

Multivariate Statistical and Spatial Assessment of Groundwater Quality in the Tolon-Kumbungu District, Ghana

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Abstract: The study was conducted to assess the quality of groundwater in 47 boreholes in the Tolon Kumbungu District of Ghana, using multivariate statistical and spatial techniques. The results indicate that physicochemical parameters exhibit wide variability. About 8.5% of the samples recorded pH outside World Health Organization recommended limit of 6.5-8.5. Approximately 43% of samples recorded conductivity levels higher than 1000 $\mu\text{S}/\text{cm}$, while close to 19% of boreholes recorded total iron concentrations above 0.3 mg/L. Approximately 3.4% of boreholes recorded arsenic concentrations above 0.01 mg/L. Alkalinity ranged from 28 to 766 mg/L CaCO_3 ; and groundwater in the area can be considered to have relatively high buffering capacity. Turbidity was associated with mineral matter suspension (Fe). Principal component analysis indicates that the data is a three-component system explaining 65% of the total variance. The first two components account for more than 50% of the total variance. Cluster analysis categorised the sampling locations into three spatially dissimilar groups. The natural hydrochemistry of the groundwater system appears to explain much of the variability of the data. However, a groundwater monitoring programme is recommended to characterise the variability of the parameters over longer temporal scales.

Key words: Contamination, Ghana, groundwater, multivariate, physicochemical, spatial

INTRODUCTION

Groundwater is Africa's most valuable natural resource, providing reliable water supplies for more than 100 million people and, potentially, millions more (Adelana and MacDonald, 2008). Groundwater has countless advantages as a source of supply, mainly where populations are still largely rural and demand is spread over large areas (Adelana and MacDonald, 2008). Specifically, natural groundwater storage offers a buffer against climatic variability; quality is often good, and infrastructure is affordable to poor communities. Groundwater occurrence depends basically on geology, geomorphology/weathering and rainfall (both current and historic). The interaction of these three factors gives rise to complex hydro-geological environments with myriad variations in the quantity, quality; ease of access and renewability of groundwater resources.

Surface water-based resources, are contaminated and a major contributor to the disease and poverty, endemic in many rural communities in Ghana (Gyau-Boakye *et al.*, 2008; Armah *et al.*, 2010a). Currently, only 52% of the rural inhabitants have access to improved safe water supplies – which are mainly derived from groundwater

sources (Gyau-Boakye *et al.*, 2008). In Ghana, developing groundwater is regarded as the most cost-effective means of providing safe water supplies to rural settlements which are usually dispersed.

Quist *et al.* (1998) have delineated four factors that render groundwater as an attractive source of potable water supply in Ghana. To begin with, there are aquifers in several areas of the country that can frequently be tapped at shallow depths close to the water demand centres in response to the dispersed nature of rural settlements (Gyau-Boakye *et al.*, 2008). Some of these aquifers (e.g., the Birimian System) have been moderately assessed and their characteristics are reasonably recognized. Next, water stored in aquifers is for most part protected naturally from evaporation and pollution, and well yields are in many cases adequate, offering water supply security in regions prone to protracted droughts as is common in the northern parts of Ghana. Thirdly, with adequate aquifer protection, groundwater has excellent microbiological and chemical quality, and requires minimal or no treatment at all. Lastly, the capital cost of groundwater development as opposed to the conventional treatment of surface waters is relatively modest and the



Fig. 1: Geological map of the Tolon Kumbungu District

resource lends itself to flexible development capable of being phased in with rising demand.

Dependence on groundwater will remain a priority for rural communities in Ghana especially in northern Ghana which is among the driest parts of Ghana. Northern Ghana is drought prone and the impacts of climate variability and change are expected to affect this area disproportionately (Armah *et al.*, 2011). Threats to groundwater in these areas result from both geogenic and anthropogenic sources (Carpenter *et al.*, 1998), with the latter becoming prominent progressively. Groundwater quality is central to providing information about the geological history of the host rock and further provides some clues about the types of minerals, which the groundwater has come into contact with.

Several groundwater studies have been conducted in Ghana (Gyau-Boakye *et al.*, 2008; Agyekum and Dapaah-Siakwan, 2008; Martin and de Giesen, 2005; Smedley

et al., 1996; Pelig-Ba *et al.*, 1991). However, the spatial and statistical aspects are still not well understood. Consequently, multivariate statistical and spatial dimensions of groundwater quality need to be assessed to inform relevant stakeholders on steps required to sustain this fragile natural resource. Multivariate statistics of groundwater has been carried out mostly in southern Ghana (Armah *et al.*, 2011; Armah, 2010b), but that of the sahelian northern section of the country is non-existent. The objective of the study therefore was to reveal information about:

- The natural and anthropogenic origin of contaminants in ground water
- The possible non-point sources of contamination
- The contributions of possible sources to concentrations of the determined parameters in the Tolon Kumbungu area

- The spatial variability of these contaminants.

MATERIALS AND METHODS

Study area: The study area is located between latitudes 9°17' N and 10°06' N, and longitudes 0°55' W and 1°21' W. Tolon Kumbungu is bordered to the north by the West Mamprusi District, to the south by Central Gonja District, to the east and southeast by the Savelugu-Nanton District and the Tamale Metropolitan area, respectively. The district shares borders with West Gonja District to the west. The district is remarkably flat, forming a gently rolling low-lying relief with topographic elevations ranging from 120 to 180 m above mean sea level. The area falls within the White Volta River Basin and is drained by the Zulabong and Kulda tributaries. The district lies within the Tropical Continental or Interior Savannah Climatic Zone (Dickson and Benneh, 2004). It experiences a single rainfall season, which starts from May and ends in October. The annual rainfall ranges between 1005 and 1150 mm, with the heaviest rains occurring in August.

Daily temperatures are generally high (above 35°C) except in the harmattan season (November-February) when the temperatures can get as low as 20°C or less, especially during the night. The mean monthly temperatures vary from about 36°C in March/April to about 27°C in August. Relative humidity is high during the rainy season (65-85%) but may fall to as low as 20% during the dry season.

The area falls within the savannah vegetation zone, which is characterised by tall grasses that grow in tussocks, and widely scattered trees such as baobab, the dawa-dawa, acacia and shea trees. Middle Voltaian Palaeozoic rocks (the Obosum and Oti beds) that comprise shale, mudstone, sandstone, limestone and conglomerate form practically the basement rocks that underlie the area (Kesse, 1985). Upper Voltaian sandstone and quartzite underlie a small portion of the district at the extreme northwest Fig. 1.

The hydrogeological characteristics of the Palaeozoic Voltaian sedimentary rocks are similar to that of hard rocks. The sandstones are themselves largely impervious but contain openings along joints and fractures, bedding and cleavage planes. Where these openings are extensive and are not filled with impervious material, percolation of considerable water into the regolith might occur to form groundwater reservoirs. The main sources of groundwater supply are the weathered layer or regolith developed on the rocks, and fractures within the bedrock (Gill, 1969). The aquifers are phreatic to semi-confined in character, are structurally dependent and often discontinuous in occurrence. Lateritic cover renders the shale poor in groundwater and areas underlain by mudstones are generally impermeable. Water is tapped by wells located

in the fractures or fracture zones with saturated regolith rather than from extensive aquifers.

Borehole depths in the study area ranged from 25.0 to 96.0 m with a mean of 43 m. Borehole yield is highly variable, ranging from 4.5 to 600 L/min (mean 32.6 L/min). The static water level (SWL) in the study area ranges from 3.6 to 38.1 m (mean 10.9 m). The assessment of the SWL in the area is based on statistical averaging due to the discontinuous nature of groundwater occurrence in the study area (Darko *et al.*, 2006).

Water sampling and laboratory analysis: Water samples were collected for the analysis of major ions and trace metals from November, 2009 to January, 2010. The fundamental principles underlying the general procedures for sampling, as provided in the Standard Methods for the American Public Health Authority (1998), and the WHO/UNEP/UNESCO/WMO (1988), were followed. Samples for major ions were collected into clean 1 litre polyethylene bottles and that for trace metal analyses, into 12 mL polyethylene bottles. Samples for trace metal analysis were acidified (pH<2) with 0.5 mL concentrated nitric acid. *In situ* measurements of pH and conductivity were done using an Eijkelkamp water quality field kit. Samples were stored in ice-chests and transported to the CSIR-Water Research Institute laboratory in Tamale for analysis. Those for trace metal analysis were sent to the CSIR Water Research Laboratory in Accra for analysis. Visual comparison and turbidimeter were used to determine colour and turbidity respectively. Silica, fluoride, orthophosphate, nitrate-nitrogen and sulphate contents were analysed using the molybdosilicate, SPADNS, stannous chloride, hydrazine reduction and turbidimetric methods, respectively. A flame photometer (Jenway model PFP 7) was used to determine sodium and potassium while EDTA titration was used for calcium and total hardness. Chloride contents were determined by argentometric titration and total alkalinity by strong acid titration. Calcium and magnesium hardness, on the other hand, were determined by calculation. The trace metals Fe, Mn, and Pb were determined using a Unicam 696 Atomic Absorption Spectrophotometer (AAS); arsenic was however determined using an arsenator.

Data analysis: Statistical analysis was performed using SPSS 16.0 software. Visually communicating hydrochemical maps were constructed using ARCVIEW 8.3 software to delineate spatial variation of various groundwater quality parameters. One half of the values of the detection limit of the various parameters was substituted for values below the limit of detection and used in the statistical analysis. The data was subjected to normality tests by fitting them with Normal and Lognormal distributions, on the premise that the observations were independent and identically distributed

Table 1: Multivariate statistics of physico-chemical parameters measured in the district

Parameters (N = 47)	Min - Max	Mean	SD	Skewness	Kurtosis
pH	6.21-8.88	7.62	0.62	-0.218	-0.417
Turbidity (NTU)	0.1-44	2.4	0.9	1.9	1.7
Conductivity ($\mu\text{S}/\text{cm}$)	47.4-8970	1379	16	2.9	10.0
Sodium	3.3-1513	242	31	2.7	7.9
Potassium	0.8-21.0	2.8	0.9	2.9	1.8
Calcium	3.2-216	26.4	3.2	4.9	2.6
Magnesium	4.3-8-58.8	19.1	1.9	1.4	2.4
Chloride	3.0-2897	255	8.6	3.3	1.9
Nitrate-N	0.02-17.3	1.9	0.4	0.8	2.7
Sulphate	5.0-165	22.6	2.7	3.4	5.5
Alkalinity	28-766	303	18	0.42	-0.42
Bicarbonate	34.2-935	367	21	0.5	-0.3
T. Hardness	34-564	149	6.2	2.4	8.6
Fluoride	0.01-2.4	0.7	0.2	1.7	2.0
T. Iron	0.01-1.6	0.18	0.1	3.2	5.7
Manganese	<0.01-6.3	0.3	0.1	0.9	5.3
Arsenic	<0.01-0.01	0.005	0.001	1.0	1.5

Concentration (mg/L); unless otherwise stated

over the area and sampling period. The Lognormal distribution is capable of representing skewed environmental data, which are generally positively skewed. Quality assurance was applied to analytical results by applying anion-cation balance. Investigations of water quality often require that numerous variables be examined simultaneously.

It is not unusual for data sets to consist of a large number of samples each containing, for example, the concentrations of major ions, organic compounds, and/or nutrients. Simultaneous analysis of the data with conventional methods would be, at best, very difficult. Herein is the strength of Principal Components Analysis (PCA). It was developed to help summarise and facilitate the interpretation of multi-variable data sets (Gauch, 1982). The term "Principal component" is derived from the concept that of the n descriptors, x_1, x_2, \dots, x_n describing the attributes of each sample, e.g. groundwater quality variables describing the characteristics of the water column, there exists a fundamental group of independent descriptors which determine the values of all x points. These fundamental descriptors are called "components", with the most important of these termed "Principal components". The components must meet two conditions (although departures are tolerated if PCA is used for descriptive purposes only):

- The descriptors are normally distributed
- They are uncorrelated

Principal Component Analysis reduces the multi-dimensionality of a complex data set to two or three dimensions by computing principal components or factors. This computation is achieved by transforming the observations from each sample (e.g., concentrations of contaminants) into a "linear combination" of contaminant

concentrations. Principal Component Analysis produces several important outputs:

- **A correlation or covariance matrix:** A summary table of the correlations for each pair of variables in the data set.
- **Eigenvalues:** The variances accounted for by the component
- **Eigenvectors:** That specifies the directions of the PCA axes.

RESULTS AND DISCUSSION

Physico-chemical parameters: Data obtained for the study are presented in Table 1. Physico-chemical parameters measured from all 47 boreholes during the study showed wide variability. pH ranged from 6.21 at Tolon to 8.88 at Shingbuni. About 8.5% of the samples recorded pH outside WHO recommended limit of 6.5-8.5. Conductivity similarly ranged from 47.4 $\mu\text{S}/\text{cm}$ in Apeyayili to 8970 $\mu\text{S}/\text{cm}$ at Gbanzogu Kukuo. About 43% of samples recorded conductivity levels higher than 1000 $\mu\text{S}/\text{cm}$. Conductivity levels in certain areas were moderate to high imply some amount of mineralization of the groundwater. Within the same period minimum and maximum turbidity values of 0.1 Nephelometric Turbidity Units (NTU) and 44 NTU were obtained for Tolon and Apeyayili respectively.

Chemical parameters such as Na, Ca, Mg, HCO_3 , SO_4 , Cl^- and F^- also showed wide variations in concentration. A low value of 3.3 mg/L was obtained for Na at Apeyayili and a high of 1513 mg/L at Gbanzogu Kukuo. About 34% of boreholes analysed recorded Na concentrations above 200 mg/L, which is the WHO recommended limit (World Health Organization, 2004) for potability. The minimum Ca value was recorded at Tali (3.2 mg/L) and a maximum of 216 mg/L was recorded at Gbanzogu Kukuo. About 2% of boreholes

Table 2: Percentage of variance explained by principal components

Component	Initial eigen values			Extracted sums of squared loadings		
	Total	% of Variance	Cumulative (%)	Total	% of variance	Cumulative (%)
1	4.695	33.536	33.536	4.695	33.536	33.536
2	2.969	21.205	54.742	2.969	21.205	54.742
3	1.436	10.255	64.997	1.436	10.255	64.997
4	1.326	9.475	74.472	1.326	9.475	74.472
5	0.923	6.590	81.061	0.923	6.590	81.061
6	0.861	6.151	87.213	0.861	6.151	87.213
7	0.688	4.914	92.127	0.688	4.914	92.127
8	0.462	3.301	95.428	0.462	3.301	95.428
9	0.337	2.409	97.838	0.337	2.409	97.838
10	0.166	1.187	99.024	0.166	1.187	99.024
11	0.131	0.933	99.957	0.131	0.933	99.957
12	0.005	0.034	99.991	0.005	0.034	99.991
13	0.001	0.007	99.998	0.001	0.007	99.998
14	0.000	0.002	100.000	0.000	0.002	100.000

Table 3: Extracted components of groundwater quality parameters in Tolon-Kumbungu

Component	Component													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
pH	0.359	0.638	0.299	0.424	-0.010	-0.129	-0.319	-0.047	0.10	1-0.187	-0.171	0.000	2.720E	-50.000
Conductivity	0.977	0.067	0.081	-0.010	-0.122	0.058	0.086	0.036	-0.007	-0.026	0.059	-0.059	0.000	0.001
Alkalinity	-0.236	0.092	0.094	-0.006	-0.015	0.165	0.121	-0.161	0.077	0.051	0.069	-0.002	0.005	-0.012
Turbidity	-0.213	-0.465	0.660	-0.034	0.074	0.350	0.115	0.205	0.344	0.010	-0.019	0.001	1.711E	-50.000
Calcium	0.814	-0.052	0.00	1-0.192	-0.086	-0.079	0.424	-0.207	0.043	0.111	-0.217	0.008	-0.002	0.000
Magnesium	-0.080	0.664	0.166	-0.393	-0.366	-0.073	-0.037	0.451	-0.133	0.07	1-0.067	0.004	-0.001	3.694E-5
Sodium	0.963	0.062	0.089	0.042	-0.148	0.081	0.059	0.021	-0.005	-0.090	0.136	0.026	-0.020	-0.002
Potassium	0.385	0.170	0.239	-0.382	0.440	-0.61	8-0.102	0.017	0.154	0.063	0.077	0.001	0.000	0.000
Bicarbonate	-0.240	0.919	0.075	-0.035	-0.018	0.169	0.134	-0.166	0.093	0.044	0.077	0.004	0.000	0.012
Sulphate	0.422	0.268	-0.022	-0.242	0.682	0.407	0.02	20.102	-0.205	-0.061	-0.056	0.003	0.000	7.747E-5
Chloride	0.965	-0.124	0.068	0.003	-0.162	0.006	0.08	10.052	-0.019	-0.078	0.080	0.022	0.023	0.001
Fluoride	0.764	-0.006	-0.148	0.237	0.010	0.236	-0.452	0.005	0.065	0.269	-0.006	0.005	0.000	0.000
Iron	-0.129	-0.233	0.872	0.001	-0.067	-0.011	-0.102	-0.229	-0.309	0.067	0.021	8.939E-5	5.707E-5	0.000
Arsenic	-0.013	0.159	0.098	0.831	0.219	-0.201	0.34	10.225	-0.093	0.096	0.023	0.001	0.000	0.000

Extraction Method: Principal Component Analysis

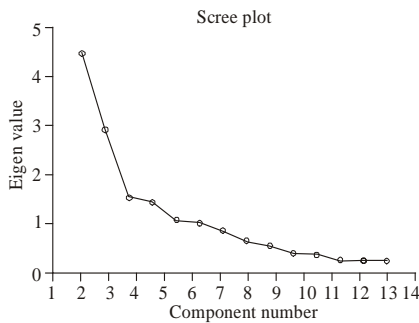


Fig. 2: Scree plot showing eigen values and principal components

recorded Ca concentrations above 200 mg/L. Mg values ranged from 4.3 mg/L (Shedua BH 1) to 58.8 mg/L (Jegbo BH2), while K concentrations ranged from a low of 0.8 mg/L at Tali to a high of 21.0 mg/L at Tolon. Bicarbonate values varied from 34.2 mg/L at Tolon to 935 mg/L at Jegbo BH2. Values for SO₄ ranged from 5.0 mg/L at Dabogoshie and 165 mg/L at Nyankpala while, Cl⁻ ranged from 3.0 mg/L at Tali-Botinli and 2897 mg/L at Gbanzogu Kuku. About 19% of boreholes recorded Cl⁻ levels above 250 mg/L which is the recommended WHO limit.

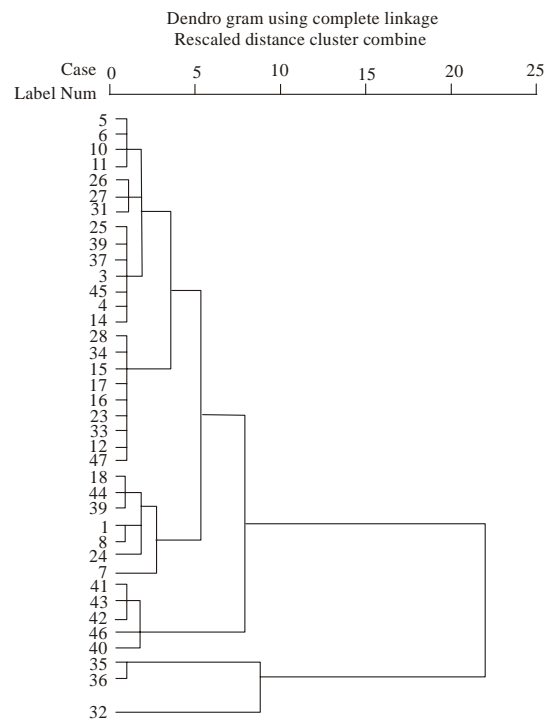


Fig. 3: Dendrogram showing the clustering of sampling sites



Fig. 4: Spatial variation of pH

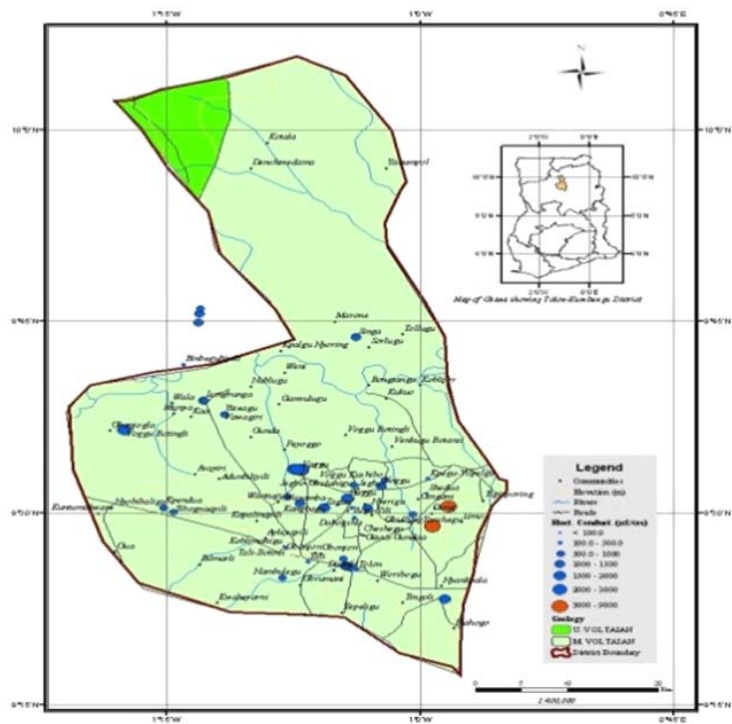


Fig. 5: Spatial variation of conductivity

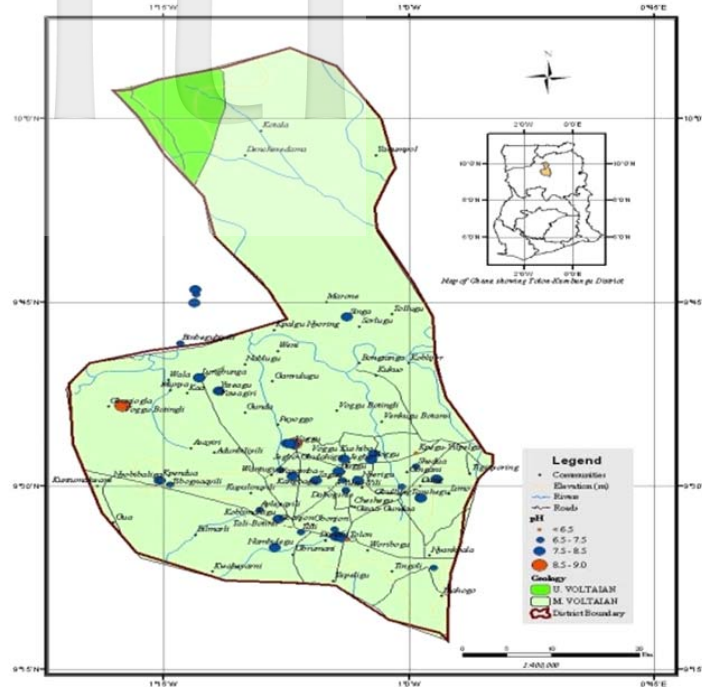


Fig. 6: Spatial variation of Cl

Fluoride levels were generally low ranging from 0.01 mg/L at Apleyayili to 2.4 mg/L at Voggu Botingli BH1. Only 2% of boreholes recorded fluoride levels above the recommended WHO limit of 1.5 mg/L (Fig. 8). Fluorides in these boreholes are mainly from natural sources from the dissolution of fluorite in the underlying bedrock (Apambire *et al.*, 1997). Fluoride in drinking water is important for health, in that it prevents tooth decay. However, high levels may lead to dental fluorosis. At elevated levels it may increase the rise of skeletal fluorosis. At higher concentrations fluoride is known to be poisonous and perhaps carcinogenic (Baird, 1999). The presence of high fluoride in borehole water at these locations in the district give cause for concern, especially given that high fluoride have been recorded in groundwater from some other areas in the region in previous studies (Apambire *et al.*, 1997; Dey *et al.*, 2004). The highest total iron and manganese concentrations were recorded at Ganvulugu BH2 (1.63 mg/L) and Shingbuni (6.3 mg/L) respectively during the study.

About 19.1% of boreholes recorded total iron concentrations above 0.03 mg/L (WHO limit) and 5.35% of samples recorded Mn concentration above 0.5 mg/L. It is important to note that Fe values were total concentrations (including particulate material), rather than dissolved concentrations measured after filtering of the water samples. The presence of iron could be as a result of chemical weathering of the host rocks. Only 3% of boreholes recorded As levels above 0.01 mg/L (WHO

limit). Concentrations of nitrate (as N) in most groundwater analyses reported from Ghana are below the WHO guideline value of 10 mg/L. Almost all groundwater samples from this study had $\text{NO}_3\text{-N}$ concentrations less than 10 mg/L. Only a few shallow hand-dug wells from the study area had values in excess of this (observed range <math><0.2</math> mg/L to 17.3 mg/L) (Fig. 7). The nitrate in these wells is derived from surface pollution. Nitrate appears not to be a serious water quality problem in areas studied.

Principal component analysis: Multivariate analysis of groundwater data was subjected through Principal Component Analysis (PCA) (Johnson and Wichem, 1998; Millard and Neerchal, 2001; Yidana *et al.*, 2010). The data sets were first summarised (Table 1). From Table 1, it is observed that the values of the coefficients of variation of the variables (Conductivity, Turbidity, TDS and others) were much larger than 1/3 (33.33%), except the variable pH. This suggests that the data is positively skewed - very few of the measurement scores lie below the average measurement scores.

Table 2 and Fig. 2 both indicate that the data can be considered to be a three-component system explaining 65% of the total variance. The first two components account for more than 50% of the total variance. From the component matrix (Table 3), Component 1 shows high loadings on conductivity, calcium, sodium, and chloride. The long residence times and incomplete flushing of

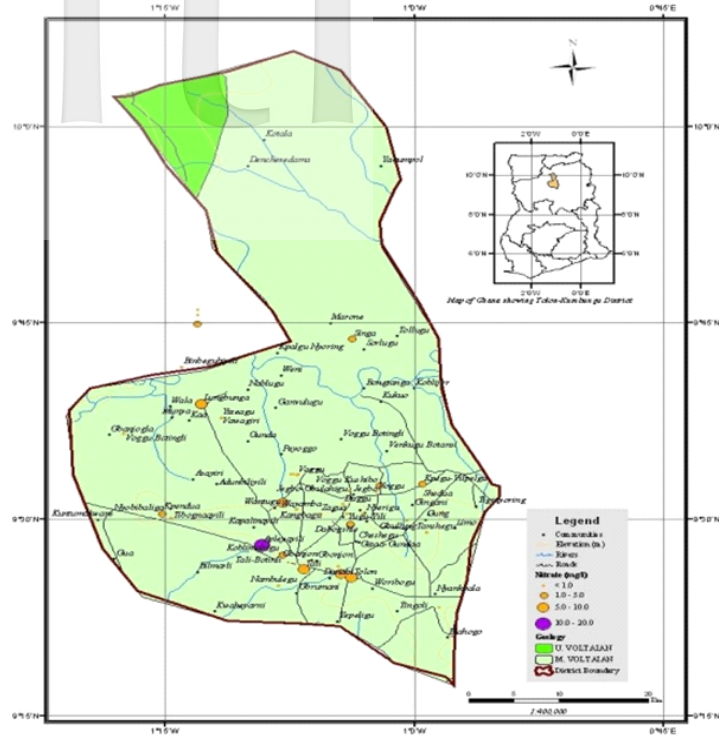


Fig. 7: Spatial variation of $\text{NO}_3\text{-N}$

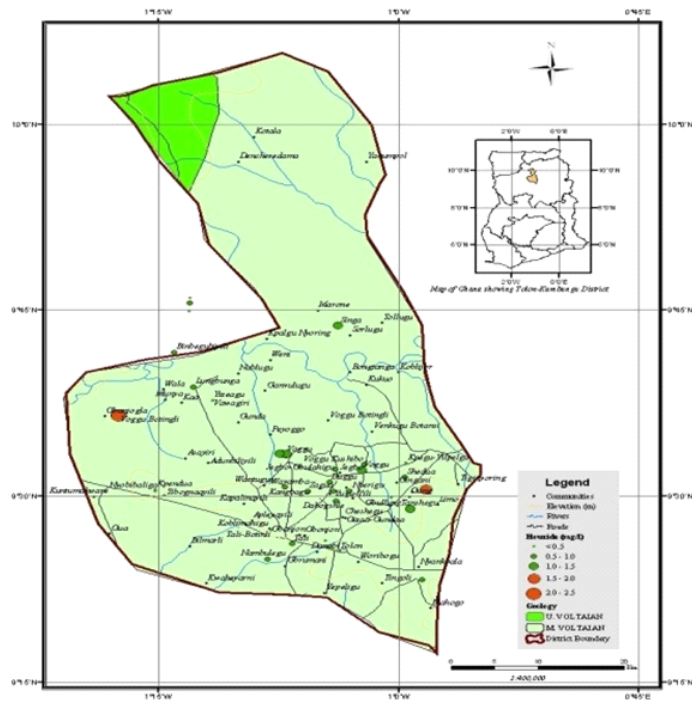


Fig. 8: Spatial variation of fluoride

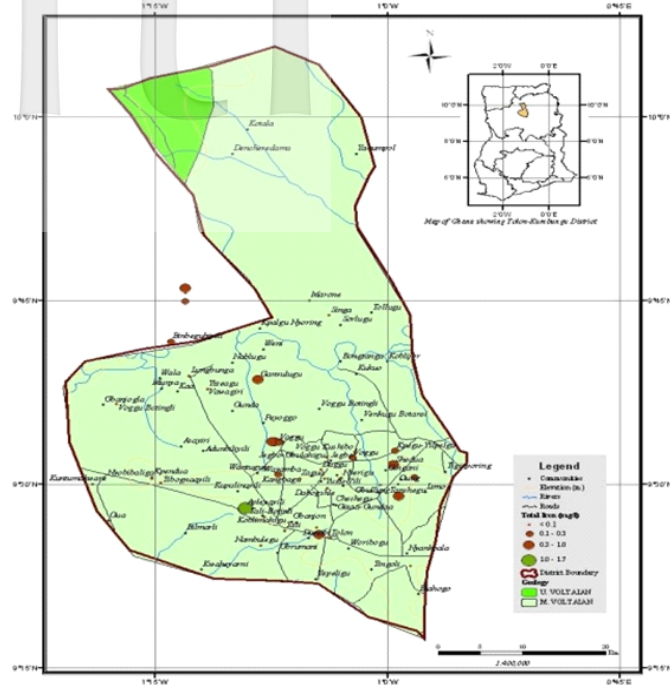


Fig. 9: Spatial variation of total iron

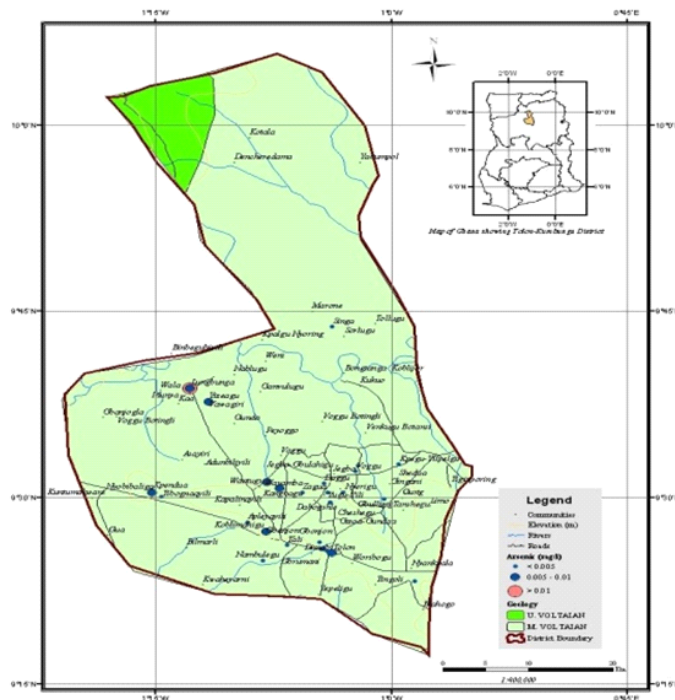


Fig. 10: Spatial variation of arsenic

soluble minerals produce groundwaters which are generally of the sodium chloride type.

This could be attributed to natural sources. Component 1 is the natural hydrochemistry of the groundwater system. Component 2 shows high loadings on alkalinity and bicarbonate. The alkalinity of water is controlled by the sum of the titratable bases. It is mostly taken as an indication of the concentration of carbonate, bicarbonate and hydroxide, but may include contributions from borate, phosphates, silicates and other basic compounds. Waters of low alkalinity (<24 ml/L as CaCO₃) have a low buffering capacity and can, therefore, be susceptible to alterations in pH, for example from atmospheric, acidic deposition. In this study however, alkalinity ranged from 28 mg/L to 766 mg/L; and can be considered to have relatively high buffering capacity. Component 3 shows high loadings on Fe and turbidity indicating that the latter could be associated with mineral matter suspension.

Cluster analysis: The cluster analysis used to identify the spatial similarity between the sampling sites based on the levels of chemical concentration, grouped 47 sampling sites into three statistically significant clusters as depicted by the Dendrogram (Fig. 3). The Dendrogram is the graphical display of all the steps in a hierarchical clustering procedure (Alvin, 2002; Richard and Dean, 2002). It is essential in determining variables of significant importance and source of pollution for appropriate mitigation. The cluster membership shows that strong associations exist among the sites. Of the 47 sites grouped into three clusters, thirty-nine of the samples belong to cluster 1, while cluster 2 had five members. However, clusters 3 had three members. This high number of members in cluster 1 suggests uniformity in the degree of impacts on the samples with regard to the parameters analyzed; and further suggests that the impacts possibly originate from a common source.

Spatial variability of physical and chemical parameters in groundwater: Spatial variations of parameters such as pH, conductivity, Cl⁻, NO₃⁻-N, F⁻, total iron and As are presented in Fig. 4 to 10. These diagrams help in understanding the spatial variability of measured parameters in the district more easily by providing a visual representation in great detail (Burgos *et al.*, 2006).

The diagrams are also useful in the determination of the direction of groundwater flow, as normally ionic concentration is likely to increase in the flow direction (Singhal and Gupta, 1999). Majority of boreholes with low pHs below 8.5 were concentrated in the southern part of the district (Fig. 4). Groundwater with high electrical conductivities is located in the south eastern part of the district (Fig. 5), while boreholes with high chloride concentrations were located across the western,

southern and the eastern section (Fig. 6). Boreholes with high total iron were located in the southern part (Fig. 9) while those with high arsenic were located in the western corner of the district (Fig. 10).

CONCLUSION

Groundwater is central to helping Ghana meet the Millennium Development Goals for water supply. Improvement of drinking water supply and sanitation is one of the main concerns for the population of the northern regions of Ghana. Groundwater is usually the only safe water source where surface water is limited. The groundwater quality of the Tolon-Kumbungu district of northern Ghana was assessed in this study. Groundwater quality was observed (generally TDS < 1000 mg/L) to be suitable for potable use, provided the boreholes and hand-dug-wells are properly protected from sources of pollution and contamination. Most of the physicochemical parameters measured for groundwater samples were within the limits set by the World Health Organisation. Principal component analysis indicates a three-component data system explaining 65% of the total variance. The first two components account for more than 50% of the total variance. The natural hydrochemistry of the groundwater system appears to explain much of the variability of the data.

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