	6.70	185.6	87.2	8.54	0.153	<0.001	2.5
Esselkwa	BH	6.02	24.4	1204.0	520.8	0.540	6.60	40.00	31.5	61.0	9.20	127.1	137.0	8.05	0.031	8.38	4.8
Amanfor	BH1	5.58	23.9	841.65	348	0.350	7.20	21.20	41.3	101.0	7.20	158.8	153.0	8.78	0.098	0.27	7.5
Amanfor	BH2	6.03	28.2	987.1	389.9	0.388	9.60	21.20	35.00	71.5	7.80	163.9	121.9	11.71	0.306	1.15	-0.7
Namonwura	BH2	5.89	27.8	256.4	101.7	0.096	8.00	31.40	21.9	43.0	4.80	94.7	82.88	9.76	0.183	17.7	2.6
Ohiawanwu	BH	5.37	26.3	603.9	249.1	0.245	5.47	21.20	9.75	70.0	11.00	131.6	83.99	6.67	0.137	1.32	-3.8
Kwesikukwa	BH	4.77	25.3	336.2	143.0	0.139	5.60	21.20	27.4	25.8	9.00	53.25	115.48	6.83	0.161	<0.001	7.7
Doato	BH1	5.42	24.0	562.55	229.4	0.227	5.00	37.15	31.3	57.0	10.30	182.3	42.0	6.10	0.051	2.35	7.6
Doato	BH2	5.73	22.8	708.6	305.5	0.308	5.60	32.33	21.2	21.0	9.10	99.8	64.5	6.83	0.051	<0.001	3
Kanyanko	BH2	5.98	24.5	850.55	275.1	0.253	4.00	40.00	10.60	65.5	11.90	118.9	96.3	4.88	0.074	<0.001	5.2
F.Bawjoase	BH1	6.20	24.5	1106.0	455.1	0.461	5.00	39.73	5.30	98.0	11.50	182.3	62.2	6.10	0.07	<0.001	3.3
F.Bawjoase	BH2	5.75	24.7	875.35	360.2	0.364	5.60	35.37	31.80	89.5	8.30	225.7	64.8	6.83	0.091	<0.001	4.3
Kofikumkwa	BH	6.05	28.5	542.05	267	0.263	6.00	42.30	32.4	43.0	7.70	124.1	104.0	7.32	0.032	<0.001	8.7
Oboyambo	HDW1	6.81	28.0	1340.5	665.8	0.689	11.20	42.00	35.40	123.9	16.10	168.7	209.0	13.66	0.206	<0.001	7.5
Oboyambo	HDW2	5.98	27.8	297.65	137.1	0.133	4.53	31.00	5.30	76.4	10.60	118.8	90.8	5.53	0.203	0.41	2.2
Oboyambo	HDW3	7.06	28.2	464.6	184.6	0.179	1.20	21.20	26.50	33.2	4.30	87.0	98.5	1.46	0.056	0.25	3
Okaekrom	BH	5.75	27.7	821.55	402.5	0.403	7.13	42.40	21.80	118.0	6.80	207	98.4	8.70	0.184	<0.001	7
Alabra	BH	7.10	26.85	960.1	620.7	0.632	9.97	55.65	10.6	116.0	2.00	184.6	164.0	12.16	0.191	0.10	-0.4
Kokroko	BH	5.99	28.1	1012.6	400.1	0.400	16.00	8.75	43.5	109.0	8.60	243.2	43.46	19.52	0.146	5.23	4.5
Kokroabo	BH	6.20	28.0	515.3	204.8	0.200	18.60	40.10	24.80	51.0	5.70	113.8	80.5	22.69	0.132	5.10	8.6

Appendix 3.0: Trace metal concentrations for groundwater sampled in 31 communities in the Ayensu Basin.



Location	TYPE	Fe	Cu	Zn	Cr	Cd	Mn	Al	Fe
Ojobi	BH	1.20	<0.003	0.006	<0.001	0.002	0.101	0.32	1.20
Ojobi	HDW	0.44	<0.003	0.091	<0.006	0.058	0.035	<0.030	0.44
Kweikrom	HDW2	<0.006	<0.006	0.017	<0.006	<0.002	0.011	0.24	<0.006
Gyangyanadze	BH	1.465	<0.003	0.027	0.003	<0.002	0.006	0.44	1.465
Dominase	HDW	0.475	<0.003	0.06	<0.006	0.073	<0.002	<0.030	0.475
Penin	BH1	0.027	<0.003	0.051	<0.006	<0.002	<0.002	,0.030	0.027
Penin	BH2	0.116	<0.003	0.002	0.005	<0.002	<0.002	0.35	0.116
Osimpo	BH	0.009	<0.003	0.035	<0.006	<0.002	<0.002	0.26	0.009
Ayensuako	BH	0.233	0.353	0.05	<0.006	0.065	<0.002	<0.030	0.233
Obosomase	BH	<0.006	<0.003	0.194	<0.006	<0.002	0.027	<0.030	<0.006
Kokoado	BH	<0.006	<0.003	0.098	<0.001	<0.002	0.043	0.32	<0.006
Mensakwa	BH	<0.006	0.004	0.101	<0.006	<0.002	0.276	<0.030	<0.006
Esselkwa	BH	<0.006	<0.003	0.146	<0.006	<0.002	0.06	<0.030	<0.006
Amanfor	BH1	<0.006	0.006	0.172	<0.006	<0.002	0.016	<0.030	<0.006
Amanfor	BH2	<0.006	<0.003	0.012	<0.001	<0.002	0.011	0.3	<0.006
Namanwura	BH2	<0.006	<0.003	0.361	<0.006	<0.002	<0.002	0.28	<0.006
Ohiawanwu	BH	<0.006	<0.003	0.067	<0.006	<0.002	0.391	0.31	<0.006
Kwesikumkwa	BH	0.924	0.136	0.704	0.006	<0.002	<0.002	0.24	0.652
Doato	BH1	<0.006	0.028	0.151	<0.006	<0.002	<0.002	0.36	<0.006
Doato	BH2	<0.006	<0.003	0.009	0.008	<0.002	<0.002	<0.002	<0.030
Kanyanko	BH2	<0.006	0.015	0.388	,0.006	<0.002	<0.002	<0.030	<0.006
Fanti Bawjwase	BH1	<0.006	<0.003	0.116	<0.006	<0.002	0.012	<0.030	<0.006
Fanti Bawjwase	BH2	<0.006	<0.003	0.107	<0.006	<0.002	0.011	<0.030	<0.006
Kofikumkwa	BH	<0.006	<0.003	0.15	<0.006	<0.002	<0.002	0.05	<0.006
Oboyambo	HDW1	<0.006	<0.003	0.032	<0.006	<0.002	0.027	0.25	<0.006
Oboyambo	HDW2	<0.006	<0.003	0.058	<0.001	<0.002	<0.002	0.31	<0.006
Oboyambo	HDW3	<0.006	<0.003	0.056	<0.001	<0.002	<0.002	0.26	<0.006
Okaikrom	BH	0.099	<0.003	0.26	<0.006	<0.002	0.065	<0.030	0.099
Alabra	BH	0.219	<0.003	0.046	<0.006	<0.002	0.00	<0.030	0.219
Kokroabo	BH	<0.006	<0.003	0.021	<0.001	<0.002	<0.002	0.31	<0.006
Kokroko	BH	0.018	<0.003	0..035	0.009	<0.002	<0.002	0.27	0.018