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Physico-Chemical Analysis of Surface and Groundwater in the Ayensu River Basin in the Central Region of Ghana

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Abstract

The hydrochemistry of the Ayensu river basin in the central Region of Ghana has been established. The methodology consisted of physicochemical sampling and laboratory analysis of both groundwater and surface water resources in the Basin and basic statistical analysis of the laboratory results.. Generally, the groundwater is weakly acidic with a mean pH value of 6.33±0.01, had high electrical conductivity and TDS values in the range, 297.65 to 6011.0 and 100.85 to 2746.0 respectively. Three main hydrochemical facies have been identified in the basin. These are Na- Cl, Ca- Mg - Cl and Ca - Mg - SO_4 water types. Groundwater is to a large extent potable. However, approximately 24% and 22% respectively of groundwater samples had chloride and sulphate concentrations slightly exceeding the respective WHO maximum acceptable limits for drinking water. The concentrations of aluminium, iron and manganese were the only minor ions that significantly exceeded their respective detection limits. Nearly 43% of the groundwater samples had the Al^{3+} concentrations exceeding the WHO acceptable limit of 0.2 mg/l for drinking water, which reflects the acidic nature of the groundwater. The main geochemical process influencing the hydrochemistry of the Ayensu river basin is mineral dissolution.

Keywords Groundwater quality, hydrochemistry, Mineral dissolution, Central Region Ghana.

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1. Introduction

The availability of freshwater is one of the great issues facing mankind today- in some ways the greatest, because problems associated with it affect the lives of many millions of people. The rapid growth of population coupled with 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 and 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). Acidic groundwater may encourage dissolution of minor and trace elements such as Al, As, Mn, and Fe from most minerals if they are present in the rock matrix and render the ground water unsafe for drinking (Kortatsi, 2007). It has therefore, become imperative to assess the physical and chemical quality of the groundwater in the Ayensu Basin. The major objective is to establish the hydrochemical facies in the area and the possible sources of the various ions in groundwater.

2.0 The study area

The study area is located in the Central Region of Ghana (Fig. 1). The area covers approximately 1,709 km^2 and lies between latitudes 5^O 150'N - 6^O 00'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, from where it flows generally southward to the sea. The Ayensu Basin is bounded on the east by the western boundary of the Densu Basin, on the north by the southeastern boundary of the Pra Basin, on the west by the eastern boundary of the Ochi-Nakwa Basin, on the south by the Gulf of Guinea. (WRMS, 2008).

The basin has a varied climatic and vegetation characteristics. The upper reaches of the Ayensu 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. The original vegetation cover of the basin consisted of moist evergreen forest at the summits of the Atiwa ranges in the headwater areas, the moist and dry semi-deciduous and the marginal transition forest in the middle basin through to the coastal sub-humid savannah with scrub thicket and grasses to patches of mangrove swamps and wetlands along the coast (WRCS, 2008).. 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 (WRMS, 2008). 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. Large numbers of cattle are known to be kept on the coastal plains while coconut plantations occur behind the beaches.

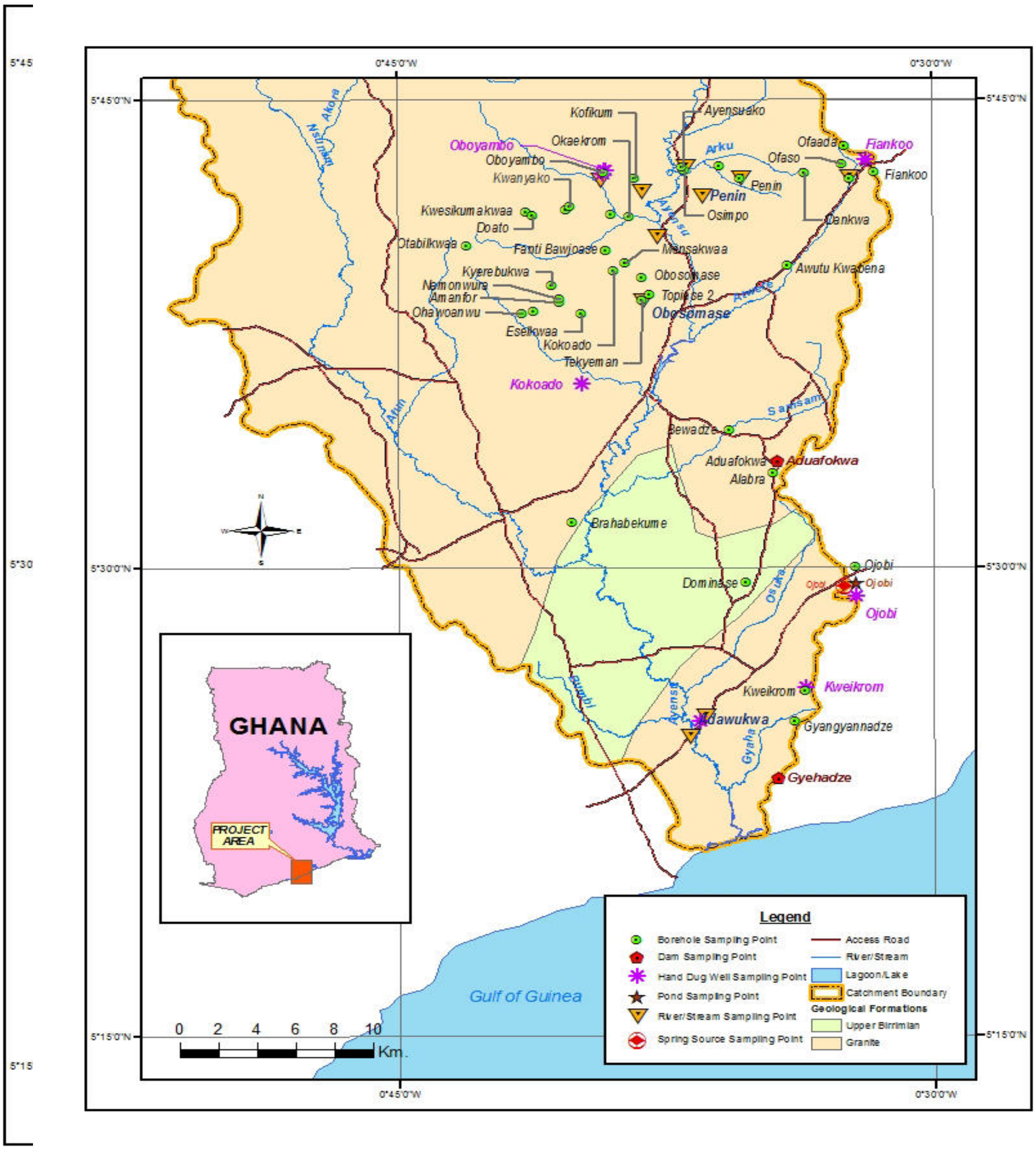

Figure 1 : Map showing the catchment areas a of the Ayensu River

3.0 Hydrogeology of the area

The Ayensu Basin is predominantly underlain by Cape Coast granite complex consisting largely of granites, schists, and gneisses which has resulted in the occurrence of such soil groups as Forest and Savannah Ochrosols, and Forest and Savannah Lithosols on the uplands and Forest and Savannah Gleisols within the valley bottoms. There are however, small areas within the northwest and southwest (Winneba area) underlain by upper Birimian basic rocks which give rise to the occurrence of Savannah Ochrosol- Rubrisol Intergrades and Tropical Black Clays. Within the northeastern and southeastern sections, there are limited areas underlain by metamorphosed sediments of the Togo and Voltaian systems consisting of mainly of quartzites, sandstones, and conglomerates. (WRMS, 2008).

The hydrogeological conditions prevailing are governed by the geological and tectonic structures of the area. The Sediments posses primary porosities and also have acquired variable secondary porosity and permeability through jointing, fracturing and shearing along which decomposition and weathering have taken place. These porosities help in the storage and flow of water to the wells. The Crystalline rocks particularly Granitoids on the other hand do not posses any primary porosity, but have acquired secondary porosity and permeability through fissuring, which is the main reservoir for groundwater storage and channel for transport of groundwater to the wells.. The deep ground water taps into these fractures. The Ayensu basin the rocks are relatively more deformed to allow mobility of fluid that aids the 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).

4.0 Materials and Methodology

A total of 54 water samples were collected, comprising 42groundwater samples from deep boreholes fitted with pumps and shallow hand dug wells and 12 surface water samples collected from the main Ayensu river, its tributaries, a pond and 2 dams. The water samples were collected on 14th and15th January 2010 in the dry season and on 13th and 15th May 2010. 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. The filtered 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 with 0.16 N H_2SO_4 using HACH Digital Titrator Model 16900.

All samples were transported to the laboratory in ice-filled coolers, and kept refrigerated at approximately 4^o C until analyzed. In the laboratory, 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. Later titration was used to analyse for chloride (Cl^-), PO_4^{3-} and SO_4^{2-} were determined using spectrophotometer. The ionic balance was determined for the results of the major cations and anions and the results are presented in Appendix A table 3. For all the water samples analyzed the ionic balance varied between -3.63% and 5.94%.

5.0 Results and Discussion

5.1 Summary statistics

A statistical summary of hydrochemical parameters measured in the 42 groundwater samples is presented in Table.1 and the actual results are presented in appendices 1 and 2.

Table 1. . Statistical summary of the parameters determined in the 42 groundwater samples

ITERM	Min.	Max.	Mean	Median	Std	WHO guideline limit
Temp.	21.95	29.40	26.61	26.83	1.34	
pH	5.38	8.38	6.33	6.09	0.68	6.5 - 8.5
EC	297.65	6011.00	1168.68	998.22	904.37	
TDS	100.85	2746.00	590.26	474.93	449.63	
Alk	10.95	59.20	24.15	22.23	10.55	
Ca	6.36	623.00	74.38	56.70	90.47	200.0
Mg	6.08	302.10	37.71	25.72	46.29	200.0
Na	24.00	363.83	86.08	63.65	66.99	200.0
K	2.80	30.67	8.14	6.75	5.21	
HCO3	14.97	72.22	30.87	28.99	11.93	
Cl	73.80	1680.14	244.27	189.00	254.67	250
SO4	31.03	482.99	106.91	81.90	77.02	250
NO3	0.00	155.28	32.46	16.56	40.53	50
PO4	0.00	17.75	1.81	0.23	4.18	
Zn	0.00	0.39	0.10	0.07	0.09	3.00
Cu	<0.003	0.35	0.04	0.01	0.09	2.00
Fe	<0.006	1.67	0.46	0.17	0.55	0.300
Cr	<0.001	0.01	0.01	0.01	0.00	0.050
Cd	<0.002	0.08	0.07	0.06	0.03	0.030
Mn	<0.002	0.39	0.06	0.03	0.09	0.500
Al	<0.030	0.37	0.22	0.27	0.12	0.200
Salinity	0.13	1.42	0.51	0.43	0.29	

The groundwater pH is in the range 5.033 – 8.383 with the mean and median values of 6.33 and 6.09, respectively. The groundwater is slightly acidic with majority of the samples (over 80%) lying within the range 4.5 to 6.9 thus within natural water pH range 4.5- and 9.0 (Langmuir, 1997). The electrical conductivity values are in the range 297.65 – 6011.o µS cm^{-1} with mean and median values of 1088 µS cm^{-1} and 980.3 µS cm^{-1} respectively. About 93% of the groundwater samples have TDS values less than 1000 mg/l recommended for domestic water which are classified as fresh water (WHO, 1996). The TDS values range between 100 mg/l and 2746 mg/l with a mean of 570 mg/l and median value of 464mg/l. There were three exceptions. Three boreholes at Gyangyanadze, Alabla and Brahabekume had TDS values of 1222.5 mg/l, 1456.0 mg/l and 1291.0 mg/l respectively. Gyangyanadze is near the coast, Adabra is also not far from the coast but Brahabekume is far inland. 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 24.0mg/l to 363.83mg/l with a mean of 86.08. The dominant anion in the samples is Cl^- followed by SO_4^{2-}, HCO_3^- and then NO_3^-. Cl^- varies from 73.801mg/l to 1680.1mg/l with a mean of 244.3mg/l. approximately 24 % of the water samples exceeded the permissible levels of 250mg/l for Cl^- ion (WHO, 2008). Nearly 22% of the groundwater samples have their NO_3^- concentrations exceeding the WHO maximum acceptable limit of 50 mg/l. This may cause health problems for infants using such waters as source of drinking water.

5.2 Hydrochemical facies

The chemical composition of the water samples from the Ayensu Basin is shown on the phase diagram in fig. 2 . Most of the boreholes and hand dug wells and some surface waters cluster towards Na - Cl and Ca - Mg - Cl section. A few show Ca - Mg - SO_4 water type. Some of the surface waters and a few hand dug wells plot mainly in the mixed water type where there is neither dominant cation nor anion. The ionic dominance pattern of the groundwater samples were

Na > Ca > Mg > K and $Cl^- > SO_4^{2-} > HCO_3^- > NO_3^-$.

From figure 3 it is realized that about 40% 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 Na^+ versus Cl^- graph suggesting that either sea aerosol or halite dissolution is partially responsible for Na^+ in the groundwater. The geology of the study area however does not associate halite with the rocks in the area implying sea aerosols is partially the likely source of Na in the groundwater.

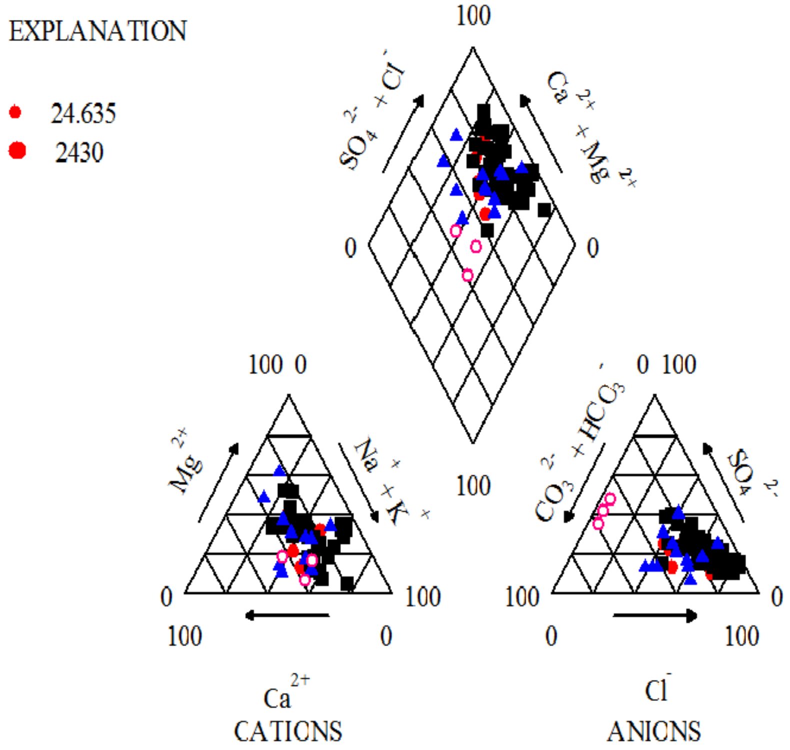

Figure 2. Phase diagram for water samples from the Ayenu Basin

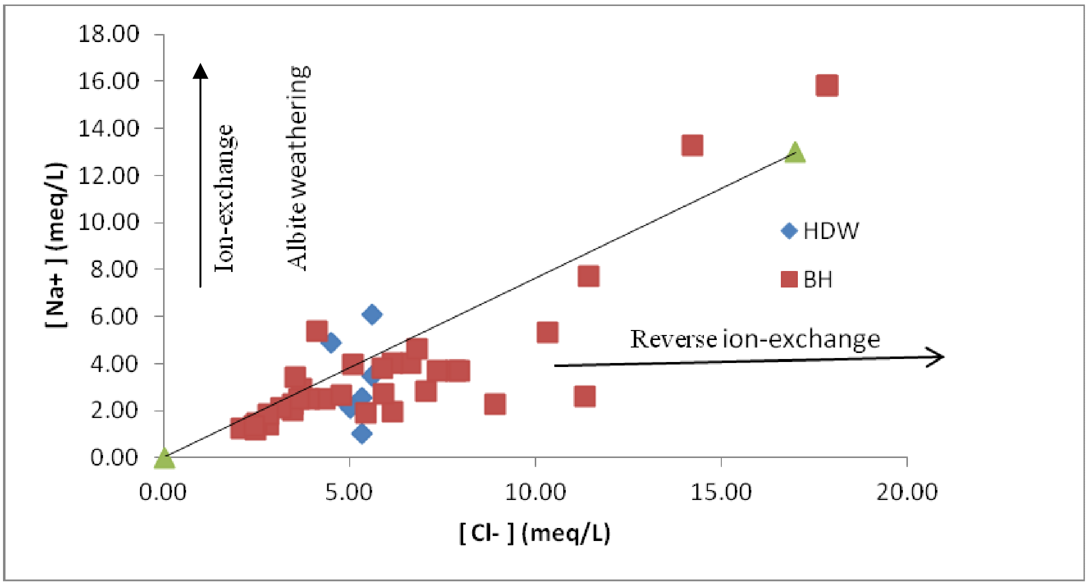

Fig..3 [Na^+] versus [Cl^-] of Ground waters in the Ayensu River Basin

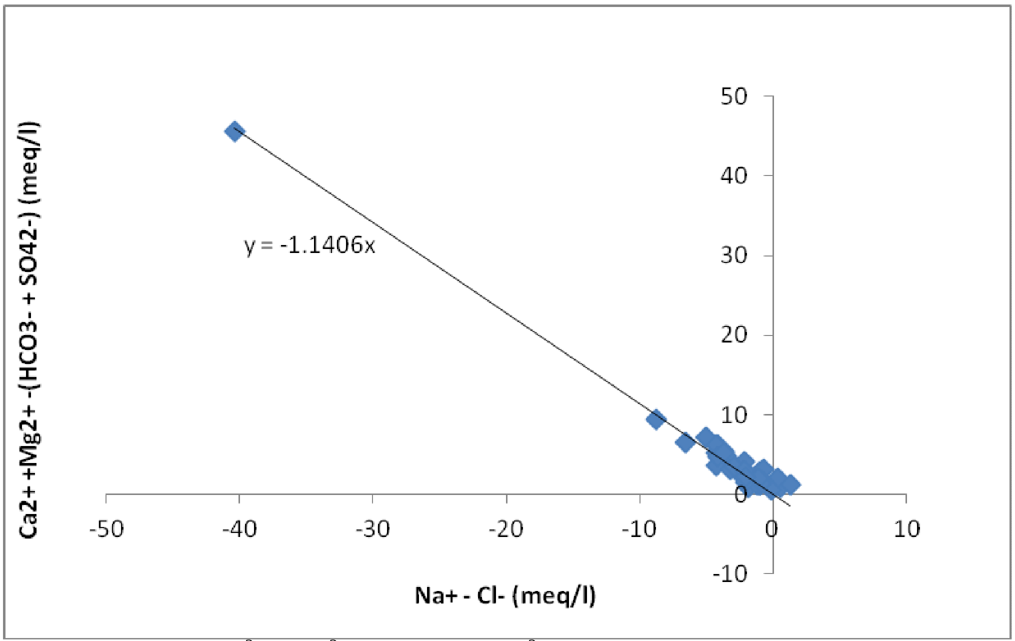

Fig. 4: Relationship between Ca^{2+} + Mg^{2+} - (HCO_3^- + SO_4^{2-}) versus Na^+ - Cl^- for the groundwaters of the Ayensu Basin

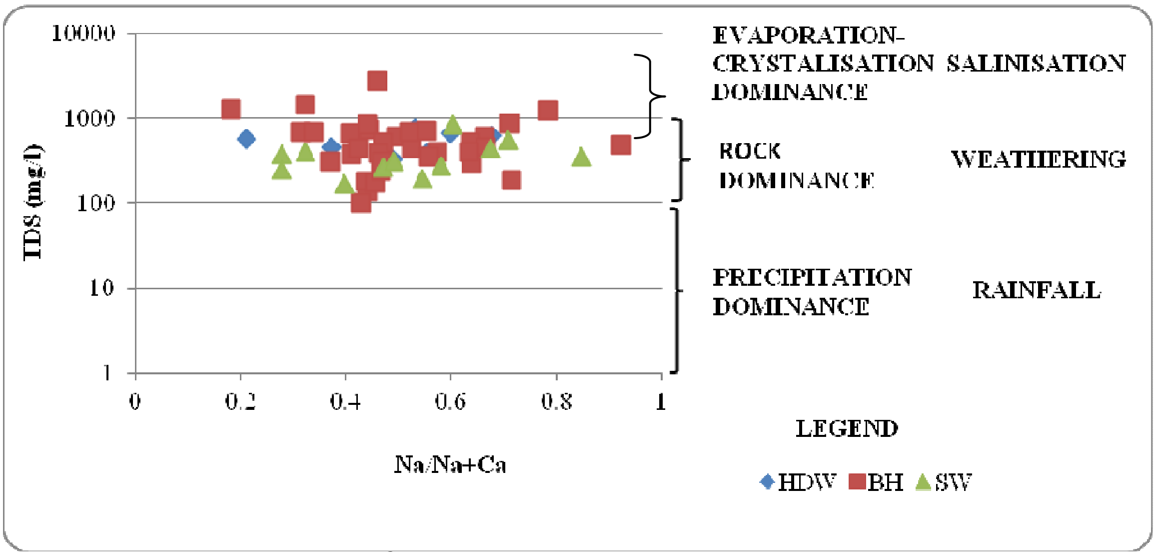

Fig. 5 Gibb's Diagram: Na^+ / Na^+ +Ca^{2+} as function of TDS showing some hydrochemical processes influencing groundwater chemical evolution

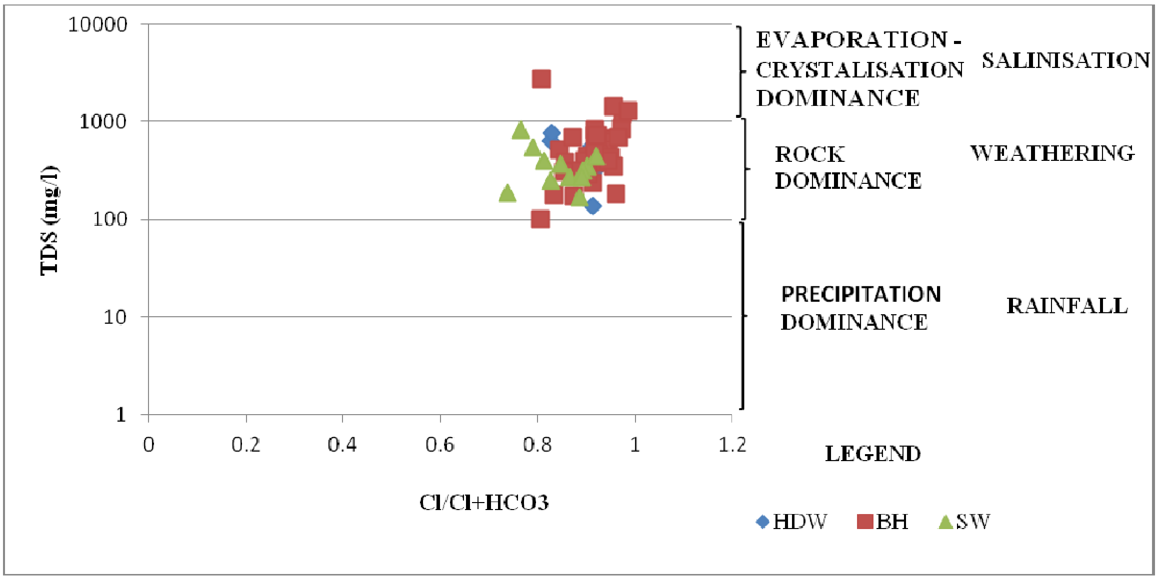

Fig. 6 $Cl^-/Cl^- + HCO_3^-$ as function of TDS showing some hydrochemical processes influencing groundwater chemical evolution.

About 57% of the water samples plot below and away from the 1:1 line suggesting reverse ion exchange as a major process responsible for chemical evolution of groundwater in the Ayensu basin. These water samples have their TDS values greater than 600 mg/L. A few samples plot above the 1:1 line in Na versus Cl graph indicating other Na sources such as cation exchange or alumino-silicate dissolution (Kortatsi, 2007). The source of Cl- may be from atmospheric inputs. Concentration of these ions in the soil zones as a result of evaporation may be responsible for the NaCl waters in the area. A possible source of Na^+ is albite weathering as shown in the equation below:

$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4$
(Albite) (Kaolinite)

Fig 4 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 Ayensu river basin. The plot shows a negative linear trend with a slope of more than unity (- 1.14) with some 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, as seen in Fig. 4, ion exchange process alone is not controlling the groundwater chemistry in the area. The other possible processes like silicate weathering and halite dissolution may also be taking place. The $Mg^{2+}/(Mg^{2+} + Ca^{2+})$ equivalent ratio for approximately 36% of the samples is greater than 0.5, suggesting silicate (mainly, ferromagnesian mineral) weathering is likely (Hounslow, 1995). Normally, the dissolution of the carbonate minerals of calcite and dolomite can be written as follows (Hete and Cheng, 1996):

$CaCO_3 + H^+ = Ca^{+2} + HCO_3^-$ --------------------------- (1)
(Calcite)

$CaMg(CO_3)_2 + 2H^+ = Ca^{+2} + Mg^{+2} + 2HCO_3^-$ ---------(2)
(Dolomite)

If dolomite dissolves according to equation 2, the molar proportions of [Ca + Mg] to [HCO3] should be linear, with a slope of 1. However, most of the water samples do not follow the trend predicted by the dolomite dissolution model and are highly enriched in calcium and magnesium relative to bicarbonate ([Ca + Mg]/ [HCO_3] > 1). This reflects that additional sources of Ca and Mg exist within the subsurface. Gypsum ($CaSO_4.H_2O$) and anhydrite ($CaSO_4$) are not known to occur in the rock matrix in the Ayensu basin. The predominance of sulphate and chloride over bicarbonate in the groundwater indicates that other processes are controlling water chemistry in this area (Al-Amry, 2008).

The mechanism controlling chemical relationships of groundwater based on aquifer lithology had been studied following Gibbs (1970). Fig.5 and 6 represent Gibb's plot of groundwater quality data of Ayensu basin. The Gibbs ratio for the ions Na/ (Na + Ca) and Cl/ (Cl + HCO_3) of groundwater samples were plotted against the respective values of TDS. The plots indicate that more than 90% of the groundwater samples fall in the rock dominant category (rock weathering) and the rest fall in the evaporation field. Rock dominance of most of the samples is caused by the interaction between the aquifer rocks and groundwater (Kannan and Sabu,2010).. The sources of Ca^{2+}, Mg^{2+}, Fe^{2+} and K^{+} could be due to the weathering of plagioclase feldspars (anorthite, biotite, hornblende and pyroxenes) that are components of the granitoids, schist and gneisses (the granite complex) that underlain the Ayensu basin.

5.3 Minor and trace ions

Aluminium, iron, zinc and manganese showed concentrations significantly above their detection limits in most of the water samples. Al^{3+} ion varies in concentration in the groundwater samples from < 0.030 mg/l to 0.366 mg/l with a mean value of 0.222 mg/l.

Most of the water samples had the Al^{3+} ion concentrations below detection limit but approximately 43% of the samples had Al^{3+} concentrations above the WHO maximum acceptable limit of 0.200 mg/l for drinking water (WHO, 2004). Fe concentration varies from <0.006 mg/l to 1.47mg/l with a mean value of 0.27 mg/l and median value of 0.168 mg/l. Approximately, 10% of the groundwater samples have their Fe^{2+} concentration greater than the WHO guideline maximum value of 0.300 mg/l. This does not pose major aesthetic problems to groundwater usage for domestic purposes in the Ayensu Basin. Mn^{2+} concentration varies < 0.002 mg/l to 0.391 mg/l with a mean value of 0.055 mg/l. The Mn^{2+} concentration of all the water samples in the Basin are below the WHO permissible limit for portable water of 0.300 mg/l. Thus the manganese concentration in the groundwater does not pose any major quality problem in the Ayensu river basin. All the water samples have Zn^{2+} concentration below the WHO limit of 3.00 mg/l.

6. Conclusions

The study assessed the groundwater and surface water quality 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 5.41. 24% and 22% of the sampled groundwater recorded chloride and sulphate concentrations respectively, exceeding the WHO permissible limit for portable water. 7% of the groundwater have TDS greater than 1000 mg/l which indicates saline water bodies whilst the rest area classified as fresh water. 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 the Ayensu basin.

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Appendix 1: Physico-chemical parameters of water samples in the Ayensu basin

ID	TYPE	pH	TEMP.	EC	TDS	ALK	Ca	Mg	Na	K	Cl^-	SO_4^{2-}	HCO_3^-	NO_3^-	PO_4^{3-}	CBE%
Ojobi	BH	7.13	26.35	1601.2	856.3	21.00	108.4	12.15	305.0	10.40	505.36	153.0	25.62	31.748	0.76	4.19
Ojobi	HDW	7.41	26.4	1300.9	636.82	59.20	58.4	7.29	140.0	7.20	198.8	68.898	72.224	89.578	5.09	0.69
Ojobi	SW	7.66	27.0	998.12	549.12	52.89	28.80	8.02	80.0	3.50	131.67	10.37	60.40	9.099	1.68	5.72
Ojobi	SW	6.70	27.05	596.7	350.32	9.00	5.60	0.78	35.75	3.75	57.98	7.91	10.98	9.4525	0.94	-3.27
Kweikrom	BH	6.73	27.08	1253.9	677.04	15.20	53.80	22.53	92.5	21.23	235.45	67.78	23.67	33.53	0.00	0.88
Kweikrom	HDW	6.76	26.6	1042.7	565.37	21.87	78.40	24.30	24.0	10.40	189.0	81.9	32.21	1.80	0.42	-2.24
Kweikrom	HDW	6.93	29.4	1009.3	452.03	26.10	86.40	13.61	59.0	4.90	189.0	81.9	26.19	2.00	0.21	4.18
Gyangyanadze	BH	7.72	28.15	2043.8	1222.5	24.07	86.96	29.57	363.8	15.20	633.6	169.2	29.66	2.091	0.00	2.52
Gyehadze	SW	7.43	29.7	706.5	442.07	16.27	33.20	7.78	79.0	3.50	130.0	6.85	19.52	120.93	0.91	-2.03
Adawukwa	SW	8.43	27.63	484.1	190.13	31.47	24.50	7.80	33.55	6.40	64.5	19.4	39.37	36.1	0.67	0.71
Adawukwa	SW	8.29	26.1	131.0	842.8	45.23	39.00	8.25	68.0	14.60	104.0	49.6	55.17	57.41	0.212	1.49
Dominase	HDW	8.38	26.9	1222.8	765.1	52.67	86.00	17.00	112.0	4.40	159.8	135.0	56.41	85.98	7.265	5.29
A.Kwabenya	BH	6.88	26.47	1538.8	731.3	30.67	92.0	48.64	84.5	8.20	278.3	85.14	42.32	155.3	0.00	-1.08
A.Kwabenya	BH	6.68	27.23	1263.0	683.5	24.53	82.00	26.73	43.3	4.40	192.8	54.48	28.70	21.99	0.61	5.94
A.Kwabenya	SW	7.58	24.57	787.6	401.4	45.60	54.06	20.1	29.60	1.50	140.8	30.05	55.50	0.158	0.063	1.74
Ofaso	BH	6.00	22.0	1301.7	662.7	20.60	81.59	41.18	64.6	3.75	250.0	89.94	25.17	5.20	0.00	5.05
Dankwa BH	6.12	25.5	869.1	449.1	19.00	50.7	6.075	52.0	11.80	122.7	40.82	23.18	26.2	0.18	4.63	
Fianko	BH	5.70	26.35	1198.5	618.8	20.20	75.0	46.49	85.0	13.60	261.4	79.40	29.44	89.25	0.37	3.23

Appendix 1 continued

Penin	BH1	5.94	26.87	1605.0	835.0	46.80	135.1	51.15	122.7	30.67	366.8	139.6	57.1	76.72	1.03	5.29
Penin	BH2	5.70	26.67	980.3	515.0	27.80	83.33	56.57	85.6	8.85	282.7	98.59	33.92	84.54	1.89	3.59
Penin	SW	5.99	25.47	711.8	374.4	23.40	44.76	13.77	19.9	2.50	91.98	38.33	28.55	7.52	0.00	4.05
Osimpo	BH	6.07	27.68	1260.0	603.8	27.20	47.1	47.5	106.5	6.10	241.9	79.39	36.76	126.4	1.029	-0.04
Osimpo	SW	5.74	19.38	553.1	268.8	36.70	50.10	1.82	51.3	4.30	127.8	39.85	34.24	0.921	0.22	-0.09
Ayensuako	BH	7.09	27.6	806.8	518.4	37.53	61.6	16.2	124.0	6.30	146.6	118.0	46.12	100.6	2.22	5.36
A.Tekyeman	BH	5.6	28.6	742.1	444.5	17.07	53.77	23.67	68.0	12.20	131.3	56.99	20.82	117.9	2.23	5.32
Kwakwa	SW	7.87	27.3	286.3	169.4	15.33	40.91	5.27	30.9	4.20	84.02	48.03	18.71	1.06	0.08	3.17
Mankrong-N	SW	8.18	27.78	440.7	252.0	14.63	19.21	9.02	8.5	1.70	48.35	15.11	17.44	1.744	2.22	3.27
Obosomase	SW	6.58	27.9	416.4	315.0	12.80	33.49	20.0	37.0	6.50	89.22	85.00	18.43	5.07	0.77	4.59
Obosomase	BH	6.26	24.75	644.3	178.2	28.47	35.90	23.8	32.00	4.40	99.40	60.34	33.92	23.20	8.38	2.88
Kwesikumkwa	BH	6.04	24.4	1652	686.7	31.93	97.17	14.31	57.0	9.80	154.0	214.0	39.20	0.15	0.82	-3.63
Mensakwa	BH	6.01	26.13	1357.3	722.5	24.00	64.00	17.8	91.0	6.70	180.1	131.0	26.03	0.195	0.00	3.37
Esselkwa	BH	5.94	24.4	970.9	463.9	10.95	34.3	24.7	78.4	5.30	125.0	137.0	17.76	0.00	17.75	4.67
Amanfor	BH1	5.64	26.17	775.0	381.9	15.61	57.6	31.3	46.0	3.40	123.5	153.0	16.27	16.24	1.32	2.58
Amanfor	BH2	5.56	27.3	987.1	389.9	40.00	62.0	52.0	61.3	5.80	169.0	190.0	48.8	0.098	1.O5	3.67
Namanwura	BH1	5.39	27.05	400.2	173.4	17.07	35.0	15.0	33.7	4.80	89.22	68.0	22.05	7.057	0.00	2.04
Namanwura	BH2	5.91	26.0	311.8	100.9	25.07	33.0	23.9	28.3	5.75	73.80	68.0	30.47	40.96	17.75	3.72
Ohiawanwu	BH	5.38	27.1	603.9	239.6	18.76	56.7	13.3	57.0	7.20	139.0	76.0	22.89	10.97	1.324	4.39
Doato	BH1	5.91	26.43	531.9	291.0	18.20	28.00	13.4	57.0	10.30	129.0	42.0	23.54	8.22	2.347	2.25

Appendix 1 continued

Kanyanko	BH1	5.81	26.2	780.6	402.3	12.27	31.8	8.4	49.0	9.90	112.3	31.03	22.12	6.34	0.00	4.48
Kanyanko	BH2	5.76	26.4	739.7	315.8	11.07	40.0	21.2	27.0	2.80	87.98	96.3	21.39	4.24	0.00	1.10
Fanti-Bawjwase	BH1	6.47	24.5	980.5	436.7	14.65	53.00	42.3	45.0	4.60	218.0	53.5	20.05	23.41	0.88	1.78
Fanti-Bawjwase	BH2	5.86	24.7	787.4	352.7	11.90	43.3	31.8	62.8	7.10	210.4	64.8	16.19	0.124	0.00	1.19
Kofikum	BH	6.39	27.2	521.8	309.4	16.53	42.40	10.0	43.0	5.70	99.95	54.20	29.61	16.32	0.00	2.86
Oboyambo	HDW1	6.97	27.1	1271.3	386.1	25.87	56.70	42.4	80.6	6.80	198.5	209.0	31.56	0.21	0.00	-2.04
Oboyambo	HDW2	5.98	27.0	297.7	333.5	20.27	53.0	31.3	58.2	7.30	169.8	90.80	24.73	24.35	0.41	3.26
Oboyambo	HDW3	7.06	26.7	464.6	139.1	24.00	53.00	31.80	48.2	3.70	178.4	67.90	29.28	0.06	0.56	3.95
Okaekrom	BH	6.26	26.95	786.9	184.6	12.27	31.8	41.29	92.0	3.40	218.0	82.5	14.97	5.99	0.51	5.29
Bewadze	BH	6.54	28.9	1521.8	399.6	22.60	89.40	64.23	178.0	15.3	405.5	189.7	41.36	16.00	0.00	4.79
Adabra	BH	7.18	26.9	1141.6	1456.0	19.87	96.50	66.00	120.0	5.40	316.0	164.0	24.24	16.8	5.10	-0.86
Topiase	BH	5.82	27	2814.0	687.5	18.78	47.70	108.2	59.5	8.90	402.3	76.86	24.98	25.04	0.231	1.68
Brahabekume	BH	6.97	27.2	6011.0	1291.0	28.76	623.0	302.1	159.0	4.8	1680.4	483.0	38.85	25.04	0.00	4.05
Kyerebuakwa	BH	6.36	28.4	678.7	2746	28.8	31.8	21.2	31.0	6.40	86.5	33.7	35.14	41.49	5.23	5.24
Asabrekwa	SW	6.79	28.15	635.6	269.7	24.00	39.2	22.7	62.3	6.30	139.0	84.95	29.28	0.80	5.10	4.22
Kokroko	BH	5.52	26.8	1012.6	486.0	25.00	6.36	41.64	88.0	6.90	208.4	53.8	31.72	0.10	0.00	1.82

Concentrations in mg-1, pH in pH-units, EC in µScm-1, TDS in mg/l, Temperature in °C. SW : surface water, BH: Borehole . HDW :Hand dug well, RA :River Ayensu.

Appendix 2: Trace metal concentrations of groundwater in the Ayensu Basin

ID	TYPE	Fe	Cu	Zn	Cr	Cd	Mn	Al
Ojobi	BH	1.20	<0.003	0.006	<0.001	0.002	0.101	0.32
Ojobi	HDW	0.44	<0.003	0.091	<0.006	0.058	0.035	<0.030
Ojobi	POND	0.524	<0.003	0.141	<0.006	0.082	0.16	<0.030
Ojobi	SPRING	1.554	<0.003	0.056	<0.006	0.079	0.03	<0.030
Kweikrom	BH	<0.006	0.054	0.0177	<0.006	<0.002	<0.002	<0.030
Kweikrom	HDW1	<0.006	<0.003	0.007	<0.006	<0.002	<0.002	0.315
Kweikrom	HDW2	<0.006	<0.006	0.017	<0.006	<0.002	0.011	0.239
Gyangyanadze	BH	1.465	<0.003	0.0273	0.003	<0.002	0.006	0.438
Gyehadze	DAM	1.67	0.016	0.3006	<0.006	<0.002	<0.006	<0.030
Adawukwa	RA1	0.989	<0.003	0.073	<0.006	0.081	0.016	0.107
Adawukwa	RA2	0.01	0.028	0.151	<0.006	<0.002	0.353	<0.003
Dominase	HDW	0.475	<0.003	0.06	<0.006	0.073	<0.002	<0.030
A. Kwabenya	BH	0.038	<0.003	0.0177	<0.006	<0.002	0.041	0.211
A. Kwabenya	BH	0.044	0.003	0.1028	<0.006	<0.002	0.034	<0.030
A. Kwabenya	SW	0.311	<0.003	0.086	<0.006	0.081	0.048	<0.030
Ofaso	BH	0.117	<0.003	0.059	<0.006	<0.002	<0.006	<0.030
Dankwa	BH	0.045	<0.003	0.0716	<0.006	<0.002	0.003	<0.030
Fianko	BH	<0.006	<0.003	0.0651	<0.006	<0.002	<0.002	<0.030
Appendix 2 continued								
Penin	BH	0.027	<0.003	0.0513	<0.006	<0.002	<0.002	, 0.030
Penin	BH	0.116	<0.003	0.002	0.005	<0.002	<0.002	0.354
Penin	SW	0.876	<0.003	0.057	<0.006	0.081	0.034	<0.030
Osimpo	BH	0.009	<0.003	0.0349	<0.006	<0.002	<0.002	0.262
Osimpo	SW	0.605	<0.003	0.125	<0.006	0.078	0.17	0.101
Ayensuako	BH	0.233	0.353	0.05	<0.006	0.065	<0.002	<0.030
A.Tekyeman	BH	0.045	<0.003	0.0716	<0.006	0.002	0.00	<0.030
Kwakwa	RA	1.385	<0.003	0.101	<0.006	0.047	0.149	0.00
Mamkrong=N	RA	1.243	<0.003	0.062	<0.006	0.074	0.024	0.073
Obosomase	SW	0.049	0.01	0.092	<0.006	<0.002	0.008	<0.030
Obosomase	BH	<0.006	<0.003	0.194	<0.006	<0.002	0.027	<0.030
Kwesikumkwa	BH	<0.006	<0.003	0.098	<0.001	)<0.002	0.043	0.321
Mensakwa	BH	<0.006	0.004	0.101	<0.006	<0.002	0.276	<0.030
Esselkwa	BH	<0.006	<0.003	0.146	<0.006	<0.002	0.06	<0.030
Amanfor	BH1	<0.006	0.006	0.172	<0.006	<0.002	0.016	<0.030
Amanfor	BH2	<0.006	<0.003	0.012	<0.001	<0.002	0.011	0.301
Namanwura	BH1	<0.006	<0.003	0.332	<0.006	<0.002	0.101	<0.030
Namanwura	BH2	<0.006	<0.003	0.361	<0.006	<0.002	<0.002	0.279
Ohiawanwu	BH	<0.006	<0.003	0.067	<0.006	<0.002	0.391	0.308
Doato	BH	<0.006	0.028	0.151	<0.006	<0.002	<0.002	0.362
Kanyanko	BH1	<0.006	<0.003	0.18	<0.006	<0.002	<0.002	<0.030
Kanyanko	BH2	<0.006	0.015	0.388	,0.006	<0.002	<0.002	<0.030

Fanti-Bawjwase	BH1	<0.006	<0.003	0.116	<0.006	<0.002	0.012	<0.030
Fanti-Bawjwase	BH2	<0.006	<0.003	0.107	<0.006	<0.002	0.011	<0.030
Kofikum	BH	<0.006	<0.003	0.15	<0.006	<0.002	<0.002	0.052
Oboyambo	HDW	<0.006	<0.003	0.032	<0.006	<0.002	0.027	0.25
Oboyambo	HDW	<0.006	<0.003	0.058	<0.001	<0.002	<0.002	0.309
Oboyambo	HDW	<0.006	<0.003	0.056	<0.001	<0.002	<0.002	0.258
Okaekrom	BH	0.099	<0.003	0.26	<0.006	<0.002	0.065	<0.030
Bewadze	BH	0.046	<0.003	0.0191	<0.006	<0.002	0.00	<0.030
Adabla	BH	0.219	<0.003	0.0462	<0.006	<0.002	0.00	<0.030
Topiase	BH	<0.006	0.005	0.142	<0.006	<0.002	0.01	0.279
Brahabekume	BH	<0.006	0.006	0.126	<0.006	<0.002	0.037	0.366
Kyerebuakwa	BH	<0.006	<0.003	0.021	<0.001	<0.002	<0.002	0.307
Asabrekwa	SW	0.034	<0.003	0.129	<0.001	<0.002	<0.002	0.201
Kokroko	BH	0.018	<0.003	0..035	0.009	<0.002	<0.002	0.272