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Hydrogeochemical Evaluation of Groundwater Quality in Dukwi Wellfield in Botswana

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There has been a decline in groundwater quality in most wellfields in Botswana. This study evaluated the groundwater quality in Dukwi Wellfield for drinking and irrigation purposes and characterised the dominant hydrochemical processes in the wellfield area during winter and summer seasons. The parameters used to assess the water quality for irrigation purposes were percent sodium (%Na) and Sodium Adsorption Ratio (SAR), while for drinking purposes, Water Quality Index (WQI) was assessed. A piper plot was used for the geochemical characterisation of the groundwater while Gibbs plot was used to determine the dominant processes that govern groundwater chemistry. The results show that water from Borehole BH 2985 is excellent for drinking and irrigation as the average %Na, SAR and WQI values were 14.60%, 0.60 and less than 48.37 respectively. The water from Borehole BH 7521 is unsuitable for drinking and irrigation due to the high %Na values (> 90.47%). Also water from Borehole BH 4649 is of poor quality (WQI values > 162.15). The piper plots revealed that 70% of the samples of water in the area has sodium chloride while the Gibbs plots show that the groundwater is highly influenced by rock weathering and moderately by evaporation precipitation.

Keywords: *Groundwater quality, hydrogeochemical, water quality index, sodium absorption ratio, Gibbs plot*

1. INTRODUCTION

Water is a crucial natural resource which forms the core of the ecological system (Selvam *et al.*, 2013). The demand for groundwater increases with factors such as population increase and the pollution of surface water bodies by anthropogenic activities that include agriculture and industrialisation. The Dukwi Wellfield is the source of supply of water for drinking, domestic, agricultural and industrial purposes in the Dukwi, Nata, Dukwi Refugee Camp and Sowa Town areas of Botswana. The wellfield is experiencing a continuous decline in groundwater levels and deterioration in water quality. In this study, the chemical and physical parameters of the groundwater from the wellfield were exhaustively determined. The chemical parameters included hydrogen ion concentration (pH), Total Dissolved Solids (TDS), Total Hardness (TH), Electrical Conductivity (EC) and all the major cations and anions. The physical parameters were turbidity and temperature. The main objective of this study was to assess the groundwater quality for drinking and agricultural purposes and to characterise the dominant hydrochemical processes in the wellfield area.

2. STUDY AREA

The Dukwi Wellfield Phase II is bound by longitudes 26° 21' E and 26° 29' E and latitudes 20° 31' S and 20° 35' S with a coverage area of approximately 483 km^2 in the Central District of Botswana (see Fig. 1).

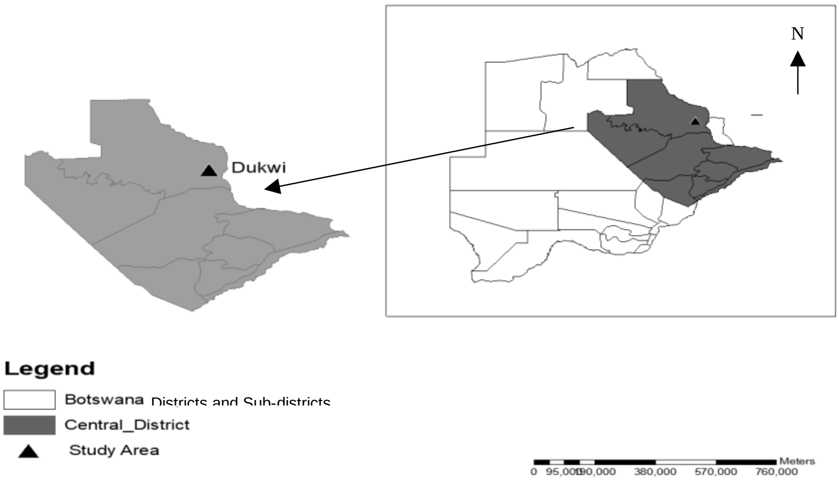

Fig. 1 Location of Study Area in the Central District

It is located about 135 km northwest of Francistown and about 50 km southeast of Nata. The wellfield was identified by the Department of Water Affairs, Botswana in 1995, as one of the most important sources of potable water supply in the area. The wellfield (Fig. 2) consists of four production boreholes (BH 7674; BH 7675; BH 7678 and BH 7687); 32 private boreholes for abstraction of water for livestock and domestic purposes, 2 production boreholes (Z6503 and Z6504) owned by Soda Ash Botswana Mine and 28 monitoring wells for groundwater levels and water quality monitoring (Legadiko, 2015; Geotechnical Consulting Services, 1998).

The lithology of the study area consists of clay and sedimentary rocks such as sandstone, shale and mudstones of the Lower Carboniferous to Upper Jurassic age including igneous rocks such as basalt and dolerite of the Post-Karoo age. The Mea Arkose aquifer is categorised as the main aquifer of the wellfield with an average yield of 22 m^3/hr (Geotechnical Consulting Services, 1998). Other aquifers in the area include the Dwyka, Tlapana and the Ngwasha formations with average yields of 3 m^3/hr, 5 m^3/hr and 11 m^3/hr respectively. The Mea Arkose Aquifer is highly heterogeneous and anisotropic due to records of variable and broad range of transmissivity values of the aquifer that range from 1.5 m^2/day to 1760 m^2/day. The base of the Mea Arkose aquifer is defined by the mudstones of the Dwyka formation and granitic and gneissic basement rocks. The Mea Arkose aquifer is confined towards the north by the overlying Tlapana mudstones over most of the area but unconfined conditions occur where the formation outcrops in the south-eastern part.

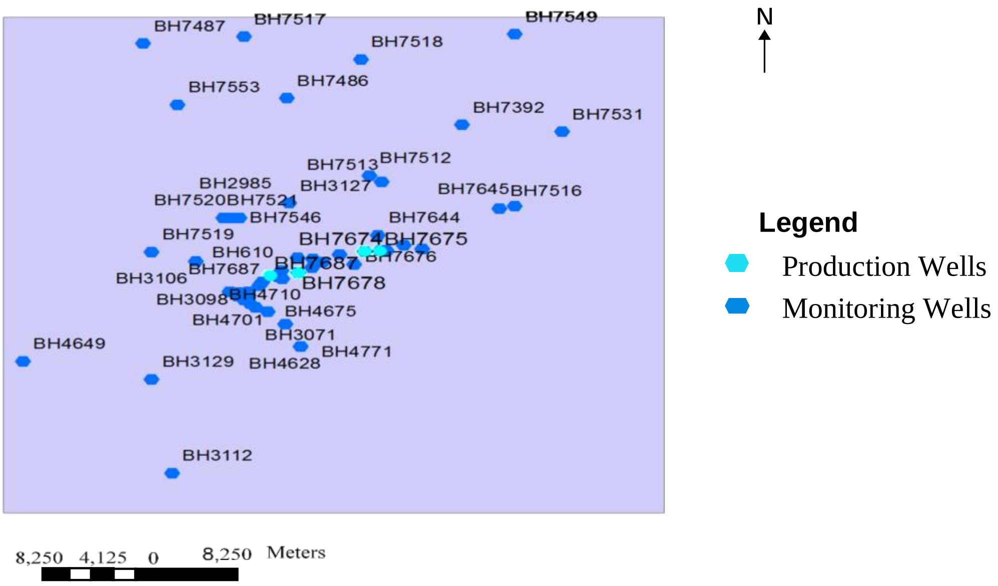

Fig. 2 Monitoring Wells and Production Boreholes in Study Area

The degree of confinement increases towards the north where the overlying silts and mudstones of the Ngwasha formation increase the thickness of the confining layer (Department of Water Affairs, 1976). Temperatures during winter periods (May to August) are normally below 18 ºC with very low humidity and almost no rainfall. Transition from winter to summer occurs around September and October, where the temperature starts to increase up to a maximum of 40 ºC in late October. Rainfalls are unreliable and unevenly distributed, mostly occurring between October and March (Legadiko, 2015).

3. LITERATURE REVIEW

Groundwater is the most important component of fresh water supply in various regions around the world, and it is of vital importance to the water security of many communities (Taylor *et al.*, 2013). In Botswana, 65% of the water supply is obtained from groundwater resources with the remaining 35% from surface water resources (Du Plessis and Rowntree, 2003). There have been studies worldwide to reveal the groundwater quality and its suitability for drinking and irrigation purposes and to identify the main sources of contamination (Adimalla and Venkatayogi, 2017; Houatmia *et al.*, 2016; Li *et al.*, 2016). Houatmia *et al.* (2016) state that rock-water interaction and evaporation are the main factors which control groundwater chemistry in north-eastern Tunisia. Li *et al.* (2016) from a study in the semi-arid region of north-west China, determined that the hydrochemistry of groundwater is mostly influenced by rock-water interaction. Adimalla and Venkatayogi (2017) studied the groundwater quality in the Medak region, South India and found that rock-water interaction and the geogenic sources are the main mechanisms controlling the chemistry of groundwater.

According to Sahu and Sikdar (2008), Water Quality Index (WQI) is one of the most effective tools that can be used to determine the suitability of groundwater for drinking purposes, while the salinity hazard, percent sodium (%Na), sodium adsorption ratio (SAR) and the corrosivity ratio (CR) are also important parameters that can be used to determine the quality of irrigation water (Tripathi *et al.*, 2012). The Gibbs plot is widely used to evaluate the difference between water governed by water-rock interaction (i.e leaching and dissolution), evaporation and precipitation processes (Gibbs, 1970; Mamatha and Rao, 2010), while a piper diagram is commonly used to indicate the hydrochemical composition of water with respect to the presence of ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, Cl- and SO_4^{2-}(Purushotham *et al.*, 2012).

3.1 Water Quality Index (WQI)

WQI is defined as a rating that reveals the effect of individual groundwater parameters such as chloride and sodium on the overall water quality at a given place (Akoteyon *et al*., 2018; Sahu and Sikdar, 2008). Sahu and Sikdar (2008) classified WQI values into five categories as Excellent water (< 50); Good water (50 - 100); Poor water (100 - 200); Very poor water (200 - 300) and Water not suitable for drinking (> 300).

3. 2 Salinity Hazard

Salinity hazard is used to determine the salinity and availability of irrigation water to crops (Shafiullah, 2017). This is determined using Electric conductivity (EC) as it reflects the TDS in groundwater. Based on the salinity hazard, water can be classified as excellent (< 250 µS/cm), good (250 - 750 µS/cm), fair/medium (750 - 2250 µS/cm) and poor/bad (> 2250 µS/cm) (Richard, 1954).

3.3 Percentage Sodium (%Na)

The concentration of sodium is important in the classification of the quality of irrigation water as it commonly reacts with the soil and reduces its permeability (Purushothaman *et al.*, 2012). High sodium content in irrigation water is absorbed by the clay particles of the soil. This results in an exchange of Na^+ in the water and replacing Ca^{2+} and Mg^{2+} from the soil. High percentage of sodium concentration in water used for irrigation may slow down the growth of plants (Todd, 1980). Wilcox (1955) suggested a classification based on %Na as excellent (< 20%), good (20 - 40%), permissible (40 - 60%), doubtful (60 - 80%) and unsuitable (> 80%).

3.4 Sodium Adsorption Ratio

The Sodium Adsorption Ratio (SAR) is used to determine the suitability of groundwater for irrigation as it measures the amount of sodium relative to calcium and magnesium in groundwater (Kaur *et al.*, 2017). Excess sodium in irrigation water reduces the soil permeability and destroys the soil structure (Todd, 2005). This is because the sodium ions in groundwater are absorbed by the clay particles, hence replacing the magnesium and calcium ions (Ali and Ali, 2018).

Using SAR, irrigation water can be classified into four classes as Excellent when SAR < 10; Good (10 - 18); Doubtful (18 - 26) and Unsuitable when SAR > 26 (Richards, 1954). The US Salinity Laboratory's diagram is usually used to evaluate the quality of irrigation water by plotting the SAR values against EC values (Richard, 1954). EC indicates the index salinity hazard while SAR shows the sodium hazards for irrigation water.

3.5 Corrosivity Ratio (CR)

Corrosivity ratio is used to give information about the water supply. Groundwater is considered to be safe for transport in metal pipes if the CR is less than 1, while CR > 1 indicates that the groundwater is corrosive and unsafe to be transported through metal pipes (Tripathi *et al.*, 2012).

4. MATERIALS AND METHODS

The materials and methods used in this work are outlined in the following sections.

4.1 Hydrochemical Analysis

Water samples were collected during winter (in July 2019) and summer (October 2019) from six monitoring wells and the four production boreholes of the wellfield for this study. After sampling from the boreholes, the water samples were stored in appropriate plastic bottles and transported in ice chests to avoid further chemical reactions due to heat during transportation to the laboratories of Department of Water Affairs, Water Utilities Corporation and Botswana International University of Science and Technology (BIUST) Department of Earth and Environment Sciences, all in Botswana, for water chemistry and quality analysis. The water samples submitted to the BIUST laboratories were filtered through a 0.45 µm filter and the concentrations of major cations including magnesium and calcium and major anions such as chloride and sulphate were determined using Thermo Scientific Dionex Chromeleon ion chromatography while the heavy metals such as iron and lead were determined by the Inductively Coupled Plasma Optical Emission Spectroscopy (Thermo Scientific iCAP PRO ICP-OES). The water chemistry analysis for bromine, carbonate, aluminium and manganese from the monitoring wells BH 2985, BH 4649, BH 7516, BH 7521, BH 7639 and BH 7546 was done at the laboratories of the Department of Water Affairs, while the water chemistry analysis for bromine, carbonate, aluminium and manganese from the production boreholes BH 7674, BH 7675, BH 7678 and BH 7687 was done at the Water Utilities Corporation laboratories.

The Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH, temperature and turbidity of the groundwater samples were measured in-situ using a Hanna HI9829 multiparameter waterproof meter. Total Hardness (TH) was calculated using equation 1 (Fournier, 1981):

$$TH = 2.5\ Ca\ (mg/L) + 4.1\ Mg\ (mg/L) \qquad (1)$$

where: Ca = Calcium, Mg = Magnesium

4.2 Water Quality Index (WQI) of the Groundwater

The WQI was used to determine the suitability of the groundwater for human consumption. The analysis was done using 13 parameters namely Total Dissolved Solids (TDS), pH, Total Hardness, Electrical Conductivity (EC), Bicarbonate, Chloride, Sulphate, Nitrate, Calcium, Magnesium, Sodium, Potassium and Iron (Fe). The analysis for WQI was done in four stages as outlined below.

i. Weighting of each of the analysed parameters according to their relative importance in the overall quality of water based on the WHO (2017) guidelines for drinking water quality (Table 1).

Table 1 Relative Weight of Groundwater Parameters

Parameters	WHO Guidelines (2017)	Weight (*wi*)	Relative Weight (*Wi*)
TDS (mg/l)	500	5	0.11
pH	6.5 - 8.5	4	0.09
Total Hardness (mg/l)	200	2	0.04
EC (µS/cm)	500	4	0.09
Bicarbonate (mg/l)	500	3	0.07
Chloride (mg/l)	250	3	0.07
Sulphate (mg/l)	250	4	0.09
Nitrate (mg/l)	50	5	0.11
Calcium (mg/l)	75	2	0.04
Magnesium (mg/l)	30	2	0.04
Sodium (mg/l)	200	4	0.09
Potassium (mg/l)	200	2	0.04
Iron (mg/l)	0.3	4	0.09
-	-	$\sum wi = 44$	$\sum Wi = 0.97$

ii. Determination of the relative weight (Wi) of each parameter using equation 2:

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \quad (2)$$

where: Wi = relative weight, wi = weight of each parameter and n = number of parameters

iii. Assigning the quality rating scale (qi) of each parameter using equation 3:

$$qi = \left(\frac{Ci}{Si}\right) \times 100 \quad (3)$$

where: qi = quality rating, Ci = Concentration of each parameter in (mg/l), Si = WHO (2017) drinking water guideline for each chemical parameter in mg/l.

iv. Determination of WQI based on equations 4 and 5:

$$SIi = Wi \times qi \quad (4)$$

$$\text{WQI} = \sum_{i=1}^{n} SIi \quad (5)$$

where: SIi = Sub-index of the i^{th} parameter, qi = the rating according to the concentration of the i^{th} parameter and n = number of parameters.

4.3 Assessment of Groundwater Quality for Irrigation Purposes

The suitability of groundwater for irrigation purposes was assessed based on the computed values of the parameters in equations 6 to 9:

$$\text{Salinity hazard (Richard, 1954)} = \text{Values of EC } (\mu S/cm) \quad (6)$$

$$\text{Percentage Sodium (\%Na; Wilcox, 1955)} = \left(\frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}}\right) \times 100 \text{ (in meq/l)} \quad (7)$$

$$\text{Sodium Adsorption Ratio (SAR; Richards, 1954)} = [Na^{+}] / \sqrt{\left(\frac{[Ca^{2+}] + [Mg^{2+}]}{2}\right)} \text{ (in meq/l)} \quad (8)$$

$$\text{Corrosivity Ratio (CR; Tripathi et al., 2012)} = \frac{\left[\frac{Cl^{-}}{35.5} + 2\left(\frac{SO_4^{2-}}{96}\right)\right]}{2\left(\frac{HCO_3^{-} + CO_3^{2}}{100}\right)} \text{ (in ppm)} \quad (9)$$

where: Na^{+} = Sodium; K^{+} = Potassium; Ca^{2+} = Calcium; Mg^{2+} = Magnesium; Cl^{-} = Chloride; SO_4^{2-} = Sulphate; CO_3^{2} = Carbonate; HCO_3^{-} = Bicarbonate

5. DATA ANALYSIS

The data analysis is outlined in the following sections.

5.1 Physicochemical Parameters of groundwater

Hydrochemical analysis was carried out on a batch of 10 groundwater samples each collected during the winter and summer seasons. The results are summarised in Tables 2 and 3 respectively.

The dominance of the major cations that were analysed during winter season based on averages was in the order of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ whereas the dominance of the major cations during summer season was found to be $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$. Sodium is the dominant cation and its average concentration was 279 mg/l and 307 mg/l during winter and summer respectively. The average concentration of potassium was relatively low during winter at 8 mg/l while the magnesium concentration was low at 28 mg/l in summer.

During winter, the order of abundance of anions was $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^- > NO_3^-$ while during summer the order of abundance of anions was $Cl^- > HCO_3^- > SO_4^{2-} > CO_3^- > NO_3^-$. Thus chloride was the dominant anion in the groundwater with an average concentration of 249 mg/l during winter and 322 mg/l during summer. Nitrate had the least average concentrations of 2 mg/l in both seasons. The average concentrations of iron were also low ranging from 0.02 mg/l in winter to 0.04 mg/l in summer.

Table 2 Physicochemical characteristics of groundwater samples collected during winter season in July 2019 (Department of Water Affairs, 2019; Water Utilities Corporation, 2019)

Parameter	Borehole Number										Average
	BH 2985	BH 4649	BH 7516	BH 7521	BH 7546	BH 7639	BH 7674	BH 7675	BH 7678	BH 7687	
pH	7.21	7.23	7.52	8.69	7.14	7.12	7.16	7.63	7.23	7.17	7.41
Temp	20.1	19.3	18.5	19.8	20.4	19.7	19.7	19.4	19.7	19.5	19.6
Turbidity	0.14	0.82	0.53	0.68	0.17	0.19	0.57	0.23	0.17	0.24	0.37
EC	544	3096	1532	2408	1532	1562	1530	1463	1516	1549	1673
TDS	96	2024	1119	1588	832	918	1167	951	790	1007	1049
TH	550	903	334	18	407	436	467	378	249	279	402
Fe	0.00	0.01	0.02	0.00	0.02	0.00	0.02	0.06	0.07	0.05	0.02
CO_3^-	57	42	44	0	32	16	32	36	81	44	38
HCO_3^-	115	85	89	1	65	32	64	74	165	89	78
Cl^-	40	480	223	256	254	250	354	197	231	205	249
SO_4^{2-}	4	18	122	1	132	106	115	102	185	107	89

NO_3^-	2	2	1	1	1	1	3	1	3	1	2
Ca^{2+}	92	237	62	22	88	100	114	81	89	41	91
Mg^{2+}	78	76	43	2	45	45	44	43	6	43	42
Na^+	32	388	252	540	225	203	254	388	267	240	279
K^+	17	19	9	2	9	8	6	6	2	5	8

All values are in mg/l, except pH, Temp (ºC), Turbidity (NTU) and EC (µS/cm).
(Fe = Iron; NO_3 = Nitrate)

Table 3 Physicochemical characteristics of groundwater samples collected during summer season in October 2019 (Department of Water Affairs, 2019; Water Utilities Corporation 2019)

Parameter	Borehole Number										Average
	BH 2985	BH 4649	BH 7516	BH 7521	BH 7546	BH 7639	BH 7674	BH 7675	BH 7678	BH 7687	
pH	7.23	7.09	7.69	8.51	7.17	7.14	7.14	7.24	7.64	7.27	7.41
Temp	24.6	26.3	27.3	25.1	24.4	23.5	23.2	25.2	23.5	25.7	24.9
Turbidity	0.20	0.96	0.53	0.51	0.32	0.32	0.62	0.54	0.68	0.58	0.526
EC	622	3097	1578	1542	1421	1540	1457	1432	1518	1553	1576
TDS	195	2026	872	859	841	855	1150	947	1384	1009	1014
TH	558	336	201	130	413	12	463	416	162	462	315
Fe	0.00	0.01	0.02	0.00	0.02	0.10	0.02	0.06	0.08	0.05	0.04
CO_3^-	58	44	46	1	35	18	32	40	82	46	40
HCO_3^-	119	89	93	1	72	37	66	82	167	93	82
Cl^-	50	929	225	187	256	232	367	338	270	370	322
SO_4^{2-}	5	89	93	1	72	37	66	82	167	93	70
NO_3^-	3	0	1	0	1	2	3	3	3	3	2
Ca^{2+}	94	113	5	49	89	4	112	94	52	113	72
Mg^{2+}	79	13	5	2	46	1	44	44	8	44	28
Na^+	33	752	256	562	228	238	238	256	272	238	307
K^+	21	17	16	15	9	45	6	256	2	5	39

All values are in mg/l, except pH, Temp (ºC), Turbidity (NTU) and EC (µS/cm).

5.2 Water Quality Index

The assessment of groundwater quality in the study area for drinking purposes was done using the Water Quality Index (WQI) values. The WQI values obtained from the groundwater samples are summarised in Table 4.

Table 4 Water Quality Indices of Groundwater Samples of Winter and Summer Seasons

Borehole No.	WQI (Winter)	Classification	WQI (Summer)	Classification
BH 2985	48.37	Excellent	47.68	Excellent
BH 4649	162.15	Poor	167.93	Poor
BH 7516	90.83	Good	90.49	Good
BH 7521	106.74	Poor	57.12	Good
BH 7546	86.82	Good	85.26	Good
BH 7639	86.96	Good	71.12	Good
BH 7674	100.31	Poor	98.71	Good
BH 7675	80.70	Good	93.11	Good
BH 7678	77.34	Good	93.17	Good
BH 7687	85.02	Good	98.21	Good

From Table 4, the WQI values were within a broad range (48.37 - 162.15) during winter and between 47.68 and 167.93 during summer. In both seasons, water samples from Borehole BH 2985 were of excellent quality with low values ranging from 47.68 to 48.37. During the winter season, water samples from Boreholes BH 4649, BH 7521 and BH 7674 were of poor quality as their values were high (162.15, 106.74 and 100.31 respectively). During the summer, the water quality in all the boreholes except for Borehole BH 4649 was suitable for drinking purposes as the WQI values ranged from 47.68 to 98.71.

5.3 Suitability of groundwater for irrigation purposes

Table 5 summarises the values of SAR, %Na and CR of the groundwater quality for irrigation purposes during the winter and summer seasons.

Table 5 Suitability of Groundwater Samples in the Study Area during Winter and Summer Seasons for Irrigation Purposes

Borehole Number	Winter Season			Summer Season		
	SAR	%Na	CR	SAR	%Na	CR
BH 2985	0.59	14.22	1.03	0.61	14.98	1.33
BH 4649	5.61	48.94	8.85	17.84	83.16	18.70
BH 7516	6.01	63.07	5.89	7.92	74.48	6.24
BH 7521	29.52	94.90	0.00	21.37	90.47	0.00
BH 7546	4.88	55.38	4.81	4.88	55.19	5.33
BH 7639	4.23	50.92	2.24	27.65	97.62	2.40
BH 7674	5.11	54.57	6.00	4.82	53.24	6.21
BH 7675	5.02	56.69	4.19	5.46	57.50	7.19
BH 7678	7.38	70.22	12.73	9.26	78.47	12.72
BH 7687	6.24	65.40	5.34	4.81	53.05	9.04

The results in Table 5 show that during the winter season, water samples from Borehole BH 7521 had the highest %Na content of 94.90% as compared to the other boreholes. Hence, it is not suitable for irrigation purposes. This is supported by the values of SAR which indicate that water samples from Borehole BH 7521 had the highest value (29.52) making it unsuitable for irrigation. It is also collaborated by the high EC value of 2408 µS/cm for Borehole BH 7521 during winter season (see Table 2) that water samples from Borehole BH 7521 are poor in quality. Also from Table 5, during the summer season, water samples from Borehole BH 7639 had the highest %Na and SAR values of 97.62% and 27.65 respectively making it unsuitable for irrigation purposes. Also, the high %Na values (> 90.47%) of water samples from Borehole BH 7521 show that the water is unsuitable for irrigation in both seasons.

Water samples from Borehole BH 2985 had the least %Na values of 14.22% and 14.98% during winter and summer seasons respectively (see Table 5). Thus, the water quality is excellent in both seasons. This is supported by the low SAR values of 0.59 and 0.61 of the water samples from Borehole BH 2985 during winter and summer respectively.

The CR values of most water samples during both seasons were more than 1 indicating that the water is unsafe to be transported through metal pipes. However, Borehole BH 7521 has CR values of 0.00 in both seasons, indicating that the groundwater can be safely transported through metal pipes for irrigation.

5.3 The US Salinity Diagram

To determine the salinity of the groundwater of the wellfield, plots of EC versus the SAR values was done using the US salinity diagram (Fig. 3) for both the winter and summer seasons.

From Fig. 3, during winter season 10% of the water samples fall in the C2-S1 class. This indicates that the water is good for irrigation purposes due to the low sodium and medium salinity hazard levels. The C3-S1 class which indicates low sodium and high salinity hazards is occupied by 40% of the water samples while the C3-S2 class, which represents water of medium sodium and high salinity hazards has 40% of the samples. Ten percent of the water samples fall into the C3-S4 class which shows water of very high sodium and high salinity hazards. During summer, the plots indicate that 10% of the water samples fall in C2-S1 class while 40% are of C3-S1 class. Twenty percent of the water samples fall in the C3-S2 class while 30% of the water samples are in the C3-S4 class. This shows that 90% of the water samples have high salinity in both seasons which make them unsuitable for irrigation purposes.

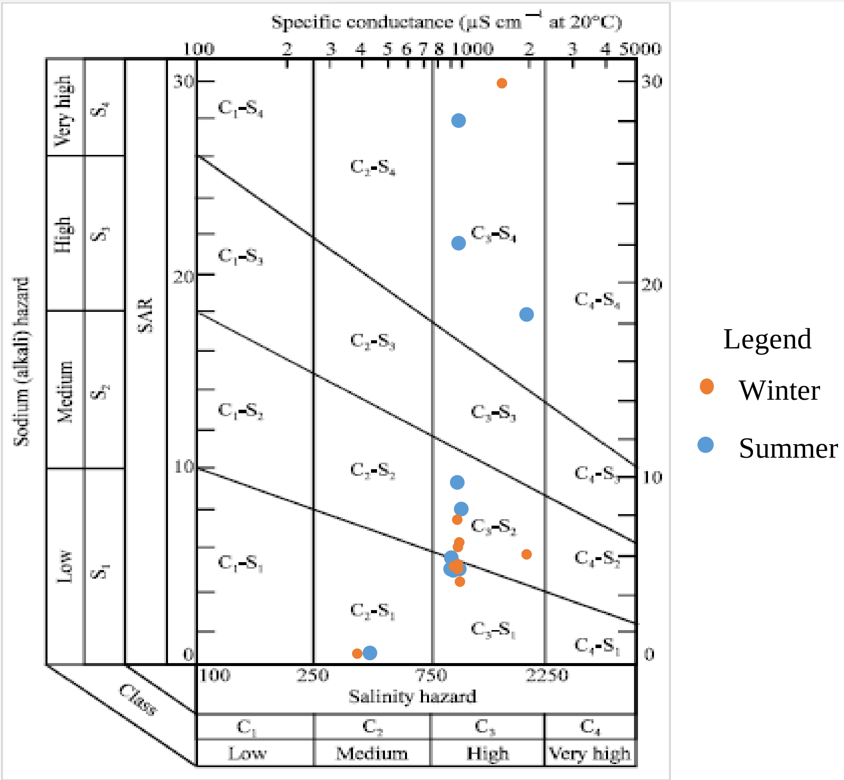

Fig. 3 US Salinity Laboratory Diagram of Water Samples Collected During the Winter and Summer Seasons

5.4 Hydrogeochemical Facies

Piper plots of 10 water samples each taken during both the winter season (Fig. 4) and summer season (Fig. 5) from the study area were done for geochemical characterisation of groundwater at the wellfield. Analysis of the piper diagrams indicate that during both seasons, the alkali metals ($Na^+ + K^+$) are the dominant cations at the study area, as they are contained in 80% and 70% of the water samples during winter and summer seasons respectively. The diagram for the winter season (Fig. 4), reveals that there is no dominant anion type, while during summer (Fig. 5), the strong acids (SO_4+ Cl) are dominant anions (60%). The main water type during both seasons has sodium chloride in 70% of the water samples.

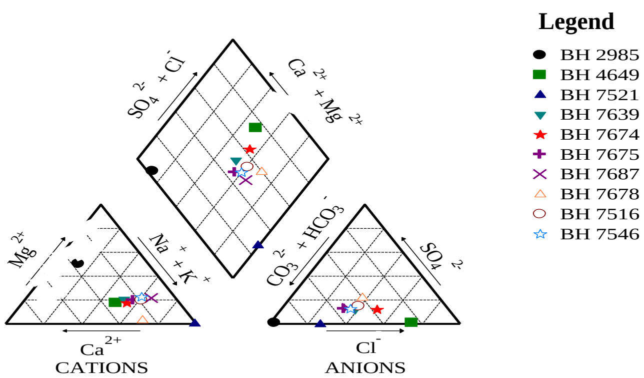

Fig. 4 Piper Plot for the Study Area (July 2019)

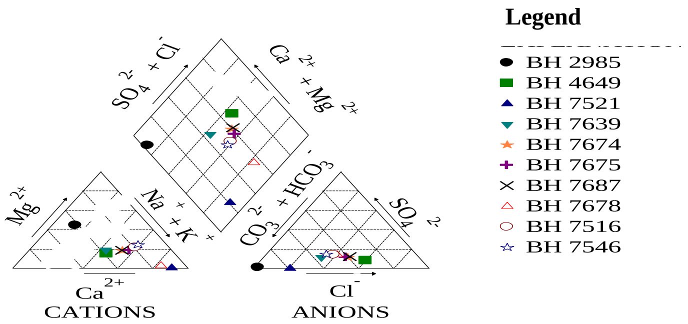

Fig. 5 Piper Plot for the Study Area (October 2019)

5.5 Gibbs Plot

To determine the dominant hydrochemical processes that control the groundwater chemistry with respect to cations and anions at the study area, Gibbs plots were done on the water samples collected during winter (Figs. 6a and 6b) and summer seasons (Figs. 7a and 7b). The Gibbs plot which is categorised into three zones namely precipitation-dominance, rock-dominance and evaporation-dominance, represents the ratio of the dominant anions $[Na^+ + K^+)/(Na^+ + K^+ + Ca^{2+})]$ and cations $[Cl^-/(Cl^- + HCO_3^-)]$ plotted against the TDS values. Figs. 6a and 6b show that during winter season, 60% of the water samples plot in the rock dominance field while 40% of the water samples plot in the evaporation dominance field and outside its margin. Figs. 7a and 7b show that during summer season, 70% of the water samples plot in the rock dominance field while 30% plot in the evaporation dominance field.

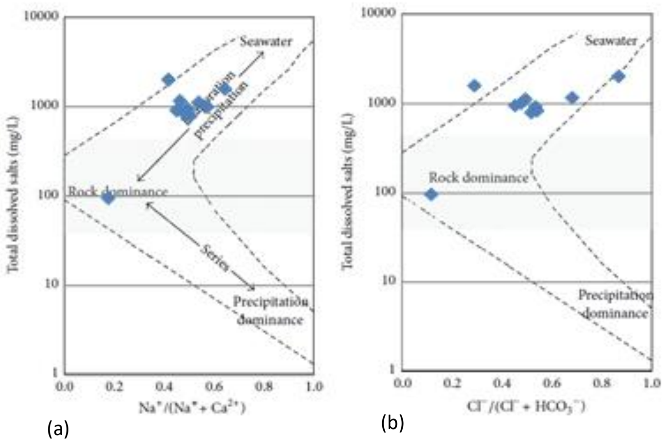

Fig. 6 Gibbs Diagram for Processes that Control Groundwater Chemistry during the Winter Season

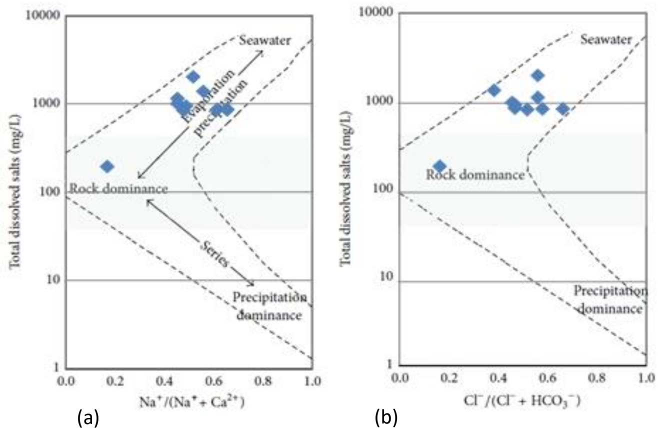

Fig. 7 Gibbs Diagram for Processes that Control Groundwater Chemistry during the Summer Season

6. DISCUSSION OF RESULTS

Parameters such as water quality index, suitability of groundwater for irrigation, hydrogeochemical facies and Gibbs plot are discussed in the following sections.

6.1 Water Quality Index

The values of WQI obtained in this study show that for both seasons, water samples from Borehole BH 2985 are of excellent quality (47.68 - 48.37). This is likely due to the low TDS concentrations of 96 mg/l (see Table 2) and 195 mg/l (Table 3) which occurred during the winter and summer seasons respectively as compared to the other boreholes. TDS of water is considered to be the most important parameter for drinking water quality analysis as it is directly linked to other parameters such as EC and turbidity. For both seasons, the WQI values of Borehole BH 4649 (see Table 4) show that it has poor water quality (162.15 - 167.93). This may be due to the high concentrations of parameters such as TDS (2024 - 2026 mg/l) and chloride (480 - 929 mg/l) as compared to the other boreholes.

6.2 Suitability of Groundwater for Irrigation

In both seasons, water samples from Borehole BH 7521 are unsuitable for irrigation purposes due to the high %Na values that range from 90.47% to 94.90%. The SAR values of the water samples from Borehole BH 7521 were also high (i.e., 29.52) making it unsuitable for irrigation. This is likely influenced by the high sodium concentrations of 540 mg/l and 562 mg/l which occurred in July and October 2019 respectively (see Tables 2 and 3). These concentrations are higher than the calcium concentrations that range from 22 to 49 mg/l and magnesium concentrations of 2 mg/l. The very high sodium concentrations compared to those of calcium and magnesium found in the water samples could result in poor soil permeability and poor plant growth if this type of water is used continuously for irrigation.

In both seasons, water from Borehole BH 2985 fell within the excellent class as it had the least %Na values that ranged from 14.22 - 14.98% (Table 5). The SAR values for Borehole BH 2985 were also low (0.59 - 0.61) mainly due to the low sodium concentrations of 32 - 33 mg/l as compared to the calcium concentrations of 92 - 94 mg/l and magnesium concentrations that ranged from 78 to 79 mg/l. When the sodium concentration is lower than those of calcium and magnesium in the water samples, it influences highly permeable soils making them suitable for plant growth.

6.3 Hydrogeochemical Facies

The piper plots for both seasons (Figs. 4 and 5) indicate that the major water type in the area has sodium chloride in 70% of the water samples. The sodium ions may be influenced by the dissolution of clay and sedimentary rocks such as shales which consist of sodium-bearing minerals such as montmorillonite while the chloride ions may be due to the dissolution of igneous rocks such as basalt and dolerite which consist of biotite and hornblende minerals. The hydroxyl ions in the biotite and hornblende are likely to be substituted by the chloride ions from the rainwater that recharges the Mea Arkose Aquifer. The chloride ions in rainwater are likely due to the movement of chloride ions from the soil which usually has sodium chloride by the air masses which carry these ions from the soil to the atmosphere.

6.4 Gibbs Plot

During the winter season, the Gibbs diagrams (Figs. 6a and 6b) show that 60% of the samples plot in the weathering dominance field while 40% of the water samples plot in the evaporation dominance field and outside its margin. During the summer season, the Gibbs diagrams (Figs. 7a and 7b) show that 70% of the water samples plot in the weathering dominance field while 30% plot in the evaporation dominance field. This suggests that the chemistry of groundwater at the study area is mainly controlled by the weathering of the rocks, and to some extent, evaporation is the dominant factor that contributes to the high salinity and therefore poor groundwater quality. This is expected as evaporation greatly increases the concentration of ions that result from chemical weathering of rocks leading to increased salinity of groundwater.

7. CONCLUSIONS

From the foregoing analysis, it is concluded that:

a) Water samples from Borehole BH 2985 are of excellent quality and are suitable for both drinking and irrigation purposes. This is due to the low WQI values that range from 47.68 - 48.37, %Na values of 14.22% to 14.98% and SAR values of 0.59 to 0.61.
b) In both seasons, the water from Borehole BH 7521 is unsuitable for irrigation purposes due to the high Na ion values that range from 90.47% to 94.90%.
c) Water from Borehole BH 4649 is unsuitable for drinking purposes in both seasons due to the high WQI values that range from 162.15 to 167.93.
d) The main water type has sodium chloride in 70% of the samples in both seasons.
e) The chemistry of groundwater is highly influenced by rock weathering and moderately by evaporation precipitation.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.