Research Article

Hydrochemical characteristics of groundwater in sedimentary, metamorphic and volcanic aquifers in Ndian Division, South West Region, Cameroon.

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ABSTRACT

Wells and springs are the dominant potable water sources in the area of study used by the population. Studies of the characteristics of aquifer types and the hydrochemistry of groundwater in sedimentary, metamorphic, and volcanic aquifers in the southern part of Ndian Division indicated the presence of the following three types of aquifers-sedimentary (alluvial), metamorphic (weathered/fractured gneisses) and volcanic (jointed basalts and pyroclastic materials). Fieldwork involved collecting details on rock characteristics such as the mineralogy, grain-size and texture. Physical parameters (pH, EC and temperature) were measured in-situ. Cations were determined by AAS and anions by ion chromatography. The pH values for sedimentary aquifers (5.50-8.00), metamorphic (6.10-7.40) and volcanic (5.80-7.60), reflected slightly acidic, neutral and basic water sources. The mean concentration of total dissolved solids (TDS) in the groundwater increased from metamorphic (8.84 mg/l), to volcanic (17.08 mg/l), and to sedimentary (40.48 mg/l) aquifers, representing the degree of mineralisation in these rock types. Alkalinity increased from metamorphic (14.53 mg/l), volcanic (19.18 mg/l), to sedimentary (57.64 mg/l). Based on the electrical conductivity, all the water sources were suitable for drinking and for irrigation. Relating the major groundwater chemical facies to their geologic occurrence showed that the water in sedimentary rocks was characterised by $Na\text{-}HCO_3$ (90%) and $Ca\text{-}(HCO_3)_2$ (10%), in the metamorphics by $Na\text{-}HCO_3$ (100%) and in the volcanic aquifers by $Ca/Mg\text{-}(HCO_3)_2$ (70%) and $Na\text{-}HCO_3$ (30%) water types. Based on WHO (2004) norms for potable water, 37 water sources were suitable for drinking and one water source (open well at Bekora) unsuitable due to excess nitrate and bromide concentrations of 77.28 mg/l and 0.08 mg/l respectively. Relatively based on EC and TDS, the most mineralised water was found in the sediments, the volcanics intermediate and the least mineralised water was in the metamorphic formations. The results constitute useful baseline information for future provision and management plans of water resources in the area.

Keywords: Ndian Division, rock types, hydrochemistry, physical properties, groundwater, unconfined aquifers.

Résumé

Les puits et les sources sont les points d'eau dominants utilisées par la population dans cette région. Les études sur les caractéristiques des types d'aquifères et des types hydrochimiques des nappes phréatiques dans la partie sud du département du Ndian ont indiqué la présence des trois types d'aquifères suivants: sédimentaire (alluvions), métamorphiques (gneiss friables et fracturés) et volcaniques (basaltes joints et matériaux pyroclastiques). Les mesures relevées du terrain inclus les détailles des roches et les paramétrés physiques (d'acidité, les conductivités électriques et la température). Les analyses de laboratoire d'ions (cations et anions), était déterminé par le AAS pour les cations et ion chromatographie pour les anions. Les évaluations du terrain des paramètres physiques des nappes phréatiques ont indiqué des valeurs de pH de 5,50 à 8,00 pour les aquifères sédimentaires de 6, 10 à 7,40 pour les métamorphiques et de 5,80 à 7,60 pour les aquifères volcaniques. Ceci reflète des sources d'eau faiblement (légèrement) acides, neutres et basiques. La moyenne de la concentration de la dissolution totale des solides (DTS) dans la nappe phréatique croît des aquifères métamorphiques (8,84 mg/l), aux volcaniques (17,08 mg/l), puis aux sédimentaires (40,48 mg/l), représentant le degré de minéralisation des eaux contenus dans ces types de roches. L'alcalinité augmente de la manière suivante : aquifères métamorphiques, 14,53 mg/l, volcaniques, 19,18 mg/l, et sédimentaires, 57,64 mg/l. En se basant sur la conductivité électrique (CE), tous les points d'eau étaient appropriés pour la consommation et l'irrigation. En associant les différents types chimiques des eaux des nappes phréatiques à leurs occurrences géologiques, il a été démontré que l'eau contenue dans les roches sédimentaires était caractérisée par $Na\text{-}HCO_3$ (90 %) et $Ca\text{-}(HCO_3)_2$ (10 %), dans les roches métamorphiques par $Na\text{-}HCO_3$ (100 %) et dans les roches volcaniques par $Ca/Mg\text{-}(HCO_3)_2$ (70 %) et $Na\text{-}HCO_3$ (30 %). Sur la base des normes de l'OMS (Organisation Mondiale de la Santé) 37 points d'eau potables étaient appropriés pour la consommation alors qu'un point d'eau exposé (aux intempéries) à Bekora ne l'était pas, à cause d'une concentration excessive de nitrate et bromide de 77,28 et 0,08 mg/l respectivement. Relativement, sur la base de DTS et CE, l'eau la plus minéralisée a été trouvée dans les aquifères sédimentaires, suivie des volcaniques et enfin les métamorphiques. Les résultats constituent une ligne de fond et une information utile pour l'approvisionnement et pour le plan de gestion des points d'eau dans cette région.

Mots clés : département du Ndian, types de roches, hydrochimiques, propriétés physiques, nappes phréatiques, aquifères non-confinés

INTRODUCTION

Groundwater is a fundamental resource vital for domestic, industrial and agricultural uses. Its quality is controlled by many factors including the composition of precipitation, the mineralogy of the aquifers, climate, topography, and anthropogenic activities. These factors lead to different water compositions temporally and spatially. High concentrations of some elements may render groundwater unsuitable for potability, irrigation and health (Apello and Postma, 1993). Therefore understanding the quality of groundwater of a remote region of the country is an important step for initiating the provision of pipe-borne water to communities and for sustainable management and use of this resource.

Ndian Division is an area characterized with varied geological settings and forms part of the extension of the western margin of the Niger Delta (Regnoult, 1986) situated in the South Western Coast of Cameroon at the western end of the Gulf of Guinea (Figure 1).

The climate is equatorial Cameroonian type (Etia, 1980) with alternating rainy season of more than 8 months (March-October) and a dry season of 4 months from November to February (Gabche and Smith, 2002) and it is characterized by a high annual mean rainfall of over 5,000 mm (Zimmerman, 2000). The drainage pattern is dendritic and dominated by the Rivers Ndian, Moko, Meme, Mungo and Akwayafe which have watersheds from high altitudes (800-1050 m) which include the Rumpi Hills, the Manengouba mountains and the highlands of the Korup National Park. It has a varied geological setting comprising of Cretaceous limestones, Tertiary and Quaternary sediments which are essentially clastics which are terminated landward by basaltic lava flows from the Rumpi Hills and by Precambrian basement rocks composed of gneisses, micaschists, and quartzites (Dumort, 1968; Obenesaw et al., 1997; Njoh and Petters, 2008). The soils are ferralitic (Gavaud and Muller, 1980), yellowish in colour, and varying from clayey, silty, sandy to lateritic clay sub soils. Agricultural rich areas have

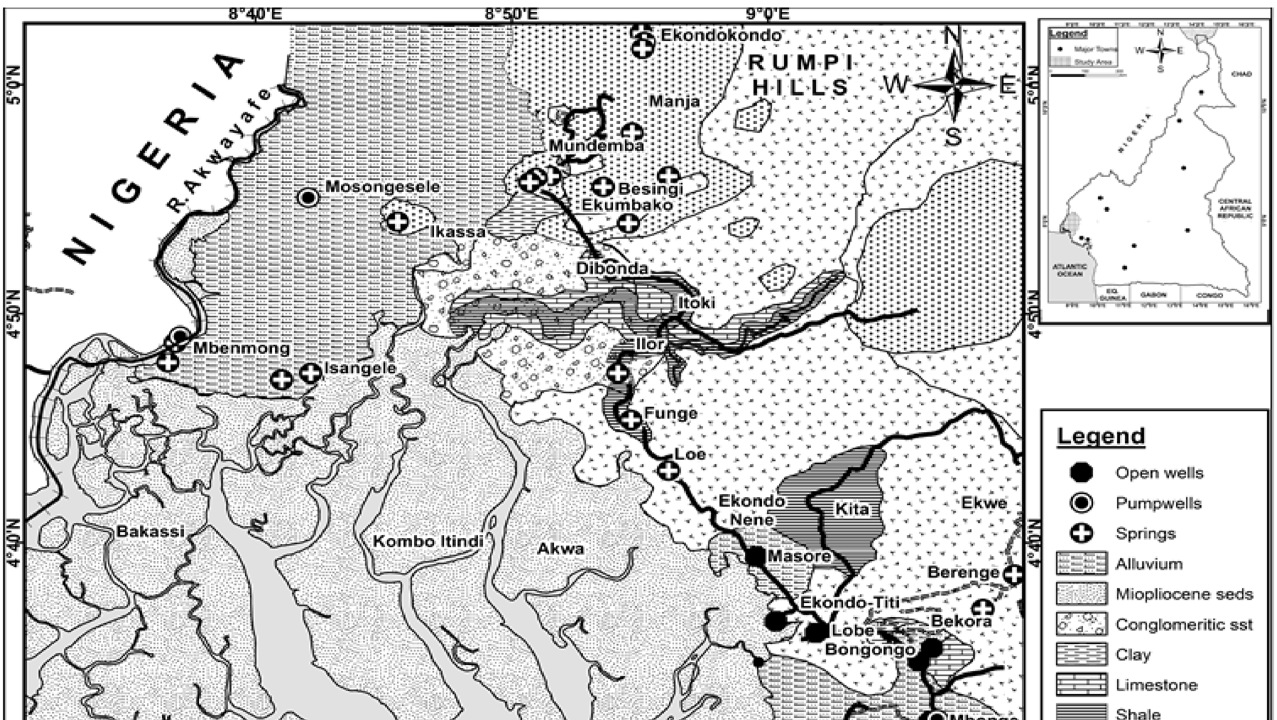

Figure 1: Map (georeferenced) showing location of study area, sample points and the geology (modified after Dumort, 1968).

been extensively cultivated for at least the last 200 years (Gartland, 1986), with large oil palm plantations of over 60 km^2 extent of both the parastatal - PAMOL Plantations Ltd and individuals of the communities especially around Mundemba and Ekondo-Titi (Lawson, 1993).

Unfortunately, hydrogeologic information on this region especially with regards to the potability of the water sources used by the population in the various settlements is completely absent while geologic information on this remote part of the country is scanty. The varied geology of the area which is composed of volcanic, sedimentary and metamorphic rocks may result in variation in the quality of the groundwater resources. As demonstrated by Fantong et al. (2013), the nature of rock types of an aquifer can be deleterious to the quality of the groundwater within it especially during the dry season. Eighty percent (80%) of the population depends on groundwater sources which are mainly springs and hand-dug wells within aquifers due to the absence of pipe-borne water. Poor citing of wells without a prior knowledge of the geology has led to problems of water shortages in some of the communities especially during the dry seasons. These communities therefore resort to poor quality water from streams, rivers and the creeks for household use during such periods.

This study was therefore, aimed at determining the types of rocks which constitute the aquifers and to assess the physical properties and hydrochemistry of groundwater used by communities as potable water sources. The results will hopefully be useful towards the generation of a preliminary baseline data necessary for groundwater development in the area.

MATERIALS AND METHODS

Field mapping involved collecting details on rock characteristics such as the mineralogy, grain-size and texture from outcrops along road cuttings, wells, springs, stream channels and river banks (Figure 1). A global positioning system (GPS) Explorist 100 was used at each location to record the coordinates and altitude used as reference material for the subsequent georeferenced geological map produced. The lithology that describes the physical makeup, including the mineral composition, grain size, texture and structure was based on guidelines described by Freeze and Cherry (1979) on the field identification of aquifers and aquitards. Groundwater sources used by the population which were mainly hand-dug wells and springs were located and the GPS used to record their coordinates for a subsequent georeferenced map of their locations. In the crystalline metamorphic and volcanic rocks, the lithology and structures such as joints, fractures and vesicles were used to determine their aquifer properties.

Groundwater sampling and chemical analyses

Thirty eight (38) groundwater samples were collected from sedimentary (20 samples), metamorphic (11 samples) and volcanic (7 samples) aquifers. The physical parameters were measured using the standard procedures described by APHA (1998). The pH, temperature and total dissolved solids (TDS) were measured using the Hanna 98128 multi parameter type while the electrical conductivity (EC) values were measured using the Model 3301 Conductivity Meter. These meters were calibrated before and during fieldwork using buffer solutions in accordance with the directives of the manufacturers.

At each sampling site, water was collected into 100 ml and 1,500 ml plastic bottles after thorough rinsing with distilled water and the water to be sampled. Water from hand-dug wells was drawn using a bucket attached to a rope. The samples were then filtered through a 0.45 μm membrane filter which allowed the removal of particles, bacteria and viruses that could modify the water contents as described by Atteia (2005). Nitric acid (1%) with a pH of less than two was added to the samples to be used for cation analysis to keep metal ions in solution (Rodier et al., 2005).

The samples were preserved airtight in order to minimize oxygen contamination and the escape of dissolve gases and then stored in ice-chest containers at 4 ^{0}C to exclude microbial activity and unwanted chemical activity, air freighted within a week to Japan for laboratory analysis. The samples in the 1,500 ml bottles were transported to the Soil and Water Laboratory of the Institute of Agronomic Research for Development (IRAD) Ekona within 8 hours of sampling for Total Alkalinity (HCO_3) test through titration. The 100 ml containers were transported to the Chemistry Laboratory, Tokai University, Japan for major ions analysis.

Chemical analyses

The cations: sodium (Na^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined by the Flame Technique in a High Resolution Continuum Source AAS (ContrAA700) as described by Welz et al. (2006). Samples with EC values >100 ìS/cm were diluted 5 or 10 times, to acquire an absorbance within the range of the standards for Na^+, K^+, and Ca^{2+}. Measurements of the anions: chloride (Cl^-), sulphate (SO_4^{2-}), nitrate (NO_3^{2-}), phosphate (PO_4^{2-}), fluoride (F^-), and bromine (Br^-) were done using an Ion Chromatography (Dionex ICS-900). The charge balance for reliability of chemical measurements calculated after Domenico et al. (1990) was within the acceptable limit of ±5 %. Microsoft Excel 2007 spreadsheet was used for statistical analyses.

RESULTS AND DISCUSSION

Aquifer Types and Characteristics

Metamorphic aquifers

Bedrock (metamorphic) aquifers are common in the north of the study area especially within Mundemba and environs (Figure 1; Table 1).

Table 1: Groundwater sources, aquifer materials and rock units observed in the study area

Locality	Source	Aquifer material	Rock type
Besingi	Spring	Gneiss	Metamorphic
Bulu Camp, Mundemba	Spring	Gneiss	Metamorphic
Ekondokondo I	Spring	Gneiss	Metamorphic
Ekondokondo I	Spring	Gneiss	Metamorphic
Ekondokondo I	Spring	Gneiss	Metamorphic
Ghana Quarter, Mundemba	Spring	Gneiss	Metamorphic
Idibawase	Spring	Gneiss	Metamorphic
Ikassa Camp, Mundemba	Spring	Gneiss	Metamorphic
Last Camp, Mundemba	Spring	Gneiss	Metamorphic
Mission Camp, Mundemba	Spring	Gneiss	Metamorphic
Pamol Camp, Mundemba	Spring	Gneiss	Metamorphic
Akwa, Kombo Abedimo	Pump well	Sand	Sedimentary
Bekora	Openwell	Sand	Sedimentary
Big Bongongo I	Openwell	Gravely clay, sand	Sedimentary
Ekombe Liongo	Spring	Sand	Sedimentary
Ekombe Liongo	Openwell	Sand	Sedimentary
Ekombe Liongo	Spring	Sand	Sedimentary
Ekombe Liongo	Spring	Sand	Sedimentary
Ekombe Mofako	Pump well	Sand	Sedimentary
Ekondo Titi	Openwell	Sand, gravel	Sedimentary
Ekondo Titi	Openwell	Sand, gravel	Sedimentary
Funge	Spring	Sandstone	Sedimentary
Gov't quarter, Isangele	Spring	Sand	Sedimentary
Idiba Nyanga	Spring	Silt, clay	Sedimentary
Iloani	Open well	Sand	Sedimentary
Massore	Openwell	Sand gravel	Sedimentary
Mbengmong, Akwa II	Spring	Gravely clay, sand	Sedimentary
Mbonge	Pump well	Sand	Sedimentary
Mbonge	Openwell	Sand	Sedimentary
Mosongesele	Pump well	Sand, sandstone	Sedimentary
Oron, Isangele	Spring	Sand	Sedimentary
Dibonda	Spring	Basalt	Volcanic
Ekumbako	Spring	Basalt	Volcanic
Ekwe	Spring	Basalt, pyroclastic	Volcanic
Ilor	Spring	Basalt	Volcanic
Loe	Spring	Basalt, pyroclastic	Volcanic
Mekagolo	Spring	Basalt	Volcanic
Njima	Spring	Basalt	Volcanic

The main aquifer material in these aquifers was fractured and weathered gneisses found outcropping close to springs, at the banks of streams and along road cuttings (Figure 1). The observed gneisses are banded (black and white bands) and characterised with a medium to coarse grain texture. The white bands in these rocks are muscovite and quartz and the dark band is biotite. These aquifers consisted of deeply weathered and fractured crystalline rocks from which minor but extensive aquifers could be tapped through hand-dug wells.

Sedimentary aquifers

The types of rocks (geology) of any locality play significant roles in the groundwater source containment and its physical and chemical characteristics. Sedimentary rocks (Figure 1) were found in the north, northwest, west, south, and southeast of the study area adjacent to major river systems (e.g. Rivers Meme, Ndian and Akwayafe; Table 1) and along road cuttings in the north and northwest of the study area. They were composed of friable sands which ranged from silt to coarse grained conglomeritic sandstones and imbedded quartz grain, thus constituting alluvial aquifers. The observed sands were well sorted, with grain-sizes that ranged from 1-2 mm with few pebble sized grains, and occur in association with siltstones and mudstones in some sections. The well-sorted sands thus permitted groundwater to move laterally and vertically along the interstices of the coarse-grained sediments which constituted the most prolific producer of groundwater in the area. According to Fetter (1988), the porosity and permeability of these unconsolidated aquifers are enhanced by their medium to coarse grain texture and well-sorted sub-rounded to rounded grains. The alluvial sands were probably as a result of deposition from rivers and beaches through several cycles of transgression and regression during the Quaternary resulting in sediment deposition reworking and redeposition.

Limestone aquifers were observed at Dibonda and Ilor where springs flowed through fractures (Figure 1; Table 1). Due to the highly consolidated texture of these limestones, together with the fact that they occurred in association with shales which act as impermeable materials, they transmitted very little water.

Volcanic aquifers

Basalts were the major volcanic aquifers observed in the north, east and northeast of the study area (Figure 1; Table 1). These rocks had similar characteristics in all the localities. They were characterised with a dark colour, aphanitic to porphyritic in texture with olivine and augite crystals found imbedded in some of them. Some of the basalts had cooling cracks/fractures and joints which enhanced the porosity and permeability. A perched aquifer which is a locally developed water saturated body located above the regional water table due to the presence of an underlying impermeable rock layer was observed at Loe and Ekwe (Figure 1; Table 1) and served as the only sources of potable water. Here, pyroclastic materials overlying impermeable basalts form perched aquifers from which springs provided the only sources of potable groundwater to these communities.

Water sources

A total of 26 springs were sampled in different localities and different rock types that ranged from friable sands and volcanic to crystalline metamorphic rocks. Some of the springs showed a varied geology. For example at Eriba Kuke in Dibonda (Figure 1) friable fine to coarse grain conglomeritic sandstone were observed overlying massive basaltic rocks. Crystalline basement gneissic rocks equally hosted springs flowing through fractures within Mundemba and Ikassa.

Wells were the dominant drinking water sources in the northwest and southeast of the study area (Figure 1) especially in Ekondo-Titi where they served as the only potable water sources. Lithostratigraphic sections (Figure 2) from hand dug wells showed that the area is made up of medium to coarse-grained sand, and gravely sand and clay at the top (Figure 2). Geophysical logs by UNESCO ISARM (2011) showed that drilled boreholes west of the study area (Isobo and Akwa) were made up of fine to coarse sands inter-bedded with clay (Figure 3). These logs indicated both unconfined aquifers at 0-7 m and confined aquifers at 41-54 m deep. The aquifer materials from these logs (Figure 3) gave recorded values

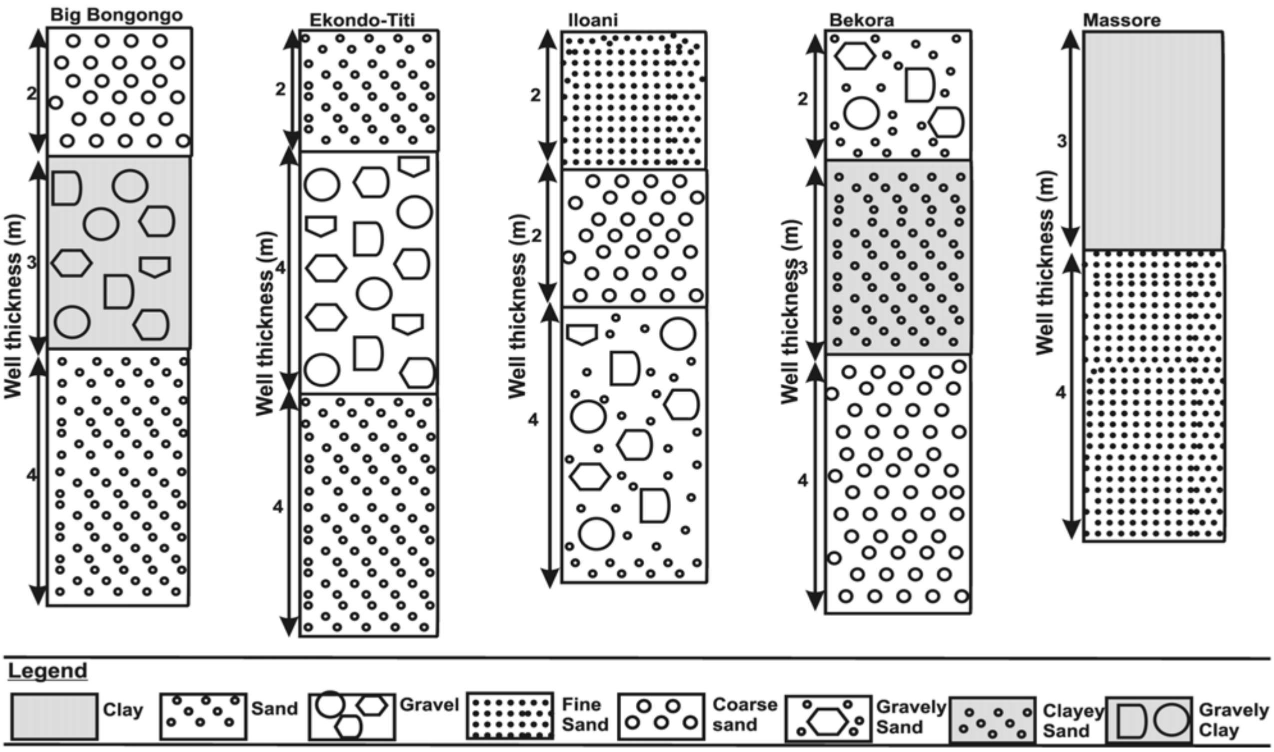

Figure 2. Lithostratigraphic sections of some hand-dug wells in the study area

of 2.61 x 10^{-1} m^2s^{-1}, 5.85 x 10^{-4} m^2s^{-1} and 4.45 x 10^{-5} ms^{-1} for transmissivity, discharge and permeability respectively for boreholes in Akwa. These transmissivity values according to Todd (1980) suggest that these aquifers represent excellent sources of groundwater. The depths of the geophysical logs (UNESCO-ISARM, 2011) of the unconfined aquifers of Isobo and Akwa were similar to the depths of the hand-dug wells observed in the study area (Figure 2). This implies that wells in the study area which usually dry up during the dry season could produce water if they are dug into the confined aquifer at depths of more than 40 m.

The types of aquifers here are similar in geology to those of the Niger Delta west of the study area (Okereke et al., 1998; Edet, 2009). According to Edet (2009), the Oligocene Benin and the Eocene Ogwashi/Asaba aquifers within the Niger Delta Basin are the most prolific in Nigeria. These unconfined aquifers are characterized by alternating layers of gravels, sands, silts and clays thus giving rise to a multi-aquifer system as also described in the Douala Basin by Regnoult (1986) Mafany et al., (2006) and Takem et al. (2010) who equally described confined aquifers similar to those described by UNESCO – ISARM, (2011) in the study area.

According to Yidana (2010), the Birimian Formation in Ghana which consists of granites, gneisses, with some argillaceous sediment metamorphosed to schist, slate and phyllite, equally constitutes aquifers similar to those around Mundemba. Although these metamorphic rocks are inherently impermeable, fracturing and weathering has produced secondary permeability and porosity thereby transforming them into prolific aquifers which deliver groundwater of high quality for domestic consumption and plantation agriculture in the area.

Hydrochemistry of the water sources

The results of analysis of physical and chemical parameters (Table 2) are indicative of groundwater temperature variation from 21.3^{0}C-29.3^{0}C with a mean of 27.2^{0}C as compared to the mean air temperature of 28.4^{0}C. This reflects the unconfining nature of the aquifers. The ranges of pH values (Table 2) for volcanic aquifers (5.80-

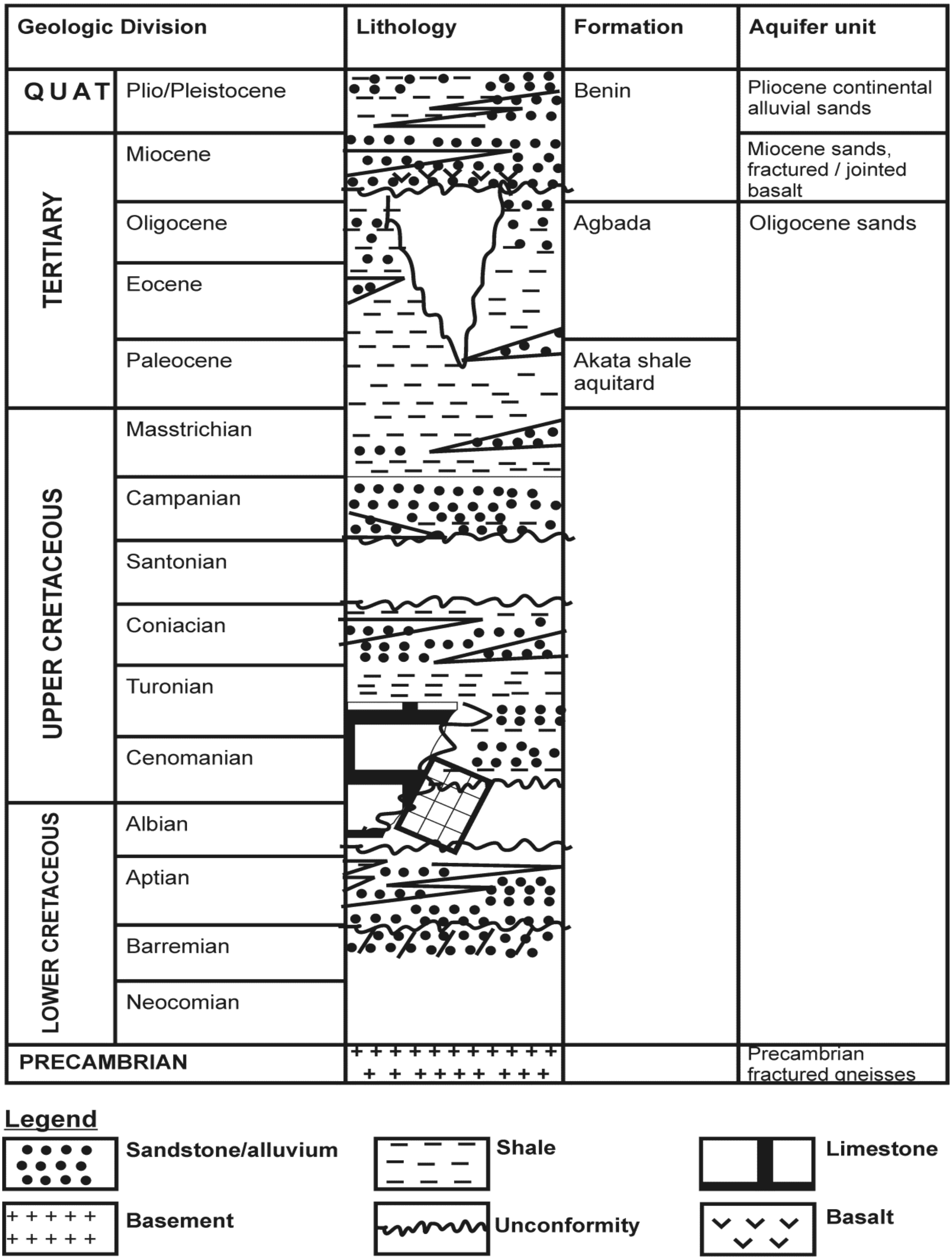

Figure 3. Hydrostratigraphic column of the Rio del Rey Basin showing the various aquifer units modified from UNESCO-ISARM (2011).

7.60), metamorphic aquifers (6.10-7.40) and sedimentary aquifers (5.5-8.0), reflecting slightly acidic, neutral and basic water sources. Sixty percent (60%) of the groundwater samples were slightly acidic (5.5-6.4) and out of the WHO (2004) standard (6.5-8.5) for drinking water and 40 % was neutral to basic (Table 2). The slightly acidic water sources from the aquifers suggest groundwater reaction with lateritic soils and humic acids from these rocks. The decomposition of organic matter in the sedimentary rocks led to acidification from dissolved carbon dioxide (CO_2; Wotany et al., 2013). The mean concentration of total dissolved solid (TDS) concentrations increased from metamorphic (8.84 mg/l), volcanic (17.08 mg/l) to sedimentary (40.48 mg/l) rocks. These values are representative of waters experiencing slight mineralisation. Relatively, the most mineralized water was found in the sediments, the volcanics intermediate, and the least mineralized was in the metamorphic formations. The electrical conductivity (EC) values (Table 2) met the WHO (2004) standard of 750 iS/cm for drinking water and for irrigation (Wilcox, 1955; Ako et al., 2011).

Sodium (Na^+) concentration increased from metamorphic (1.75 mg/l), volcanic (1.84 mg/l) to sedimentary (4.40 mg/l). The primary source of sodium is from the release of soluble products during the weathering of feldspars (albite) and clay minerals. The concentrations of sodium ion in the study area are within the WHO (2004) limit of 100 mg/l (Table 2). Potassium mean concentration increased from volcanic (0.84 mg/l), metamorphic (0.98) to sedimentary (3.00 mg/l). Potassium (K^+) increases in metamorphic more than volcanic because of feldspar (orthoclase) weathering from the gneisses and relatively increased in sedimentary aquifers which suggest the weathering of clay minerals.

Table 2: Physico-chemical data of groundwater in the study area.

Sedimentary Aquifers n = 20

Localities	Water source	pH	EC	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	NO_3	PO_4	F	Br
Bongongo I	OW	5.50	65.00	42.25	9.50	5.54	0.84	0.53	12.06	0	75.56	25.94	0	0	0.02
Ekombe Liongo	OW	7.20	142.00	92.30	5.84	9.13	1.63	12.87	6.05	11.00	106.20	6.44	0.05	0	0.08
Mbonge	OW	6.10	78.00	50.83	7.03	7.53	0.24	0.14	12.16	1.00	89.20	10.95	0	0	0.03
Iloani	OW	5.90	19.00	12.16	1.56	0.59	0.02	0.19	0.50	2.00	98.20	0	0	0.01	0
Bekora	OW	5.70	274.00	178.10	20.80	12.47	6.88	2.82	38.38	1.00	88.13	77.28	0	0.05	0.06
Ekondo Titi	OW	6.40	27.00	17.55	2.31	0.74	1.10	1.49	2.50	1.00	85.96	11.33	0	0	0
Massore	OW	5.80	16.00	10.40	1.43	1.65	0.74	0.45	1.82	0.00	102.00	7.65	0	0	0
Ekondo Titi	OW	6.40	12.00	7.80	1.19	1.72	0.76	0.23	1.34	1.00	90.25	1.81	0	0	0
Mbonge	PW	6.10	7.00	4.45	2.19	0.75	0.16	0.06	1.75	1.00	13.42	0	0	0	0.03
Akwa, Kombo Abedimo	PW	5.90	45.00	29.25	3.28	1.22	1.41	0.41	3.39	1.00	10.98	8.50	0	0	0
Ekombe Mofako	PW	7.20	172.00	111.48	9.06	1.97	1.23	6.48	0.99	1.00	101.26	1.26	0	0.33	0
Mosongesele	PW	8.00	159.00	103.35	5.83	8.19	8.60	0.89	1.50	6.00	86.01	4.54	0	0.05	0
Mbengmong	SP	6.30	15.00	9.75	0.33	0.31	0.05	0.05	0.51	1.00	8.54	0.03	0	0.06	0
Ekombe Liongo	SP	6.40	14.00	9.10	2.11	1.08	0.03	0.13	0.34	2.00	14.64	0.03	0	0	0
Ekombe Liongo	SP	7.60	122.00	79.30	5.09	1.99	1.66	11.56	2.53	2.00	118.34	0.79	0.39	0	0
Ekombe Liongo	SP	6.40	5.00	3.25	1.89	0.62	0.03	0.09	0.13	1.00	15.86	0	0	0	0
Oron, Isangele	SP	6.20	11.00	7.35	0.41	0.71	0.05	0.08	0.62	1.00	6.83	0.15	0	0	0
Gov't quarter Isangele	SP	5.60	11.00	7.28	0.54	0.21	0.03	0.04	0.54	1.00	7.32	0.39	0	0.06	0
Idiba Nyanga	SP	7.00	38.00	24.77	5.28	2.47	0.22	0.20	3.00	0.00	14.64	8.10	0.10	0	0.04
Funge		7.00	13.00	8.45	2.23	1.07	0.17	0.42	0.41	2.00	19.52	0.04	0	0	0
Minimum		5.50	5.00	3.25	0.33	0.21	0.02	0.04	0.13	0.00	6.83	0	0	0	0
Maximum		8.00	274.00	178.10	20.80	12.47	8.60	12.87	38.38	11.00	118.34	77.28	0.39	0.33	0.08
Mean		**6.44**	**62.25**	**40.46**	**4.40**	**3.00**	**1.29**	**1.96**	**4.53**	**1.80**	**57.64**	**8.26**	**0.03**	**0.03**	**0.01**
STD		0.69	73.86	47.98	4.76	3.55	2.29	3.82	8.70	2.50	42.94	17.46	0.09	0.07	0.02
WHO (2004)		6.5-8.5	750	500	200	100	75	30	250	250	200	10	0.30	1.50	0,01
Samples out of WHO (%) GD		**60**	0	0	0	0	0	0	0	0	0	**10**	0.50	0	**16.0**

NB: All variables (cations, anions and Total Dissolved Solids (TDS)) are in mg/l. EC = Electrical Conductivity is in µs/cm; STD = standard deviation, OW = Open wells, PW = Pump wells, SP = Springs and GD = guideline.

Table 2 Continued

Metamorphic Aquifers n = 11

Localities	Water source	pH	EC	TDS	Na	K	Ca	Mg	Cl	SO_4	HCO_3	NO_3	PO_4	F	Br
Bulu Camp, Mundemba	SP	7.40	9.00	5.85	2.17	1.99	0.07	0.14	1.21	1.00	14.64	0.62	0	0.02	0
Mission Camp, Mundemba	SP	6.10	24.00	15.60	3.58	1.43	0.50	0.80	0.47	1.00	29.28	0.27	0	0.06	0
Ikassa Camp, Mundemba	SP	7.10	17.00	11.05	2.75	1.54	0.45	0.90	0.95	2.00	9.76	0.56	0	0.05	0
Last Camp, Mundemba	SP	6.80	9.00	5.85	2.10	0.72	0.19	0.34	0.41	1.00	15.86	0.30	0	0.06	0
Ekondokondo I	SP	6.90	8.00	5.20	1.52	1.23	0.30	0.50	0.67	1.00	15.86	0.74	0	0.03	0
Ekondokondo I	SP	7.10	11.00	7.15	1.92	0.72	0.46	0.62	0.56	1.00	19.52	1.66	0	0.03	0
Ekondokondo I	SP	7.00	7.00	4.55	1.40	0.81	0.29	0.61	0.53	0	15.86	0.63	0	0.03	0
Pamol Camp, Mundemba	SP	6.80	26.00	16.71	1.10	0.64	0.55	0.58	0.51	0	12.20	5.15	0	0.02	0
Ghana quarter, Mundemba	SP	6.50	11.00	6.83	0.87	0.55	0.09	0.16	0.44	0	4.88	0.08	0	0.05	0
Idibawase	SP	7.00	14.00	8.97	1.18	0.45	0.05	0.16	0.25	0	13.42	0.20	0	0.01	0
Besingi	SP	6.50	15.00	9.43	0.71	0.69	0.13	0.20	0.55	0	8.54	2.03	0	0.02	0
Minimum		6.10	7.00	4.55	0.71	0.45	0.05	0.14	0.25	0	4.88	0.08	0	0.01	0
Maximum		7.40	26.00	16.71	3.58	1.99	0.55	0.90	1.21	2.00	29.28	5.15	0	0.06	0
Mean		**6.84**	**13.73**	**8.84**	**1.75**	**0.98**	**0.28**	**0.46**	**0.60**	**0.64**	**14.53**	**1.11**	**0**	**0.03**	**0**
STD		0.36	6.37	4.11	0.86	0.49	0.19	0.27	0.27	0.67	6.37	1.47	0	0.02	0
Volcanic Aquifers n = 7															
Localities	**Water source**	**pH**	**EC**	**TDS**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**SO_4**	**HCO_3**	**NO_3**	**PO_4**	**F**	**Br**
Mekagolo	SP	6.70	20.00	13.00	0.94	0.39	0.81	1.83	0.37	0.24	29.28	0.76	0	0	0
Ekumbako	SP	6.00	7.00	4.55	1.49	0.56	0.20	0.37	0.45	0	14.67	2.18	0	0	0
Dibonda	SP	5.80	3.00	1.95	0.37	0.14	0.11	0.26	0.37	0	9.76	0.72	0	0	0
Njima	SP	7.60	74.00	48.23	4.16	1.83	0.60	2.74	0.70	0	39.04	0.68	0.34	0	0
Ilor	SP	7.10	14.00	8.97	0.95	0.53	0.31	0.45	0.25	0	9.76	0	0	0.01	0
Loe	SP	6.20	16.00	10.34	0.64	0.13	0.27	0.46	0.44	0	6.48	1.10	0	0.02	0
Ekwe	SP	7.60	50.00	32.50	4.54	2.30	0.40	0.80	1.10	1.00	25.26	1.46	0.21	0.11	0
Minimum		5.80	3.00	1.95	0.37	0.13	0.11	0.26	0.25	0	6.48	0	0	o	0
Maximum		7.60	74.00	48.23	4.54	2.30	0.81	2.74	1.10	1.00	39.04	2.18	0.34	0.11	0
Mean		**6.71**	**26.29**	**17.08**	**1.87**	**0.84**	**0.39**	**0.99**	**0.53**	**0.18**	**19.18**	**0.99**	**0.08**	**0.02**	**0**
STD		0.74	25.98	16.94	1.73	0.86	0.24	0.94	0.29	0.37	12.20	0.69	0.14	0.04	0

Calcium mean concentration increased from metamorphic (0.28 mg/l), to volcanic (0.39 mg/l) and to sedimentary (1.29 mg/l) aquifers. The calcium was from the weathering of feldspar (plagioclase), pyroxenes, and clay minerals. Magnesium (Mg^{2+}) mean concentration increases slightly in volcanic aquifers (0.99 mg/l) more than those of the metamorphic (0.46 mg/l) due to the weathering of ferromagnesian minerals (pyroxene, olivine) in the basalts. Fluoride mean concentrations varied from 0.02-0.03 mg/l. The source of fluoride suggests the weathering of amphibole (hornblende), and mica (Chapman, 1996). These concentrations are below the recommended WHO (2004) norm of 1.5 mg/l (Table 2), for potable water as also observed in Ndop, Northwest Region (Wirmvem et al., 2013). At low concentrations (< 0.2 mg/l), F^- in drinking water may result in dental carries (Edmunds and Smedley, 1996).

The increase in alkalinity is from metamorphic (14.53 mg/l), volcanic (19.18 mg/l), to sedimentary (57.64 mg/l). The concentration in all the samples was far below the WHO (2004) limit of 200 mg/l (Table 2). According to Elango et al. (2003), the source of bicarbonate (HCO_3^-) suggests the reaction of silicate minerals with carbonic acid in the presence of water which released HCO_3^-. The nitrate (NO_3^-) mean concentration increases from volcanic (0.99 mg/l), to metamorphic (1.11 mg/l) and to sedimentary (8.28 mg/l). These values suggest an anthropogenic source of NO_3^- from the use of agrochemicals in the surrounding plantations and inputs from domestic waste that infiltrates into the groundwater sources in the sedimentary aquifers. The relative abundance of cations and anions were as follows:

$Na^+ > K^+ > Mg^{2+} > Ca^{2+}$ and $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ for sedimentary aquifers;

$Na^+ > K^+ > Mg^{2+} > Ca^{2+}$ and $HCO_3^- > NO_3^- > Cl^- > SO_4^{2-}$ for metamorphic aquifers, and

$Na^+ > Mg^{2+} > K^+ > Ca^{2+}$ and $HCO_3^- > NO_3^- > Cl^- > SO_4^{2-}$ for volcanic aquifers

Sodium was the dominant cation and bicarbonate the dominant anion. The dominance of Na^+ is suggestive of its release from silicate (feldspar) weathering in the process of exchange of Mg^{2+} and Ca^{2+} in water with Na^+ and K^+ in rocks (cation-anion exchange reaction). A plot of these ions on the Piper (1944), diagram (Figure 4a-c) revealed two main water types; Na-HCO_3 (31 samples) and Ca-HCO_3 (7) water samples). Relating the major groundwater chemical facies to their geologic occurrence showed that the

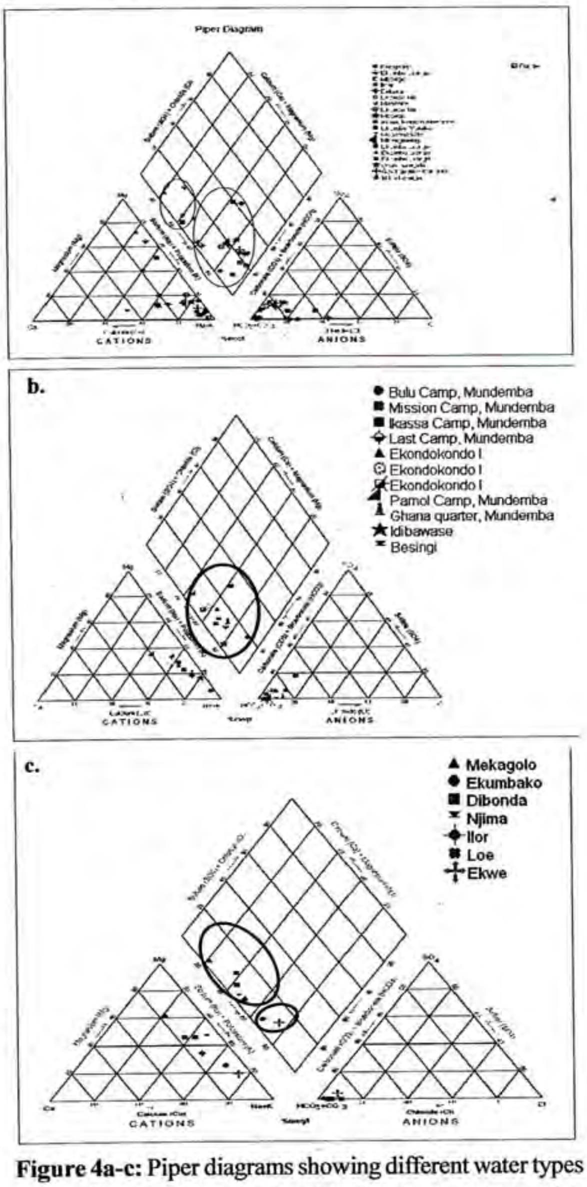

Figure 4a-c: Piper diagrams showing different water types in **a.** sedimentary **b.** metamorphic and **c.** volcanic aquifers

(70%) and Na-HCO_3 (30%), the metamorphics Na-HCO_3 (100%) and the sediments Na-HCO_3 (90%) and Ca-$(HCO_3)_2$ (10%) water types (Figure 4a-c). The Ca-HCO_3 water type indicates shallow fresh groundwater in jointed and fractured basalts and pyroclastic materials, while the Na-HCO_3^- water type indicates deeper fresh groundwater influenced by ion exchange in sediments and weathered/fractured gneisses. Based on the major ions, 37 water sources were suitable for drinking and one water source (open well at Bekora) unsuitable due to excess nitrate concentration of 77.28 mg/l and bromide (0.08 mg/l) which are out of the WHO (2004) standard range (Table 2) for drinking water.

CONCLUSION

Water sources in the study area developed from three geological ranges: sedimentary (alluvial), metamorphic (weathered/fractured gneisses) and volcanic (jointed basalts and pyroclastic materials). The pH values varied from sedimentary aquifers (5.50-8.00) metamorphic (6.10-7.40) and volcanic (5.80-7.60), reflecting slightly acidic (60 %), neutral and basic (40 %) water sources. Based on the EC and TDS values, the most mineralized water was found in the sediments, followed by the volcanics and the least mineralized in the metamorphic formations. The relative abundance of cations and anions are indicative of predominantly sodium bicarbonate rich waters in the sedimentary and metamorphic aquifers and calcium/magnesium bicarbonate rich waters in the volcanic aquifers. Based on the major ions, 37 water sources according to WHO (2004) were suitable for drinking and one water source (open well at Bekora) unsuitable due to excess nitrate and bromide concentrations of 77.28 mg/l and 0.08 mg/l respectively. Based on the Electrical conductivity, all the water sources were suitable for irrigation.

Wells dry up in these localities during the dry season which requires that, boreholes be drilled in the sedimentary rocks to meet confined aquifers as demonstrated in Niger Delta (Nigeria) west of the study area. Such drilling should however be preceded by geophysical surveys, remote sensing (radar) studies, and further ground geological investigations. Regular physical and hydrochemical analysis of the groundwater should be carried out as this will be helpful in an early detection of any future degradation of the aquifers.

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