Journal of Geoscience and Environment Protection, 2019, 7, 184-211
http://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Geogenic Imprint on Groundwater and Its Quality in Parts of the Mamfe Basin, Manyu Division, Cameroon

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How to cite this paper: Akoachere, R. A. II, Eyong, T. A., Egbe, S. E., Wotany, R. E., Nwude, M. O., & Yaya, O. O. (2019). Geogenic Imprint on Groundwater and Its Quality in Parts of the Mamfe Basin, Manyu Division, Cameroon. *Journal of Geoscience and Environment Protection, 7,* 184-211.
https://doi.org/10.4236/gep.2019.75016

Received: March 12, 2019
Accepted: May 27, 2019
Published: May 30, 2019

Abstract

Groundwater studies in parts of the Mamfe basin are sparse and the Mamfe area has the highest population density in the Mamfe basin. An in-depth study of groundwater rock interaction and groundwater quality is of vital importance. This same part of the basin is the economic centre and as such development of businesses in this area requires knowledge of the groundwater quality. Therefore, this study was undertaken to determine the input of the rock formations on the groundwater solute chemistry and groundwater domestic-agro-industrial quality using hydrogeochemical tools and physico-chemical parameters: Ionic ratios, Gibbs diagrams, Piper diagrams, Durov diagrams and water quality indices. From physicochemical parameters, in the rainy season, pH ranged from, 4.3 - 8.6; EC, 3 - 1348 µS/cm; Temperature, 24.4˚C - 30.1˚C and TDS, 2.01 - 903.16 mg/L and in the dry season, pH ranged from 5.5 - 9.3; EC, 6 - 994 µS/cm; Temperature, 25˚C - 38.6˚C and TDS, 4.02 - 632.48 mg/L. Forty groundwater samples: 20 per season, wet and dry were analysed. The major ions fell below WHO acceptable limits for both seasons. The sequences of abundance of major ions were: $Ca^{2+} > K^+ > Mg^{2+} > NH_4^+ > Na^+$, $Cl^- > HCO_3^- > SO_4^{2-} > HPO_4^{2-} > NO_3$ in wet season and $Ca^{2+} > Mg^{2+} > K^+ > Na^+$, $HCO_3^- > Cl^- > SO_4^{2-} > HPO_4^{2-} > NO_3^-$ in dry season. Ion-exchange, simple dissolution and uncommon dissolution processes determined groundwater character. Groundwater ionic content was as a result of ion exchange from rock-weathering. Water types are: $CaSO_4$ and $MgHCO_3$ in both seasons. Hydrogeochemical facies are Ca-Mg-Cl-SO_4 and Ca-Mg-HCO_3. SAR for wet season 0.05 - 0.06 and dry season 0.00 - 0.05, %Na wet season 3.64 - 16.59 and dry season 1.22 - 10.97, KR wet season 0.01 - 0.02 and 0.00 - 0.02 dry season, PI wet season 0.89 - 68.63 and dry season 18.75 -

73.35, MAR wet season 13.3 - 67.88 and dry season 27.02 - 77.01, WQI wet season 0 - 70.79 and 0 - 276.60 dry season, RSC wet season −4.59 to −0.33 and dry season −5.13 - 0.31 and groundwater was excellent-good for irrigation purposes. Some physicochemical parameters: pH, EC and TDS exceeded permissible limits.

Keywords

Geogenic Imprint, Hydrogeochemical Facies, Groundwater Quality, Mamfe, Cameroon

1. Introduction

Water is an important natural resource essential for the existence of life and is basic human entity. Water resources are used for various purposes like drinking, agricultural, industrial, household, recreational, and environmental activities. Groundwater is one of the major sources of drinking water all over the world (Bear, 1979). There has been tremendous increase in the demand for fresh water due to growth in population. Since groundwater is a renewable natural resource and a valuable component of the ecosystem, it is vulnerable to natural and human impacts. It is estimated that approximately one-third of the world's population uses groundwater for drinking (Nickson et al., 2005). In most parts of the Mamfe basin, groundwater is the major source of water supply for drinking and agricultural purposes. Few studies on groundwater quality have been carried out in this area, thus the groundwater might present a potential health hazard as such there was a need to determine the domestic-agro-industrial quality. Groundwater quality data give important clues to the geologic history, rock type and indications of groundwater recharge, discharge and storage (Walton, 1970). Variations in groundwater quality in an area are a function of physical and chemical parameters that are greatly influenced by geological formations and anthropogenic properties (Kumar et al., 2011). According to Babiker et al. (2007), the chemistry of groundwater is not only related to the lithology of the area and the residence time the water is in contact with rock material, but also reflects inputs from the atmosphere, from soil and weathering as well as from pollutant sources such as mining, land clearance, saline intrusion, industrial and domestic wastes. Groundwater used for domestic and irrigation purposes can vary greatly in quality depending upon type and quantity of dissolved salts. It contains a wide variety of dissolved inorganic chemical constituents in various concentrations, resulting from chemical and biochemical interactions between water and the geological materials. Dissolved salts should be present in irrigation water in relatively small but significant amounts. They originate from dissolution or weathering of the rocks and soil, including dissolution of lime, gypsum and other slowly dissolved soil minerals. Research on groundwater studies in parts of the Mamfe basin is sparse and Mamfe area has the highest population density in the basin. An in-depth study of groundwater rock interaction and groundwater quality is of vital importance. This same part of the basin is the economic centre and as such development of business in the study area requires knowledge on groundwater quality. Therefore, the present study was carried out to determine the contribution of the formations to groundwater chemistry, groundwater quality and its suitability for drinking and agricultural uses in parts of the Mamfe basin.

2. Geologic Background of the Study Area

Mamfe and environs is situate between latitude 5.65 - 5.85N and longitude 9.25 - 9.55E **Figure 1**. Manyu Divisionis made up of four sub-divisions and occupied by four main ethnic groups: the Anyangs, Kenyangs, Akwayas, and Ejaghams. It has a population of over 200,000 inhabitants (Mamfe Council, 2014). The area is made up of mostly farmers, business people and civil servants from almost every ethnic group in Cameroon and some from other countries. The climate in this division is hot and humid and consists of a rainy and a dry season modified by the deviation of the monsoon and the relief of Mount Cameroon (Ndip et al., 2018). The vegetation is dominantly that of the equatorial rain forest, and the drainage system is principally that of the Cross River whose main source is found in Mount Bambouto. The sources of its main tributaries the Munaya and Badi Rivers are at Mount Rumpi and Nda Ali respectively (Ndip et al., 2018).

The study area forms part of the Mamfe basin which lies along the Cameroon Volcanic Line. Sedimentation began in the Mamfe basin during the Albian (Dumort, 1968) and lithologies making-up the body of sediments are: basal conglomerates, conglomeratic sandstones, mudstones, shales, calcareous and carbonaceous rocks **Figure 2** that are highly fractured (Lordon et al., 2017). The Mamfe basin is a south-eastern trending Cretaceous rift basin that bifurcates off

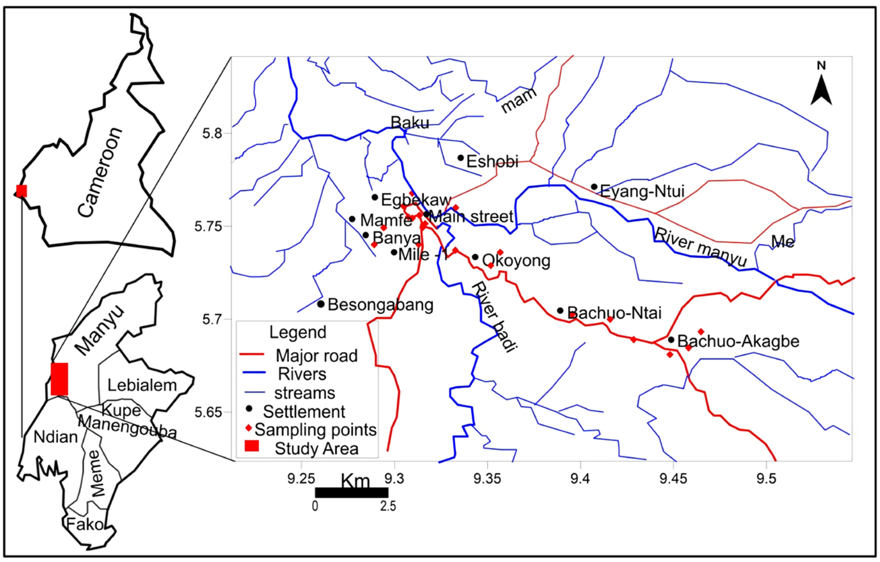

Figure 1. Location map of the study area showing field tested and sampling points.

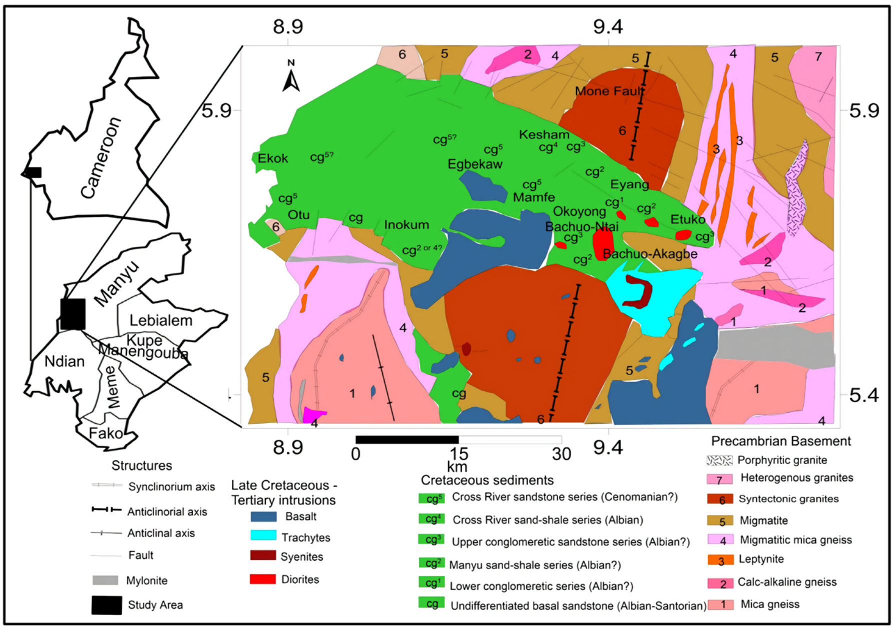

Figure 2. Geologic map of Mamfe (Adapted from Lordon et al., 2017).

the Benue trough and is linked with the West Central African Rift System (CWARS) thought to have formed during the Albian to Cenomanian (Eyong et al., 2013) as a result of basement rifting associated with the reactivation of E-W trending mylonite zones within the Pan-African basement (Dumort, 1968). The basin narrows towards the east and widens towards the west across the Cameroon/Nigeria border into the Benue trough were Albianmarine deposits of Abakaliki Formation outcrops. The basin is fringed by reactivated, fault-bounded granite-gneissic rocks of the Pan-African Mobile Belt (550 ± 100 Ma) and are both intruded by volcanic rocks (Eyong et al., 2013).

Mamfe Basin lies in a NW-SE trending trough with a length of 130 km and a width of 60 km and constitutes a small prolongation of the Benue trough (Nguimbous-Kouoh et al., 2012). Ndougsa-Mbarga et al. (2007) described the Mamfe basin as the smallest of three side rifts associated with the Benue trough of west-central Africa. It extends from the lower Benue trough in Nigeria into Southwestern Cameroon where it narrows and terminates under the Cameroon volcanic line.

The Mamfe basin is bordered to the south by the Oban Massif granito-gneissic Precambrian Basement Complex which separates it from the Rio del Rey Basin and to the North by the Precambrian rocks of the Obudu Massif. To the West the Basin is open and continues as a part of Anambra basin of Nigeria and in the East and Northeast it narrows and terminates under the CVL.

3. Materials and Methods

3.1. Materials

The field materials and equipment used in the study are listed in **Table 1**.

Table 1. Field equipment, specifications and functions.

Equipment/Softwares	Specifications	Functions
Bike	Commercial bikes (Bensikin)	To transport fieldworkers to wells
GPS	GARMIN GPSMAP 60CSx	To measure longitude, latitude and elevation of wells
EC Meter	HANNA HI 98304/HI98303	To measure Electrical Conductivity of water.
pH Meter	HANNA HI 98127/HI98107	To measure pH of water.
Water level indicator	Solinst Model 102M	To indicate static water levels of water in wells
Measuring Tape	Weighted measuring tape	Measurement of well diameter and depth.
Digital Thermometer	Extech 39240 (−50˚C to 200˚C)	To measure temperature of water
Total Dissolved Solid meter	Hanna HI 96301 with ATC	To measure Total dissolved solids in water
Water sampler	Gallenkampf 1000 ml	To collect well water sample from well
Sample bottles	Polystyrene 500 ml	To hold sample for onward transmission to laboratory
ArcGIS	Version 10.1	GIS Drawing sampling/Tests location maps
Global Mapper	Version 15	GIS Geolocation of wells
Surfer Golden Software	Version 12	GIS plotting contours for spatial distribution
AqQA/Aquachem	Version 15	For the analysis/interpretation of water chemistry

3.2. Methods

A reconnaissance survey was carried out to identify wells, springs and streams in June 2016 as per ISO 5667-1 (2006). Seasonal tests/measurements were carried out in September 2016 wet season and Dry season February 2017 respectively. 53 dug wells, were measured/tested in situ for: coordinates of wells, Surface elevation, Well water level, Dug wells depths well diameter, Electrical conductivity (EC), pH, Total dissolved solids (TDS) and Temperature (˚C). Forty (40) groundwater samples 20 in wet and dry seasons were collected in a high density polyethylene (HPDE) 500 ml bottles sealed and sent to the laboratory as per sampling protocols; ISO 5667-3 (2003), ISO 5667-11 (2009) using the standard methods APHA (1995) to analyze for:

1) Major cations in mg/L: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and NH_4^+.

2) Major anions in mg/L: HCO_3^-, Cl^-, SO_4^{2-}, HPO_4^{2-} and NO_3^-

Ionic ratio for indicative elements is a useful hydrogeochemical tool to identify source rock of ions and formation contribution to solute hydrogeochemistry Hounslow (1995). These were used in this study.

Gibbs Diagram is a plot of $Na^+/(Na^+ + HCO_3^- Ca^{2+})$ and $Cl^-/(Cl + HCO_3^-)$ as a function of TDS are widely employed to determine the sources of dissolved geochemical constituents. These plots reveal the relationships between water composition and the three main hydrogeochemical processes involved in ions acquisition; Atmospheric precipitation, rock weathering or evaporation crystallisation.

Pipers Diagram is a graphical representation of the chemistry of water sample on three fields; the cation ternary field with Ca, Mg and Na + Kapices, the anion ternary field with HCO_3, SO_4 and Cl^- apices. These two fields are projected onto a third diamond field. The diamond field is a matrix transformation of the graph of the anions [sulfate + chloride]/Σ anions and cations [Na + K]/Σ cations. This plot is a useful hydrogeochemical tool to compare water samples, determine water type and hydrogeochemical facies Langguth (1966). This has been used here for these purposes.

Durov diagram is a composite plot consisting of two ternary diagrams where the milliequivalent percentages of cations are plotted perpendicularly against those of anions; the sides of the triangles form a central rectangular binary plot of total cation vs. total anion concentrations. These are divided into nine classes by Lloyd and Heathcoat (1985) which give the hydrogeochemical processes determining the character of the water types in the aquiferous formation Langguth (1966).

WQI was calculated by adopting Weighted Arithmetical Index method considering thirteen water quality parameters (pH, EC, TDS, total alkalinity, total hardness, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, NH_4^{+}) in order to assess the degree of groundwater contamination and suitability **Table 2**.

For Agro-industrial suitability the following parameters were used; sodium adsorption ratio SAR, permeability index PI, Magnesium adsorption ratio MAR, percent sodium %Na, Kelly's ratio KR and Residual sodium carbonate RSC and Wilcox diagram **Table 2**.

The following sofwares; Surfer 12, Global mapper 11 and AqQA 1.5 AGIS 10.3 were used for data presentation, interpretation and analysis.

4. Results and Interpretation

4.1. Physicochemical Parameters

The physicochemical parameters groundwater in Mamfe: Temperature, pH, EC

Table 2. Indices used in the calculation of water quality and irrigation water quality.

	Formula	Reference
Percentage Sodium	$\%Na = \frac{Na^{+} + K^{+}}{Na^{+} + K^{+} + Ca^{2+} + Mg^{2+}} \times 100$	Wilcox (1955)
Kelly Ratio	$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}}$	Kelley (1940)
Magnesium Absorption Ratio	$MAR = \left(\frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}}\right) \times 100$	Paliwal (1972)
Total Hardness	TH ($CaCO_3$) mg/L = 2.5 Ca^{2+} + 4.1 Mg^{2+}	Todd (1980)
Residual Sodium Carbonate	$RSC = \left(CO_3 + HCO_3 - (Ca + Mg)\right)$	Eaton (1950)
Sodium Absorption Ratio	$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$	Richards (1954)
Permeability Index	$PI = \frac{\left((Na + K) + \sqrt{HCO_3}\right) * 100}{Ca + Mg + Na + K}$	Doneen (1962)
Water Quality Index	$WQI = \sum_{i=1}^{n} W_i q_i \left[\sum_{i=1}^{n} W_i\right]^{-1}$	Sisodia and Moundiotiya (2006)

and TDS for 53 wells were evaluated as shown in Table 3. From Table 3 all physicochemical parameters vary with seasons indicating seasonal influence phreatic aquifer.

Water Level Fluctuations

Depth-to statues water values (m) of groundwater in Mamfe ranged from: 0.5 - 9.5 in the Wet season and 0.5 - 14.5 in the dry season Figure 3.

Groundwater flow direction

Groundwater flows towards the Northwestern part of the study area during the wet season and dry season but during the dry season some water flows towards Bachuo-Akagbe Figure 4.

Temperature

Temperature values ˚C of Mamfe groundwater ranged from: 24.4 - 30.1 wet season 25˚C - 38.6˚C Figure 5.

pH

The pH value of most of the groundwater samples in the study area ranged from 4.3 - 8.6 in the wet season and 5.5 - 9.3 in the dry season Figure 6. This

Table 3. Basic Statistics of the physicochemical parameters found in groundwater, min, max, mean and standard deviation of these elements in both the wet season and dry season.

Parameters	Wet				Dry			
	Min	Max	Mean	Std.	Min	Max	Mean	Std.
T(˚C)	24.4	30.1	27.77	0.98	25	38.6	28.04	2.46
PH	4.3	8.6	6.11	0.87	5.5	9.3	7.53	0.75
EC (μS/cm)	3	1348	178.9	202.5	6.0	944	174.89	162.03
TDS (mg/L)	2	903.16	119.89	135.65	4.02	632.48	100.13	108.52

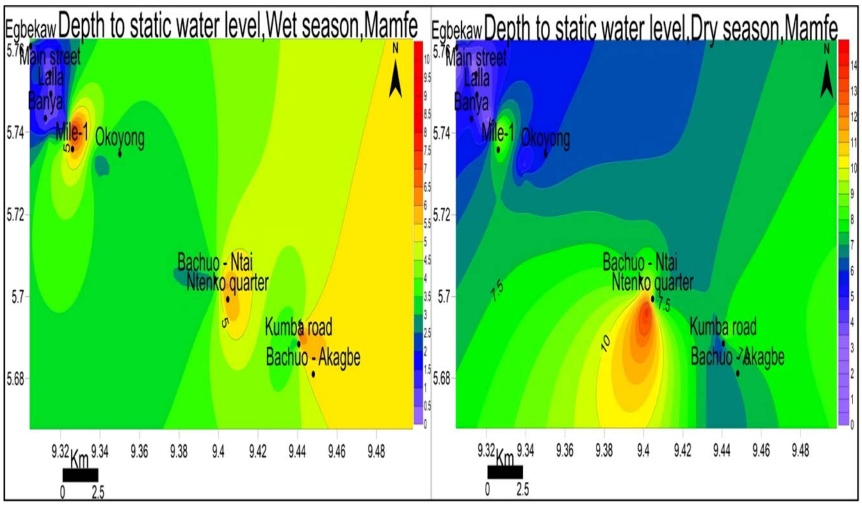

Figure 3. Depth to static water level in Mamfe (a) wet season (b) dry season. Note high water level is recorded during the dry season than in the wet season. High values are at-Bachuo-Ntai, Mile-1 and Bachuo-Akagbe in the wet season with high values in Mile-1 during the dry season.

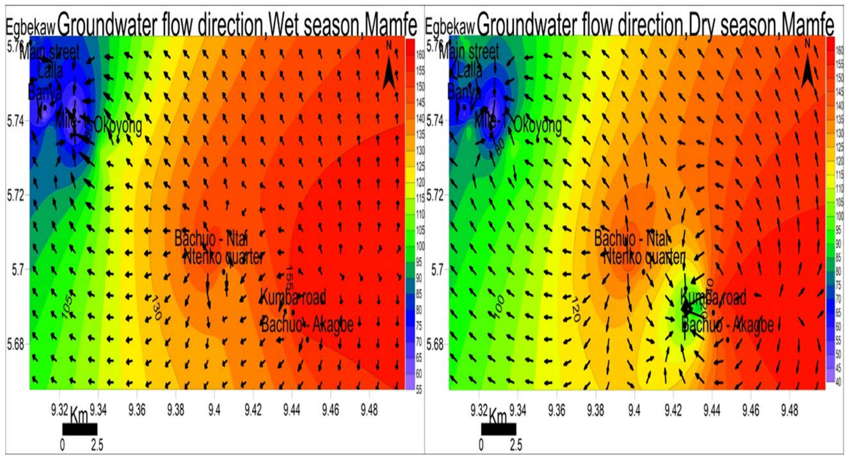

Figure 4. Groundwater flow direction in Mamfe indicating that water flows towards the Northwestern part of the study area that is towards mile-1but during the dry season some water flows towards Bachuo-Akagbe indicating that it is a recharge zone.

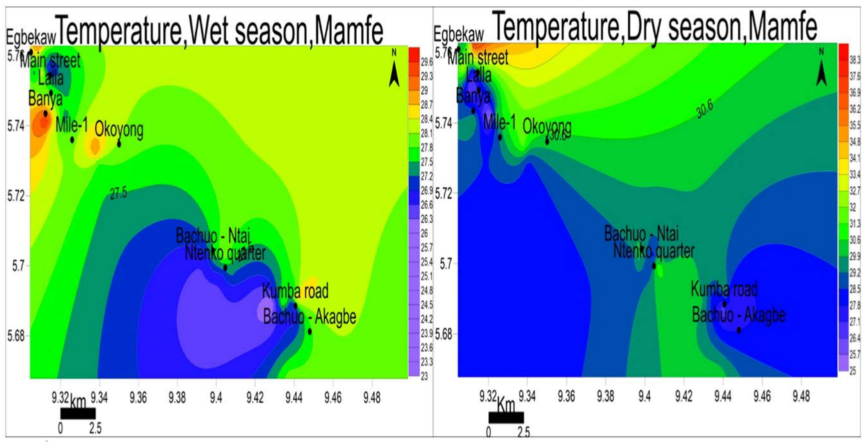

Figure 5. Variation of Mamfe groundwater temperatures. Temperatures are generally higher in the dry season and lower in the wet season. High temperatures are in Banya, Egbekaw and Okoyong while low value are in Bachuo-Akagbe and Bachuo-Ntaiin the wet season and during the dry season the highest values are found Egbekaw and Main Street.

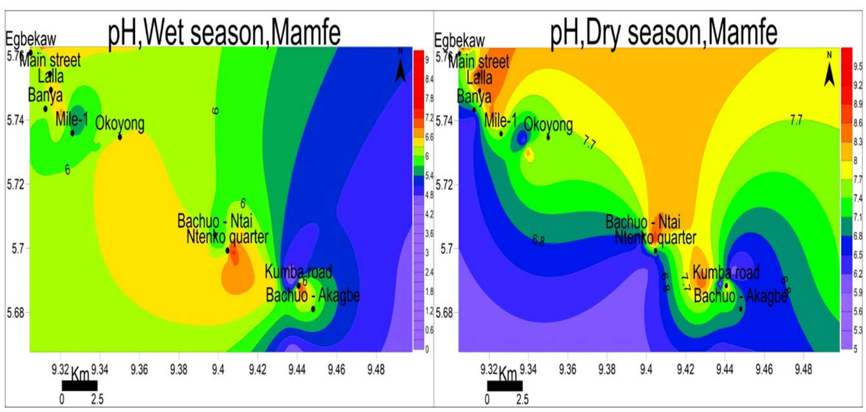

Figure 6. Spatial variation of dug well water pH in Mamfe during (a) wet season (b) dry season; Note decrease in pH values wet season around Bachuo-Akagbe while in the dry seasons the pH values increase around Main Street, Lalla and Bachuo-Ntai.

clearly shows that the groundwater in the study area is slightly acidic to alkaline in both seasons.

Electrical conductivity (EC)

The EC ranges from 3 - 1348 µS/cm during the wet season and 6 - 944 µS/cm during the dry season Figure 7.

The high electrical conductivity is due to high solute concentration in water.

Total dissolved solids (TDS)

The total dissolved solids range from 2.0 - 903.16 mg/L in the wet season and 4.02 - 632.48 mg/L in the dry season Figure 8.

4.2. Chemical Parameters of Groundwater

The results of the chemical analysis varied in both seasons Table 4(a) and Table 4(b) (Figure 9 & Figure 10).

Mechanism controlling water chemistry

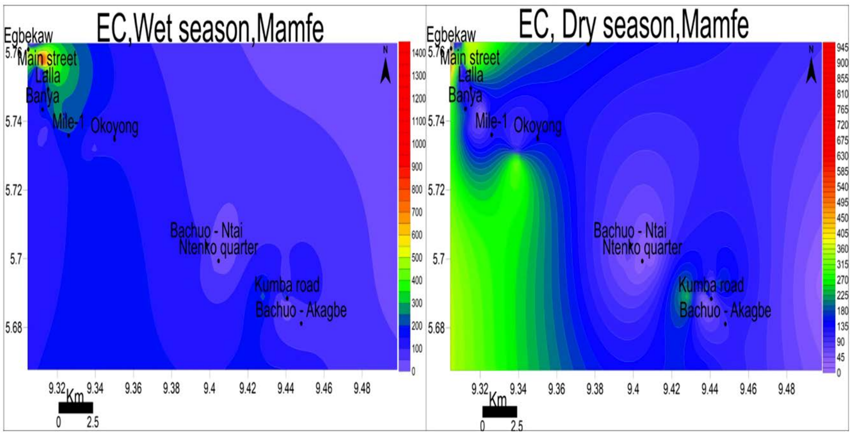

Figure 7. Spatial variation of dug well water Electrical Conductivities (µS) in Mamfe during (a) wet season (b) dry season; EC is at maximum in the wet season and minimum in the dry season.

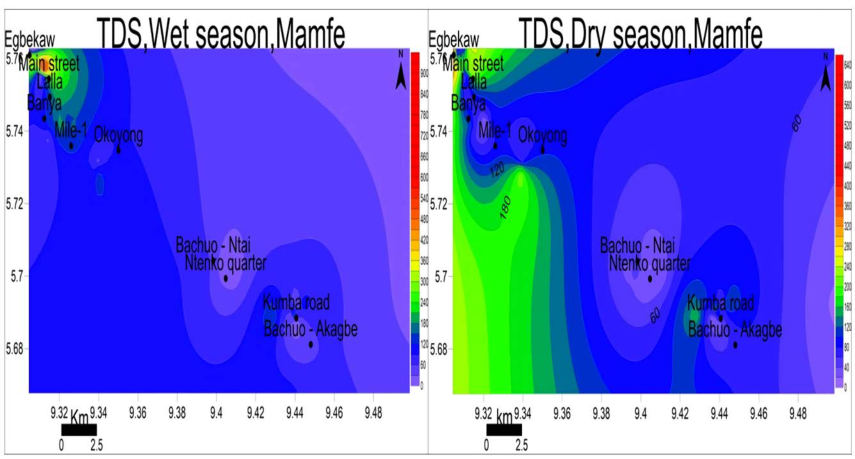

Figure 8. Spatial variation of dug well water total dissolved solids mg/L in Mamfe during wet and dry season. TDS is highest in the wet season and lowest in the dry season. In the wet season the highest value is at Main Street.

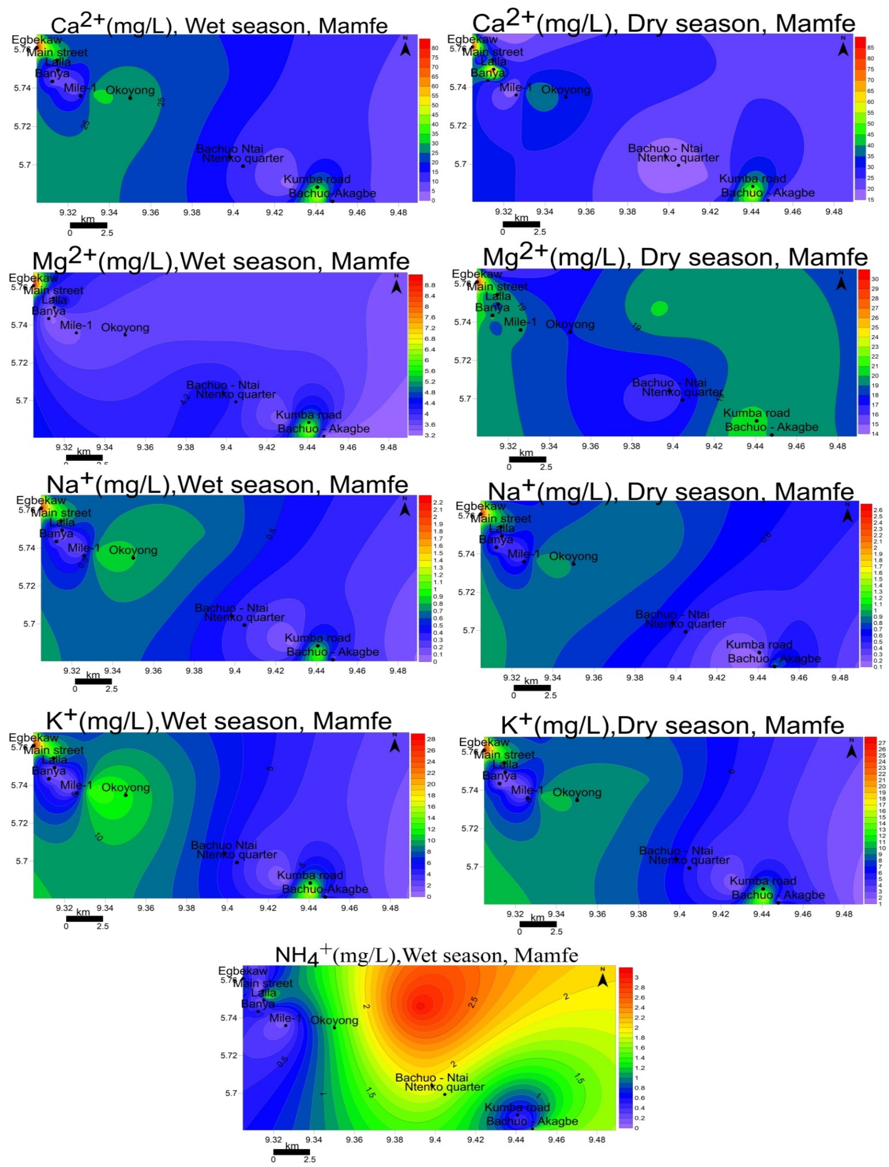

Figure 9. Spatial distribution of Cations; Ca^{2+}, Mg^{2+}, Na, K^{+}, NH_4^{+} in Mamfe Groundwater showing variations for both wet and dry seasons.

Table 4. (a) Results of chemical analysis during wet season: The values of rainwater, springs, streams, Rivers and groundwater are similar indicating connectivity typical of recharge zones in phreatic aquifers; (b) Results of chemical analysis during dry season: The values of rainwater, springs, streams, Rivers and groundwater are similar indicating connectivity typical of recharge zones in phreatic aquifers.

(a)

Wet Season (mg/L)											
SN	Names	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	NH_4^{+}	HPO_4^{2-}	NO_3^{-}	SO_4^{2-}	CL^{-}	HPO_4^{2-}
1	Bachuo-Akagbe 1	0.51	7.45	18.6	3.41	1.76	34.16	0.01	1.55	16.00	0
2	Bachuo-Akagbe 2	0.09	0.86	5.40	3.22	1.71	3.66	0.00	1.46	36.00	0.06
3	Bachuo-Akagbe 3	0.15	1.64	5.40	3.22	0.65	6.10	0.00	1.50	10.00	0.05

Continued

4	Bachuo-Ntai 1	1.17	18.17	50.6	6.64	0.35	15.86	0.01	4.09	28.00	0.00
5	Bachuo-Ntai 2	0.06	0.51	2.66	3.41	0.94	4.88	0.00	1.74	0.00	0.00
6	Bachuo-Ntai 3	0.41	6.2	15.98	4.39	1.91	0.00	0.00	1.97	8.00	0.36
7	Okoyong 1	0.90	13.26	32	3.71	0.53	3.66	0.00	2.72	14.00	0.00
8	Mile-1	0.69	7.41	21.4	3.61	3.06	0.00	0.00	3.38	26.00	0.00
9	Garri quarter	0.62	6.83	21.4	4.97	1.59	28.06	0.02	5.64	20.00	0.07
10	Banya	0.41	4.76	18.6	3.41	0.41	28.06	0.01	5.73	10.00	0.00
11	New layout 1	0.62	6.83	21.4	4.19	0.82	10.98	0.01	2.44	36.00	0.02
12	New layout 2	0.62	6.83	21.4	4.28	0.24	14.64	0.01	3.71	32.00	0.00
13	Small Mamfe	0.3	3.32	8.00	3.41	0.71	4.88	0.00	2.54	6.00	0.04
14	Tanjong Street	0.97	13.49	34.6	3.22	0.00	7.32	0.00	6.72	18.00	0.00
15	Lalla	0.14	1.01	8.00	3.31	0.12	0.00	0.00	1.93	10.00	0.06
16	Egbekaw 1	0.51	5.69	18.6	5.08	0.24	37.82	0.01	7.99	14.00	0.00
17	Egbekaw 2	2.23	29.52	82.6	9.36	0.71	18.3	0.01	3.76	96.00	0.00
18	Spring	0.18	1.13	8.00	3.31	0.35	10.98	0.01	2.44	0.00	0.00
19	River Badi	0.14	1.13	5.32	3.52	0.11	8.54	0.00	2.82	0.00	0.00
20	Rain water	0.28	2.61	10.66	2.93	0.00	2.44	0.00	1.60	4.00	0.00
	Min	0.06	0.51	2.66	2.93	0.00	0.00	0.00	1.46	0.00	0.00
	Max	2.23	29.52	82.60	9.36	3.06	37.82	0.02	7.99	96.00	0.36
	Mean	0.55	6.93	20.53	4.13	0.81	12.02	0.01	3.29	19.20	0.03
	Std.	0.50	7.13	18.78	1.51	0.80	11.63	0.01	1.88	21.41	0.08

(b)

Dry Season (mg/L)											
SN	Names	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	HPO_4^{2-}	NO_3^-	SO_4^{2-}	CL^-	HPO_4^{2-}
1	Bachuo-Akagbe 1	0.64	9.34	21.45	20.14	0.00	45.24	0.00	0.15	12.00	0.00
2	Bachuo-Akagbe 2	0.28	1.45	20.2	18.75	0.00	91.18	0.00	0.18	17.00	0.04
3	Bachuo-Akagbe 3	0.94	2.38	20.15	18.94	0.00	90.25	0.00	0.14	10.00	0.02
4	Bachuo-Ntai 1	0.13	16.23	60.14	21.1	0.00	121.05	0.00	1.42	15.00	0.00
5	Bachuo-Ntai 2	0.18	1.88	21.25	20.01	0.00	51.25	0.00	0.14	0.00	0.00
6	Bachuo-Ntai 3	0.64	6.95	16.75	15.95	0.00	150.00	0.00	0.11	0.00	0.25
7	Okoyong 1	0.95	10.45	41.34	18.25	0.00	48.00	0.00	0.18	10.00	0.00
8	Mile-1	0.88	8.95	28.05	20.25	0.00	120.00	0.00	1.12	16.00	0.00
9	Garri quarter	0.85	8.81	27.45	20.34	0.00	45.00	0.01	2.24	10.00	0.04
10	Banya	0.71	6.84	28.11	18.25	0.00	46.00	0.01	2.16	18.00	0.00
11	New layout 1	0.84	8.74	25.00	19.74	0.00	37.00	0.01	0.19	0.00	0.01
12	New layout 2	0.83	8.46	25.00	19.63	0.00	46.00	0.01	0.21	12.00	0.00
13	Small Mamfe	0.45	2.94	17.00	20.41	0.00	23.95	0.00	1.18	10.00	0.01

Continued

14	Tanjong Street	0.99	11.88	37.45	20.22	0.00	24.00	0.00	3.05	12.00	0.00
15	Lalla	0.35	2.05	80.21	18.18	0.00	91.00	0.00	0.13	94.00	0.04
16	Egbekaw 1	0.63	7.15	16.00	14.25	0.00	101.33	0.00	4.17	0.00	0.00
17	Egbekaw 2	2.64	28.11	85.45	30.45	0.00	100.00	0.00	1.22	0.00	0.00
18	Spring	0.49	2.03	16.49	22.00	0.00	132.00	0.00	0.19	0.00	0.00
19	River Badi	0.37	2.05	12.94	20.00	0.00	130.00	0.00	0.18	0.00	0.00
20	Rain water	0.57	4.90	8.00	16.26	0.00	19.79	0.02	0.16	0.00	0.02
	Min	0.13	1.45	8.00	14.25	0.00	19.79	0.00	0.11	0.00	0.00
	Max	2.64	28.11	85.45	30.45	0.00	150.00	0.02	4.17	94.00	0.25
	Mean	0.72	7.58	30.42	19.66	0.00	75.65	0.00	0.93	11.80	0.02
	Std.	0.52	6.29	21.26	3.15	0.00	41.40	0.01	1.16	20.49	0.06

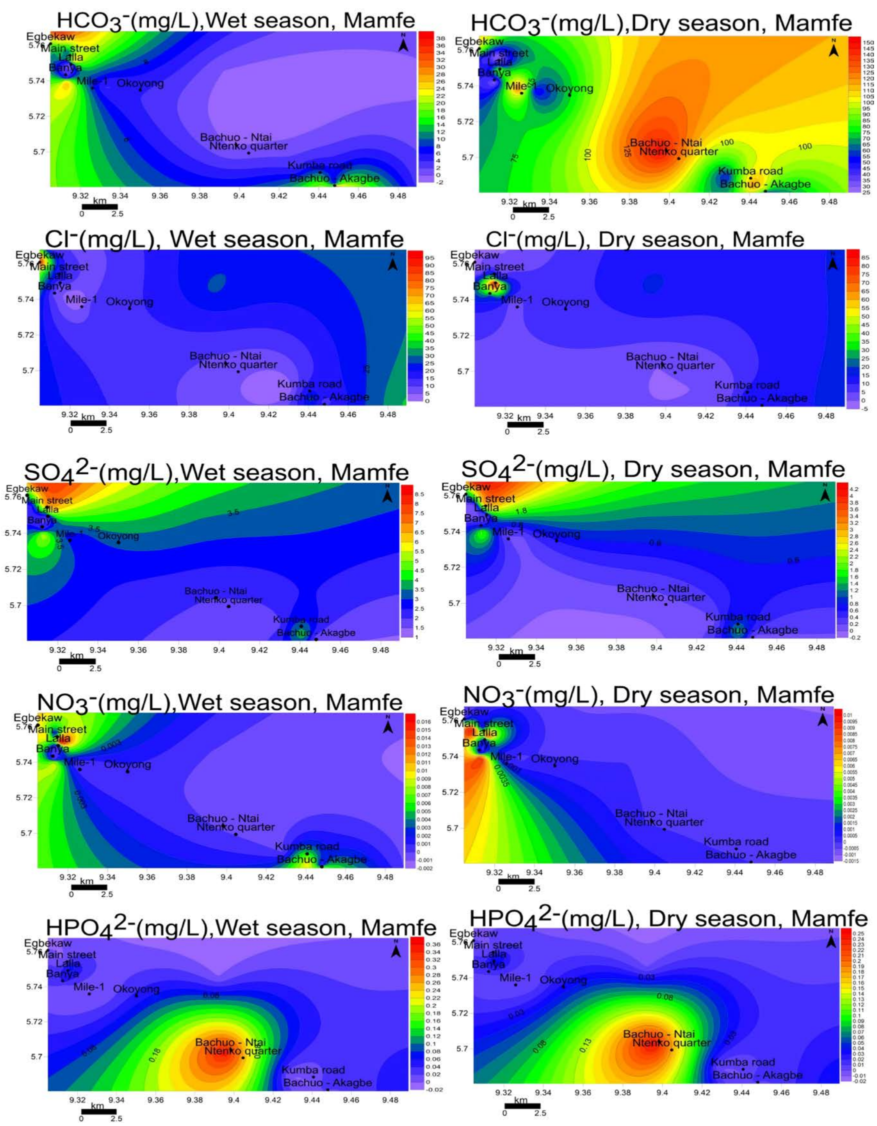

Figure 10. Spatial distribution of Anions; HCO_3^-, CL^-, SO_4^{2-}, HPO_4^{2-}, NO_3^- in Mamfe Groundwater showing variations for both wet and dry seasons.

Ionic ratios of groundwater in Mamfe

18 ionic ratios in groundwater were used to deduce formation inputs in parts of the Mamfe basin, as follows Tables 5(a)-(c).

Table 5. (a) Ionic ratios groundwater in Mamfe; (b) Ionic ratios groundwater in Mamfe; (c) Ionic ratios for wet and dry seasons with determined formation input.

(a)

SN	SO_4/Cl	Na/Cl	Mg/Cl	Na/HCO_3	Ca/HCO_3	Ca/SO_4	Ca/Mg	Ca + Mg/Na + K	HCO_3/ΣAn	NO_3/ΣAn	SO_4/ΣAn	Mg/Ca	Na/Na + Cl	Mg/Ca + Mg	Ca/Ca + SO_4)	Ca + Mg SO_4	Cl/ΣAn	Na + K-Cl/Na + K + Cl-Ca
1	0.10	0.03	0.21	0.01	0.54	12.00	0.00	0.00	0.05	0.00	0.00	0.18	0.03	0.15	0.92	14.20	0.02	0.30
2	0.04	0.00	0.09	0.02	1.48	3.70	1.68	9.07	0.01	0.00	0.00	0.60	0.00	0.37	0.79	5.90	0.05	0.87
3	0.15	0.02	0.32	0.02	0.89	3.60	1.68	4.82	0.01	0.00	0.00	0.60	0.01	0.37	0.78	5.75	0.01	0.60
4	0.15	0.04	0.24	0.07	3.19	12.37	7.62	2.96	0.02	0.00	0.01	0.13	0.04	0.12	0.93	14.00	0.04	0.15
5	0.00	0.00	0.00	0.01	0.55	1.53	0.78	10.65	0.01	0.00	0.00	1.28	1.00	0.56	0.60	3.49	0.00	−0.27
6	0.25	0.05	0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.05	0.22	0.89	10.34	0.01	0.08
7	0.19	0.06	0.27	0.25	8.74	0.00	8.63	2.52	0.01	0.00	0.00	0.12	0.06	0.10	0.92	13.13	0.02	−0.01
8	0.13	0.03	0.14	0.00	0.00	6.33	0.00	3.09	0.00	0.00	0.00	0.17	0.03	0.14	0.86	7.40	0.04	0.46
9	0.28	0.03	0.25	0.02	0.76	3.79	4.31	3.54	0.04	0.00	0.01	0.23	0.03	0.19	0.79	4.68	0.03	0.37
10	0.57	0.04	0.34	0.01	0.66	3.25	0.00	0.00	0.04	0.00	0.01	0.18	0.04	0.15	0.76	3.84	0.01	0.21
11	0.07	0.02	0.12	0.06	1.95	0.00	5.11	3.43	0.02	0.00	0.00	0.20	0.02	0.16	0.90	10.49	0.05	0.57
12	0.12	0.02	0.13	0.04	1.46	0.00	5.00	3.45	0.02	0.00	0.01	0.20	0.02	0.17	0.85	6.92	0.05	0.53
13	0.42	0.05	0.57	0.06	1.64	3.15	2.35	0.00	0.01	0.00	0.00	0.43	0.05	0.30	0.76	4.49	0.01	0.23
14	0.37	0.05	0.18	0.13	4.73	0.00	10.75	0.00	0.01	0.00	0.01	0.09	0.05	0.09	0.84	5.63	0.03	0.09
15	0.19	0.01	0.33	0.00	0.00	4.15	2.42	9.83	0.00	0.00	0.00	0.41	0.01	0.29	0.81	5.86	0.01	0.53
16	0.57	0.04	0.36	0.01	0.49	2.33	3.66	3.82	0.05	0.00	0.01	0.27	0.04	0.21	0.70	2.96	0.02	0.30
17	0.04	0.02	0.10	0.00	0.00	0.00	8.82	0.00	0.03	0.00	0.01	0.11	0.02	0.10	0.96	24.46	0.14	0.44
18	0.00	0.00	0.00	0.02	0.73	3.28	2.42	8.63	0.02	0.00	0.00	0.41	1.00	0.29	0.77	4.64	0.00	−0.20
19	0.00	0.00	0.00	0.02	0.62	1.89	1.51	6.96	0.01	0.00	0.00	0.66	1.00	0.40	0.65	3.13	0.00	−0.31
20	0.40	0.07	0.73	0.11	4.37	6.66	3.64	4.70	0.00	0.00	0.00	0.27	0.07	0.22	0.87	8.49	0.01	0.09
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.09	0.60	2.96	0.00	−0.31
Max	0.57	0.07	0.73	0.25	8.74	12.37	10.75	10.65	0.05	0.00	0.01	1.28	1.00	0.56	0.96	24.46	0.14	0.87
Mean	0.20	0.03	0.25	0.04	1.64	3.40	3.52	3.87	0.02	0.00	0.00	0.34	0.18	0.23	0.82	7.99	0.03	0.25
Std.	0.18	0.02	0.20	0.06	2.16	3.63	3.25	3.52	0.02	0.00	0.00	0.28	0.35	0.12	0.09	5.26	0.03	0.31

(b)

SN	SO_4/Cl	Na/Cl	Mg/Cl	Na/HCO_3	Ca/HCO_3	Ca/SO_4	Ca/Mg	Ca + Mg/Na + K	HCO_3/ΣAn	NO_3/ΣAn	SO_4/ΣAn	Mg/Ca	Na/Na + Cl	Mg/Ca + Mg	Ca/Ca + SO_4	Ca + Mg/SO_4	Cl/ΣAn	Na + K-Cl/Na + k + Cl-Ca
1	0.01	0.05	1.68	0.01	0.47	143.00	0.00	0.00	0.03	0.00	0.00	1.68	0.05	0.48	0.99	277.27	0.01	0.09
2	0.01	0.02	1.10	0.00	0.22	112.22	1.08	22.51	0.05	0.00	0.00	1.10	0.02	0.48	0.99	216.39	0.01	0.43
3	0.01	0.09	1.89	0.01	0.22	143.93	1.06	11.77	0.05	0.00	0.00	1.89	0.09	0.48	0.99	279.21	0.01	0.25
4	0.09	0.01	1.41	0.00	0.50	42.35	2.85	4.97	0.07	0.00	0.00	1.41	0.01	0.26	0.98	57.21	0.01	−0.02
5	0.00	0.00	0.00	0.00	0.41	151.79	1.06	20.03	0.03	0.00	0.00	0.00	1.00	0.48	0.99	294.71	0.00	−0.11

Continued

6	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.08	0.00	0.00	0.00	1.00	0.49	0.99	297.27	0.00	−0.83
7	0.02	0.10	1.83	0.02	0.86	0.00	2.27	5.23	0.03	0.00	0.00	1.83	0.09	0.31	1.00	331.06	0.01	−0.04
8	0.07	0.06	1.27	0.01	0.23	25.04	0.00	4.91	0.07	0.00	0.00	1.27	0.05	0.42	0.96	43.13	0.01	0.18
9	0.22	0.09	2.03	0.02	0.61	12.25	1.35	4.95	0.03	0.00	0.00	2.03	0.08	0.43	0.92	21.33	0.01	0.01
10	0.12	0.04	1.01	0.02	0.61	13.01	0.00	0.00	0.03	0.00	0.00	1.01	0.04	0.39	0.93	21.46	0.01	0.27
11	0.00	0.00	0.00	0.02	0.68	0.00	1.27	4.67	0.02	0.00	0.00	0.00	1.00	0.44	0.99	235.47	0.00	−0.62
12	0.02	0.07	1.64	0.02	0.54	0.00	1.27	4.80	0.03	0.00	0.00	1.64	0.06	0.44	0.99	212.52	0.01	0.10
13	0.12	0.05	2.04	0.02	0.71	14.41	0.83	0.00	0.01	0.00	0.00	2.04	0.04	0.55	0.94	31.70	0.01	0.28
14	0.25	0.08	1.69	0.04	1.56	0.00	1.85	0.00	0.01	0.00	0.00	1.69	0.08	0.35	0.92	18.91	0.01	−0.02
15	0.00	0.00	0.19	0.00	0.88	617.00	4.41	41.00	0.05	0.00	0.00	0.19	0.00	0.18	1.00	756.85	0.05	0.53
16	0.00	0.00	0.00	0.01	0.16	3.84	1.12	3.89	0.06	0.00	0.00	0.00	1.00	0.47	0.79	7.25	0.00	−0.95
17	0.00	0.00	0.00	0.00	0.00	0.00	2.81	0.00	0.06	0.00	0.00	0.00	1.00	0.26	0.99	95.00	0.00	−0.56
18	0.00	0.00	0.00	0.00	0.12	86.79	0.75	15.27	0.07	0.00	0.00	0.00	1.00	0.57	0.99	202.58	0.00	−0.18
19	0.00	0.00	0.00	0.00	0.10	71.89	0.65	13.61	0.07	0.00	0.00	0.00	1.00	0.61	0.99	183.00	0.00	−0.23
20	0.00	0.00	0.00	0.03	0.40	50.00	0.49	4.44	0.01	0.00	0.00	0.00	1.00	0.67	0.98	151.63	0.00	−2.16
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.18	0.79	7.25	0.00	−2.16
Max	0.25	0.10	2.04	0.04	1.56	617.00	4.41	41.00	0.08	0.00	0.00	2.04	1.00	0.67	1.00	756.85	0.05	0.53
Mean	0.05	0.03	0.89	0.01	0.47	74.38	1.26	8.10	0.04	0.00	0.00	0.89	0.43	0.44	0.97	186.70	0.01	−0.18
Std.	0.08	0.04	0.85	0.01	0.37	138.60	1.13	10.29	0.02	0.00	0.00	0.85	0.48	0.12	0.05	174.24	0.01	0.61

(c)

Ionic ratio	Wet	Dry	Comment	Interpretation
SO_4/Cl	0.00 - 0.57	0 - 0.25	high	Additional sources of SO_4 from weathering of sulfates
Na/Cl	0.00 - 0.07	0 - 0.01	low	No Na-adsorption during freshening and a little silicate weathering
Mg/Cl	0.00 to 0.73	0 - 2.04	high	Cation-exchange and silicate weathering of sandstones.
Na/HCO_3	0.01 - 0.25	0 - 0.004	high	Substantial weathering of Na-feldspar or other Na-silicates
Ca/HCO_3	0.00 - 8.74	0 - 1.56	high	Calc-carbonate dissolution or Calc-silicate weathering
Ca/SO_4	1.53 - 21.97	3.84 - 617	high	Gypsum dissolution present
Ca/Mg	0.00 - 10.75	0 - 4.41	high	Cation-exchange of weathering of silicate rocks.
Ca + Mg/Na + K	0.00 - 10.65	0.00 - 41.00	high	Carbonate weathering
HCO_3/ΣAnions	0.00 - 0.05	0.01 - 0.08	high	Weathering reactions and input of dissolved species in recharge area
NO_3/ΣAnions	0.00 - 2.8E−6	0.00 - 5.6E−6	very low	No anthropogenic contribution
SO_4/ΣAnions	0.00 - 0.01	0.00 - 2.3E−3	very low	No oxidation of sulphides.
Mg/Ca	0.09 - 1.28	0.00 - 2.04	low	Weathering of Silicate rocks
Na/Na + Cl	0.00 - 1.00	0.00 - 1.00	high	Sodium source other than halite-albite, ion exchange
Mg/Ca + Mg	0.09 - 0.56	0.18 - 0.67	high	Dolomite dissolution, calcite precipitation or saltwater
Ca /Ca + SO_4	0.60 - 0.96	0.79 - 1.00	high	Calcium source other than gypsum
Ca + Mg/SO_4	2.96 - 24.46	7.25 - 756.85		
Na + K-Cl/Na + K-Cl + Ca	−0.31 - 0.87	−2.16 - 0.53	high	Plagioclase weathering unlikely
Cl/ΣAnions	0.00 - 0.14	0.00 - 0.05	low	Rock weathering

12 of the 18 66.7% ionic ratios calculated gave indices indicating weathering of geologic formations in the Mamfe basin as a source of solute concentration in the groundwater while nitrate ratio indicates no anthropogenic contribution and sulfate indices indicates no oxidation of sulfides. Ca is sourced from gypsum while Na is sourced from halite-albite and ion exchange. Mg is contributed by dolomite dissolution, calcite precipitation or saltwater. There is no plagioclase weathering. These high indices values are found in the following localities Lalla, Okoyong, Bachuo-Ntai, Bachuo-Akagbe and Egbekaw.

Gibbs diagrams of groundwater in Mamfe

The Gibbs diagrams were used. In the wet season 17 samples 85% plot in the rock-weathering dominance field and 3 samples 85% plot in the atmospheric precipitation dominance field. In the dry season 16 samples 80% plot in the rock-weathering dominance field and 4 samples 20% plot in atmospheric dominance field Figure 11. This indicates the mechanism contributing solute to groundwater in Mamfe is rock-weathering 80% - 85% followed by atmospheric precipitation 15% - 20% in the dry and wet season respectively (Table 6).

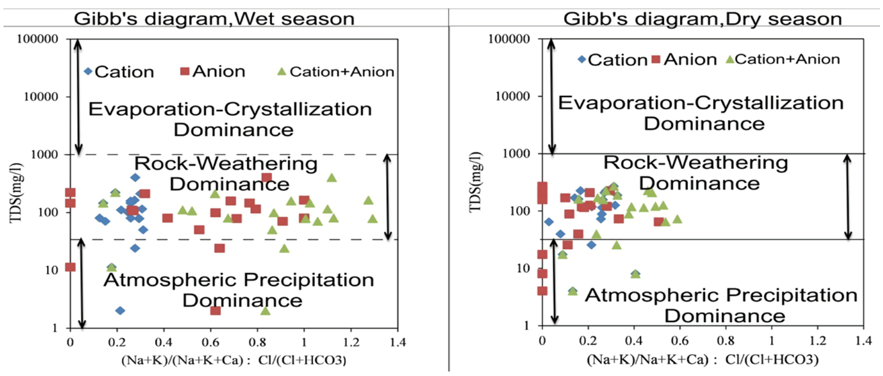

Figure 11. Gibbs diagrams for Mamfe groundwater (Gibbs, 1970): In the wet season 17 samples 85% cations and 17 samples 85% anions plot in the rock-weathering dominance field and 3 samples 15% cations and 3 samples 15% anions plot in atmospheric dominance field; In the dry season 16 samples 80% cations and 16 samples 80% anions plot in the rock-weathering dominance field and 4 samples 20% cations and 4 samples 20% anions plot in atmospheric dominance field; indicating the mechanism contributing groundwater constituents in the study area is rock-weathering and atmospheric precipitation.

Table 6. Gibbs Classification of groundwater in Mamfe and environs (Gibbs, 1970).

Type	Range	Wet				Dry			
		Cation	%	Anion	%	Cation	%	Anion	%
Rock - Weathering dominance	50 - 1000	17	85	17	85	16	80	16	80
Atmospheric Precipitation dominance	1 - 50	3	15	3	15	4	10	4	20

Groundwater types

The diamond field of piper diagram after Piper (1944) has further been divided into seven fields classifying water types and designated with alphabets from A to G, Langguth (1966). Using this classification, the water from the study area is distinguished into the A, B, and C categories. The D, E, F, and G water types are absent. In the rainy season; Category A, 3 samples 15%; characterized by normal earth alkaline water with prevailing bicarbonate. Category B, 3 samples 15% are characterized by normal earth alkaline water with prevailing sulfate or chloride and Category C, 14 samples 70% **Figure 12** are characterized by alkaline earth water with increased portions of alkalis with prevailing bicarbonate. In the dry season; Category A, 14 samples 70%, Category B, 5 samples 25% Category C, 1 sample 5%. The dominant water types are Category C 70%; Normal earth alkaline water; prevailing SO_4^{2-} or Cl^- in the wet season and Category A 70%; Normal earth alkaline water; prevailing NO_3^- in the dry season. The water types in Mamfe groundwater are Ca-SO_4 and Mg-HCO_3 for both seasons **Table 7**.

Piper's Hydrogeochemical facies

From the Piper's diagrams, field I: Ca-Mg-Cl^--SO_4 hydrogeochemical facies has 15 samples 75% in the rainy and 2 samples 10% in the dry season demonstrating the dominance of alkaline earths over alkali Ca + Mg > Na + K and strong acidic anions over weak acidic anions. Field IV, Ca-Mg-HCO_3 hydrogeochemical facies has 5 samples 25% in the rainy and 18 samples 90% in the dry season **Table 8** signifying the dominance of alkaline earths over alkali and weak acidic anions over strong acidic anions. This facies is characteristic of freshly recharged groundwater that has equilibrated with CO_2 and soluble carbonate minerals under an open system conditions in the vadose zone typical of shallow groundwater flow systems in crystalline phreatic aquifers.

No samples plotted on field II and field III. The dominance of Ca-Mg-HCO_3 hydrogeochemical facies in this area could be due to dissolution of gases and minerals, particularly CO_2 and CO_2-related compounds from the atmosphere

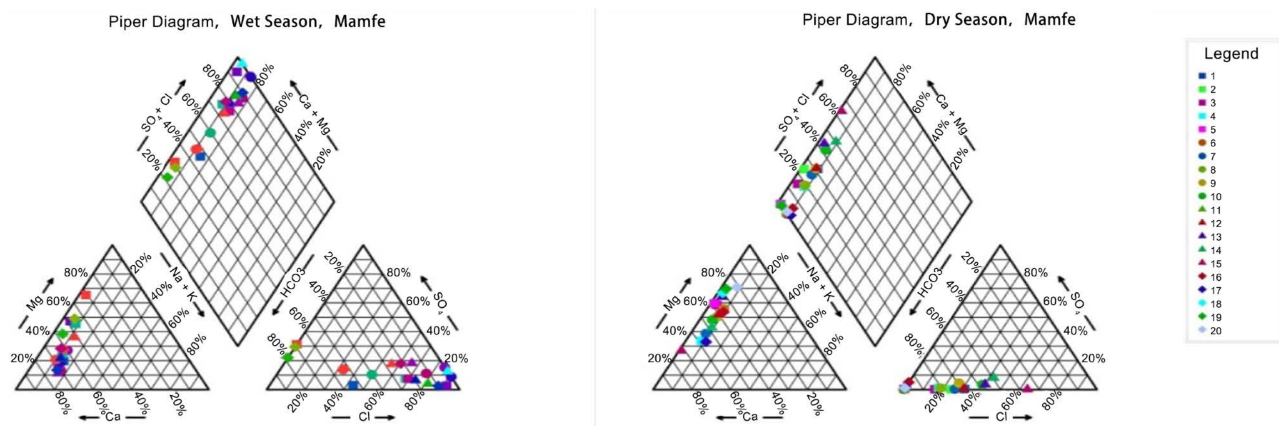

Figure 12. Piper's diagram for Mamfe groundwater samples; during rainy season in Category A, 3 samples 15%; characterized by normal earth alkaline water with prevailing bicarbonate. Category B, 3 samples 15% are characterized by normal earth alkaline water with prevailing sulfate or chloride and Category C, 14 samples 70% are characterized by alkaline earth water with increased portions of alkalis with prevailing bicarbonate. In the dry season; Category A, 14 samples 70%, Category B, 5 samples 25% and Category C, 1 sample 5% are characterized by alkaline earth water with increased portions of alkalis with prevailing bicarbonate. Diamond field I: Ca-Mg-Cl-SO_4 hydrogeochemical facies has 15 samples 75% in the rainy and 2 samples 10% in the dry season. Field IV, Ca-Mg-HCO_3 hydrogeochemical facies has 5 samples 25% in the rainy and 18 samples 90% in the dry season. No samples plotted on field II and field III in both seasons. Langguth (1966).

Table 7. Classification of Mamfe groundwater based on Piper diagram (Langguth, 1966) to depict water types.

		Wet		Dry	
Class	Description of Water Types	No	%	No	%
A	Normal earth alkaline water with prevailing bicarbonate	3	15	14	70
B	Normal earth alkaline water with prevailing bicarbonate and sulfate or chloride	3	15	5	25
C	Normal earth alkaline water with prevailing Sulfate or Chloride	14	70	1	5
	Cations field				
1	Calcium rich	18	90	6	30
2	Magnesium rich	2	10	14	70
	Anion Field				
4	Bicarbonate rich	6	30	19	95
5	Chloride rich	14	70	1	5

Table 8. Classification of water based on Piper diagram (Langguth, 1966).

Field	Hydrogeochemical facies	Wet	%	Dry	%
Field I	$Ca\text{-}Mg\text{-}Cl\text{-}SO_4$	15	75	2	10
Field IV	$Ca\text{-}Mg\text{-}HCO_3$	5	25	18	90

dissolved in precipitation and during groundwater infiltration through the vadose zone.

Durov diagram

Based on the classification of Lloyd and Heathcoat (1985): Six classes of processes occur in the rainy season; Class 1 recharging waters: 10 samples 50%; Class 2 ion exchange water: 5 samples 15%; Class 3 ion exchange water: 1 samples 5%; Class 5 simple dissolution or mixing: 1 samples 5%; Class 6 probable mixing or uncommon dissolution influences: 1 sample respectively 5% and Class 7 2 samples respectively 10%; Cl and Na dominant is frequently encountered, Otherwise the water may result from reverse ion exchange of Na-Cl waters Table 9. Five classes of processes occur in the dry season: Class 2 ion exchange water: 1 sample 5%; Class 3 ion exchange water: 3 samples 15%; Class 5 simple dissolution or mixing: 1 sample 5%; Class 6 probable mixing or uncommon dissolution influences: 11 samples 55% respectively Figure 13. There are no Classes 4 and 9 in the rainy season and no Classes 1, 7 and 9 in the dry season samples in groundwater from Mamfe. In the rainy season, fresh recently recharging water exchanges ions with the matrix of the formation, while simple dissolution or mixing also goes on between the recently recharging and the existing groundwater in the formation. In the dry season, recharged groundwater having spent more time in the formation continues to exchange ions to a lesser extent with the matrix of the formation while increasingly; simple dissolution or mixing also goes on between the recently recharged groundwater and the pre-existing groundwater in the formation.

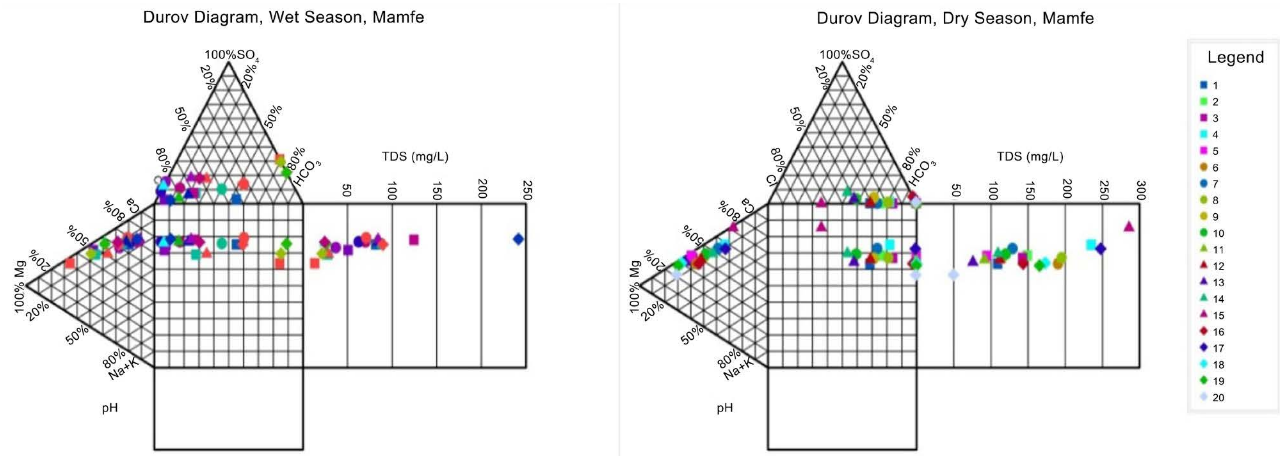

Figure 13. From Durov diagrams: Six classes of processes occur in the wet season: Class 1 recharging waters: 10 samples 50%; Class 2 ion exchange water: 5 samples 25%; Class 3 ion exchange water: 1 samples 5%; Class 5 1 sample 5% simple dissolution or mixing: Class 61 sample 5% probable mixing or uncommon dissolution influences: and Class 72 sample respectively 10%; Cl and Na dominant is frequently encountered. Otherwise the water may result from reverse ion exchange of Na-Cl waters. Five classes of processes occur in the dry season: Class 2 ion exchange water: 1 sample 5%; Class 3 ion exchange water: 3 samples 15%; Class 5 simple dissolution or mixing: 5 samples 25%; Class 6 probable mixing or uncommon dissolution influences: 11 samples 55% respectively. Durov's 1948; Lloyd & Heathcoat (1985).

Table 9. Classification of Water based on Durov diagram (Lloyd & Heathcoat, 1985).

		Wet		Dry	
SN	Description of Water Types	No	%	No	%
1	HCO_3 and Ca dominant, frequently indicates recharging waters in limestone, sandstone, and many other aquifers	10	50	0	0
2	This water type is dominated by Ca and HCO_3 ions. Association with dolomite is presumed if Mg is significant. However, those samples in which Na is significant, an important ion exchanged is presumed	5	25	1	5
3	HCO_3 and Na are dominant, normally indicates ion exchanged water, although the generation of CO_2 at depth can produce HCO_3 where Na is dominant under certain circumstances	1	5	3	15
5	No dominant anion or cation, indicates water exhibiting simple dissolution or mixing	1	5	5	25
6	SO_4 dominant or anion discriminate and Na dominant; is water type that is not frequently encountered and indicates probable mixing or uncommon dissolution influences.	1	5	11	55
7	Cl and Na dominant are frequently encountered or the water may have resulted from reverse ion exchange of Na-Cl waters	2	10	0	0

4.3. Water Quality

Domestic Water Quality

Ionic content of water in the study area was used to evaluate groundwater suitability for domestic use: The recommended values are of the WHO (2017) guidelines. The quality standards for drinking water have been specified by the World Health Organization (WHO) 2017. The suitability of groundwater in the study area based on WQI and total hardness H_T are discussed below.

Water quality index (WQI)

The WHO (2017) permissible values of ions present in the groundwater have been used to calculate WQI values, Asadi et al. (2007). Water Quality Index WQI considered the most effective tool to convey the water quality information in the simplest form to the public (Babaei, 2011). The WQI values range from 0 - 70.79 in the wet season and 13.2 - 276.6 in the dry. 80% of the water samples in the wet season can be considered suitable for domestic and other utilitarian purposes as they belong to excellent to good water quality classes Table 10. Remaining 20% of the samples are said to be unfit for consumption as they belong to poor class Figure 14 whereas 20% of the water samples in the dry season can be considered suitable for domestic and other utilitarian purposes as they belong to excellent to good water quality classes. Remaining 80% of the samples are said to be unfit for consumption as they belong to poor, very poor and unsuitable classes Table 10.

Total hardness (TH)

The total hardness of groundwater samples range from 20.63 - 244.87 mg/L in the wet season and 86.66 - 338.47 mg/L in the dry season Figure 15. 80% of groundwater in the study area can be classified as soft, 10% fall into the moderately hard category, and just 10% in the wet season is hard water that may be a potential health risk factor whereas in the dry season 0% of groundwaters in the study area can be classified as soft, 65% fall into the moderately hard category, 30% is hard water and just 5% is very hard Table 11.

Table 10. WQI classification indicating the suitability of water for drinking.

Index	Quality	WQI-wet	%	WQI-dry	%
0 - 25	Excellent	10	50	1	5
26 - 50	Good	6	30	3	15
51 - 75	Poor	4	20	2	10
76 - 100	Very poor	0	0	0	0
>100	Unsuitable	0	0	14	70

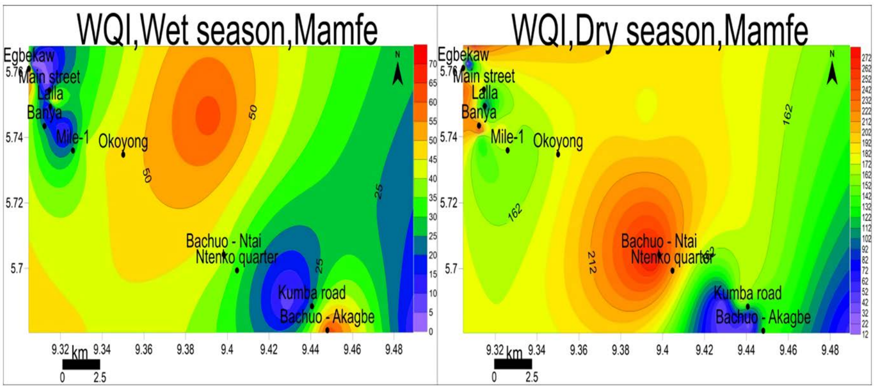

Figure 14. Spatial variation in water quality index (WQI) values of dug well water in Mamfe during wet season and dry seasons. Note increase in WQI values during the dry season and decrease WQI values in the wet season.

Table 11. Hardness classification of groundwater of the study area (Sawyer & McCarty, 1967).

		Wet		Dry	
Hardness (mg/L)	Classification	No	%	No	%
0 - 75	Soft	16	80	0	0
76 - 150	Moderately Hard	2	10	13	65
151 - 300	Hard	2	10	6	30
>300	Very Hard	0	0	1	5

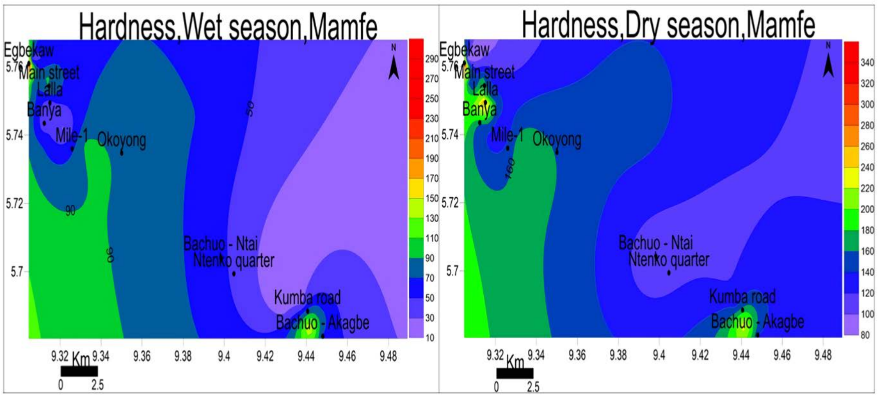

Figure 15. Spatial variation of dug well water total hardness in study area during wet and dry season; 80% of groundwaters in the study area can be classified as soft, 10% fall into the moderately hard category, and just 10% in the wet season is hard water season; 0% of groundwaters in the study area can be classified as soft, 65% fall into the moderately hard category, 30% is hard water and just 5% is very hard in the dry season.

4.4. Water Quality for Irrigational Use

The important parameters which determine the irrigation water quality of the study area are discussed below;

Sodium percent

Sodium percent values range from 3.64 - 16.59 in wet season and 1.22 - 10.97 dry season. Sodium along with carbonate forms alkaline soil; while sodium with chloride forms saline soil; both of these are not suitable for the growth of plants (Pandian & Shankar 2007). The quality classifications of irrigation water based on the values of sodium percentage as proposed by Wilcox (1955) suggest that the groundwater of the study area is good to permissible category both in the wet and dry season **Figure 16** indicating the water is suitable for irrigation (**Figure 17**).

Sodium adsorption ratio

SAR values range from 0.005 - 0.075 in rainy season and 0.01 - 0.14 during dry season. Based on the SAR values, all samples have low sodium hazard and on plotting over the USSL Salinity diagram (USSL 1954) **Figure 18**. All the 20 groundwater samples fall in the S_1-C_{0-3} classes **Table 12** for both rainy season and dry season considered suitable for irrigation (**Figure 19**).

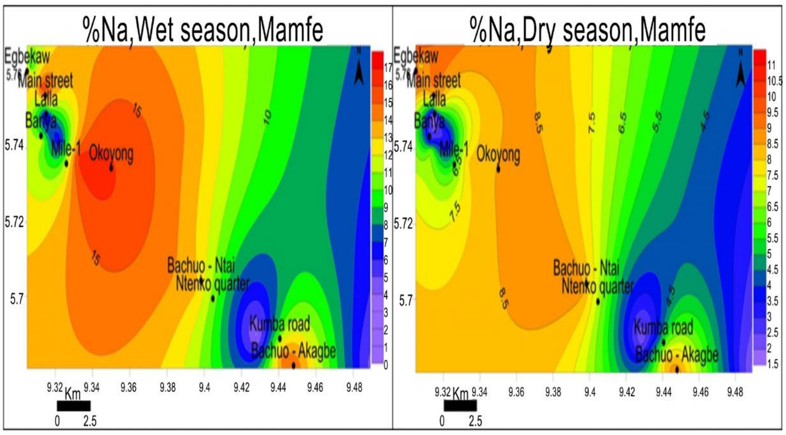

Figure 16. Spatial variation of dug well water sodium percentage %Na in Mamfe during wet season and dry season. Note decrease in %Na values in the dry season while in the wet the %Na values increases.

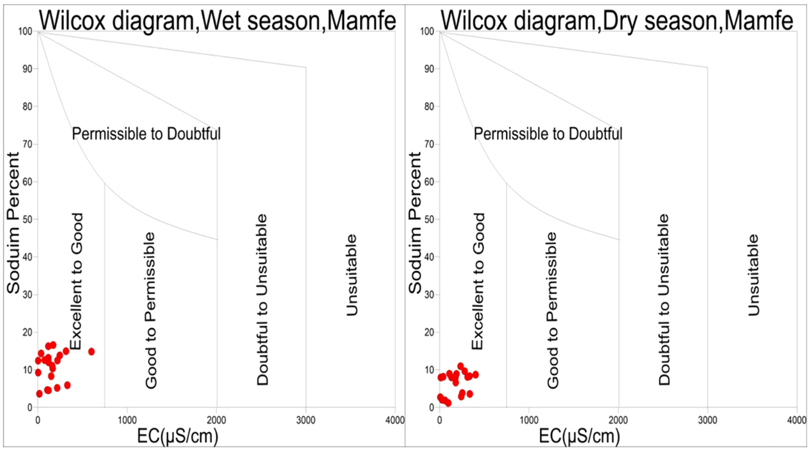

Figure 17. Wilcox diagram showing groundwater suitability for irrigation with all the water samples plotting in excellent to good fields in both wet and dry seasons indicating that the water is suitable for irrigation in both seasons.

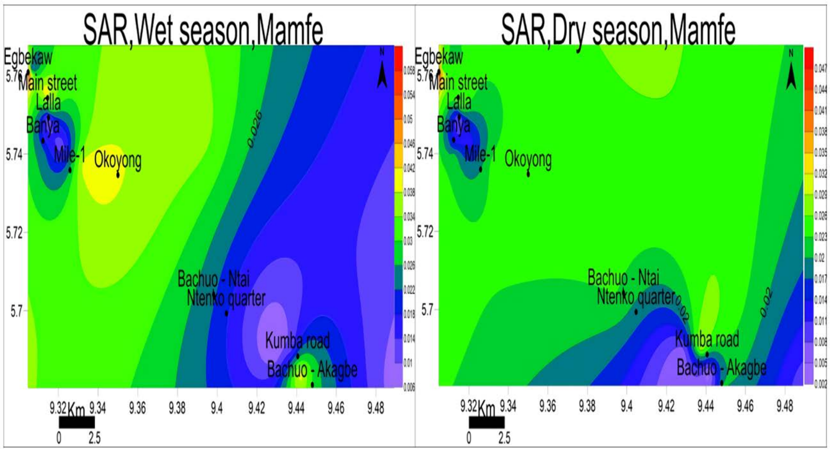

Figure 18. Spatial variation of dug well water Sodium absorption ratio SAR in Mamfe during wet season and dry seasons. Note increase in SAR values during the wet season while in the dry season the SAR values decreases.

Table 12. Water quality classification based on EC of Mamfe groundwater.

Hazard Class	EC (μS/cm)	Quality	Wet		Dry	
			No	%	No	%
C0	0 - 100	Excellent	4	20	6	30
C1	101 - 250	Very Good	13	65	8	40
C2	251 - 750	Good	3	15	6	30

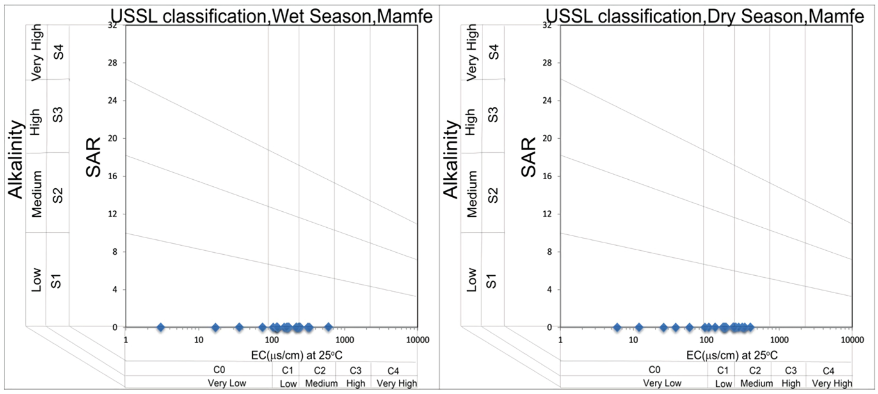

Figure 19. Residual Salinity Hazard classification, Mamfe; The S_1C_0, S_1C_1, and S_1C_2 make up the excellent, very good and good classes respectively. In the Wet season 4 samples 20% plotted in the excellent class, 13 samples 65% plotted in the very good class and 3 samples 30% potted in the good class whereas during the dry season 6 samples 30% plotted in the excellent class and 8 samples 40% plotted in the good field and 6samples 30% potted in the good class.

Permeability index

The PI values range 0.89 - 68.63 in the wet season and 18.75 - 73.35 in the dry season Figure 20. The classification of irrigation waters has been attempted on the basis of permeability Index, as suggested by Doneen (1962). The groundwater samples of the study area fall in class-I and II as per Doneen chart, the groundwater samples of the study area are of good quality for irrigation. The increased percentage of groundwater samples under class–I is due to dilution and subsequently the lower values of permeability index (**Figure 21**).

Magnesium Adsorption Ratio

Magnesium Ratio adsorption values range from 13.3 - 67.88 in the wet season and 27.02 - 77.01 in the dry season Figure 22. Magnesium Ratio adsorption less than 50% it is considered as suitable for irrigation purpose. In the study area, 90% of the samples are suitable for irrigation during the wet season whereas 25% of the samples are suitable for irrigation during the dry season.

Residual Sodium Carbonate

The RSC values −4.59 to −0.33 in the wet season and −5.13 - 0.3 mg/L in the dry season Figure 23. RSC values < 1.25 mg/L are considered as safe for irrigation while those from 1.25 mg/L to 2.5 mg/L are marginally suitable for irrigation. If RSC values are >2.5 the groundwater is unsuitable for irrigation (Eaton, 1950; Richards, 1954). All the RSC values are <1.25 in the study area thus rendering the water suitable for irrigation in both seasons.

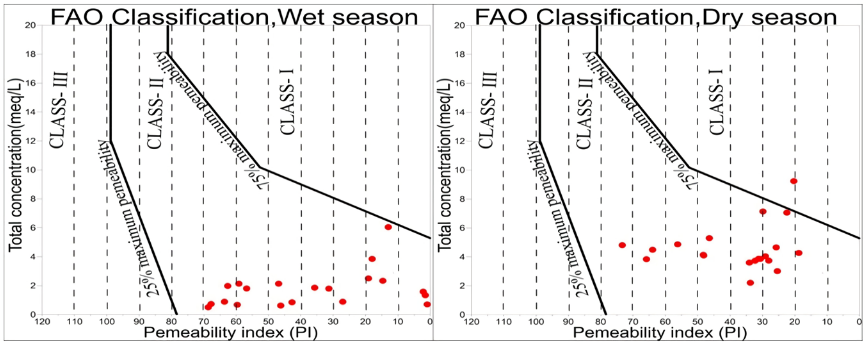

Figure 20. FAO classification of groundwater for irrigation indicating that the water is suitable for irrigation in the dry season as it is observed that the samples plot in class I and class II field indicating that the water is suitable for both seasons.

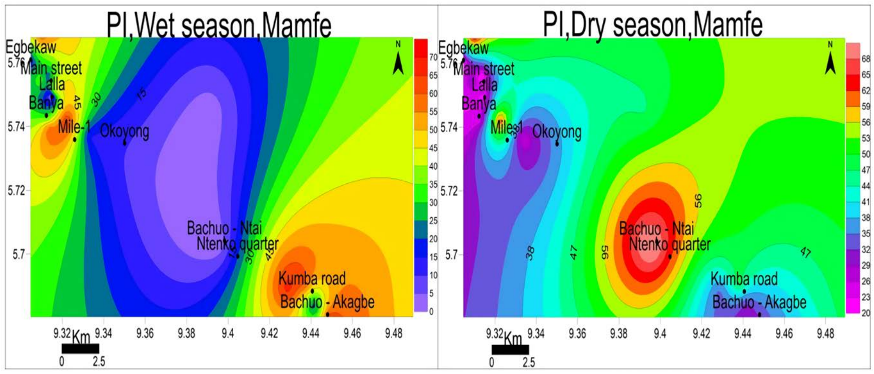

Figure 21. Spatial variation of permeability index in Mamfe; (a) Wet season (b) dry season; Permeability index is highest during the dry season at Bachuo-Akagbe and Ntenko quarter and lowest during the wet season at Bachuo-Ntai and Okoyong.

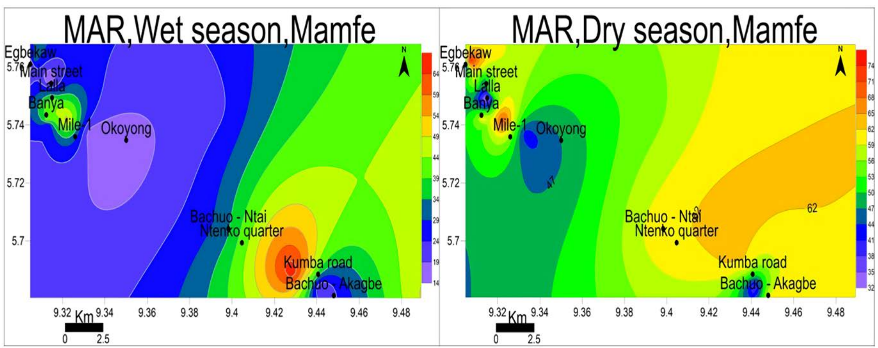

Figure 22. Spatial variation of dug well water Magnesium adsorption ratio in the study area during wet season and dry season. Note decrease in MAR values during the wet season while in the dry seasons the MAR values increases at Egbekaw, Bachuo-Ntai, Kumba road, Mile-1 and Ntenko quarter.

Kelly's Ratio (KR)

KR < 1 is considered suitable for irrigation and KR > 1 is unsuitable. During rainy season, KR values vary between 0.01 - 0.02 and during the dry season the values vary between 0.00 - 0.02 Figure 24. All groundwater samples in Mamfe are suitable for irrigation for both seasons.

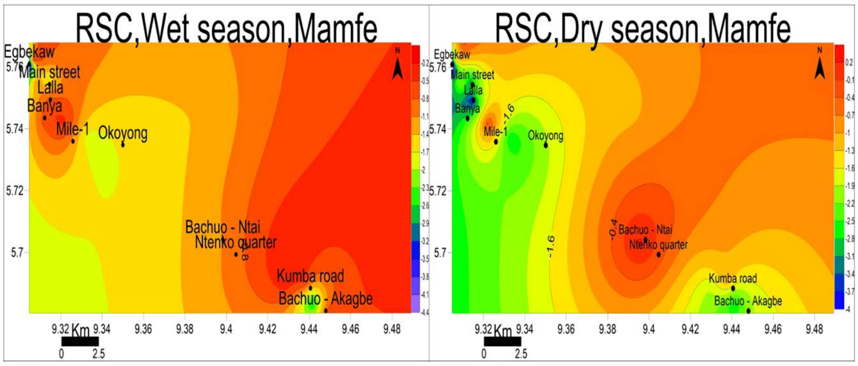

Figure 23. Spatial variation of dug well water residual sodium carbonate in the study area during wet season and dry season. Note decrease in RSC values during the wet season while in the dry seasons the RSC values increases.

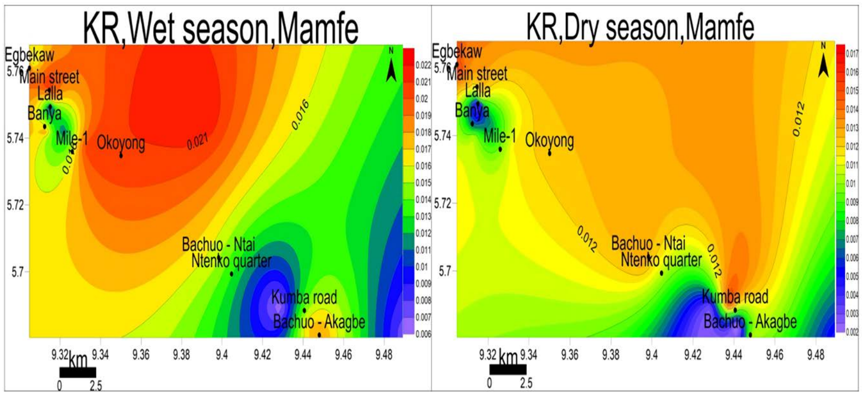

Figure 24. Spatial variation of dug well water Kelly's ratio in the study area during wet season and dry season. Note decrease in KR values during the wet season and dry seasons.

5. Discussion

Temperature, pH, EC and TDS vary with seasons as such the groundwater is in hydraulic connectivity with the atmosphere indicative of a phreatic aquifer. All major ions fell below WHO (2017) acceptable limits for both seasons. From ionic ratios there are additional sources of SO_4, silicate weathering possibly of the sandstones, conglomerates and other rocks in this area. Weathering of Na-feldspar or other Na-silicates and Ca-carbonate dissolution or Ca-silicate weathering. Cation-exchange of the silicate rocks with the groundwater. Ironic ratio values for nitrate and sulfate are very low as such there are no anthropogenic contribution and no oxidation of sulphides. Solutes from weathering reactions and inputs of dissolved species in precipitation get into the aquifer indicating a recharge zone. From Gibbs diagram there is the dominance of rock-weathering and atmospheric precipitation dominance. From Durov diagrams the processes involve are ion exchange, dissolution and mixing. From the Piper's diagrams, the dominant hydrogeochemical facies are Ca-Mg-Cl-SO_4 and Ca-Mg-HCO_3 for both seasons. This facies is characteristic of freshly recharged groundwater that has equilibrated with CO_2 and soluble carbonate minerals under an open system conditions in the vadose zone typical of shallow groundwater flow systems in crystalline phreatic aquifers.

From the above groundwater synthesis, WQI values indicate that 80% of the groundwater in the wet season can be considered suitable for domestic use, 20% are classified to be unfit for consumption whereas in the dry season 20% are suitable for domestic purposes and 80% are unfit for consumption as they belong to poor, very poor and unsuitable classes. Therefore the water in Mamfe is more suitable for domestic purposes in the wet season than in the dry season similar to work done in Kumba, by Akoachere et al. (2018).

The values of SAR, PI, %Na, KR and WQI, RSC and Wilcox diagram indicate that most groundwater in the study area are suitable for irrigation purposes but of MAR with values higher in Mile-1, Kumba road, Egbekaw, and Bachuo-Ntai rendering the water unfit for irrigation.

Since there exist little hydrogeological or hydrological work in this part of the basin, there is little to compare the results here-in, this being the first study that sheds light into these unexplored aspects of the basin.

6. Conclusion

The geogenic input to groundwater is the weathering of rocks possibly of the granites, gneisses, sandstones, conglomerates, shales and other rocks in this area.

Groundwater ionic content was as a result of ion exchange from rock-weathering of the aquiferous formations in the area, dissolution and recharge from precipitation.

Water types are: $CaSO_4$ and $MgHCO_3$ in both seasons. Precipitation recharge, ion-exchange and simple dissolution are the processes determining groundwater character.

Hydrogeochemical facies are Ca-Mg-Cl-SO_4 and Ca-Mg-HCO_3.

All major ions concentrations are below WHO acceptable guidelines for both seasons.

Water quality indices: SAR, PI, %Na, KR and WQI, RSC and Wilcox diagram indicate that water in the study area is irrigation suitability assessment but of MAR were the values that are higher in Mile-1, Kumba road, Egbekaw, and Bachuo-Ntai rendering the water unfit for irrigation.

There is a need for more studies in order to determine the aquifer extent: lateral and vertical, aquifer boundaries, aquifer hydraulic parameters (permeability, transmissivity and storage capacity), the biological and organic water quality, necessary tools for a good management of this important resource in the aquiferous formations in Mamfe. These more detailed studies will throw more light on the groundwater capacity and residence time in the different aquiferous formations in the Mamfe Basin.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

None.

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