Hydrogeochemical Characterisation and Groundwater Quality appraisal of the shallow underground waters of Southern Iullemmeden (Sokoto) Basin, North-western, Nigeria

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Abstract

The sediments of Sokoto basin were deposited during the continental Mesozoic and Tertiary phases, with an intervening marine Maastrichtian to Palaeocene phase. The considerable lithological variations and occurrence of industrial minerals in the basin necessitates the quest to characterise and determine the quality of the groundwater in some of the formations to ascertain the impact of these variations on the groundwater character and chemistry. Fifty-three paired groundwater samples were collected from boreholes and hand dug wells sunk into the Gundumi, Kalambaina, Rima and the Gwandu formations of the basin. for anion and cation analysis. The TDS, pH, temperatures, and electrical conductivity (EC) were determined on the field using a portable digital meter. The anions were determined by titrimetric methods while the cations were determined using the UV spectroscopy method. The results show that for the Gundumi samples, cationic concentration is in the order Na>Ca>K>Mg ,while the anion concentration is in the order HCO_3> SO_3>Cl> NO_3; that of Rima formation showed the order of cationic abundance to be Mg>Ca>Na>K while that of the anion is in the order HCO_3> SO_4 >Cl> NO_3; the Kalambaina formation samples an order of cationic abundance to be Ca>Na>K>Mg while that of the anions is in the order NO_3>HCO_3>Cl>SO_4 and the samples from Gwandu formation. The order of cationic abundance for the Gwandu formation water samples is Mg>Ca>Na>K while that of the anions is in the order HCO_3> SO_4> Cl >NO_3. Further geochemical characterization of the water samples showed that water samples from Kalambaina formation are predominantly Ca-HCO_3 water type; that of Gwandu are a combination of Na-HCO_3 and Ca-HCO_3 water types, the Gundumi samples are predominantly Na-HCO_3 and Na-Cl water types and the samples from Rima formation are predominantly Ca-HCO_3 water type. The plots of the Log of TDS versus the ratio of Na/ (Ca+Na) for the water samples also show that the groundwater samples from all the formations had been influenced more by the by the action of weathering than dilution and evaporation, a strong indication that the groundwater samples had interacted effectively with the lithologic units that constituted the aquifer materials. The calculated Ca/Mg ratio of water samples obtained from the Kalambaina formation gave values greater than four (>4) signifying a Limestone dominated aquifer. The various results indicate that the groundwater character and quality from within the basin are determined by rock-water interactions, agricultural as well as other human activities. The rock-water interactions had resulted in the dissolution and leaching of the aquifer materials by the groundwater system while the presence of abundant nitrate in some of the groundwater samples is an indication of the leaching of fertilizers into the ground water system especially in the very porous and permeable formations.

Key words: Groundwater, Sokoto basin, lithologic, Geochemical, Characterisation

INTRODUCTION

The need to ascertain groundwater quality as well as determination of influence of aquifer materials on the chemical composition of groundwater has assumed a global status. This is more so as various cases of ailments had been linked to the type and quality of water consumed by human and livestock. Issues of groundwater chemical characterisation have assumed greater importance in areas where evidence of considerable mineralisation has been reported in the geologic formations that constitute the aquifer materials of the area. It therefore becomes important to ascertain the role and chemical contribution of such mineralization to the chemical character and ultimately the quality of the groundwater within such geologic materials. This is very important as bedrock chemistry had been demonstrated to have considerable impact on the chemical character of groundwater (Price and Velbel, 2006, Tijani et al., 2006, Taylor and Eggleton, 2001, Tijani and Nton 2009, Abimbola et al.2001, Tijani et al.2005, and Olatunji et al. 2001).

The Sokoto basin in north-western Nigeria has been reported to host substantial industrial minerals which include limestone, marl, gypsum, lignite, and phosphates. The Sokoto basin is predominantly made up of a gentle undulating plain with an average elevation varying from 250m to 400m above sea level (Kogbe, 1979). The sediments of the Sokoto basin were deposited during the continental Mesozoic and Tertiary phases, with an intervening marine Maastrichtian to Paleocene phase.

Overlying the Pre-Cambrian basement unconformably is the Illo and Gundumi Formations, made up of grits and clays. These are overlain unconformably by the Maastrichtian Rima group, consisting of mudstones and friable sandstones also known as the Taloka and Wurno Formations. They are however separated by the fossiliferous shaly Dukamaje Formation. The Dange and Gamba (Paleocene) shales are separated by the Calcareous Kalambaina Formation. The Gwandu Formation, which is Tertiary in age and continental in nature, brings up the rear. Several of the formations host varied secondary mineralization. These include the shaly Maastrichtian Dukamaje (Rima Group), containing lignite and gypsum interbedded with limestone and mudstone. The Palaeocene Dange Formation made up of grey shales interbedded with marls is associated with numerous disseminated fibrous gypsum and phosphate nodules. The Kalambaina Formation is made up of marls and hard crystalline limestone while the Gamba Formation which is also Palaeocene consist grey laminated shale with irregularly shaped phosphate nodules (Figure 1 and Table 1).

Groundwater in the Sokoto basin is abstracted through several hand dug wells and drilled boreholes through most of the formations constituting the basin. The considerable deposit of various industrial minerals found in the basin necessitates the quest to characterise and determine the quality of the groundwater in some of the formations to ascertain whatever impact or otherwise this mineralisation has on the groundwater character and chemistry. To achieve this, groundwater samples from boreholes and hand dug wells sunk into the Gundumi, Kalambaina, Rima and the Gwandu formations, within the basin, were sampled and analysed for their cationic and anionic constituents.

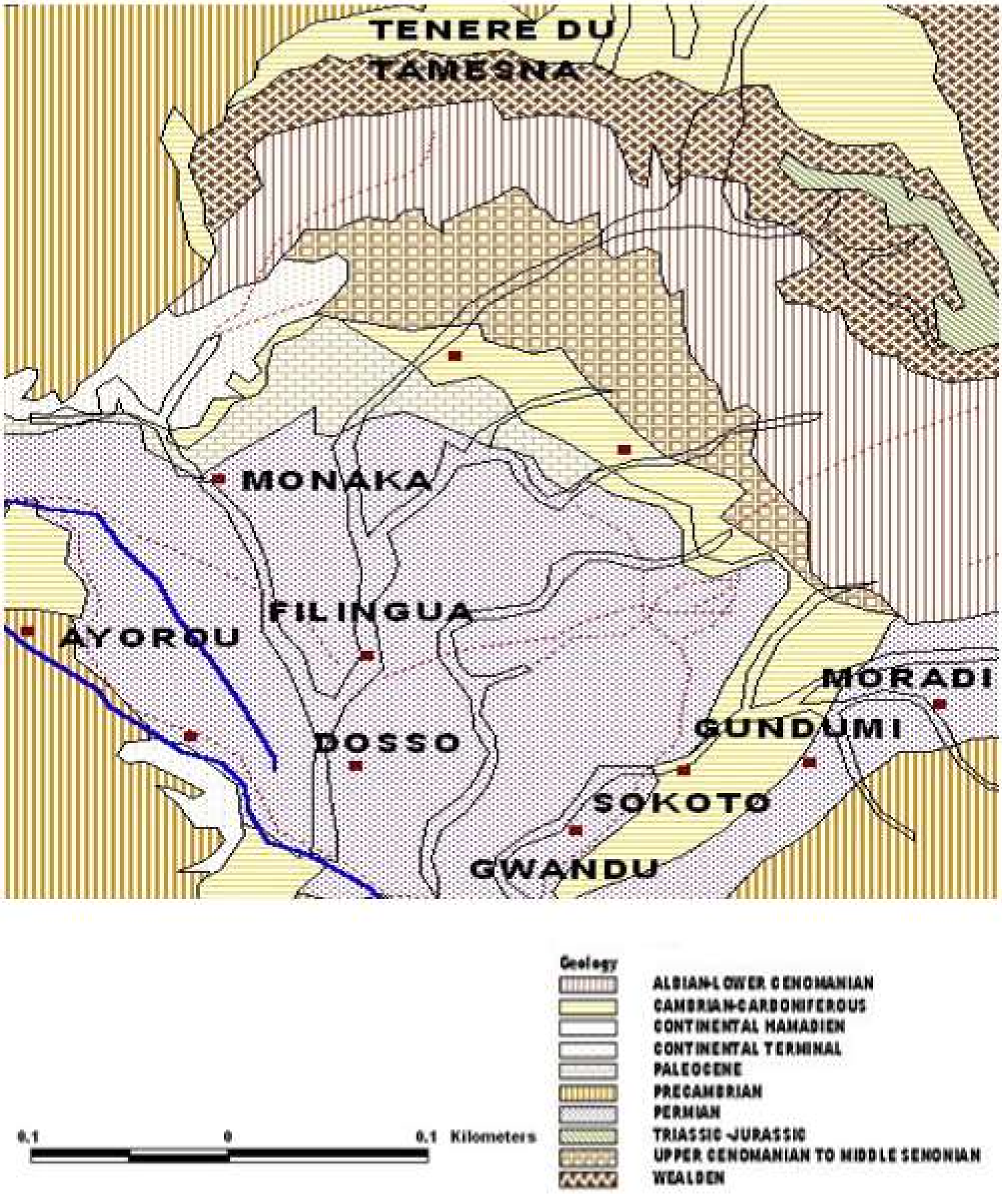


Figure 1: Geological map of Iullemmeden basin (modified from Gerigert and Pouquet, 1965)

Lithologic units of the sampled formations

Gundumi Formation

The Gundumi formation is a fluvio-lacustrine deposit which lie unconformably on the basement rocks. The formation is made up of feldspathic clayey grits, clays and pebbly sand that are conglomeratic in some places with ferruginized sandstone at the top (Kogbe, 1982). The formation had been described as made up of false bedded, massive, feldspathic, clayey grits, clays and pebbly sand that are conglomeratic in some places (Kogbe, 1982). The sands are poorly sorted, semi-consolidated, fine to coarse in texture and range from reddish-brown through pink to yellowish-brown in colour (Fig 2). The formation is over 250m thick.

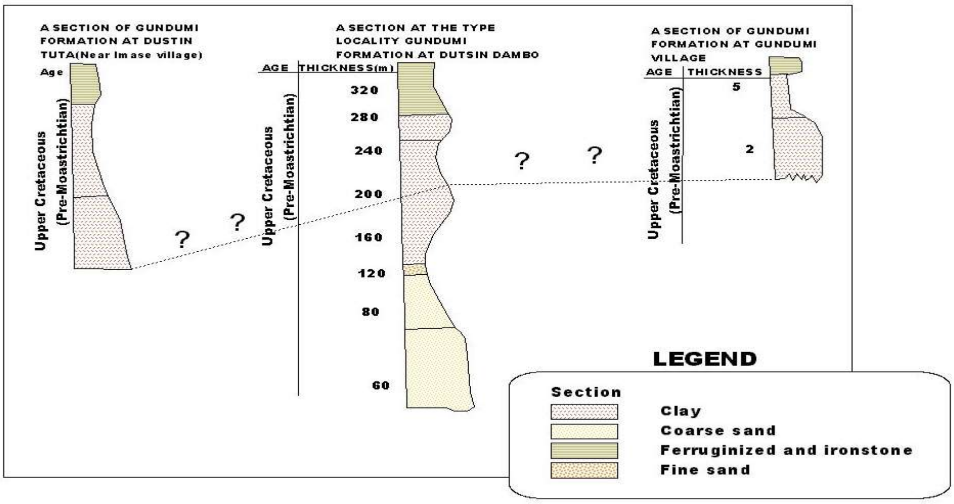


Figure 2: Type sections of the Gundumi Formation

Rima Formation

The Rima formation is made up of siltstones that are whitish-grey and reddish-brown in colour, thin beds of carbonaceous shale with black lignitic siltstone (Kogbe, 1982).

Kalambaina Formation

The Kalambaina formation contains marine white, clayey limestone, and shale (Fig 3). The thickness of the formation is variable with a thickness of about 20m encountered in drilled boreholes (Kogbe, 1982). The Kalambaina formation is overlain by the Gamba formation which is in turn succeeded by the oolitic ironstone unit. The Gamba formation may sometimes contain phosphatic nodules.

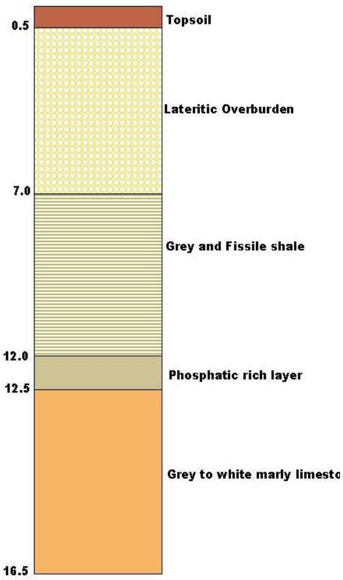


Figure 3: Exposed Lithology of the Kalambaina Formation at the CCNN Quarry

Gwandu Formation

The Gwandu formation is made up of thick series of predominantly red and mottled clays with sandstone intercalations. The formation consists of massive white clays interbedded with coarse and medium grained red sandstones and mudstones with occasional peat bands.

MATERIAL AND METHODS

Seven water samples were collected from the Kalambaina formation, fourteen samples from the Gundumi formation, eleven samples from the Rima group and nineteen samples from the Gwandu formation making a total of fifty-three (53) water samples that were collected for analysis.

The samples were collected in pairs; a set was collected in 500ml plastic containers for anion determination while the second set was collected in 250ml plastic containers. The set for the cations were acidified using two drops of concentrated HNO_3 to prevent the cations from adhering to the surface of the plastic container. All physical parameters of the groundwater samples were determined on the field using a digital meter equipped with probes that can measure, pH, TDS, temperatures, and electrical conductivity (EC).

The water samples were then stored in ice boxes for transmission to the laboratory for analysis. In the Laboratory, the samples were stored in the refrigerator during the period of the analysis. The samples were subsequently analysed for the anions and cations. The anions were determined by titrimetric methods while the cations were determined using the UV spectroscopy method.

The results obtained were then subsequently evaluated hydrogeochemically. The usability of the groundwater samples for domestic and agricultural purposes was ascertained by comparing the water chemistry with drinking water standards from the World Health Organisation (WHO) and the United States Department of Agriculture Standard for irrigation purposes.

RESULTS AND DISCUSSIONS

Groundwater Chemistry

Gundumi Formation

The result for the groundwater samples analysis from the Gundumi formation revealed that the concentration of SiO_2 ranges from 12.0-21.0 mg/l with a mean of 14.5mg/l, Fe ranges from Below Detection Limit (BDL)-15.0mg/l with a mean of 6.2mg/l, Mn ranges from Bdl-1.8mg/l with a mean of 0.4mg/l, Ca ranges from 1.0-292.0mg/l with a mean of 29.3mg/l, Mg ranges from 0.2-21.0mg/l with a mean of 3.3 mg/l, Na ranges from 1.2-800.0mg/l with a mean of 90.9mg/l, K ranges from 1.1-27.0mg/l with a mean of 8.1mg/l, HCO_3 ranges from Bdl-175.0mg/l with a mean of 70.9mg/l, SO_3 ranges from 0.6-116.0mg/l with a mean of 36.2mg/l, Cl ranges from 1.0-1640.0mg/l with a mean of 137.7mg/l, Fl ranges from Bdl-0.8mg/l with a mean of 0.3mg/l, NO_3 ranges from Bdl-0.6mg/l with a mean of 0.2mg/l, B ranges from Bdl-0.9mg/l with a mean of 0.2mg/l respectively. The physical parameters showed that TDS ranges from 28.0-2980.0mg/l with a mean of 357.4mg/l, Hardness ranges from Bdl-705.0mg/l with a mean 0f 57.2mg/l, Electrical Conductivity ranges from 24.0-4900.0µS/cm, the pH ranges from 3.7-8.7 with a mean of 7.1. Calculated sodium percentage ranges from 13.0-96.0% with a mean of 44.9% while the calculated Sodium Absorption Ratio (SAR) ranges from 0.2-32.0 with a mean of 4.7(Tables 1 and 5). The cationic concentration of the Gundumi water samples follows the order Na>Ca>K>Mg while the anion concentration is in the order HCO_3> SO_3>Cl> NO_3 (Figs 4a and 4b)

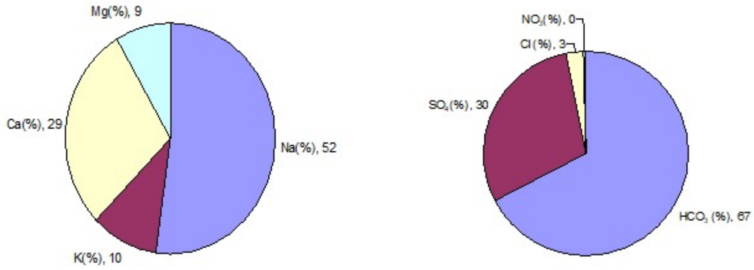


Figure 4: Percentage cationic and anionic composition of Gundumi water samples

Rima Formation

Results from the analysis of samples from Rima formation showed the concentration of SiO_2 to range from 3.6-19.0 mg/l with a mean of 15.0mg/l, Fe ranges from Below Detection Limit (BDL)-14.0mg/l with a mean of 3.2mg/l, Mn ranges from Bdl-0.8mg/l with a mean of 0.2mg/l, Ca ranges from 4.0-137.0mg/l with a mean of 34.5mg/l, Mg ranges from 0.5-53.0mg/l with a mean of 9.0 mg/l, Na ranges from 1.7-157.0mg/l with a mean of 25.3mg/l, K ranges from 1.6-23.0 mg/l with a mean of 7.8 mg/l, HCO_3 ranges from 8.0-291.0 mg/l with a mean of 97.9 mg/l, SO_3 ranges from 9.4-588.0 mg/l with a mean of 89.0 mg/l, Cl ranges from Bdl-1640.0mg/l with a mean of 8.6 mg/l, Fl ranges from Bdl-1.4 mg/l with a mean of 0.4 mg/l, NO_3 ranges from Bdl-29.0 mg/l with a mean of 6.5 mg/l, B ranges from Bdl-0.5mg/l with a mean of 0.1 mg/l respectively. The physical parameters showed that TDS ranges from 44.0-1090.0mg/l with a mean of 247.7 mg/l, Hardness ranges from 12.0-559.0mg/l with a mean of 123.0 mg/l, Electrical Conductivity ranges from 52.0-1300.2 µS/cm, the pH ranges from 6.0-8.1 with a mean of 7.3. Calculated sodium percentage ranges from 8.0-83.0% with a mean of 20.6% while the calculated Sodium Absorption Ratio (SAR) ranges from 0.1-7.5 with a mean of 1.0 (Tables 2 & 5). The order of cationic abundance for the Rima water samples is Mg>Ca>Na>K while that of the anion is in the order HCO_3> SO_4 >Cl> NO_3 (Figs 5a & 5b)

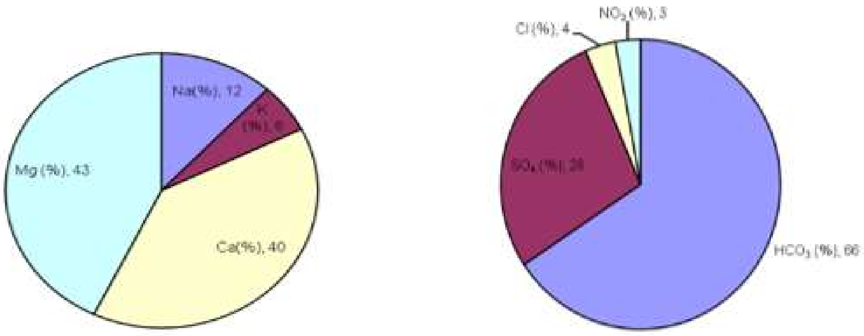


Figure 5: Percentage cationic and anionic composition of rima water samples

Kalambaina Formation

Samples from Kalambaina formation showed that SiO_2 ranges from 10.0-35.0 mg/l with a mean of 20.6 mg/l, Fe ranges from Below Detection Limit (BDL)-0.4mg/l with a mean of 0.1 mg/l, Mn ranges from Bdl-0.1mg/, Ca ranges from 18.0-214.0 mg/l with a mean of 65.6 mg/l, Mg ranges from 4.6-43.0 mg/l with a mean of 14.4 mg/l, Na ranges from 2.9-81.0 mg/l with a mean of 20.1 mg/l, K ranges from 2.6-421.0 mg/l with a mean of 74.3 mg/l, HCO_3 ranges from 20.0-180.0 mg/l with a mean of 127.3 mg/l, SO_3 ranges from 2.5-123.0 mg/l with a mean of 39.3 mg/l, Cl ranges from 3.0-194.0 mg/l with a mean of 40.8 mg/l, Fl ranges from Bdl-0.8 mg/l with a mean of 0.4 mg/l, NO_3 ranges from 21.0-1210.0 mg/l with a mean of 200.5 mg/l, B ranges from Bdl-0.2mg/l with a mean of 0.2 mg/l respectively. The physical parameters showed that TDS ranges from 194.0-2340.0mg/l with a mean of 538.8 mg/l, Hardness ranges from 12.0-643.0 mg/l with a mean of 119.0 mg/l, Electrical Conductivity ranges from 315.0-3150.0 µS/cm with a mean of 792.5 µS/cm, the pH ranges from 7.2-8.3 with a mean of 7.3. Calculated sodium percentage ranges from 4.0-20.0% with a mean of 11.8% while the calculated Sodium Absorption Ratio (SAR) ranges from 0.1-1.3 with a mean of 0.5 (Tables 3 & 5). The order of cationic abundance for the Kalambaina water samples is Ca>Na>K>Mg while that of the anions is in the order NO_3>HCO_3>Cl>SO_4 (Figs 6a & 6b).

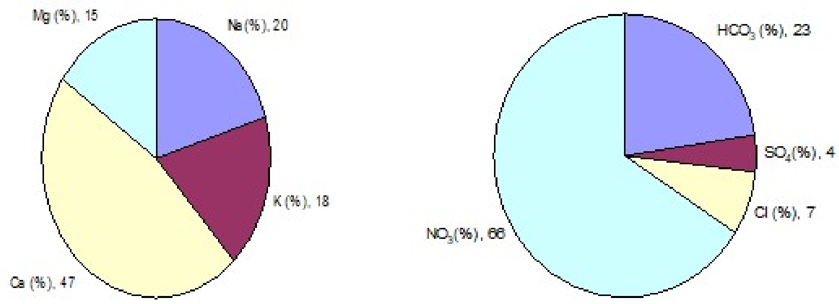


Figure 6: Percentage Cationic and Anionic Concentration in Kalambaina water samples

Gwandu Formation

The samples from Gwandu formation showed the concentration of SiO_2 to range from 8.7-25.0 mg/l with a mean of 15.10 mg/l, Fe ranges from Below Detection Limit (BDL)-0.2mg/l with a mean of 0.07 mg/l, Mn ranges from Bdl-0.2mg/l with a mean of 0.05 mg/l, Ca ranges from 2.2-18.0 mg/l with a mean of 8.87 mg/l, Mg ranges from 0.1-605.0 mg/l with a mean of 35.81 mg/l, Na ranges from 2.0-50.0 mg/l with a mean of 11.51 mg/l, K ranges from bdl-26.0 mg/l with a mean of 4.73 mg/l, HCO_3 ranges from 3.0-149.0 mg/l with a mean of 55.12 mg/l, SO_3 ranges from 0.2-34.0 mg/l with a mean of 10.74 mg/l, Cl ranges from 0.5-16.0 mg/l with a mean of 4.81 mg/l, Fl was not detected in any sample from Gwandu, NO_3 ranges from 0.9-111.0 mg/l with a mean of 13.45 mg/l, B was not detected in any of the Gwandu water samples. The physical parameters showed that TDS ranges from 22.0-272.0 mg/l with a mean of 93.85 mg/l, Hardness ranges from bdl-24.0 mg/l with a mean of 5.56 mg/l, Electrical Conductivity ranges from 33.0-405.0 µS/cm with a mean of 144.50 µS/cm, the pH ranges from 6.6-7.7 with a mean of 7.3. Calculated sodium percentage ranges from 10.0-77.0% with a mean of 30.79% while the calculated Sodium Absorption Ratio (SAR) ranges from 0.2-3.8 with a mean of 0.81(Tables 4 and 5). The order of cationic abundance for the Gwandu water samples is Mg>Ca>Na>K while that of the anions is in the order HCO_3> SO_4> Cl >NO_3 (Figs 7a & 7b)

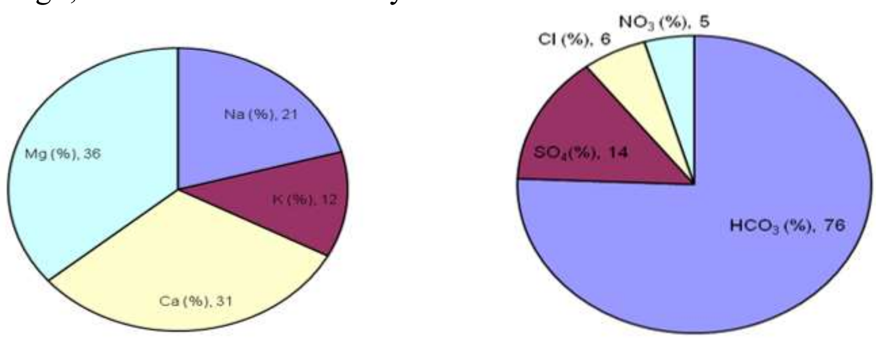
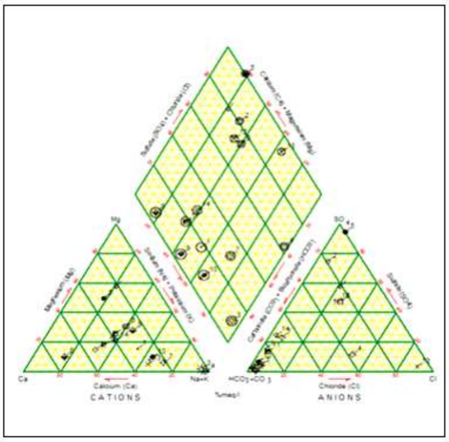


Figure 7: Percentage Cationic and Anionic composition of Gwandu groundwater samples

Groundwater Characterisation

To ascertain the influence of the geologic formations on the groundwater samples, the hydrochemical data were further evaluated using various methods which include the Piper trilinear diagram as well as the Schoeller semi-log plots of the major cations and anions. The Piper (1944) trilinear and Schoeller plots of the water samples showed that the groundwater samples from the Gundumi formation are predominantly Na-HCO_3 and Na-Cl water type (Figures8 and 9) with a few having some amount of Ca, the samples from Rima formation are predominantly Ca-HCO_3 water type (Figures 10 and 11).



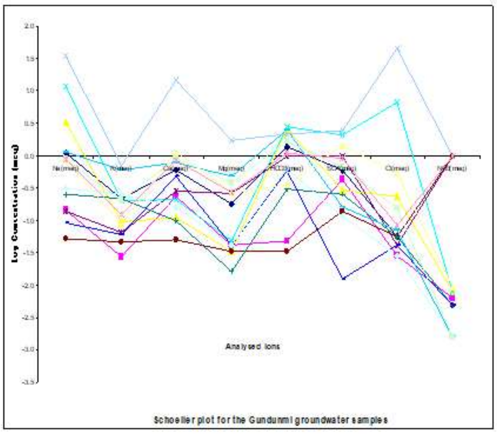
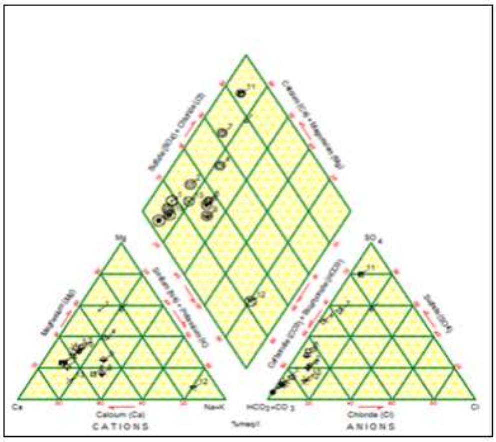


Figure 8: Piper trilinear plot for Gundumi Fig 9: Schoeller plots for Gundumi Samples



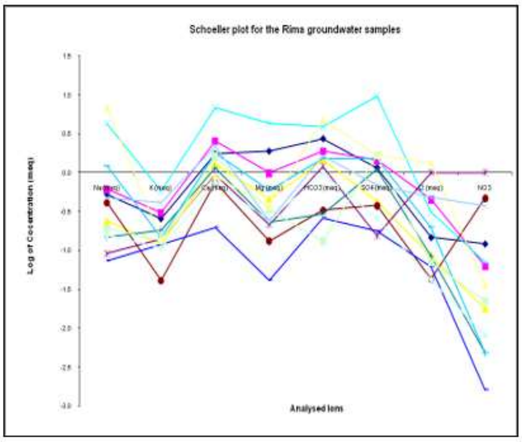
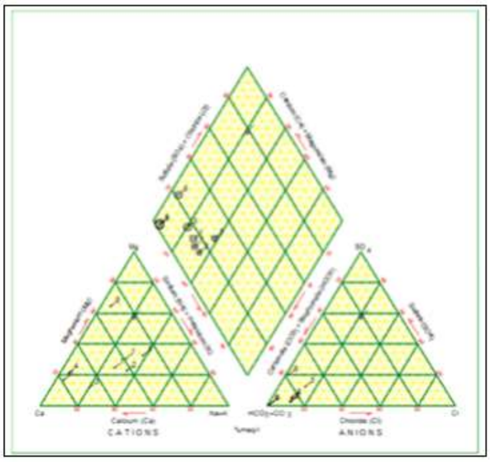


Fig 10: Piper plots for Rima samples Fig 11: Shoeller Plots for Rima samples

The samples from the Kalambaina are predominantly Ca-HCO_3 water type (Figs 12 and 13) while that of Gwandu are a combination of Na-HCO_3 and Ca-HCO_3 water types (Figs14 and 15).



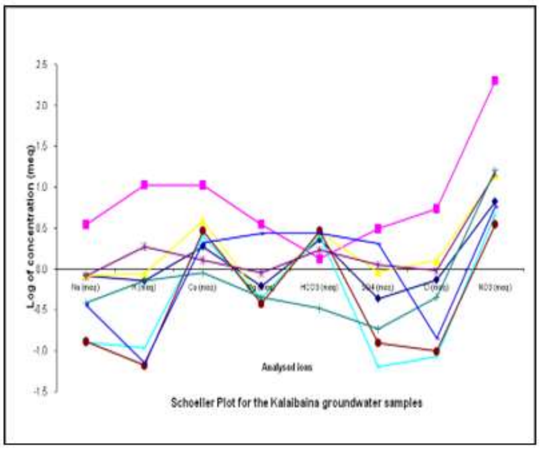
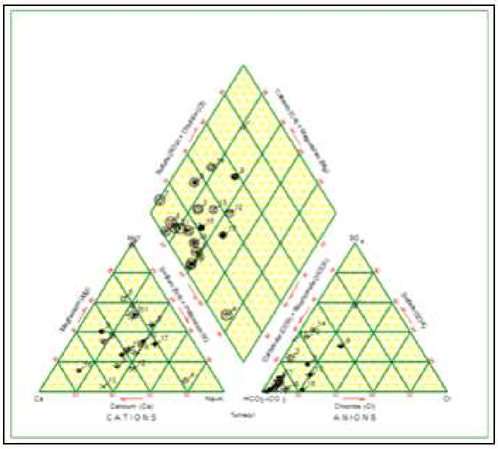


Figure 12: Piper plot for Kalambaina samples Figure 13:Schoeller plot for Kalambaina



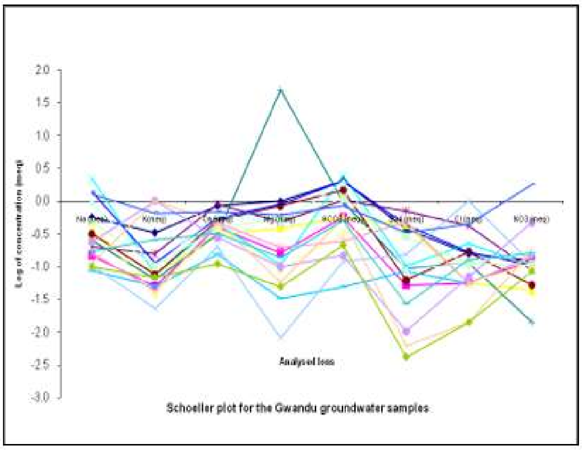
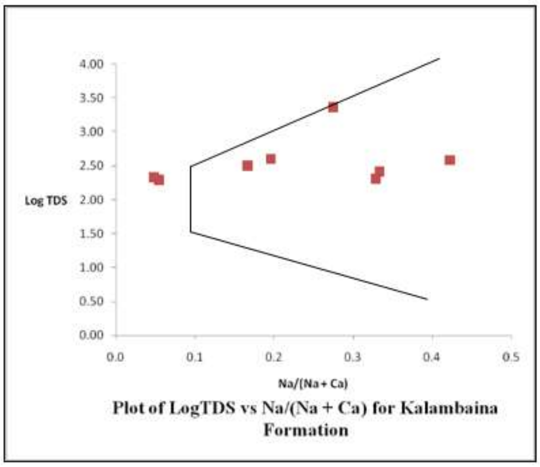


Figure 14: Piper plot for Gwandu Samples Fig 15:Schoeller plot for Gwandu samples

The groundwater character of the Sokoto basin is influenced primarily by the geologic formations within which the groundwater is found. The only exception will be from the Gwandu formations where very high nitrate content was identified in some of the groundwater samples. The presence of NO_3 in the water samples from Gwandu formation may be because of the interaction between the groundwater and the nitrogenous fertilizers that may have been used for agricultural purposes and the formation being sandy and very porous would have allowed sufficient seepage of these fertilizers to the groundwater.

The plots of the Log of TDS versus the ratio of Na/ (Ca+Na) (Boomerang Diagram) for the water samples showed that the groundwater samples from all the formations had been influenced more by the by the action of weathering activities than dilution and evaporation. (Figures 16-19). This is significant as it showed that the groundwater samples had interacted effectively with the lithologic units that constituted the aquifer materials.



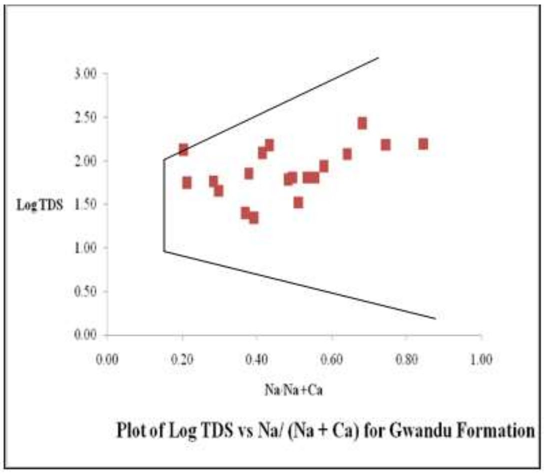
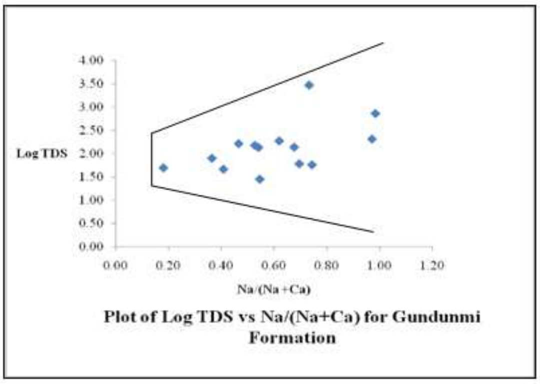


Figure 16: Plot of log TDS vs. Na/(Na+Ca) for Kalambaina Fig 17: Plot of log TDS vs. Na/(Na+Ca) for Gwandu



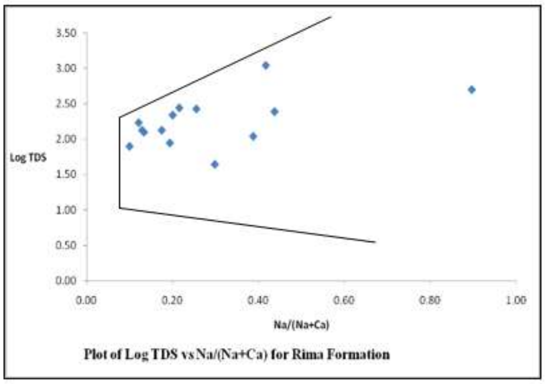
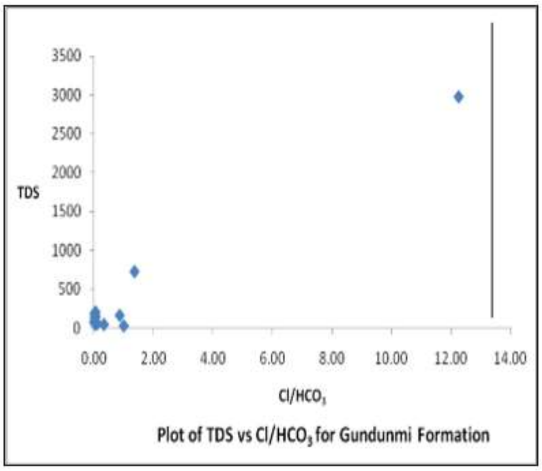


Figure 18: Plot of log TDS vs. Na/(Na+Ca) for Gundumi

Fig 19: Plot of log TDS vs. Na/(Na+Ca) for Rima

The plots of the TDS in mg/l against the ratio of Cl/HCO_3 (Sulin 1946 and Dickey1966) revealed that the groundwater samples have been sourced as meteoric, rather than intermediate and connate (Figs 20-23).



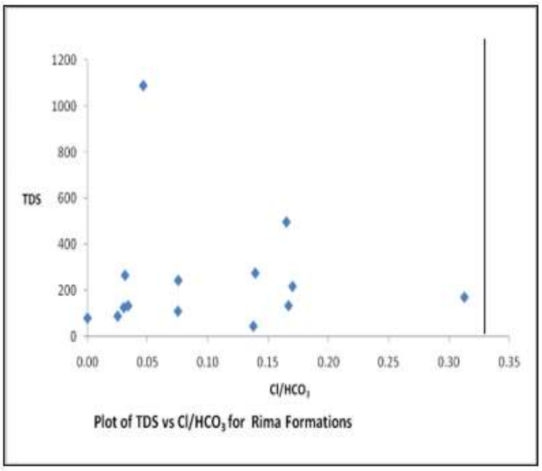
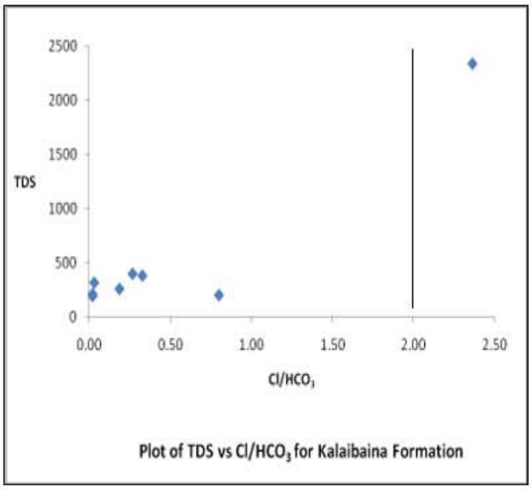


Figure 20: Plot of TDS vs. Cl/HCO_3 for Gudunmi

Fig 21: Plot of TDS vs. Cl/HCO_3 for Rima



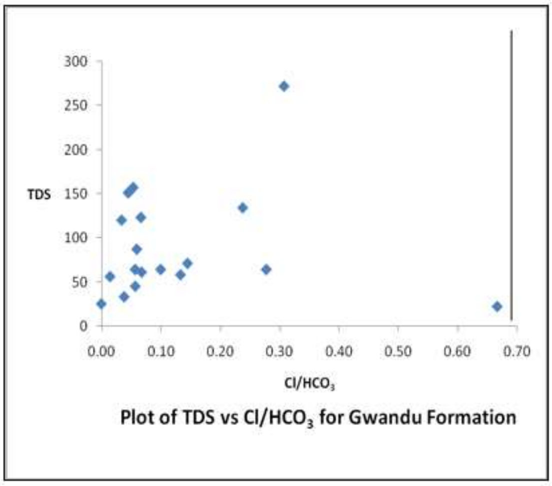


Figure 22: Plot of TDS vs. Cl/HCO_3 for Kalambaina

Fig 23: Plot of TDS vs. Cl/HCO_3 for Gwandu

Table 1: Result of Chemical Analysis of Water Samples from Kalambaina Formation

Location		**Temp**	**Na**	**K**	**Ca**	**Mg**	**HCO_3**	**SO_4**	**Cl**	**NO_3**	**SiO_2**	**Fe**	**F**	**TDS**	**TH**	**Non Carbonate Hardness**	**EC**	**pH**	**%Na**	**SAR**
Bodinga	D	32	19	28	38	7.5	140	17	26	40	15	0.06	0.7	260	126	12	455	7.9	20	0.7
Chimola	D	30	81	421	214	43	82	123	194	1210	10	0.04	0.2	2340	710	643	3150	8.2	12	1.3
Dange	D	31	19	34	78	5.2	169	36	45	84	19	Bdl	0.8	400	216	85	660	8.1	14	0.6
Kware	D	30	2.9	4.3	50	5.4	155	2.5	3	28	22	Bdl	0.2	194	147	20	320	7.5	4	0.1
Mungadi	D	31	19	74	26	11	104	44	34	89	35	0.01	0.3	383	109	24	580	8.2	17	0.8
Sokoto	D	31	3	2.6	59	4.6	180	4.9	3.5	21	24	Bdl	0.2	212	166	18	355	7.7	4	0.1
Tambuwal	D	30	8.8	28	18	5.4	20	7.2	16	97	13	Bdl	0	203	67	50	315	7.2	16	0.5
Angwan Tudu	S	32	8.4	2.8	42	33	168	80	5	35	27	0.44	0.7	318	239	100	505	8.3	7	0.2

Table 2: Result of Chemical Analysis of Water Samples from Rima Formation

Location	**Temp**	**Na**	**K**	**Ca**	**Mg**	**HCO_3**	**SO_4**	**Cl**	**NO_3**	**SiO_2**	**Fe**	**F**	**TDS**	**TH**	**Non Carbonate Hardness**	**EC**	**p H**	**% Na**	**SAR**
Birnin Kebbi	31	12	10	35	23	167	71	5.2	7.5	18	0.04	0	265	183	46	428	6.5	12	0.4
Rabah	31	14	12	51	12	115	88	16	3.9	19	0.03	0	275	175	31		6.4	14	0.5
Sokoto GRA 2	32	5.5	4.6	26	5.6	89	26	3	1.1	17	6.1	0.3	133	88	15	200	8	11	0.3
Balle	37	98	23	137	53	238	588	11	4.4	10	0		1090	559	364	1300	7.5	27	1.8
Sokoto GRA 4	33	2.1	5.4	19	2.6	73	9.4	1.5	0	3.6	4.4	0.5	79	58	10	135	7.2	9	0.1
Bodinga	33	9.5	1.6	15	1.6	20	23	1.5	29	18	0	0	109	44	28	158	7.4	31	0.6
Shuni	33	3.4	7.1	23	2.8	18	67	3	0.3	17	0.06	0.6	133	69	54	178	7.5	9	0.2
Gusau-Sokoto road	32	1.7	4.7	4	0.5	16	11	2.2	0.1	12	0	0.2	44	12	10	52	7.5	16	0.2

Girawsi	32	28	5.7	36	7.3	93	93	7	0.3	19	6.4	0.8	243	120	44	390	7	32	1.1
Girawsi	29	3.6	4.2	15	3	60	16	1.5	0.5	14	3.7	0.4	88	50	1	145	8.1	13	0.2
Sokoto ECN power station	32	4.4	5.2	32	4.1	8	100	2.5	1.4	16	14	0.2	170	97	90	255	6	8	0.2
Kaloye	35	157	5.5	18	4.4	291	102	48	2.2	15	0	1.4	497	63	10	845	7.5	83	7.5
Dange	31	11	16	44	2.9	100	42	17	23	12	0	0.4	217	122	40	370	7.5	14	0.4
Dogwandaji	32	4.3	4.3	28	2.9	83	10	2.5	17	15	0	0.1	125	82	14	200	7.9	10	0.2

Table 3: Result of Chemical Analysis of Water Samples from Gundumi Formation

Location	**Temp**	**Na**	**K**	**Ca**	**Mg**	**HCO_3**	**SO_4**	**Cl**	**NO_3**	**SiO_2**	**Fe**	**TDS**	**TH**	**Non Carbonate Hardness**	**EC**	**p H**	**%Na**	**SAR**
Rabah	31	25	8.5	12	2.2	83	29	2	0.3	15	0.07	137	39	Bdl	210	8.4	52	1.7
Dange	30	3.3	1.1	4.8	0.5	3	21	1	0.4	13	4.0	46	14	12	58	5.1	31	0.4
Sabon Birni	32	74	3.8	2.2	0.4	158	14	8.5	0.5	15	Bdl	205	7	Bdl	332	8.7	93	12
Isa	31	265	8	4.2	0.6	175	102	238	0.5	15	Bdl	728	13	Bdl	1240	8.7	96	32
Gusau-Sokoto road mile 109	30	3.2	2.6	5.6	3.2	3	48	1.5	0	13	32	79	27	27	160	3.7	14	0.3
Gusau-Sokoto road mile 105	31	1.2	1.8	1	0.4	2	6.7	2	0	14	Bdl	28	4	2	24	5.1	28	0.2
Gusau-Sokoto road mile 95	32	5.8	8.5	2	0.2	19	12	2	0.3	17	0.3	57	6	Bdl	50	7.4	42	1
Gusau-Sokoto road mile 83	33	2.1	2.4	9.6	0.5	36	0.6	1.5	0.3	14	0.3	49	26	Bdl	63	7.8	13	0.2
Gusau-Sokoto road mile 73	33	26	24	16	5.8	156	7.7	2.5	0.1	21	14	187	64	Bdl	299	8.7	37	1.4
Gusau-Sokoto road mile 93	33	7.3	10	3.2	0.5	38	5.6	1	0.1	13	14	60	10	Bdl	86	7.6	41	1
Girawsi	36	20	8	18	4.6	100	32	5.5	0.1	12	3.7	150	64	Bdl	250	7.5	37	1.1
Mungadi	30	20	3.5	23	3.3	22	69	19	0.6	13	15	163	71	53	280	6.6	37	1
Kaloye	34	800	27	292	21	134	116	1640	0	13	Bdl	2980	815	705	4900	7.7	67	12
Sainyinan Daji	35	20	4.8	17	3.3	66	43	3		15	8.4	135	56	2	223	6.8	41	1.2

Table 4: Result of Chemical Analysis of Water Samples from Gwandu Formation

Location	**Temp**	**Na**	**K**	**Ca**	**Mg**	**HCO_3**	**SO_4**	**Cl**	**NO_3**	**SiO_2**	**Fe**	**TDS**	**TH**	**Non-Carbonate Hardness**	**EC**	**p H**	**% Na**	**SAR**
Birnin Kebbi	30	13	12.9	17	12	124	18	5.6	7.6	17	0.08	151	92	Bdl	253	6.6	21	0.6
Argungu	32	3.4	2	8	2	35	2.5	2	7.7		Bdl	45	28	Bdl	82	7.5	20	0.3
Rafin Kubu	33	7.1	3	6.2	4.8	35	21	2	2.7		Bdl	64	36	8	130	7.5	28	0.5
Baoaka	38	50	3	9.2	1.3	149	5	8	6.6		Bdl	157	29	Bdl	266	7.5	77	3.8
Balle	27	4.6	6.2	18	5.8	63	34	15	5.5	8.7	0.12	134	68	16	100	7.2	10	0.2
Balle	30	7.3	3	10.3	10.3	90	3	6	3.3		Bdl	123	69	Bdl	165	7.2	18	0.4
Balle	31	5.8	2.5	6.2	605	59	4.5	4	0.9		Bdl	61	43	Bdl	115	7.3	21	0.4
Kurdula	37	32	4.5	11	11	124	21	6	6.6		Bdl	153	64	Bdl	278	7.4	50	1.8
Tangaza	32	2	2	3.1	0.4	3	4.1	2	8.8		Bdl	22	10	8	33	7.5	30	0.3
Yeldu	32	22	4	12.3	5.8	117	4.3	4	9.9		Bdl	120	54	Bdl	205	7.4	45	1.3
Karfin Sarki	34	11	4	8	6.6	67	14	4	6.6		Bdl	87	47	Bdl	159	7.5	32	0.7
Ruawuri	32	10	1.5	8	1.1	20	24	2	7.1		Bdl	64	25	8	96	7.3	45	0.8
Safia	31	2.4	0.9	4.1	0.1	7.3	7.4		7.1		Bdl	25	10	4	42	7.3	30	0.3
Danzo mu	32	3.7	1.7	9.3	2.4	15	23	2	8.9		Bdl	58	33	20	88	7.2	19	0.6
Balle	32	5.5	0	5.6	1.2	9	0.5	2.5	29	13	0.02	64	19	12	80	6.9	35	0.2
Gwandu	31	2.6	0	9.6	0.7	34	0.3	0.5	11	11	Bdl	56	27	Bdl	79	7.5	15	1.6
Kurdula	31	30	26	14	7.5	52	16	16	111	25	0.04	272	66	24	405	7.7	40	0.4
Kwakwara	32	3.9	10	6.4	1.7	31	1.3	4.5	10	18	0.21	71	23	Bdl	90	7.4	19	0.4

Table 5: Summary of Chemical Analysis of Water from the Sokoto Basin

	Kalambaina	Rima	Gundumi	Gwandu	WHO
Temp	30-32	29-35	30-35	27-37	
pH	7.2-8.3	66-8.1	5.1-8.7	6.6-7.7	
EC	315-3150	52-1300	24-4900	33-405	
TDS	194-2340	79-1090	428-2980	22-272	1000
TH	67-710	12-559	4-815	10-92	500
Non-Carbonate Hardness	12-643	10-364	Bdl-705	Bdl-24	200
Na	2.9-81	1.7-157	1.2-800	2.4-50	200
K	4.3-421	1.6-16	1.1-27.0	0.9-26	13
Ca	18-214	4-137	1-292	3.1-17	200
Mg	5.2-43	0.5-53	0.2-5.8	0.1-605	
Fe	Bdl-0.44	Bdl-1.4	Bdl-14	Bdl-0.21	0.3
HCO_3	20-169	8-291	2-175	3-149	200
SO_4	2.5-123	9.4-588	0.6-116	0.3-18	400
Cl	3-194	1.5-48	1-1640	0.5-16	250
NO_3	21-1210	Bdl-23	Bdl-0.5	0.9-111	50
SiO_2	10-35	3.6-19	12-21	Bdl-18	
F	Bdl-0.8	Bdl-1.4	Bdl	Bdl	

The Kalambaina formation is known to host deposits of marl and limestone and by calculating the Ca/Mg ratio of water samples obtained from Calcareous formations, the discrimination between dolomite dominated aquifer materials and limestone dominated aquifer materials could be ascertained. They proposed that a ratio approaching unity (1) signifies a Dolomite dominated aquifer while a ratio of greater than four (>4) signifies a Limestone dominated aquifer. The calculated Ca/Mg ratios for water samples from the Kalambaina formation revealed that most of the water samples were obtained from Limestone dominated aquifer except for those collected from Mungadi and Angwan-Tudu (Table 6).

Table 6: Carbonate Aquifer type discrimination using the Ca/Mg ratio

Sample Location	**Ca/Mg Ratio**	**Bedrock Type**
Bodinga	3.1	Limestone Dominated
Chimola	3.0	Limestone Dominated
Dange	9.1	Limestone
Kware	5.6	Limestone
Mungadi	1.4	Dolomite dominated
Sokoto	7.8	Limestone
Tambuwal	3.3	Limestone dominated
Angwan Tudu	0.8	Dolomite Dominated

Groundwater Quality and Usability

Hardness

Groundwater has also been classified based on the bases of TDS and Hardness values. Todd (1980) proposed a scheme for classifying groundwater using the hardness values (Table 7)

Table 7: Classification of Groundwater based on Hardness (Sawyer and McCarty, 1967)

Total Hardness (mg/l)	**Water Class**
0-75	Soft
75-150	Moderately Hard
150-300	Hard
>300	Very Hard

Table 8: Summary of Water Classification based on Total Hardness

Formation	Range of Hardness (mg/l)	Classification
Kalambaina	67-710	Soft-Very hard water
Rima	12-364	Soft-Very Hard
Gundumi	4-815	Soft-Very Hard
Gwandu	10-92	Soft-Moderately Hard

The water samples from the Kalambaina formation are generally moderately hard but for the samples from Tambuwal and Chimola which are soft and very hard respectively (Tables 1 & 8). The relatively hard nature of the water from the Kalambaina formation is due to the carbonate rich aquifer materials. Samples from the Rima formation are predominantly soft to moderately hard except for those obtained from Birnin Kebbi, Rabah and Balle which are hard to very hard (Tables 2 & 8). Gundumi water samples are soft except for the samples collected from Kaloye which is very hard (Tables 3 & 8). The Gwandu water samples are also soft except for the sample from Birnin-Kebbi (Tables 4 & 8).

Total Dissolved Solids

Using Carroll (1962) classification of groundwater into various classes based on total dissolved Solids (TDS) values, most of the groundwater samples from the Kalambaina formation have TDS values less than 1000mg/l which put the water samples in the freshwater class. However, the water sample from Chimola with a TDS value of 2,340mg/l can be classified as slightly saline water type. Similarly, the TDS values of water can also be used as a basis of determining the status of the groundwater either as being polluted or unpolluted.

Table 9: Summary of Water Classification based on TDS

Formation	Range of TDS (mg/l)	Classification
Kalambaina	194-2340	Fresh-Brackish water
Rima	44-1090	Fresh-Brackish water
Gundumi	28-2980	Fresh-Brackish water
Gwandu	25-157	Fresh water

The groundwater samples from Kalambaina formation are fresh water except for the sample from Chimola that has a TDS value of 2340mg/l. The high TDS may have been induced by anthropogenic activities as the NO_3 content of the same water sample is

1210mg/l (Tables 1 & 10). High nitrate content has always been associated with anthropogenic activities. The water sample from Chimola can be described as polluted. The samples from Rima formation are freshwater samples except that from Balle with a TDS value of 1090mg/l indicating a slightly brackish water sample. This sample has elevated SO_4 concentration (588mg/l) which may be because of the gypsum mineralization that are contained in the formation (Tables 2 & 10). The water samples from Gundumi formation are freshwater samples except for the sample from Kaloye with a TDS value of 2980mg/l which can be described as brackish. The chloride content of the water sample at Kaloye is 2980mg/l; this may have been introduced into the groundwater system from isolated salt beds that may have resulted from the intense evaporation and precipitation of halite in the grits overlying the basement rocks (Tables 3 & 10). The samples from Gwandu are all freshwater samples (Tables 4 and 10).

Sodium Absorption Ratio (SAR)

Wilcox, 1955 proposed a classification based on the Sodium Absorption Ratio (SAR) for irrigation water (Table 11). The water samples from all the formation have appropriate SAR that makes them suitable for irrigation purpose (Table 12).

Table 11: Classification of Groundwater based Sodium Absorption Ratio (SAR)

SAR	**Water Class**
0-10	Excellent
10-18	Good
18-26	Fair
>26	Poor

Table 12: Summary of Water Classification based on SAR

Formation	**Range of SAR**	**Water Class**
Kalambaina	4-20	Excellent
Rima	0.2-32	Excellent
Gundumi	0.1-1.3	Excellent
Gwandu	0.2-3.8	Excellent

The plots of the SAR and the EC also revealed that the water samples are within the zone of low sodium hazard, and this is a further confirmation of the suitability of the groundwater samples for irrigation purposes. However, a few of the sample's plot outside the zone (Figures 26-29)

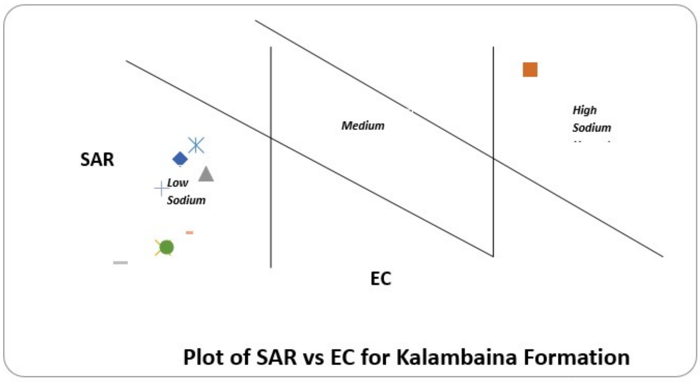


Figure 26: Plot of SAR against Electrical conductivity

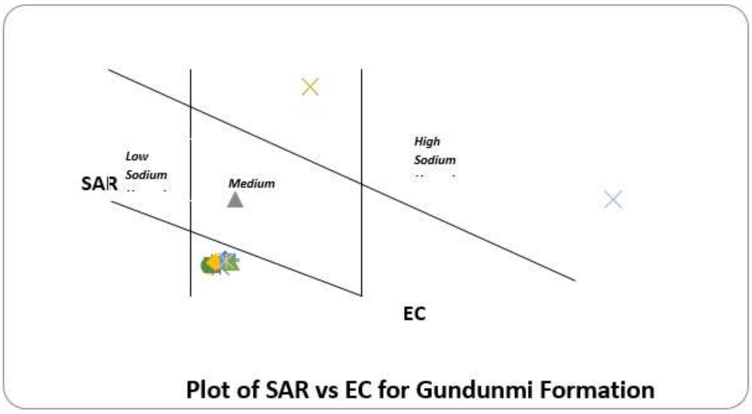


Figure 27: Plot of SAR against Electrical conductivity

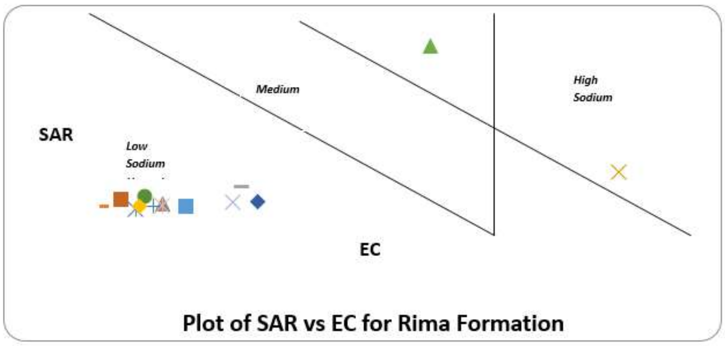


Figure 28: Plot of SAR against Electrical conductivity

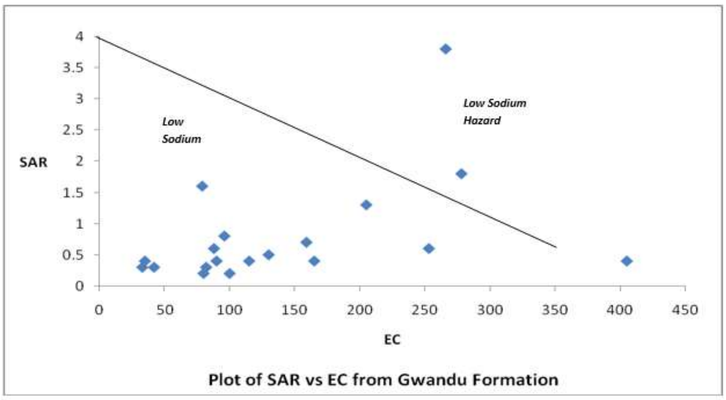


Figure 29: Plot of SAR against Electrical conductivity

Statistical Analysis

The chemical data were subjected to correlation and R-mode factor statistical analysis to ascertain the relationship between the various chemical constituents.

High positive correlations were observed for all the anions and cations except for HCO_3 where a low negative correlation was observed for the water samples from the Kalambaina formation (Table 13). The high positive correlations between the various chemical constituents indicate that they have been contributed from same sources and similar geochemical process.

The R-mode factor analysis also confirmed the correlation analysis as two groups of factors were isolated the first group consists of the anions and cations with high positive correlations, while the second factor consist of the HCO_3 anion (Table 14). This is further evidence that the chemical constituents of the groundwater samples from the Kalambaina formation is governed by several factors. The geochemical implication of this is that the chemical character of the groundwater of the Kalambaina formation is governed more by the concentration of the parameters in Factor 1 (Na, K, Ca, Mg, Cl, SO_4 and NO_3) while HCO_3 is of lesser role as it is had been sourced from the aquifer materials which is more carbonate in nature.

Table 13: Correlations Coefficients for water samples from Kalambaina formation

	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3
Na	1							
K	.98	1						
Ca	.92	.92	1					
Mg	.74	.74	.71	1				
HCO_3	-.35	-.40	-.09	-.13	1			
SO_4	.82	.79	.76	.96	-.13	1		
Cl	.99	.99	.94	.71	-.35	.79	1	
NO_3	.97	.99	.95	.76	-.38	.79	.98	1

Table 14: Principal Component Matrix for the Kalambaina water samples

	Component	
	1	2
Na	.98	-.07
K	.98	-.11
Ca	.93	.17
Mg	.84	.29
HCO_3	-.33	.91
SO_4	.88	.28
Cl	.98	-.08
NO3	.99	-.09

The samples from Rima revealed positive correlations between Na and HCO_3 and Na and Cl as well as Na and SO_4 with correlation coefficients of 0-87, 0.85 and 0.56 respectively. K displayed positive correlations with Ca, Mg, CO_3 and SO_4 with correlation coefficients of 0.89, 0.81, 0.52 and 0.79 respectively. Mg also showed positive correlation with HCO_3 and SO_4 with correlation coefficients of 0.59 and 0.93 respectively (Table 15).

The R-mode factor analysis of the data for the Rima formation samples revealed three groupings for the various chemical constituents (Table 16). Factor one comprises Na, K, Ca, Mg, HCO_3 and SO_4; Factor two comprises Cl and Factor three comprises NO_3. The presence of all the cations in the first groupings alongside the HCO_3 and SO_4 anions indicate that these have all been contributed geologically from the aquifer materials while the Cl and NO_3 may have been added to the water by anthropogenic activities.

Table 15: Correlations coefficients for groundwater samples from Rima formation

	Na	**K**	**Ca**	**Mg**	**HCO_3**	**SO_4**	**Cl**	**NO_3**
Na	1							
K	.33	1						
Ca	.39	.89	1					
Mg	.43	.81	.92	1				
HCO_3	.87	.52	.51	.59	1			
SO_4	.56	.79	.94	.93	.56	1		
Cl	.85	.23	.11	.08	.77	.18	1	
NO_3	-.13	.05	-.01	-.10	-.09	-.13	-.02	1

Table 16: Principal Component Matrix for water samples from Rima formation

	Component		
	1	2	3
Na	.74	.62	-.02
K	.84	-.34	.14
Ca	.89	-.43	.05
Mg	.89	-.38	-.07
HCO_3	.82	.48	.03
SO_4	.92	-.30	-.09
Cl	.50	.83	.14
NO_3	-.10	-.11	.98

The correlation analysis of the Gundumi water sample results revealed positive correlation among Na, K, Ca, Mg, SO_4 and Cl while all these parameters displayed a negative correlation with NO_3. This is an indication that NO_3 had been contributed to the groundwater in the Gwandu formation by anthropogenic means and not from the interaction with the aquifer materials and percolating meteoric water as the case with the other constituents (Table 17). The Principal Component Analysis also revealed two groupings with all the constituents displaying positive correlation amongst them constituting Factor one and only NO_3 constituting factor two (Table 18).

Table 17: Correlations coefficients for Groundwater from Gundumi formations

	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3
Na	1							
K	.67	1						
Ca	.94	.70	1					
Mg	.87	.78	.96	1				
HCO_3	.48	.58	.30	.35	1			
SO_4	.78	.36	.65	.63	.38	1		
Cl	.98	.68	.98	.92	.36	.71	1	
NO_3	-.20	-.41	-.34	-.42	.14	.11	-.29	1

Table 18: Principal Component Matrix for Gundumi formation water samples

	Component	
	1	2
Na	.97	.12
K	.80	-.15
Ca	.96	-.11
Mg	.96	-.17
HCO_3	.50	.52
SO_4	.74	.44
Cl	.97	-.03
NO_3	-.32	.88

The correlation analysis of the groundwater samples from Gwandu formations revealed positive correlation between Na and HCO_3 with correlation coefficients of 0.76. K exhibits positive correlations with Ca, Cl and NO_3 with positive correlation of 0.52, 0.72 and 0.80 respectively. Ca exhibits positive correlations with HCO_3, SO_4 and Cl with correlation coefficients of 0.61, 0.57 and 0.71 respectively. These various correlations showed the diverse nature of the aquifer materials that have interacted with the groundwater hence its diverse relationships. The Principal Component Analysis showed two groupings with the first factor consisting of Na, K, Ca, SO_4, Cl, and NO_3 while the second factor consist only HCO_3.

Table 19: Correlations coefficients for Groundwater from Gwandu formations

	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3
Na	1							
K	.36	1						
Ca	.36	.52	1					
Mg	-.09	-.07	-.13	1				
HCO_3	.76	.23	.61	.04	1			
SO_4	.11	.24	.57	-.14	.13	1		
Cl	.47	.72	.71	-.03	.39	.45	1	
NO_3	.32	.80	.26	-.12	-.08	.06	.58	1

Table 20: Principal Component Matrix for Gwandu formation water samples

	Component	
	1	2
Na	.654	.418
K	.800	-.458
Ca	.812	.212
Mg	-.171	.119
HCO_3	.579	.756
SO_4	.489	.066
Cl	.899	-.119
NO_3	.619	-.681

SUMMARY

The geochemical evaluation groundwater samples from the Sokoto basin had been undertaken and the various geochemical constraints that influence the groundwater character and quality outlined. The various results indicated that the groundwater character and quality from within the basin are determined by rock-water interactions, agricultural as well as other human activities. The rock-water interactions revealed that the water chemistry had been principally derived from the dissolution and leaching of the aquifer materials into the groundwater system while the presence of abundant nitrate in some of the groundwater samples is an indication of the leaching of fertilizers and soil amendments into the ground water system especially in the very porous and permeable formations. This work had further highlighted the need for the hydrochemical evaluation of the groundwater system of all geologic formations before the water is eventually deployed for industrial, domestic, or even agricultural uses.

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