

# Hydrochemical Characterisation of Groundwater in Parts of the Volta Basin, Northern Ghana\*

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## Abstract

Conventional graphical methods were applied to major ion concentrations and stable isotope data to determine the genesis and evolution of the hydrochemistry of groundwater from fractured aquifers in the northern parts of Ghana. The analyses suggest that groundwater hydrochemistry is controlled by the incongruent weathering of silicate minerals in the aquifers. Hierarchical cluster analysis confirms the results and shows that anthropogenic factors also contribute to the groundwater chemistry. Montmorillonite, apparently resulting from the incongruent dissolution of calcium and sodium rich feldspars in the rock matrix is probably the most stable clay mineral phase in the system. Chloroalkaline indices (CAI) 1 and 2, calculated from the major ion data suggest reverse cation exchange activity between  $\text{Na}^+$  and  $\text{K}^+$  in the water and  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  in the rock matrix. This study finds that the groundwater in the area is classified into Ca-Mg- $\text{HCO}_3$ , mixed Ca-Mg-Na- $\text{HCO}_3$  and Na- $\text{HCO}_3$  water types, which are typical of groundwaters influenced by silicate mineral weathering and ion exchange. Stable isotopes of oxygen and hydrogen ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) show that groundwater originates from meteoric source, derived from rainfall which rapidly recharges the aquifers through the weathered overburden and ingresses such as joints and fracture systems. Silicate mineral weathering, which appears to be the main controlling process in the hydrochemistry, does not appear to influence the stable isotope data since a plot of  $\delta^{18}\text{O}$  against EC is a straight line of zero slope.

## 1 Introduction

The reliance on groundwater by farming communities within the White Volta Basin for various purposes cannot be over emphasized. A wide variety of uses of groundwater depend largely on its chemical composition, which is controlled by natural and anthropogenic factors. Naturally, the chemistry of groundwater is altered by a variety of geochemical processes as it moves along flow lines from recharge to discharge areas. According to Freeze and Cherry (1979), dissolved constituents in groundwater provide clues on its geologic history, its interaction with the soil or rock masses through which it has passed, the presence of hidden ore deposits, and its mode of origin within the hydrologic cycle. Various workers (e.g., Hendry and Schwartz 1990; Hiscock *et al.*, 1996; Arad and Evans, 1987; and Herczeg *et al.*, 1991, 1993) agree that the major ion chemistry of groundwater is a powerful tool for determining solute sources and for describing and understanding groundwater evolution. Thus, understanding the evolution and origin of the groundwater in the fractured aquifer within the basin is very crucial. Although the quality of groundwater in Ghana is generally good for multipurpose use, sanitary conditions around the wellhead in most cases in the study area are very poor. This could lead to contamination from surface sources.

In this investigation, physical parameters such as pH, electrical conductivity (EC), total dissolved solids

(TDS) or salinity, temperature (T), and ions including  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$  and  $\text{HCO}_3^-$  were examined. This is because these parameters form the basic constituents of natural groundwater and their respective variations help in characterising the groundwater into different types. Krothe and Bergeron (1981) noted that groundwater is classified into types based on prevalent chemical dominance in milliequivalents per liter, such that groundwater of similar chemical composition form clusters, consequently, characterising the aquifer into hydrochemical facies (Fetter, 1994). The facies according to Back (1960) reflect the effects of chemical processes in the lithologic environment and the contained groundwater pattern. In this regard, Bajjali (2006) classified the water in the Nuaimah area, Jordan as  $\text{CaHCO}_3$  type and explained that, it is a result of short duration of water-rock interaction and dissolution of carbonate aquifer. Karimi *et al.* (2005) similarly used the physical, chemical and isotopic characteristics of spring water to characterise the main karst aquifers of the Alvand basin into two groups, assessed the origin of the groundwater and settled on the geology, elevation and rate of karst development as the main factors controlling the composition and seasonal variation of the groundwater. Major ion and stable isotope geochemistry, was used by Tweed *et al.* (2004) to define flow paths and inter-aquifer exchange in fractured rock aquifer system in the Dandenong Ranges, Southeast Australia. The importance of the combined use of major and minor ions with

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stable and radiogenic isotopes in groundwater studies have been expressed by Cartwright and Weaver (2005) who used the results to constrain flow systems, establish the criteria for identifying recently recharged waters and assess groundwater use and vulnerability. In the same vein, sustainable groundwater use in the White Volta Basin requires thorough knowledge of basement hydrogeology and hydrochemistry so as to completely understand the hydrochemical changes that are occurring in these extensively exploited aquifers, establish the main controls on the groundwater chemistry as well as to understand the mode and rate of replenishment of these aquifers.

The primary objective of this paper is to examine hydrochemical and isotopic data of groundwater acquired from hand-dug wells and boreholes with a view to understanding the genesis and hydrochemical evolution of the groundwater from fractured aquifers in parts of the Volta Basin. Conventional graphical methods and Hierarchical cluster analysis (HCA) have been used to characterize the groundwater into various hydrochemical facies and to define the main controls on the groundwater chemistry. Stable isotope values of oxygen ( $^{18}\text{O}$ ) and deuterium (D) were used as important indicators to determine the origin and to establish the recharge regimes of the groundwater.

## 2 Description of the Study Area

The study area is located within Longitudes  $0^{\circ} 30' \text{ W} - 3^{\circ} 00' \text{ W}$  and Latitudes  $9^{\circ} 40' \text{ N} - 11^{\circ} 00' \text{ N}$  and covers parts of three regions, namely, Upper East, Upper West and the Northern regions of Ghana. The area is bordered to the north and west by the Republic of Burkina Faso and Cote D'Ivoire respectively, south by the Brong Ahafo Region of Ghana and the east by the Republic of Togo (Fig. 1).

The topography of the study area is generally undulating with gentle slopes. Except in areas where major drainage interrupts their continuity, the undulating topography merges smoothly into one another. The drainage system of the area is composed of numerous ephemeral streams. These streams form part of two main sub-basins; the Kulpawn and the Black Volta, which drain primarily into the Volta River. While the Kulpawn is at the extreme east of the area, the Kamba and Bele River drain into the Black Volta at the extreme west.

The area falls within the tropical continental or savannah climatic zone and characterized by a single peak of rainfall and intense periodic droughts. The rains begin in March-April, with intermittent showers until August-September when the rains are at their best with monthly rainfalls as high as 200 mm. The daily temperature recorded in this region is at a minimum of  $18^{\circ}\text{C}$  with maximum values of  $42^{\circ}\text{C}$  in

May and  $34^{\circ}\text{C}$  in September. On the whole, the average annual temperature is about  $30^{\circ}\text{C}$ . Relative humidity during the wet season in the region gets to 40-70% and drops to about 15% during the rest of the year with a mean annual relative humidity in the range of 37-46%. The guinea savannah woodland vegetation belt is typical of the area and consists of grass with scattered drought resistant trees such as the shea, the baobab, dawadawa, acacias and neem.

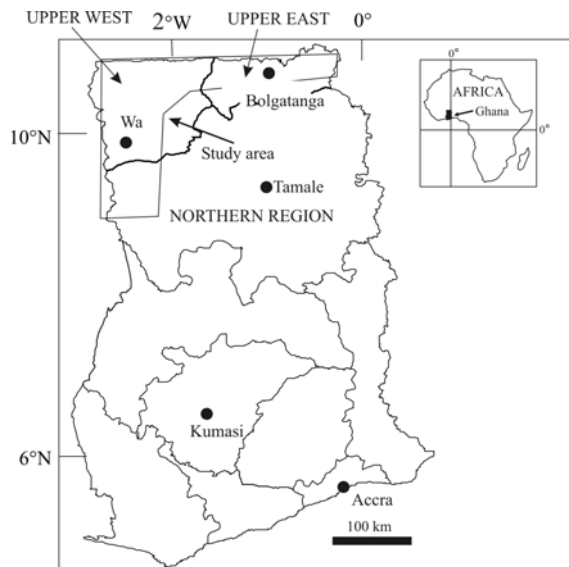
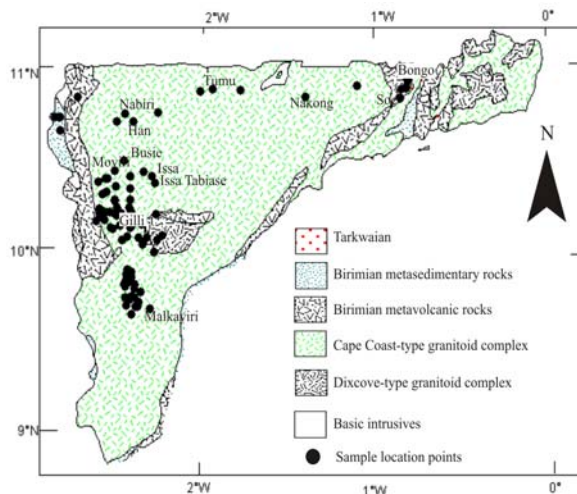


Fig. 1 Location Map of the Study Area

## 3 Geological and Hydrological Setting

The area is extensively underlain by granite-migmatite complex rocks grouped as Cape Coast granites (G1), Dixcove granites (G2) and undifferentiated granites and rocks of the Birimian Supergroup of Early Proterozoic age (Leube et al., 1990) (Fig. 2). The Birimian Supergroup is made up of rocks of Birimian Sedimentary Basins and Birimian Volcanic Belts. These rocks outcrop in a N-S direction along the border with Burkina Faso at the western periphery and in a NE-SW direction, the rocks of this supergroup lie at the central part of the Upper East Region. The rocks of the Birimian Sedimentary Basins are represented by great thicknesses of isoclinally folded, steeply dipping, alternating phyllites, schistose greywackes, sheared conglomerates, slates and argillaceous beds with some tuffaceous schist and lava. The Birimian Volcanic Belts rock is dominantly of metabasalts and meta-andesites with volcanic and pyroclastic origin. The rocks consist of green lavas, tuffs and sediments with bands of phyllites. They are largely folded and have undergone low-grade metamorphism; where the basic volcanics and pyroclastics have been altered extensively to chloritised and epidotised rocks that are termed greenstones (Kesse, 1985).



**Fig 2 Geological Map of the Study Area showing the Sampling Points**

The G1 granites form about 70% of the area and are noted to be the most abundant granites that have intruded the Birimian Sedimentary Basin, hence are sedimentary basin granitoids. They occur as large; highly migmatized synorogenic foliated batholiths. They are generally granodioritic in composition i.e. they are potash-rich biotite and muscovite granites and granodiorites, porphyroblastic biotite gneiss, aplites and pegmatites with biotite schist pendants. These granites, usually with fresh feldspars are characterized by enclaves of schist and gneisses. The G2 complex intrude the Birimian metavolcanics, hence are volcanic belt granitoids. These rocks consist of soda-rich, hornblende-biotite granite or granodiorites, which grade into quartz diorite and hornblende diorite and are commonly tonalitic in composition. Also found in association with these rocks are porphyritic biotite and biotite gneisses (Leube *et al.*, 1990).

The tectonic lines of weakness that developed during the Eburnean orogenic event facilitated extensive and deep weathering of the rocks in the study area and are enhanced where the fractures, joints, quartz veins and pegmatites are many and dense. Thick decomposed zones reaching depths of approximately 30 m to 50 m occur and are greatest in the Birimian rocks (Banoeng-Yakubo, 2000). The rocks, especially the micaceous and feldspathic schists usually weather to clays and permeability is reduced. However, relatively high yields are obtained from quartz-schists in the moderately decomposed zones. This subsequently implies that significant aquifers developed within the weathered overburden i.e., the regolith and fractured bedrock in the area. Thus, the mode of groundwater occurrence in the area is dependent primarily on the presence and extent of the weathered overburden, the saturated thickness of the weathered zone, the areal extent and interconnection of joints and fractures in the underlying bedrock

(Banoeng-Yakubo, 2000). Also, quartz veins and pegmatites that are fractured and to some extent brecciated due to brittle deformational activities which affected them contain groundwater. Norgbe (1996) grouped the aquifer types in the area into three categories: the weathered rock aquifer which is fracture related, the fractured quartz vein and the fractured unweathered rock aquifer. These aquifers are inter-related and can occur together. Recharge to the aquifers is dominantly by direct rainfall. Infiltration of recharge water and the subsequent percolation into the groundwater system is made possible only if the fractures, joints and fissures or a combination of these features are well distributed, oriented, frequent and interconnected. The aquifers in the area are characterised by low transmissivity and storativity values. Transmissivity values ranged from 7.5m<sup>2</sup>/day to 30m<sup>2</sup>/day (Norgbe, 1996) and storativity values recorded in the region ranged from 3x10<sup>-4</sup> to 8x10<sup>-3</sup> (CIDA/GWSC, 1980).

#### 4 Methodology

Ninety-five (95) groundwater samples were collected from boreholes and hand-dug wells for analysis of major and minor ions in this study. Out of this number, fifty-four samples in addition to three (3) surface water samples and a rainfall sample were also analyzed for stable isotopes of oxygen-18 (<sup>18</sup>O) and deuterium (<sup>2</sup>H). Fig. 2 shows the location of the sampling sites. The samples were collected in 250 ml sterilized polythene bottles. For all samples collected, parameters such as electrical conductivity (EC), temperature (T) and pH values were measured in the field. On-site testing was necessary for these parameters since they are likely to change during transport. These variables were measured using a WTW Universal Conductivity Meter MultiLine P4 set and probes. The pH-meter was calibrated against a standard solution of 3 mol KCl each morning and also during field work if unusual readings were made. The water samples were analyzed at the Ecological Laboratory (Ecolab) of the Department of Geography and Resource Development at the University of Ghana, Legon. The parameters analyzed include ions of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, Na<sup>+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> in milligram per liter (mg/l) using Dionex DX 120 ion chromatograph (I.C). The bicarbonate ion concentration in the water was determined by titration. The dataset used for Hierarchical Cluster Analysis (HCA) was transformed (log-transformed and standardised). Rummel (1970) contends that these transformations do not only normalize and reduce outliers but also tend to homogenise the variance of the distribution. HCA was applied with the aim of grouping a system of variables into clusters based on similarities or dissimilarities within the dataset. This was made using the Euclidean distance for similarity measurement and the Ward's method

for linkage. Guler *et al.* (2002) explained that the combined use of the Euclidean distance and Ward's method produces the most distinctive groups where each member within a group is more similar to its fellow members than any other member from outside the group.

The stable isotopes ( $^2\text{H}$  and  $^{18}\text{O}$ ) analyses were carried out at the Geological Institute of the University of Copenhagen using the Delta E class mass spectrometer. A 1-10 mg portion of the water was reduced with zinc in a zinc-reaction furnace at 400-415°C to prepare hydrogen for isotopic analysis based on Coleman *et al.* (1982) and Florkowski (1985). Measurement of  $\delta^{18}\text{O}$  was based on Dugan *et al.* (1985) technique. The isotopic compositions of water are reported as the deviation of D/H or  $^{18}\text{O}/^{16}\text{O}$  ratio from that of Vienna Standard Mean Ocean Water (VSMOW) in parts per thousand ‰.

The resulting data were subjected to internal consistency tests to ascertain sampling and analytical accuracy. Optimal analysis results showed cation-anion difference less than 5%. The graphical techniques used in this study include fingerprint diagram, Piper Trilinear diagram etc. These were prepared to aid in interpretation of the data and were made possible using softwares as Aquachem 4.0, SPSS and Microsoft Excel.

## 5 Results and Discussion

### 5.1 Hydrochemical Characterization and Geochemical Evolution of the Groundwater.

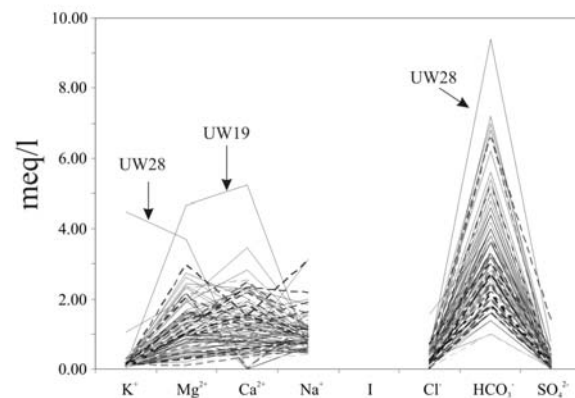
Table 1 shows a statistical summary of the hydrochemical parameters determined for the samples. The study revealed a wide range of concentrations and different compositions of the groundwater. Schoeller's fingerprint diagram (Fig. 3) gives a visual description of the comparative abundance pattern of dissolved ions in each sample and also sorts the hydrochemical data into groups. The compositional variations of calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), and sodium ( $\text{Na}^+$ ) are such that it is very difficult to pinpoint which one of them is commonly dominant with the exception of UW19 where  $\text{Ca} > \text{Mg}$  and clearly depicts a  $\text{Ca-Mg-HCO}_3^-$  water type.

Potassium ion concentrations are generally low except for UW28 where the value is high with corresponding high bicarbonate content, hence a  $\text{K-Mg-HCO}_3^-$  water type (Fig. 3). The concentration of the  $\text{K}^+$  in the water is probably influenced by reverse cation exchange activity with  $\text{Ca}^{2+}$ . Bicarbonate ion is the most dominant anion while chloride and sulphate ions (Fig. 3) are low in all the water samples. The dominance of the  $\text{HCO}_3^-$  ion in the groundwater system is not unexpected since it is a by-product of the incongruent weathering of both albitic and cal-

cium rich feldspars. The water in the area with respect to the fingerprint diagram may be grouped as various combinations of  $\text{Ca-Mg-Na}$  with  $\text{HCO}_3^-$  water types.

**Table 1 Descriptive Statistics of the Concentrations of the Water Quality Parameters.**

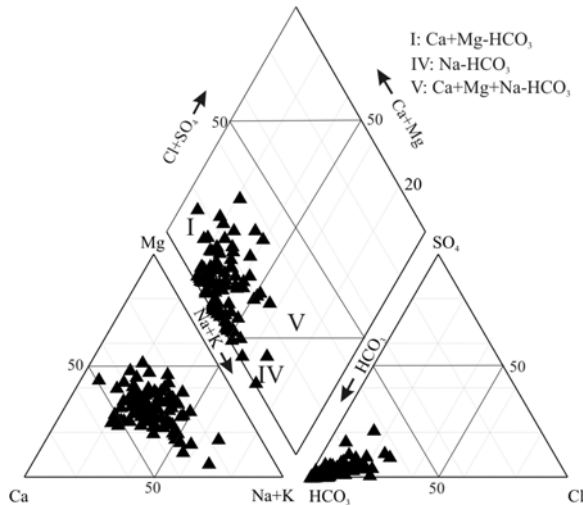
Parameters	Minimum	Maximum	Mean	Std. Deviation
pH	5.85	7.55	6.71	0.38
EC (Us/cm)	95.00	1346.00	390.79	201.94
TDS (mg/l)	58.27	728.54	214.35	109.75
$\text{Na}^+$ (mg/l)	9.00	71.85	22.85	10.87
$\text{K}^+$ (mg/l)	0.75	175.58	6.51	18.03
$\text{Mg}^{2+}$ (mg/l)	0.97	56.79	14.84	9.37
$\text{Ca}^{2+}$ (mg/l)	0.00	104.90	25.29	16.02
$\text{F}^-$ (mg/l)	0.07	3.12	0.71	0.63
$\text{Cl}^-$ (mg/l)	0.21	55.22	9.17	8.84
$\text{NO}_3^-$ (mg/l)	0.00	194.65	29.46	37.85
$\text{SO}_4^{2-}$ (mg/l)	0.00	66.45	6.55	9.54
$\text{HCO}_3^-$ (mg/l)	61.02	573.59	199.15	94.93



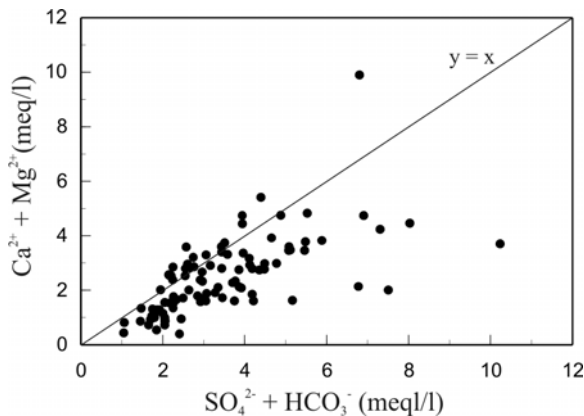
**Fig. 3 Fingerprint Diagram of the Groundwater Samples from the Study Area.**

The Piper diagram (Fig. 4) shows that the groundwater types that are significantly distinguished by the positions they occupy in the diamond shape are  $\text{Ca-Mg-HCO}_3^-$  mixed water types and in a few cases,  $\text{Na-HCO}_3^-$ . About 95% of the groundwater in the area plot in the  $\text{Ca}^{2+} + \text{Mg}^{2+}$  and  $\text{HCO}_3^- + \text{CO}_3^{2-}$  section of the diamond field. This water type is characteristic of freshwaters generated from carbonate mineral weathering and the incongruent weathering of silicate minerals. Carbonate minerals are rarely present in the matrices of the aquifers in the study area. Therefore, the incongruent weathering of sili-

cate minerals, and cation exchange processes are the most probable sources of the observed water types (Fig. 5). The observed water type also suggests active recharge and short residence time waters (Cloutier *et al.*, 2006). Na-HCO<sub>3</sub> waters form about 3% of the total samples and those that represent mixed water types form about 2%. This, according to Cloutier *et al.* (2006) may signify evolutionary processes.



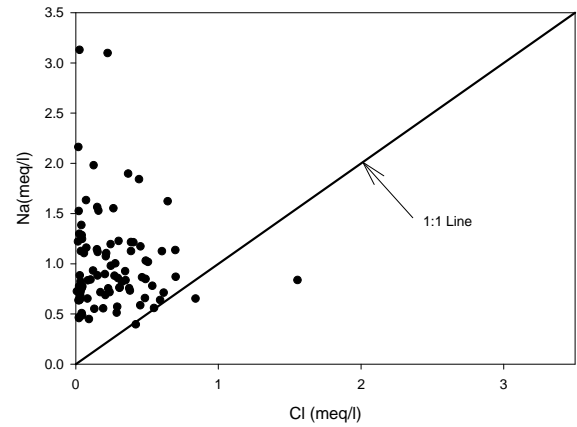
**Fig. 4 Piper Diagram for Hydrochemical Characterization of Groundwaters**



**Fig. 5 Variations in (Ca<sup>2+</sup>+Mg<sup>2+</sup>) versus (SO<sub>4</sub><sup>2-</sup> + HCO<sub>3</sub><sup>-</sup>) for Groundwaters in the Area.**

A plot of Na versus Cl (Fig 6) revealed that Na in the groundwater may have originated probably from the incongruent weathering of plagioclase particularly albitic feldspar by CO<sub>2</sub> charged meteoric recharging waters or by ion exchange reactions since most of the groundwater samples fall above the 1:1 line in the plot.

If silicate mineral weathering is an active process in the hydrochemistry, then a plot of the logs of  ${}_a\text{Ca}^{2+}/$



**Fig. 6 A plot of Na vs. Cl for the Groundwater Samples**

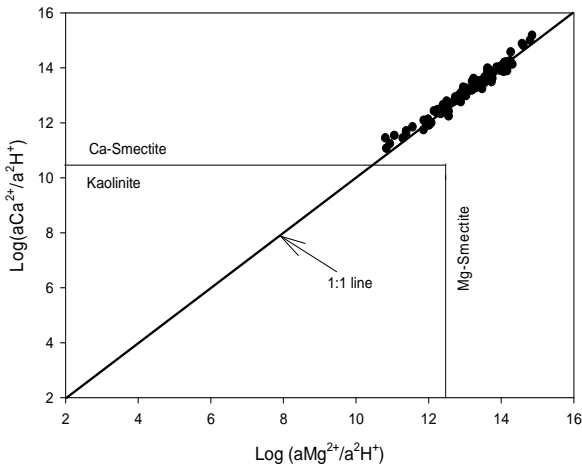
${}_a\text{H}^+$  against  ${}_a\text{Mg}^{2+}/{}_a\text{H}^+$  would be a straight line of slope 1 (Norton, 1974; Drever, 1988; Kumar *et al.*, 2008). Figure 7 is a plot of  ${}_a\text{Ca}^{2+}/{}_a\text{H}^+$  against  ${}_a\text{Mg}^{2+}/{}_a\text{H}^+$  for the study area. All the points plot close to the 1:1 line and fall within the smectite (montmorillonite) stability field. Stability in the montmorillonite field indicates arid to semiarid conditions and groundwater flow under restricted conditions. The plot cluster of the data within the Ca-smectite field implies the incongruent weathering of high temperature feldspars which are present in the aquifers in the area. Incongruent weathering of silicate minerals to their clay mineral equivalents creates suitable sites for ion exchange activity. Two indices of Base Exchange, chloroalkaline indices (CAI) 1 and 2 were used in this study to constrain the type of ion exchange occurring in the area. CAI 1 and 2 were calculated using Equations 1 and 2.

$$\text{CAI 1} = (\text{Cl}^- + (\text{Na}^+ + \text{K}^+))/\text{Cl}^- \quad \text{Eq. (1)}$$

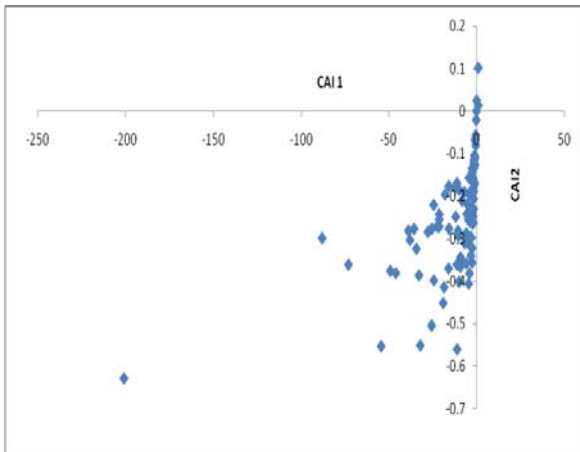
$$\text{CAI 2} = (\text{Cl}^- + (\text{Na}^+ + \text{K}^+))/(\text{SO}_4^{2-} + \text{HCO}_3^- + \text{CO}_3^- + \text{NO}_3^-) \quad \text{Eq. (2)}$$

where all species are measured in meq/l.

When there is an exchange between Na<sup>+</sup> or K<sup>+</sup> in the rock and Ca<sup>2+</sup> or Mg<sup>2+</sup> in the groundwater, both indices will be positive, and if there is reverse ion exchange prevalent in the area, both indices would be negative (Schoeller, 1965; Kumar *et al.*, 2008). A scatter plot for CAI 1 and CAI 2 (Fig. 8) for the study area shows that almost all the points fall within the negative portion for both indices, suggesting an exchange between Ca<sup>2+</sup> and Mg<sup>2+</sup> in the rock with Na<sup>+</sup> and K<sup>+</sup> in the groundwater. Na<sup>+</sup> ions are most probably generated from the weathering of albitic feldspars in the rock and then undergoing cation exchange with Mg<sup>2+</sup> and Ca<sup>2+</sup> ions.



**Fig. 7 An Activity Plot for the CaO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O System in the Study Area.**

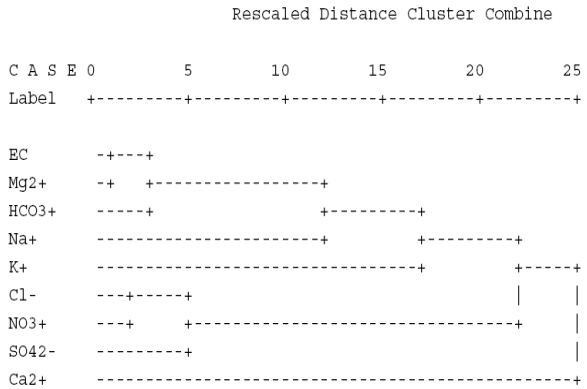


**Fig. 8 The Relationship between CAI 1 and CAI 2 for the Study Area**

The dendrogram (Fig. 9) from the HCA performed on the groundwater chemistry resulted in two main clusters; one formed by EC, Mg<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup> and the other by Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup>. The clusters reflect possible strong mutual correlations that exist among these ions while the rest of the variables show little correlation with each other. The first cluster, made up of EC, Mg<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup> shows that the chemistry of the groundwater may probably be derived mainly from leaching of minerals and weathering of rocks, particularly, the biotite-rich granitic gneiss underlying the area. It also indicates that EC in the groundwater has a dominant contribution from Mg<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup>.

The second cluster, which comprises Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup>, most likely reflects the input from contaminants arising from poor sanitary conditions around the boreholes, the use of organic and inorganic ma-

nure on farmlands and contribution of precipitation to the water chemistry. All boreholes in the area have troughs and receptacles where water is stored for animal use. Many of these troughs and receptacles are close to the boreholes and are poorly managed. The source of high nitrate could, therefore, be from animal droppings. Also the boreholes are mostly surrounded by farmyards which are manured from animal droppings and, in some cases, inorganic fertilisers such as NPK and sulphate of ammonia are administered.



**Fig. 9 Dendrogram (cluster tree) of the Hydrochemical Data from the Study Area**

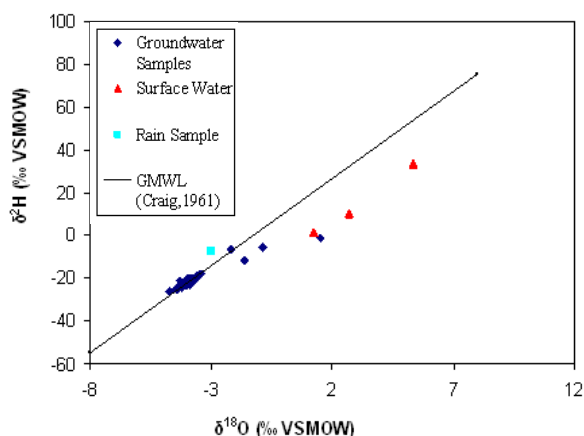
## 5.2 Environmental Isotopes

The δ<sup>18</sup>O and δ<sup>2</sup>H values for fifty groundwater samples, three surface water samples and a rainfall sample from the study area are presented on Table 2. The δ<sup>2</sup>H and δ<sup>18</sup>O data points of the groundwater samples cluster around the GMWL (Fig. 10), suggesting a meteoric recharge, derived from rainfall which rapidly recharges the aquifers through the weathered overburden and ingresses such as joints and fracture systems. However, the relatively low EC and TDS values of the groundwater in the study area suggest that groundwater is relatively young. A plot of δ<sup>18</sup>O against EC for the study area is also illustrated in Figure 11. The δ<sup>18</sup>O data does not appear to change with increasing EC, suggesting that the silicate mineral weathering which appears to influence the groundwater hydrochemistry in the area does not appear to affect the isotopic signature of the water. Generally, δ<sup>2</sup>H values are not affected by reactions within the aquifer materials at low temperatures (Drever, 1988). In addition, silicate mineral weathering in aquifers do not appreciably affect δ<sup>18</sup>O signatures at low temperatures over short periods of time (less than 1 million years or so) (Clayton et al., 1966; Drever, 1988). In Fig. 11, the δ<sup>18</sup>O values plot along a horizontal line (slope = 0) against EC, indicating that the contact between groundwater and the rock material has not been long enough to affect the δ<sup>18</sup>O.

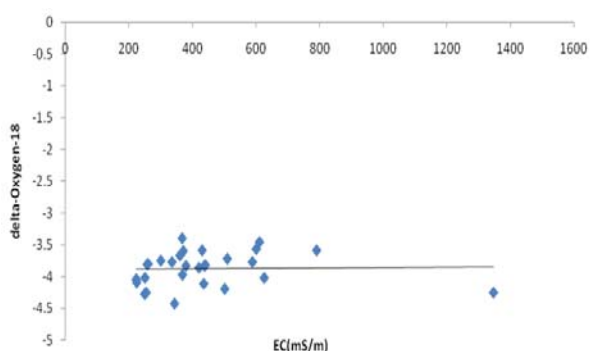


**Table 2 Results of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  on Groundwater Samples from the Study area.**

Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$	Sample ID	$\delta^{18}\text{O}$	$\delta^2\text{H}$
NG3	-4.14	-22.5	NG25	-3.9	-20.2	UW4	-3.75	-19.8
NG4	-4.14	-23.1	NG26	-3.7	-21.1	UW5	-4.02	-21.3
NG6	-4.22	-24.4	NG27	-3.53	-19.3	UW6	-3.57	-19
NG8	-4.24	-23.6	NG28	-3.76	-21.5	UW7	-3.59	-18.9
NG9	-4.21	-23.6	NG29	-2.17	-6.9	UW8	-4.02	-23.4
NG11	-4.7	-26.4	NR1	-4.11	-21.5	UW9	-3.77	-20.1
NG12	1.52	-1	NR2	-3.83	-19.9	UW10	-3.82	-20.2
NG13	-3.82	-20.6	NR3	-3.97	-20.1	UW11	-3.86	-20.8
NG14	-4.07	-22.4	NR4	-4.27	-21.2	UW12	-3.67	-21.2
NG16	-4.38	-25.1	NR6	-3.83	-22.9	UW28	-4.25	-23.7
NG17	-4.36	-24.1	NR7	-3.72	-19.6	UW39	-4.42	-25
NG18	-4.37	-25	NR8	-3.46	-17.8	UW39a	-4.25	-23.9
NG19	-4.19	-22.9	NR9	-3.81	-20.2	UW57	-3.77	-20.3
NG20	-3.72	-21.3	NR10	-4.09	-22	UW58	-3.4	-18.2
NG21	-3.69	-20.4	NR11	-3.6	-19	NG2 (Surface Water)	5.33	33.7
NG22	-1.63	-11.9	UW1	-4.19	-22.8	NG30 (Surface Water)	2.69	10
NG23	-3.58	-19.7	UW2	-3.59	-19	NG20A (Surface Water)	1.23	1.8
NG24	-0.87	-5.6	UW3	-3.8	-20.6	RN (Rain)	-2.99	-7.5



**Fig. 10 Plot of  $\delta^2\text{H}$  against  $\delta^{18}\text{O}$  of the Groundwater Samples in the Study Area showing the GMWL**



**Fig. 11 A Plot of  $\delta^{18}\text{O}$  against EC for the Study Area.**

The more negative isotope data of most of the groundwater samples relative to the rain sample in the area (Fig. 10) can be attributed to climatic and seasonal differences. More negative results of the

isotope data may be a result of differences in recharge elevation and seasonal and climatic factors (Dansgaard, 1964). Because of shifts in climatic patterns, precipitation during the Pleistocene and Tertiary differed cyclically in isotopic composition from present day precipitation (Drever, 1988).

The deviations of the surface water samples from the GMWL are a result of evaporative enrichment of the heavier isotopes. The groundwater sample that plots in line with the surface waters (Fig. 10) gives evidence of an evaporative feature.

## 6 Conclusions

Conventional graphical methods applied to the water samples from the study area identify three hydrochemical facies - Ca-Mg- $\text{HCO}_3$ , mixed Ca-Mg-Na- $\text{HCO}_3$  and Na- $\text{HCO}_3$  and finds that groundwater hydrochemistry in the study area is largely controlled by the incongruent weathering of silicate minerals in the aquifers, and reverse cation exchange activity. Hierarchical cluster analysis confirms the results and shows that the contribution of organic and inorganic manure from agricultural activities and unhygienic sanitation around wellhead in the area also control the chemistry of the groundwater. HCA indicates that EC in the groundwater has a dominant contribution from  $\text{Mg}^{2+}$  and  $\text{HCO}_3^-$ . An activity diagram plotted for the CaO-MgO- $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$ - $\text{H}_2\text{O}$  system suggests stability in the smectite field which is indicative of arid – semiarid conditions prevalent in the area.

The stable isotope ( $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ) signatures of the groundwater show that groundwater in the area originates from meteoric source. Groundwater of meteoric origin generally have low dissolved solids and are of good quality suggesting short residence times and low contact surface area. The groundwater samples have more negative isotope signatures relative to the rain sample. This can be attributed to climatic and seasonal differences.

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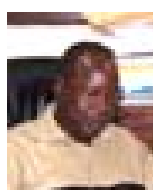
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