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Variability in Aquifer Depths Dominates Physicochemical Composition of Groundwater in Highland Areas of South-Eastern Sokoto Basin, Nigeria

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Abstract

Characterization of groundwater in highland areas of south-eastern Sokoto Basin revealed that Fe^{3+}, Zn^{2+}, Mg^{2+}, Na^{+}, PO_4^{3-} and SO_4^{2-} concentrations are above WHO and National Standard for Drinking Water Quality reference guidelines. Groundwater classification revealed Ca-Mg-SO_4-HCO_3, and mixed Mg-Na-K water type in deep aquifer. Whereas shallow aquifer, has Ca-Na-K-Cl-HCO_3 and mixed HCO_3-Cl-SO_4 water type. Scholler index was positive, indicating overall base exchange reaction in the study area. Groundwater classification using SAR revealed low salinity-low sodium and low salinity-medium sodium class. Sodium percent is less than 20 in deep aquifer and Kelly's index is less than 1, indicating water which is suitable for irrigation use. In contrast, sodium percent is greater than 20 and Kelly's index is greater than 1 in shallow aquifer. Further, about 65% of water samples from deep aquifer have Magnesium hazard greater than 50, indicating water which is unsuitable for irrigation use. However, 90% of water samples from shallow aquifer have Magnesium hazard less than 50. The mechanism controlling water chemistry revealed that precipitation is the major mechanism influencing water chemistry in the study area. While shallow groundwater can be used for irrigation with little or no risk of magnesium hazard to crops, the underlying reason for high magnesium in deep aquifer and high sodium in shallow aquifer need to be investigated. Therefore, broader study evaluating groundwater over wider spatial and temporal scales in Sokoto Basin is recommended.

Keywords: Sodium adsorption ratio; Sodium hazard; Magnesium hazard; Scholler index; Kelly's index; Molar ratio

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Introduction

Nigeria is the most fastest growing country in Sub-Saharan Africa (SSA) in terms of human population. Improved water supply which is one of the essential for a healthy living, has been constrained by uncontrolled anthropogenic activities and by lesser extent natural conditions [1,2]. Characterization of groundwater in Nigeria, is further constrained by lack of data, especially from highland areas, owing to difficulties associated with accessibility [3]. The highland areas of South-eastern Sokoto Basin (SESB) are underlain by Pre-Cambrian Basement Formation [4]. Groundwater in SESB is generally available in small quantity derived from fractures and tabular partings and from the regolith, just below the earth surface [5]. The fissures are usually most open above a depth of 91 meters but even so, yields to boreholes are relatively low and cause high drawdown [5]. While boreholes are widely used in SESB as sources for improved water supply, shallow groundwater remained the most reliable source of drinking water. However, thee geological factors in addition to changes in land use combined with rock mineral, operate jointly together and influence groundwater composition [6].

Groundwater composition is further influenced by the minerology of the aquifer and recharge pathways. As water passes through its recharge pathways from recharge to discharge points, several other types of hydrogeochemical processes alter its physical and chemical properties and in some aquifers, water may be unsuitable for drinking and agriculture [6-8]. To highlight this problem, we look at the highland areas of SESB. The SESB is underlain by intrusive granite of igneous origin

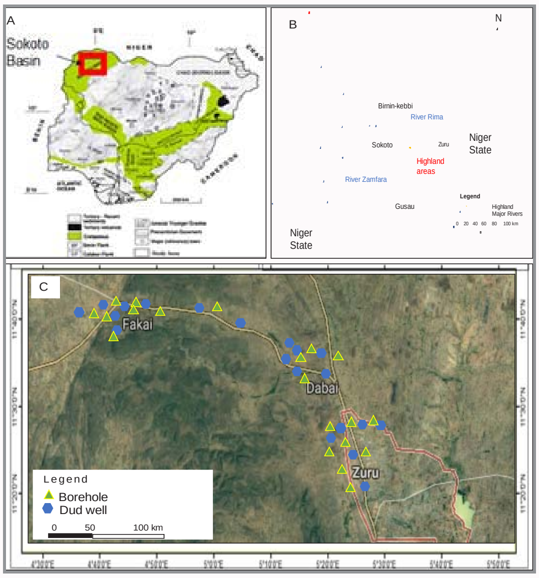

Figure 1: Map of the study area. (A) Map of Nigeria showing Sokoto Basin; (B) Map of Sokoto Basin Showing Highland areas; (C) Highland areas.

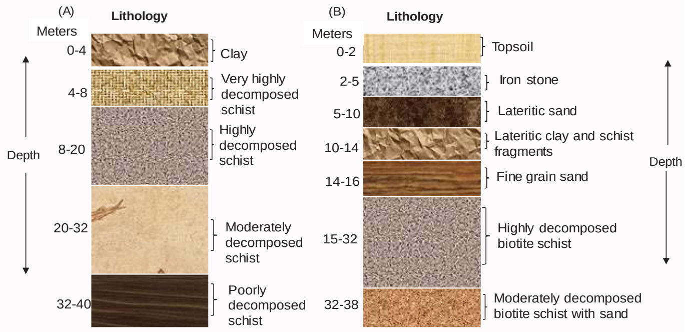

Figure 2: Lithologic section of boreholes in SESB (A) Zuru and (B) Fakai.

and deformed metamorphic rocks, chiefly gneiss, schist, hyalite, and quartzite. Groundwater in this this type of aquifer, tend to be highly mineralized. Further, the topography presents another obstacle to groundwater development [9]. Therefore, groundwater is cheaply found along low-lying areas and is haul out using handlines from shallow wells.

Groundwater quality studies in Sokoto Basin [10-18] revealed water of excellent quality and of Holocene age (100 to 10,000 years BP). But these studies were carried out in Cretaceous and Cenozoic Sediment sections of the basin. Groundwater quality in SESB remain poorly known. Evaluation of groundwater over space and time proved to be an important technique for solving different hydrogeochemical problems [6]. Because understanding the aquifer hydrochemistry is important for effective utilization of and development of this finite resource [19].

Characterization of groundwater has been carried out over different environmental settings, including (1) Urban [20-29]. Results revealed anthropogenic inputs through variation of TDS, Cl^-, SO_4^{2-}, NO_3^- and Na^+. (2) Coastal [22,30-33], which revealed intrusion of saline water in coastal aquifers. (3) Irrigation fields [34-36]. Findings showed variation in SAR and salinity levels. (4) Basins [2,37-39]. Results indicate variation in groundwater potentials and chemical properties.

However, groundwater has been studied using different techniques including (1) geothermal [2,15,37,38], to study curie-point depths and near-surface heat flow in aquifers. Isotope techniques [11,40,41], to characterize and classify groundwater. Statistical analysis including Q-mode and R-mode [32], revealed interrelations between groundwater samples and among variables; Pearson's correlation [28], revealed contamination of groundwater derived from anthropogenic activities; and Principal component analysis, showed rock mineral-water interactions in aquifers. Thus, the objective of this study is to determine the variability of groundwater between shallow and deep aquifers and assess it suitability for drinking and irrigation use by integrating empirical hydro chemical relations and chemical indices.

Materials and Methods

Geographical setting

The highland areas of SESB are in north-eastern Sokoto Basin. They are situated between Latitudes 11°20" and 11°40" N and Longitudes 4°30" E and 5°50" E (Figure 1). The highland areas cover 2,411.69km². This area covers Fakai and Zuru local government areas (LGAs). From the conglomeration point along Koko-Mahuta road, just about 40km before Mahuta, surface elevation increases steadily passing through Fakai and reaching over 400 meters above sea level in Dabai. The rock outcrops formed a triangle of basement rock outcrop,

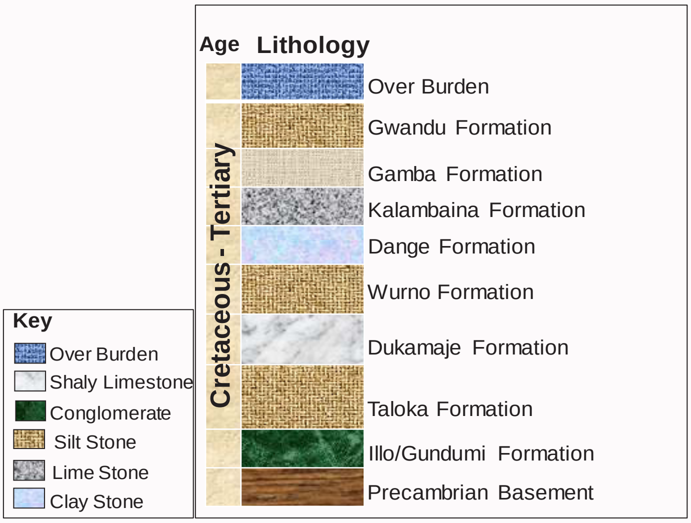

Figure 3: Generalized chronostratigraphic column for Sokoto Basin.

which extends from Fakai to Zuru and Yauri.

The climate of SESB is hot, semi-arid tropical (AW) in Koppen's classification. It is dominated by two opposing wind systems: Tropical Maritime and Tropical Continental air masses [42]. These give the study area two contrasting seasons-wet and dry. The dry season results from continental air mass blowing from the Sahara Desert. The dry season lasts from October to April, whereas wet season lasts from May to October. From March onward, temperature rises to over 40ºC. Temperature is generally high and showed marked seasonal variation. Mean maximum temperature is about 40ºC in April. Mean minimum temperature is lowest in December less than 25ºC. Analysis of soil temperature suggests. Annual rainfall ranges from 500mm in the extreme northern parts of Sokoto Basin, to over 1200mm over highland areas. Most of the precipitation falls in July, August and September [43].

Hydrogeological setting

Basement complex rocks formation underlie SESB [14,42]. This gives the study area two sets of geologic provinces. Highly metamorphosed sediments occur at the boundary between the basement complex and the cretaceous sediments, consisting of calc-silicate rocks, quartzite and high-grade schist. Boulders of rocks of the older granite group, are widespread in this area. These include intrusive granite of igneous origin and deformed metamorphic rocks, chiefly gneiss, schist, hyalite, and quartzite (Figure 2).

Geological work in Sokoto Basin dates to 1800s. Reporting of fossil fuel localities was the main objective. A Comprehensive study of groundwater was carried out by du Preez and Barber [10]. Groundwater recharge [11], is highly variable across the basin. Figure 3, illustrates the chronostratigraphic column for Sokoto Basin. Groundwater quality [5,16-18,34,44-46], is highly variable with TDS concentration ranging from 130 to 2,340 mg/l. Sodium and nitrate concentrations exceed WHO reference guidelines in some locations. The hydrogeochemical faeces [17,18,45], are predominantly of two types: calcium–magnesium–bicarbonate and calcium–magnesium–sulphate–chloride in nature. These faeces perhaps, are derived from dissolution of calcium and magnesium carbonates.

Groundwater sampling and laboratory analysis

Forty (40) groundwater samples were collected, twenty each from deep and shallow aquifers. Groundwater samples were collected mainly from shallow wells and boreholes, which are currently in use. Samples were drawn from water sources constructed by Kebbi State Government. Because these sources are expected to meet all the necessary requirements for water supply. Physical parameters-temperature, pH, EC and TDS were determined in situ using water quality probes (Table 1). Probes were first calibrated by deionised water and then by water from shallow wells and boreholes. Discrete water samples were collected in 1 litre polyethylene bottles for determination of cations (K^+, Na^+, Ca^{2+}, Cu^{2+}, Fe^{3+}, $Zn^{2+}$and Mg^{2+}) and anions (Cl^-, HCO_3^-, CO_3^{2-}, PO_4^{3-}, NO^{3-} and SO_4^{2-}). Samples were stored

Table 1: Summary of field and Laboratory methods.

Parameters		Methods	Description	Source
Physical	Temperature	Field	Temp/Salinity-meter (DKMsG01)	[63]
	Conductivity	Field	Conductivity/TDS meter	[46]
	pH	Field	pH Meter (pHep)	[32]
	TDS	“	Temp/Salinity-meter	[32]
Cations				
	Potassium (mg/l)	Laboratory	AAS	[58]
	Sodium (mg/l)	“	“	“
	Calcium (mg/l)	“	“	“
	Copper (mg/l)	“	AAS	“
	Iron (mg/l)	“	“	“
	Zinc (mg/l)	“	“	“
	Magnesium (mg/l)	“	“	“
Anions				
	Phosphate (mg/l)	“	AC	[58]
	Chloride (mg/l)	“	Titration	“
	Bicarbonate (mg/l)	“	“	“
	Nitrate (mg/l)	“	AC	“
	Chloride (mg/l)	“	“	“
	Sulphate	“	IC	“

Note: AAS: Atomic Absorption Spectrometry; AC: Automated Colorimetry; IC: Ion Chromatography.

Table 2: Summary of Physical and chemical properties of ground water (Values in bold do not follow WHO and NSDWQ reference guidelines).

Parameter	Borehole (deep aquifer)				Dugwell (shallow aquifer)				Reference guidelines	
Physical	**Mean**	**Min**	**Max**	**SE**	**Mean**	**min**	**Max**	**SE**	**WHO (2011)**	**NSDWQ (2007)**
Temperature (°C)	32.4	30	34	5.4	26.8	21.4	31	4.9	Ambient	Ambient
pH	7.9	7.3	8.4	1.3	7.4	6.8	8.1	1.3	6.5-8.5	6.5-8.5
TDS (mg/l)	180.8	65	394	62.3	142	40	320	50.6	500	500
EC (µS/cm)	363.3	136	796	125.9	95.5	10	260	41.1	1000	1000
Cations										
K^+ (mg/l)	37.7	32.3	40.7	6.4	42.9	39	78	12.3	-	-
Na^+ (mg/l)	3.9	0	9.8	1.5	**449.9**	2	**598**	94.6	12	12
Ca^{2+} (mg/l)	21.9	2.7	129.3	20.4	19.7	1.2	51	8.1	500	500
Cu^{2+} (mg/l)	0.3	0.1	0.6	0.1	0.6	0.1	1.6	0.3	1	1
Fe^{3+}(mg/l)	0.9	0.1	**3.1**	0.5	**1.6**	0.5	**2.7**	0.4	2	1
Zn^{2+} (mg/l)	**0.5**	0.2	1	0.2	**5.3**	**2**	**8.4**	1.3	3	3
Mg^{2+} (mg/l)	**19.4**	**8.2**	**26.8**	4.2	**6.6**	1	**20**	3.2	-	50-150*
Anions										
PO_4^{3-} (mg/l)	**0.4**	0.1	**0.6**	0.1	**18.4**	**11**	**23**	3.6	0.2	0.2
Cl^- (mg/l)	2.5	0.6	3.5	0.6	188.8	4	**888**	140.4	200	200
$HC0_3$- (mg/l)	14	0.3	33.3	5.3	176.9	61	549	86.8	250	250
SO_4^{2-} (mg/l)	**131.1**	45.1	**245.9**	38.9	**206.3**	67.5	**327.1**	51.7	200	100
NO_3^- (mg/l)	36	12.5	46.8	7.4	42.7	12.6	45.2	7.1	50	50

Note: *=WHO (1997) reference guidelines.

in insulated containers less than 5°C. Prior to collection of water samples, polyethylene bottles were washed twice; initially by using deionised water and then with the water from sampled boreholes and wells. All analyses were carried out in triplicates and results were found reproduceable within ±5 error limit. Table 1, summarizes field and laboratory methodologies employed in this study.

Silicate weathering reaction and ion exchange process

Ion exchange between sub-surface flows and aquifer rock during recharge and residence time can be evaluated using Scholler and Versluy's indices. Versluy's [47] used [Na / (Na + Ca + Mg)] as an index of base exchange reaction. Later, Scholler [48] trailed with three indices, thus: [Cl-(Na + K) / Cl]; [(Na + K) / Cl] and [(Ca + Mg) / $HCO_3 + CO_3 + SO_4$)]. Versluy's index, is defined thus;

$$[Na / (Na + Ca + Mg)] \qquad \text{Eq. 1}$$

Whereas Scholler index is defined, thus;

$$[Cl^- (Na + K) / Cl] \qquad \text{Eq. 2}$$

In aquifers where K^+ and Na^+ is exchanged with Ca^{2+} and Mg^{2+}, Scholler and Versluy's indices tend be positive, indicating chloro-alkaline equilibrium base exchange reaction. If indices are negative, it is an indication of chloro-alkaline disequilibrium base exchange reaction. This reaction is referred to as cation-anion exchange reaction [28].

However, molar ratio can be used to study silicate weathering reactions [49]. Molar ratio greater than1 indicates silicate weathering as the source of Na^+ in an aquifer, in the absence of anthropogenic inputs [28]. Molar ratio is determined thus;

$$[Na^+ /Cl^-] \qquad \text{Eq. 3}$$

Mechanism controlling water chemistry

Precipitation, evaporation and rock weathering are the major mechanisms controlling water chemistry [50]. The chemical compositions of fresh waters are controlled by the amount of dissolved salts furnished by precipitation. These waters comprised of tropical water sources having leaked zones of low relief in which the rate of flow of dissolved salts to water sources is very low and the quantity of dissolved salts to water sources is also very low. Normally the amount of precipitation is high exceeding proportion to the low volume of dissolved salts supplied from the rock minerals. Water sources in this group are normally found in hot and dry regions of the world. The contrary end-member of this series is rock dominance. This comprised of waters having their main source of dissolve salts from the soils and rocks derived from their basins. The third mechanism is the evaporation-fractional crystallization process. This mechanism produces a series extending from the Ca-rich freshwater, derived from rocks dominance to the opposite Na-rich high-salinity end member [50]. The mechanism controlling water chemistry is usually evaluated using a plot of weight ratio of TDS versus [Na + K] / Na + K + Ca] and [Cl] / [Cl + HCO_3].

Suitability for irrigation use

The suitability of groundwater for irrigation use can be evaluated using chemical indices including, Sodium Adsorption Ratio (SAR), Sodium Percent (SP), Kelly's Index (Ki) and Magnesium Hazard (MH).

Sodium adsorption ratio: Sodium adsorption ratio (SAR), is an effective tool for evaluation of alkali or sodium hazard to crops. SAR [51], is defined thus;

$$SAR = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+}) / 2]} \qquad \text{Eq. 4}$$

Groundwater can be classified using total concentration of soluble salts (salinity hazard) which is express in terms of specific conductance [52]. The U.S salinity diagram is used where SAR is plotted against EC. This method was first proposed by US Salinity

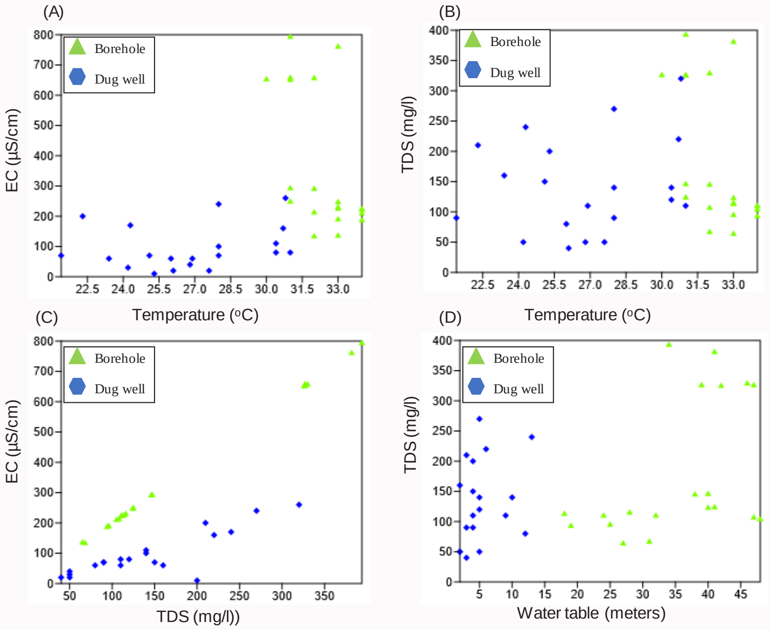

Figure 4: Relationship between physical parameters (A) Temperature and EC; (B) Temperature and TDS; (C) TDS and EC and (D) Water table and TDS.

Laboratory staff [53].

Sodium percent: Under wet conditions high Na^+ level causes cation exchange between Mg^{2+} and Ca^{2+}. Water and air circulation tend to be reduced by this process. When Na^+ level is low, it is an indication of ion exchange reaction between Ca^{2+} and Na^+. Irrigation water having sodium percent less than 20 suggest water which is suitable for irrigation use, whereas values greater than 20 designates water unsuitable for irrigation [54]. It is defined thus:

$$Na^+ (\%) = [(Na^+) \times 100 / (Ca^{2+} + Mg^{2+} + Na^+ + K^+)] \qquad \text{Eq.5}$$

Kelly's index: In this technique, Ca^{2+} and Mg^{2+} are measured against Na^+. Index greater than 1 indicates water of excellent quality for irrigation use. Whereas values less than 1 indicate water which is unsuitable for irrigation use because of alkali hazards to crops [55]. It is defined thus:

$$KI = [Na^+ / (Mg^{2+} + Ca^{2+})] \qquad \text{Eq. 6}$$

Magnesium hazard: Elevated Mg^{2+} levels in groundwater affects the soil quality by converting it to alkali which consequently reduces crop yield. Groundwater with Magnesium Hazard less than 50 are considered suitable for irrigation. Often in aquifers Ca^{2+} and Mg^{2+} are found in a state of equilibrium. Mg^{2+} concentrations in irrigation water at levels greater than Ca^{2+} accelerates the degree of Mg^{2+} saturation which destroys soil structure and consequently reduces its productivity [56]. Magnesium Hazard [57], is defined thus:

$$MH = [(Mg^{2+}) \times 100 / (Ca^{2+} + Mg^{2+})] \qquad \text{Eq. 7}$$

Statistical analysis

Groundwater data were organized and standardised using basic descriptive statistics (mean, minimum, maximum and standard error). Non-parametric statistical test (Kruskal-Wallis) was employed to test whether there is a significant difference between shallow and deep aquifers. Relationship between studied parameters was tested using Pearson's correlation (r). All statistical analysis was conducted using a significant level of $\alpha = 0.5$.

Results and Discussion

Physical properties

Groundwater composition in the study area showed a marked spatial variability both within and between aquifers (Table 2). Groundwater temperature significantly differs (H=27.36, p=<0.001) between shallow and deep aquifers. Temperature variability can be very critical especially where biochemical reactions are concerned. Because an increase of 10°C in groundwater aquifer leads to doubling of chemical reactions [58]. Solubility of gasses, ion exchange capacity, redox reaction, sorption processes, complexation, speciation, EC and pH level are all affected by variations in temperature [59]. Temperature correlates poorly with EC (r=0.15) in deep aquifer. Correlation was stronger (r=0.35) in shallow aquifer (Figure 4A). pH differs significantly (H=9.86, p=0.002) between the two aquifers. Groundwater is slightly acidic to alkaline in the study area. While pH has less effect on consumers, it is fundamental to understanding groundwater chemical composition. Moderate pH level is required depending on the composition of groundwater and aquifer properties [58]. No significant difference in TDS concentration (H=0.94, p=0.33). Groundwater classification using TDS [60], indicates groundwater of excellent quality for drinking (Table 3).

TDS correlates significantly with Na^+ (r=0.95), HCO_3^- (r=0.82), PO_4^{2-} (r=0.95) in deep aquifer and was significantly correlated only with Fe^{3+} (r=0.54) in shallow aquifer. Positive correlation between TDS and Fe3+, HCO_3^-, Na^+ and PO_4^2, suggest that large part of dissolved solids was derived from these ions. TDS correlates significantly (r= 0.51; r=0.60) with temperature in shallow and deep aquifers (Figure 4B). EC differs significantly (H=21.15, p=<001) and correlates poorly (r=0.001) with temperature (Figure 4C). Current results disagree with Anderson and Ogilbee [5]. Overall, the physical composition of groundwater in the study area indicates water of excellent quality for drinking.

The cation chemistry

Table 2, summarised the cation chemistry of groundwater in

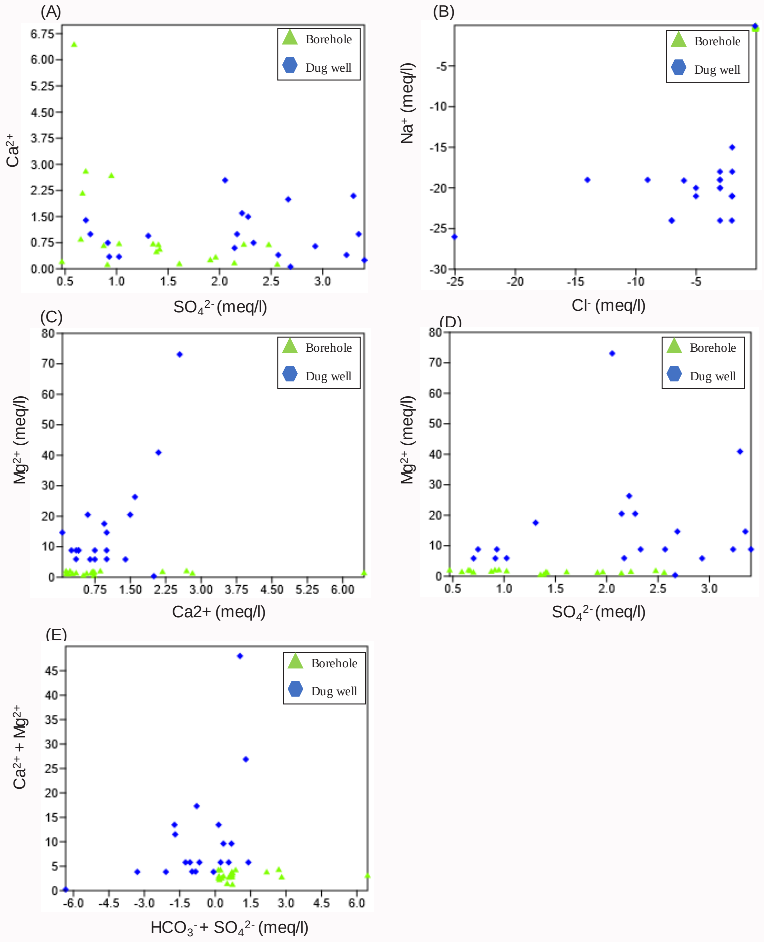

Figure 5: Relationships between cations and anions.

SESB. Potassium concentration differs significantly (H=4.41, p=0.03) between deep and shallow aquifers. Elevated K^+ level in groundwater is associated with toxicity. K^+ in most aquifers is found in low concentrations and excessive intake is not associated with any health hazard [58]. Sodium concentration differ significantly (H=25.41, p=<0.001). Na^+ is regulated in drinking water because of the joint effects it exercises with sulphate. High consumption is associated with hypertension [58]. Na^+ absorption in aquifer is dependent on temperature of the solution and the associated anion. No significant difference in calcium concentration (H=1.29, p=0.25). Elevated Ca^{2+} level is often associated with hardness. No significant difference in Cu^{2+} concentration (H=1.39, p= 0.23). Unpleasant tastes can occur at levels above 1mg/l. Cu^{2+} is not harmful to humans, therapeutic doses of ~20mg/l are occasionally permitted [58]. There is significant difference in Fe^+ concentration (H=8.7, p=0.003). Elevated Fe^{3+} levels in water can be injurious to aquatic animals even though the degree of noxiousness can be reduced by the interactions between other elements. Zinc differs significantly (H=29.37, p=<0.001) between the two aquifers. At concentrations level of about 4mg/l, unfriendly taste can occur. At levels ranging from 3 to 5 mg/l, water might look opalescent and can form an oily film when boiled. There was significant difference in Mg^{2+} concentration (H=22.74, p=<0.001). Mg^+ is the second major constituent of hardness ($CaCO_3$) [58].

Anion chemistry

There is a significant difference in PO_4^{3-} concentration (H=29.48, p=<0.001). The relevance of PO_4^{3-} is mainly related to the rate of eutrophication. Chloride differ significantly (H29.39, p=<0.001). Cl- vary widely in natural waters, reaching a maximum level of ~35,000mg/l. Excessive intake does not constitute health hazard to humans, but at levels above 250mg/l water will taste salty. In arid and semi-arid regions, Cl^- concentrations ~2000mg/l in drinking water is consumed. Elevated Cl^- levels in freshwater may render it unfit for irrigation use [58]. What is important is understanding in a sequence of outcomes from aquifers is that, Cl^- values are not absolute, rather the relative levels from one sampling point to another. Elevated Cl^- levels of ~5mg/l at one location might lead to the suspicion of groundwater contamination from sewage ejection, especially if ammonia levels are also elevated [58].

Bicarbonate differs significantly (H=29.74, p=<0.001). HCO_3^- in conjunction with Ca^{2+} and Mg^{2+} forms carbonate hardness. When groundwater designates high pH concentrations, it can be a sign of high content of carbonate and bicarbonate ions [58]. Sulphate concentrations differ significantly (H=7.99, p=0.004). High SO_4^{2-} in drinking water is associated with emetic effect, particularly when joint together with Mg^+ or Na^+. Nitrate concentration differ significantly (H=5.22, p=0.02). High NO_3^- in groundwater lead to suspicion of past anthropogenic pollution or high application of composts slurries feast over the land and inorganic fertilizers.

Rock mineral/groundwater interactions

The origin of groundwater and the process which control

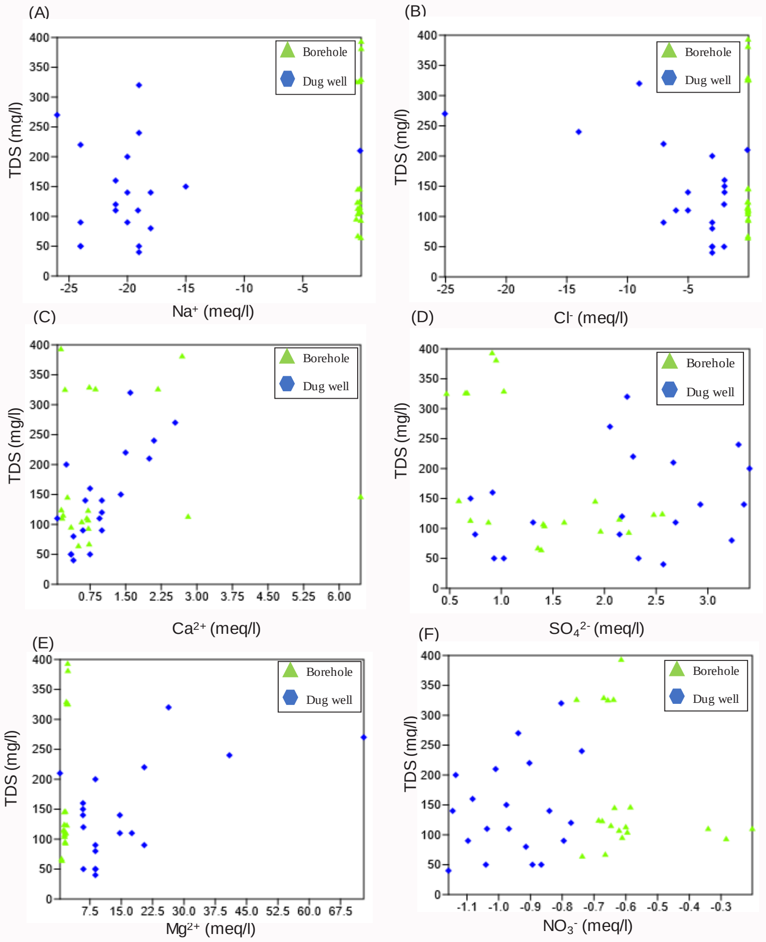

Figure 6: Correlations between cations/anions and TDS.

groundwater chemistry understood by the relationships between dissolved elements (Figure 5). It is assumed that a sizable portion of HCO_3^- in aquifers originate from dissolution of carbonate rocks by means of the action of infiltrating rainwaters enriched in CO_2. Ca-HCO_3^- water type is produced when CO_2 is released in to solution by dissolution of carbonate [28]. HCO_3^- and Ca^{2+} were significantly related (r=0.65) in deep aquifer, suggesting that calcite rocks were source of Ca^{2+}. Significant correlation between Ca^{2+} and SO_4^{2-} (r=0.82) (Figure 5A), indicates that some parts of Ca^{2+} in the deep aquifer is derived from gypsum.

Weak correlation between HCO_3^- and Ca^{2+} (r=0.004) in shallow aquifer, suggest that dissolution of gypsum may not be the source of Ca^{2+} and SO_4^{2-}. Chloride correlates positively but weakly with Na^+ in deep aquifer (r=.0.33) whereas in shallow aquifers there was a significant correlation (r=0.54). Significant correlations between these two ions suggest that Na^+ originates from halite (Figure 5B). Poor correlations (r=0.17, r=0.08), between Ca^{2+} and Mg^{2+} in both deep and shallow aquifers, suggest that the two ions might not have the same origin (Figure 5C). SO_4^{2-} and Mg^+ (r=0.06) were poorly correlated in shallow aquifer, suggesting that the two ions might not have the same origin. Weak correlation between SO_4^{2-} and Mg^+ (r=0.33), suggest that some parts of SO_4^{2-} in deep aquifer originate from the weathering of magnesium-sulphate minerals. A charge equilibrium occurs between cations and anions when Ca^{2+}, Mg^{2+}, SO_4^{2-} and HCO_3^- + SO_4^{2-} originate from simple dissolution of gypsum, dolomite and calcite [28].

Silicate weathering reaction in SESB was evaluated using Na^+/Cl^- molar ratio. About 55% of the analysed water samples from deep aquifer have molar ratio greater than 1 whereas 85% of water samples from shallow aquifer have molar ratio greater than 1. This suggests that some parts of Na^+ was derived from silicate weathering. The process of cation exchange CaRicardo Lozano-Hernández, MgRicardo Lozano-Hernández and NaRicardo Lozano-Hernández designates elevated levels of Na+. When values of molar ratio in aquifers are greater than 1, it informs deficiency [28].

Anthropogenic pollution

Variations of TDS in groundwater informs contamination from anthropogenic sources. Ions$^-$ Na^+, Cl^-, SO_4^{2-} and NO_3- are mainly derived from anthropogenic origins – sewage ejections from municipal and industrial sources as well as application of chemical fertilizer and manure. Correlations between Na^+, Cl^-, SO_4^{2-} and NO_3^- with TDS indicates how anthropogenic activities accelerate changes in groundwater composition [28]. Figure 6, presents correlations between cations/anions and TDS. The latter correlates positively with Na^+, Cl^-, Ca^{2+}, SO_4^{2-}, Mg^{2+} and NO_3^-. Positive correlations between TDS and Na^+ (Figure 6A), informs silicate weathering reaction. However, municipal and industrial sewage, effluents from mining and engineering works can result in to positive correlation between Na^+ and TDS [61]. Positive correlations between TDS and Ca^{2+} and Mg^{2+} (Figure 6C and 6E), indicate input from anthropogenic origins. Positive correlations between TDS and Cl^- and NO_3^- (Figure 6B and

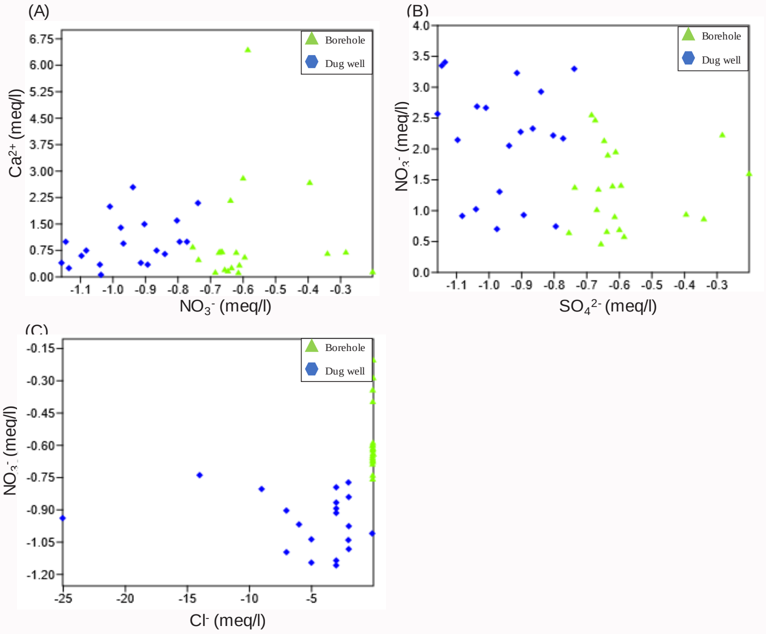

Figure 7: Correlations between NO_3^-, Ca^{2+}, SO_4^{2-} and Cl^-.

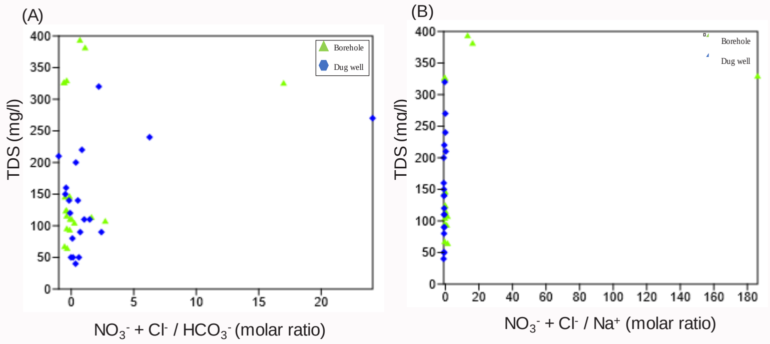

Figure 8: Variation of TDS vs. $(NO_3^- + Cl^-) / Na^+$ and $(NO_3^- + Cl^-) / HCO_3^-$.

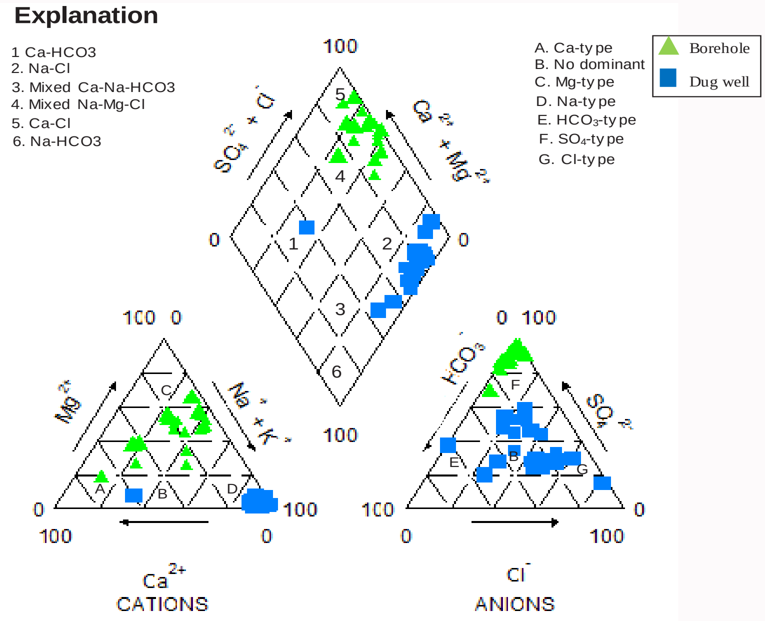

Figure 9: Groundwater classification using Piper trilinear diagram.

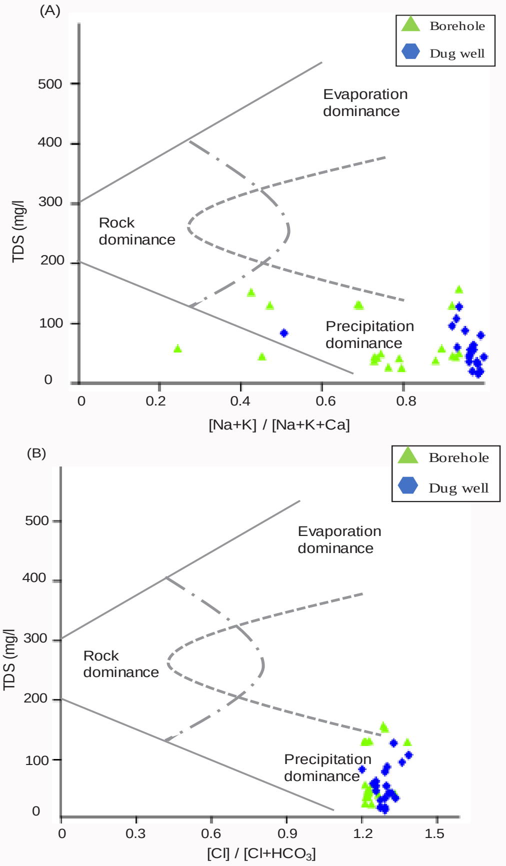

Figure 10: Gibbs plot of sources controlling groundwater chemistry.

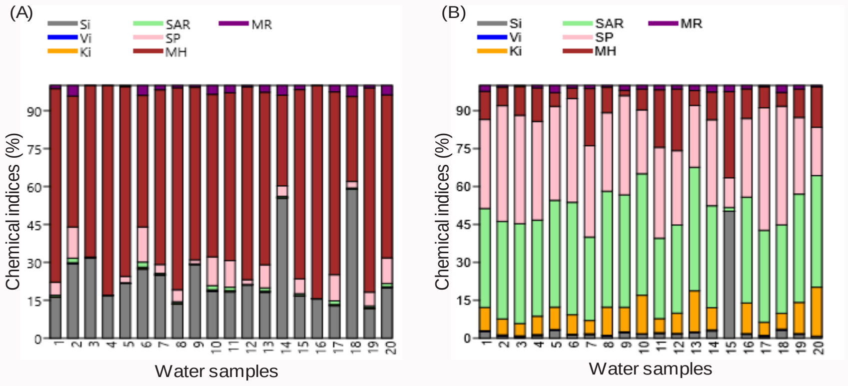

Figure 11: Variability of Chemical indices between (A) Deep aquifer and (B) Shallow aquifer.

6F), is an indicator of contamination from anthropogenic origin. Positive correlations between TDS and SO_4^{2-} (Figure 6D), indicates contamination from anthropogenic origin in the absence of geological inputs. SO_4^{2-} and NO_3^- correlates strongly in the study area suggesting the same origin of the two ions, perhaps derived from anthropogenic activities [61]. Weak correlations between Cl^- and NO_3^- (r=<0.001, r=0.14) in both the shallow and deep aquifers suggest that the two ions might have originated from a different source. Positive correlations between Ca^{2+} and NO_3^- (r=0.43, r=0.69), NO_3^- and SO_4^{2-} (r=0.18, r= 0.04) and Cl^- and NO_3^- (r=<0.001, 0.57) in both shallow and deep aquifers shows that these ions might have originated from the same source (Figure 7). TDS correlates positively with (NO_3^- + Cl^-) / Na + (r=0.20, r=0.04) and (NO_3^- + Cl^-) / HCO_3^- (r=0.10, r=<0.002). Even with the weak positive correlations the molar ratio backs the anthropogenic inputs (Figure 8).

Ion exchange process

Scholler index is used to evaluate ion exchange process. Water samples from both deep and shallow aquifers in the study area have positive Scholler index, suggesting overall base exchange reactions in the study area (Figure 11). In aquifers where alkaline rock minerals are exchanged with Na+ ions (HCO_3 > Ca + Mg) indicates base exchange soft water. Hardened water is formed when Na^+ ions are exchanged with alkaline rocks (Ca + Mg > HCO_3). Versluy's index was positive in shallow and deep aquifers, suggesting overall base exchange reaction in both shallow and deep aquifers of SESB (Figure 11).

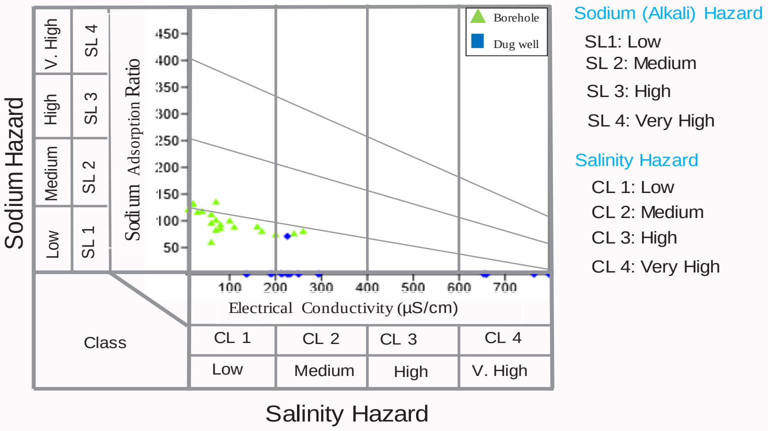

Figure 12: USDA salinity diagram showing irrigation water classification in SESB.

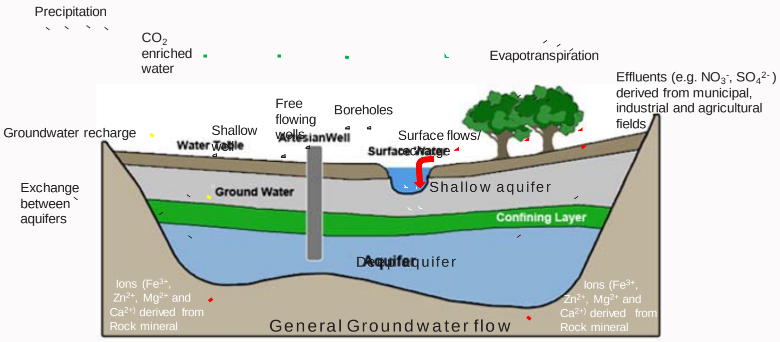

Figure 13: Conceptual schemes affecting hydrochemistry of shallow and deep aquifers **(After Socratic (2017).**

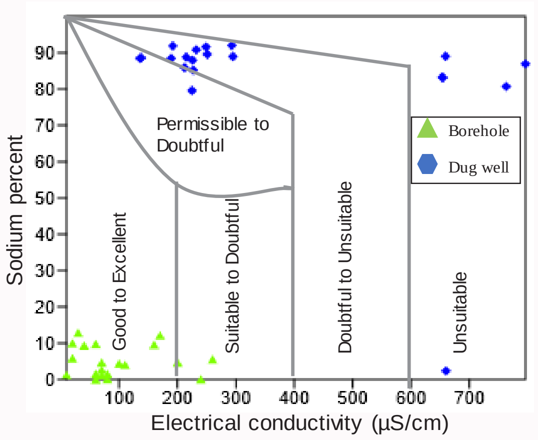

Figure 14: Wilcox plot showing irrigation water classification in SESB.

Hydrogeochemical faeces

The Piper trilinear diagram (Figure 9), shows that groundwater derived from deep aquifer fall in the class of Ca-Mg-SO_4-HCO_3, and Mixed Mg-Na-K water type. Whereas in shallow aquifer, groundwater falls in Ca-Na-K-Cl-HCO_3 and mixed HCO_3-Cl-SO_4 water type. The hydrogeochemical faeces in Sokoto Basin is mainly of two types - Ca–Mg–HCO_3 and Ca-Mg-SO_4–Cl. These faeces perhaps are derived from dissolution of Ca^{2+} and Mg^{2+} carbonates [45].

Mechanism controlling water chemistry

Figure 10, shows Gibb's plot of TDS versus [Na + K] / Na + K + Ca] and [Cl] / [Cl + HCO_3] ratios for cations and anions respectively. Precipitation appeared to be the dominant mechanism influencing groundwater chemistry in SESB. The observed mechanism is perhaps derived from the geography of the study area, which is in Sokoto Basin. Sokoto Basin has Tropical semi-arid climate. Current Finding concurs with Gibbs [50].

Groundwater suitability for irrigation use

Figure 11, summarised the chemical indices of groundwater in SESB. Kelly's index is less than 1 in deep aquifer, whereas, in Shallow aquifer, indices are in greater than 1. Sodium percent is <20 in deep aquifer, whereas 90% of water samples from shallow aquifer has sodium percent >20. Irrigation water having sodium percent greater

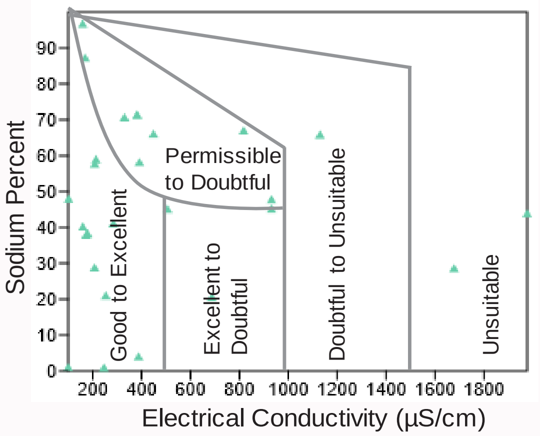

Figure 15: Wilcox plot of irrigation water classification in Sub-Saharan Africa.

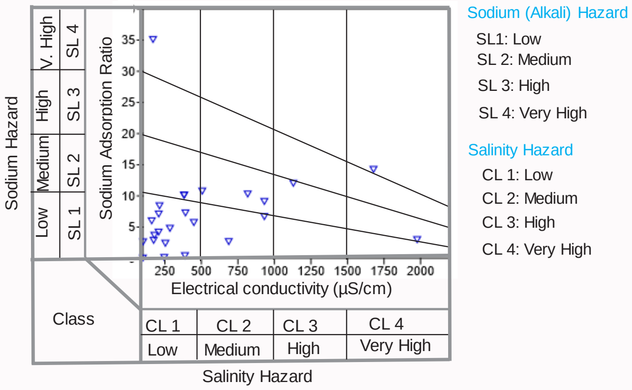

Figure 16: USDA salinity diagram showing irrigation water classification in Sub-Saharan Africa.

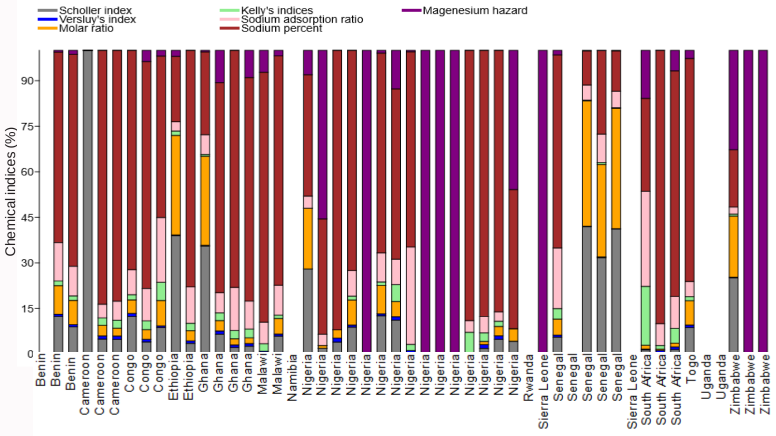

Figure 17: Variability of chemical indices by Country in Sub-Saharan Africa.

than 20 classified as unsuitable for irrigation use [62]. However, 60% of water samples from deep aquifer have MH >50. In contrast, 80% of water samples from shallow aquifer MH <50 (Figure 11). Irrigation water having MH >50 is classified as unsuitable for irrigation use [54,56].

Groundwater classification using USDA diagram indicates that, 35% of samples from deep aquifers fall in low sodium-low salinity class (SL1-CL1), 50% fall in medium sodium-low salinity class (SL2-CL1) and 15% fall in medium sodium-medium salinity class (SL2-CL2). Samples from shallow aquifer fall in low sodium-low salinity class (SL1-CL1) (Figure 12). This water type has no risk of exchangeable Na^+ [53]. However, irrigation water of very low SAR and low salinity (<200µS.m^{-1}) affects the rates of water infiltration into the soils [34]. The observed variability in chemical indices perhaps, resulted from aquifer variability, which slows exchange between deep and shallow groundwater (Figure 13). Dissolved ions in both shallow and deep aquifers are confined to individual aquifers with very slow exchange rates between them. Wilcox plot (Figure 14), showed 90% of groundwater from deep aquifer fall in good to excellent class,

Table 3: Groundwater classification based on TDS.

TDS (mg/l)	Classification	No. of Samples	% of samples
Less than 500	Required for drinking	40	100
500-1000	Acceptable for drinking	0	0
1000-3000	Suitable for drinking	0	0
Greater than 3000	Unhealthy for drinking and irrigation	0	0
Total		40	100

Table 4: Summary of chemical indices of groundwater in highland areas of south-eastern Sokoto Basin.

S/No.	Deep aquifers							Shallow aquifers						
	Si	Vi	Ki	SAR	SP	MH	MR	Si	Vi	Ki	SAR	SP	MH	MR
Sp01	12.8	0.1	0.1	0.5	4.1	60.8	1	6.4	1	23	97.6	87.9	27.8	5.8
Sp02	13.4	0.1	0.1	0.8	5.6	23.6	1.9	1.5	0.9	11.8	71.8	85.2	13.5	1.4
Sp03	15.6	0	0	0	0.1	33.2	0	0.8	0.9	9.2	74.2	80.7	21.5	0.7
Sp04	18.5	0	0	0	0.1	90.8	0	2.2	0.9	16.3	84.5	86.9	29.6	2.1
Sp05	13.8	0	0	0.2	1.6	48	0.3	7.3	1	21	100.7	88.6	13	6.7
Sp06	18.9	0.2	0.3	1.4	9.6	36	2.7	2.4	0.9	16.7	96.1	88.5	9.1	2.2
Sp07	30.8	0.1	0.1	0.6	4.4	85.3	2.1	3	0.9	11.5	72.7	79.6	50	2.6
Sp08	13.4	0.1	0.2	0.7	4.7	79.7	0.9	2.4	1	32.5	133.9	90.8	29.4	2.2
Sp09	24.8	0	0	0.2	1.3	58.1	0.6	4.7	1	21.9	100.4	88.5	4.8	4.3
Sp10	20.9	0.3	0.4	1.9	12.9	72.7	4	5.5	1	55.2	174.6	91.8	30	5.2
Sp11	16.4	0.2	0.2	1.3	9.4	59.6	2.6	4.4	0.9	13.2	76.1	85.9	54.5	4.1
Sp12	15.2	0	0	0.2	1.3	55.1	0.4	4.7	1	24.2	105.5	88.8	73.7	4.3
Sp13	19.9	0.2	0.3	1.4	10	74.9	2.9	8.2	1	61.3	184	92	22.2	7.7
Sp14	20.1	0	0	0.2	1.5	13	1.4	7.4	1	23	105.4	89	28.6	6.8
Sp15	13.4	0.1	0.1	0.6	4.7	60.3	1.3	10.3	0	0	0.3	2.4	7	0.5
Sp16	11.2	0	0	0	0	60.4	0	4.2	1	34.5	119.5	89	33.3	3.9
Sp17	15.2	0.2	0.3	1.8	12.2	85.6	3	1	0.9	8.9	62.4	83.2	14.3	0.9
Sp18	61.9	0	0	0.4	2.7	35.2	4.6	5.4	0.9	11.1	62	83.1	9.7	4.9
Sp19	12.2	0.2	0.2	0.8	5.8	85	1	4.4	1	36.4	126.2	89.5	33.3	4.1
Sp20	19.3	0.2	0.2	1.3	9.8	62.5	3.6	2.9	1	92.9	211.8	91.6	76.9	2.7

Note: SI: Scholler Index; VI: Versluy's Index; KI: Kelly's Index; SAR: Sodium Adsorption Ratio; MH: Magnesium Hazard; MR: Molar Ratio.

Table 5: Groundwater classification based on sodium percent.

Sodium percent	Boreholes		Dug wells		Classification
	No. of Samples	% of samples	No. of Samples	% of samples	
<20	20	100	1	5	Excellent
20-40	0	0	0	0	Good
40-60	0	0	0	0	Permissible
60-80	0	0	1	5	Doubtful
>80	0	0	18	90	Unsuitable
Total	20	100	20	100	

whereas 10% fall in suitable to doubtful class. In contrast, only 10% of water samples from shallow aquifer is permissible for irrigation use.

Implications for Groundwater Quality in Sub-Saharan Africa

Characterization of groundwater in SESB showed marked variability between aquifers. To better understand the composition of groundwater in rest of SSA, data from 50 locations from the literature was compiled (Table 5). Results indicate that 16.7% (n=24) of groundwater in SSA have temperatures above 30oC, 5.0% (n=40) have EC values above WHO reference guidelines (1000µS/cm). About 38.6 % (n=44) of groundwater sources in SSA are acidic to alkaline in nature. Scholler and Versluy's indices were positive, indicating overall base exchange reactions in aquifers underlying SSA [104-107]. Kelly's index is greater than 1 in about 10 locations, indicating water which is unsuitable for irrigation use. Sodium percent is greater than 20 in most locations in SSA. The high rates of sodium, indicate the absence of ion exchange reaction between Ca^{2+} and Na^{2+}. Wilcox plot, indicates that most of groundwater sources in SSA are suitable for irrigation use (Figure 15) [108-110]. Further, classification using

Table 6: Compilation of literature report of physical and chemical properties of groundwater in Sub-Saharan Africa (Values in bold do not follow WHO and NSDWQ reference guidelines).

Country	Location	ºC	EC	pH	TDS	K^+	Na^+	Cl^-	$HC0^{3-}$	Ca^{2+}	Cu^{2+}	Fe^{3+}	Zn^2	Mg^{2+}	NO_3^-	SO_4^{2-}	PO_4^{3-}	Source
Benin	Lagbe		282.5	**5.6**				28.9							26.1	1		[64]
Benin	Coastal lower aquifer (P15)		931	7	491	22.6	**76**	69.2	209	47.5		0.3		**11.1**	10.7	45.3	BD	[65]
Benin	Coastal upper aquifer (U23)		931	6.9	245	4.8	**43.7**	42.4	81.7	21.8		0.4		**7.9**	5.9	36.8	BD	[65]
Cameroon	Semi-urban Douala		164.6	**4.7**		3.7		16.7	12.9	9.3				1.4		14.2		[66]
Cameroon	Douala		101	**6.3**		1.8	4.9	3.5	55	16				2.4	1.7	10.2		[67]
Cameroon	Banana Plain	27.6	173.3	**5.8**	147.6	5.5	6.8	5.6	75.6	11.4				**5.5**	17.3	8		[68]
Congo	Brazzaville		253.5	**5.2**	135.7	20.2	10.8	20.2	31.9	16				**8.5**	1.8	7.8		[69]
Congo	Brazzaville (Wet season)		213.5	**4.7**	111.2	7.9	**31.4**	13.5	38.9	20.2		0.4		**12.5**	1.4	9.7		[70]
Congo	Brazzaville (Dry season)		169.1	**4.6**	89.8	5.4	**125.1**	12.3	36.9	16.5		0.4		**9.1**	1.4	8.3		[70]
Ethiopia	Wollega Zone		381.8	6.6	232.5	4.1	**21.7**	4.3	245.2	35.6		0.3		0.2	0.5	16.1		[71]
Ethiopia	Tigray	18.6	817	6.9	393.5	0.9	**50.3**	23.8	**420.4**	94.2				**17.3**	1.4	66.2		[72]
Ghana	Ga East	22.5	505.9	**5.7**	257.6	24.5	**116.6**	116.2	68.4	3.6		0.9	0.03	**2.4**	**302.8**	36.3		[73]
Ghana	Obuasi		178..4	**5**	146	8.6	9.6	6.4	76.7	9.2		0.4		**5**			**1**	[74]
Ghana	Densu Basin	28.9	**1129.5**	6.7		4.8	**64**	28.3	191.5	45.3				**37.4**	0.04			[75]
Ghana	Northern Ghan		391	6.7	214.4	6.5	**22.9**	9.2	199.2	16		0.7		**14.8**	37.9	6.6		[76]
Malawi	Zombawa-Phalombe Plain		448.5	6.8			**16.8**	8.1		15		0.5			4.2	0.7		[77]
Malawi	Basement aquifers		687.2	7.1	378.9	3.9	**26.2**	96	175.4	3.9		0.5		**19.3**	0.4	16.2		[78]
Namibia	Windhoek	24	24	7.8	161			24		11				**11**	0.3	4.9		[79]
Nigeria	Port Harcourt	27.7	245.8	7.7	145.5	0.5	1.6	161.5	16.7	3	0.1	0.3	**0.7**	3.2	3.2	68.8	**0.3**	[80]
Nigeria	Kaltungu		387.6	7.9	221.5	5.4	3.6	74	**342.6**	62		**4.7**		**49.8**	**103.6**	23.2		[81]
Nigeria	Ede Area		330	**5.8**		4.8	11.6			26				**5.5**		7.2		[82]
Nigeria	Akur		284.6		142	1.6	**31.6**	43.5	223	27.3				**6.7**				[83]
Nigeria	Akwa Ibom	29.2	10.5	**4.6**	4.5			0.2		72	0.1	0.1	BD	**24**	BD	3	BD	[84]
Nigeria	Ibadan	27.6	207.2	**6.2**	349.3	12.5	**37.5**	79.5	69.8	19.5		0.3		**9.1**	14	29.5	0.2	[85]
Nigeria	Konduga		160	7.1	80	11	8.9	2	218.3	6.5		0.2		2.5	2.3	1.2		[86]
Nigeria	Patigi	32	**1678**	6.7	460	312	**230**	**260**		268	0.9	0.4	**2**	0	0.3	**500**		[87]
Nigeria	Kaduna,	22.1	5	6.5	500					200	0.1	1	5	0.2			**5**	[88]
Nigeria	Kaduna		351	6.5	0.3			50			0.6	**1.7**					**3.9**	[89]
Nigeria	Lagos State		628.6	6.5	321.9			70.8				0.6	8.6	**25.1**				[90]
Nigeria	Calabar	27.5		6.9			2.1	0.3								1.7		[91]
Nigeria	Sokoto-Rima (Dug well)					4	4	3.7	6.4	0.64				**11.3**	12.2		**23.5**	[34]
Nigeria	Sokoto-Rima (Borehole)					1.1	2.1	3.7	4.4	0.8				1.9	8.3		**6.4**	[34]
Nigeria	Uyo	26.9	99.7	**4.2**	47.3		0.1	8.7		0.5	0.3	0.1	BD	1				[92]
Rwanda	Huye	21.8	87.3	6.9							0.02	0.3			6.5	1	**1**	[93]
Sierra Leone	Bombali -IDA	27.5	88.3	7.2	41.9			10		12	0.05	0.2				2		[94]
Senegal	Linguere	39.5		7	**789.1**	8	**140**	33	245.2	48.6		0.6		**22**		290		[95]
Senegal	Thiaroye area							182		68					**310.5**	45		[96]
Senegal	Diourbel	39.1		7.9	**1534.7**	8	**480**	**500**	**492.9**	4.1		**4**		2.7		43		[95]
Senegal	Kaffrine	37		7.9	**932.9**	11	**274**	**224**	**360**	13.6		0.3		**4.6**		45.1		[95]
Senegal	Kaolack	39		7.7	**1262**	15.6	**400.2**	**386.2**	**390.4**	11.2		2.9		2.7		52.8		[95]
Sierra Leone	Bombali-Msorie	28.2	336	6.9	168			32		4	0.3	0.02				2		[94]
South Africa	Western Karoo	18.6	159	7.3	**1053**	2.7	**159.4**	1.3	**312.8**	107.2	0.01	1.3	0.1	**40**	4.7	147.8		[97]
South Africa	North mine					1.1	10.9	36.3	**330.4**	172.2				**96.6**	2.1	0		[98]
South Africa	Eastern Cape		381.8	6.6	232.5	4.1	**21.7**	4.3	245.2	35.6		0.3		**18.3**	0.5	16.1		[71]
Togo	Gulf region aquifer	27.2	1977	6.2	**992.8**	0.8	10.6	12.5	2.6	2.3		0.2		2.2	0.9	2.3		[99]
Uganda	Kampala city	24.3	102	**4.6-5.6**				12.4						**26**				[100]

Uganda	Kampala	21.8	26	**4.7**				2.5							2			[101]
Zimbabwe	Harare (Well 11)		208	6.6		6	**24.6**			0.4	0.07	**12**	**0.4**	0.4				[102]
Zimbabwe	Harare (BH 1)		**1920**	**5.8**				7.9				**11**	0.06		16.6			[102]
Zimbabwe	Matsheumhlope well field	23.4	**1179**	7				151			0.01	1.2			0.04	143	**1.6**	[103]
Reference guidelines		-	1000	6.5-8.5	500	-	12	200	250	75-200*	2	0.3	4	0.3-0.5*	50	200	0.2	**WHO (2011)**
Reference guidelines		-	1000	6.5-8.5	500	-	12	200	250	-	1	0.3	3	0.2	50	100	0.2	**NSDWQ (2007)**

Note: *= EPA (2001).

Table 7: Summary of chemical indices of groundwater in Sub-Saharan Africa.

Country	Location	Si	Vi	Ki	SAR	SP	MH	MR
Benin	L1	ND	ND	ND	ND	ND	ND	ND
Benin	L2	8.9	0.5	1.1	9.1	45.2	0.4	6.8
Benin	L3	6.1	0.5	1	6.7	47.9	0.9	5.5
Cameroon	L4	2.6	ND	ND	ND	ND	ND	ND
Cameroon	L5	2.8	0.6	1.4	2.6	48	ND	2
Cameroon	L6	2.2	0.5	1.2	2.9	38	ND	1.2
Congo	L7	3.6	0.3	0.5	2.4	21.1	ND	1.3
Congo	L8	3.1	0.7	2.3	8.4	59	2.9	2.5
Congo	L9	14.3	0.9	9.9	35.1	87.4	3.1	13.7
Ethiopia	L10	129	0.8	4.7	10.1	71.4	6.5	108.5
Ethiopia	L11	3	0.7	2.1	10.3	67.1	0	2.9
Ghana	L12	58.8	0.5	1	10.8	45.2	0.8	48.6
Ghana	L13	3.6	0.6	1.4	3.7	38.4	5.9	1.9
Ghana	L14	1.8	0.7	2.3	12	65.9	0	1.7
Ghana	L15	2	0.7	2.3	7.3	58.3	7.1	1.5
Malawi	L16	0	0.7	2	5.7	66.1	5.8	ND
Malawi	L17	1.6	0.2	0.3	2.7	20.7	0.5	1.4
Namibia	L18	ND	ND	ND	ND	ND	ND	ND
Nigeria	L19	0.7	ND	ND	0.1	1	0.2	0.5
Nigeria	L20	0.2	ND	ND	0.4	4.1	6	0.1
Nigeria	L21	3	1	ND	ND	70.7	ND	2.1
Nigeria	L22	5	0.4	0.7	4.8	41.2	0	4.7
Nigeria	L23	ND	ND	ND	ND	ND	33.3	ND
Nigeria	L24	5.5	0.3	0.5	4.2	28.9	0.4	4.1
Nigeria	L25	8	0.8	4	6	40.3	9.1	3.6
Nigeria	L26	ND	0.5	0.9	14.3	28.7	0.2	ND
Nigeria	L27	ND	ND	ND	ND	ND	100	ND
Nigeria	L28	ND	ND	ND	ND	ND	3.3	ND
Nigeria	L29	ND	ND	ND	ND	ND	0.8	ND
Nigeria	L30	0	0	7	3.8	87.5	0	ND
Nigeria	L31	0.7	0.5	1.1	2.1	34.2	0	0.4
Nigeria	L32	1.7	0.4	0.6	1.1	30.4	0	1.1
Nigeria	L33	0.1	0	0	0	1.1	1.1	0.1
Rwanda	L34	ND	ND	ND	ND	ND	ND	ND
Sierra Leone	L35	0	0	0	0	0	2	0
Senegal	L36	6.7	0.8	4.2	24.2	77.1	1.8	6.4
Senegal	L37	ND	ND	ND	ND	ND	ND	ND
Senegal	L38	180.7	0.5	1	21.4	48.4	0.8	177.8
Senegal	L39	62	0.5	1.2	18.3	53.8	0.1	59.6
Senegal	L40	154	0.5	1	20.3	49.7	0.7	148.2
Sierra Leone	L41	ND	ND	ND	ND	ND	ND	ND
South Africa	L42	4.1	1	61.3	98.9	96.8	50	4
South Africa	L43	0.1	0.2	0.3	1.8	22.6	0	0.1
South Africa	L44	1.4	0.8	4.7	10.1	71.4	6.5	1.2
Togo	L45	5.2	0.5	0.8	3	44	1.6	4.8
Uganda	L46	ND	ND	ND	ND	ND	ND	ND
Uganda	L47	ND	ND	ND	ND	ND	ND	ND
Zimbabwe	L48	76.5	0.7	2.1	7.1	57.7	100	61.5
Zimbabwe	L49	ND	ND	ND	ND	ND	58.2	0
Zimbabwe	L50	ND	ND	ND	ND	ND	0.8	ND

Note: SI: Scholler Index; VI: Versluy's Index; KI: Kelly's Index; SAR: Sodium Adsorption Ratio; MH: Magnesium Hazard; MR: Molar Ratio; ND: No Data.

USDA diagram showed that groundwater in SSA, fall in low sodium-low salinity class (SL1 – CL1) (Figure 16). However, some parts of Na^+ in groundwater aquifers across SSA were not derived from silicate weathering, because Molar ratio is greater than 1 in most locations. Therefore, groundwater in SSA is not deficient in Mg^{2+} + Ca^{2+}. As a result, groundwater sources may be hard in most parts of the continent. Magnesium hazard is less than 50 in most locations. Figure 17, illustrates variability of chemical indices by country in SSA [111-115].

Conclusion

The hydro chemical characterization of groundwater in highland areas of Sokoto Basin revealed that Fe^{3+}, Zn^{2+}, Mg^{2+}, Na^+, PO_4^{3-} and SO_4^{2-} concentrations are above WHO and NSDWQ reference guidelines. Groundwater in SESB is acidic to alkaline in nature. The alkali (Na^+ and K^+) did not significantly exceed alkaline earths (Ca^{2+} and Mg^{2+}) and the strong acids (Cl^- and SO_4^{2-}) did not significantly exceed weak acid (HCO_3^- and CO_3) in deep aquifer. This results in to Ca-Mg, SO_4-HCO_3 and Mixed Mg-Na-K water type. In shallow aquifer, the alkali earths (Na^+ and K^+) significantly exceed alkaline earths (Ca^{2+} and Mg^{2+}) and the strong acids (Cl^- and SO_4^{2-}) significantly exceed weak acid (HCO_3^- and CO_3), which result in to Ca-HCO_3-Na-Cl and mixed HCO_3-SO_4 water type. Correlations between TDS and ions in addition to variations in TDS between sampled sites are evidence of anthropogenic input to groundwater contamination.

Groundwater classification using U.S salinity diagram showed most water samples fall within SL1 – CL1 class in deep aquifer, whereas in shallow aquifer, most water samples fall SL1- CL2 class. Sodium percent is generally less than 20 in deep aquifer and Kelly's index is less than 1. In contrast, sodium percent is greater than 20 and Kelly's index is greater than 1 in shallow aquifer. Results further indicates that 65% of water samples from deep aquifer have Magnesium hazard greater than 50, whereas 90% of water samples from shallow aquifer have MH less than 50. MH values greater than 50 indicates water, which is unsuitable for irrigation use. Synthesis of groundwater properties from the literature indicates that most of groundwater sources in SSA are suitable for human consumption and irrigation use. The study concludes that, while groundwater composition in Sokoto Basin vary with aquifer depth, it suitability for drinking and irrigation remain the same.

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