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Variation of groundwater depth and cation concentrations with CBRs of residual soils: Case study of three lithologic terrains from North-central Nigeria

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ABSTRACT

Twenty nine (29) water samples and 24 soil samples were collected from three lithologic terrains. The waters were subjected to Atomic Absorption Spectrophotometer (AAS). The soils were subjected to California Bearing Ratio (CBR) tests. The AAS revealed that water from gneiss/schist terrain have mean Ca^{2+}, Na^{+}, Mg^{2+} and K^{+} concentrations of 25.09, 13.14, 10.92 and 3.90 mg/l respectively; water from granite terrain have mean Ca^{2+}, Na^{+}, Mg^{2+} and K^{+} concentrations of 13.68, 6.39, 5.45 and 2.78 mg/l respectively while water from sandstone terrain have mean Ca^{2+}, Na^{+}, Mg^{2+} and K^{+} concentration of 7.82, 1.61, 1.41 and 2.16 mg/l respectively. The CBR tests revealed that the soils from gneiss/schist terrain have mean soaked and unsoaked CBRs of 12.37% and 13.75% respectively; soils from granite terrain have mean soaked and unsoaked CBRs of 35.25% and 65.53% respectively; while soils from sandstone terrain have mean soaked and unsoaked CBRs of 78.13% and 104.13% respectively. Results revealed that terrains of shallow groundwater depth are characterized by low CBRs and vice versa. This work has shown that the variation existing between the groundwater cation concentrations and overlying residual soil CBRs is based on the intrinsic properties of the lithology that formed the soil and that is hosting the groundwater.

1. Introduction

Groundwater cationic concentration is a major aspect of groundwater geochemistry. To some extent, groundwater geochemistry is a manifest of the mineralogy and weatherability of the water-bearing lithology/aquifer (Hanshaw and Back, 1979). For instance, Garrels (1976) and Datta and Tyagi (1996) had shown that the concentration of Ca^{2+} and Mg^{2+} in groundwater results, primarily from the gradual weathering of carbonate minerals (like dolomite and calcite) and alkaline earth silicate minerals (like anorthite and pyroxene) making up the aquifer. Groundwater contained in aquifer of complex mineralogy and high weatherability is expected to have higher ionic concentrations than groundwater contained in aquifer of few mineralogy and low weatherability. In addition, the ionic concentration of groundwater controls its physiochemical properties like hardness, electrical conductivity and pH. Groundwater hardness is commensurate with the Ca^{2+}, Fe^{2+} and/or Mg^{2+} concentrations, which emanate from the weathering of carbonate and ferromagnesian silicate minerals while electrical conductivity is a relative indication of the presence of ions like Na^{+}, Ca^{2+}, Mg^{2+}, K^{+}, Cl^{-}, SO_4^{2-}, CO_3^{2-} emanating from dissolution of some salts contained in the aquifer (Freeze and Cherry, 1979; CWT, 2004; Bhattacharya et al., 2008).

Parts of this water-bearing lithology (aquifer) exposed to weathering agents usually degrade to residual soil which can serve as pavement subgrade, base/sub-base or filling materials for different civil engineering facilities. The suitability of the soil to satisfactorily serve for the above stated purposes has always being assessed based on some of its (soil) geotechnical properties like California Bearing Ratios (CBRs), shear strength and Atterberg limits (FMWH, 1997; Braja, 2006; ASTM D3080/D3080M-11, 2011; Oyelami and Alimi, 2015; ASTM D1883-16, 2016). CBR is a check of soil mechanical stability; shear strength is used to determine the resistance of soil to shearing stress while Atterberg limits are important for classifying fine-grained soils. Works by Ampadu (2007), Datta and Chattopadhyay (2011) and Roshani et al. (2015) have shown that the stated geotechnical properties are dependent not only on the soil intrinsic properties like soil type and density but on the

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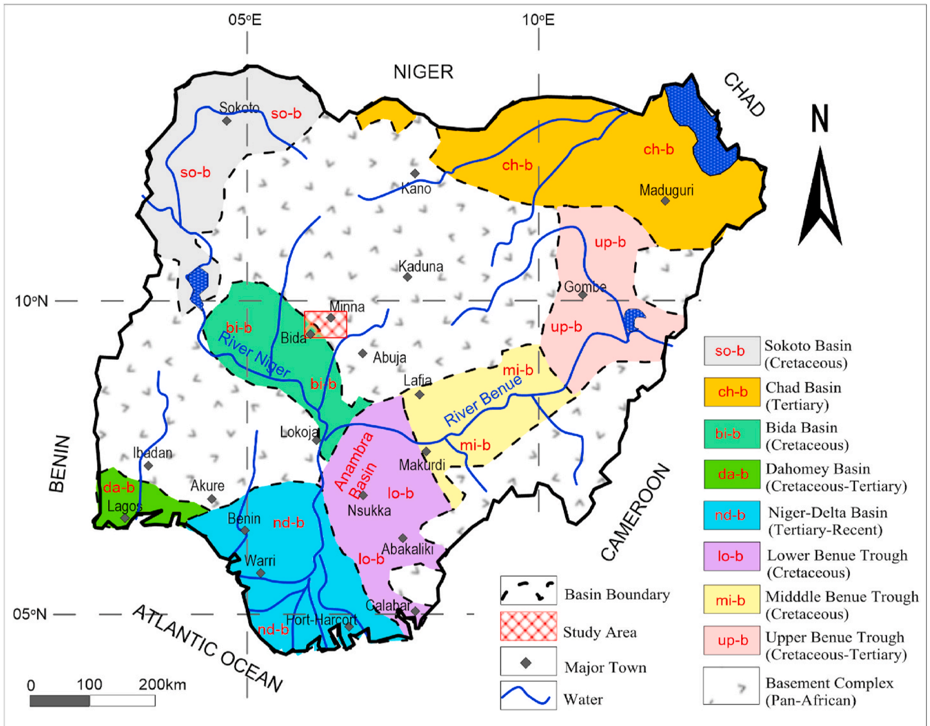

Fig. 1a. Geological Map of Nigeria showing the Study Area (modified after Obaje, 2009a,b).

groundwater parameters like its geochemistry and water table.

Groundwater can affect the overlying soil through capillary rise, which is inversely proportional to the soil grain size and dependent on the groundwater table (depth) at the time of the rise (Pal and Varade, 1971; Akujieze, 1984; Garg, 2011). Thus, the geochemistry of groundwater can affect the chemical and/or physical properties of capillary/soil water which in turn contributes to the geotechnical properties of the soil. Uma (1985) and Nwajide et al. (1988) have shown that the influx of groundwater or formation of perched aquifer (due to heavy precipitation) in soil regolith reduces the shear strength of the soil. Furthermore, in brackish shallow groundwater terrains, increase in groundwater table and capillarity can bring the capillary fringe close enough to the surface that the capillary water is evaporated resulting to saline soil, which manifests in degrading the stability of the soil (Hillel, 2004; Rengasamy, 2006 and 2008). The presence of some cations in capillary water has adverse effect on the soil mechanical stability. The concentration of Fe^{2+}/Fe^{3+} in capillary water enhances the ferruginization and lateralization of the soil while ion exchange reactions of Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} in soil water results to the concentration of Na^{+} in the soil causing changes to the soil permeability and reduction in its competency (Rosfjord et al., 2007; Lori, 2007; Hiscock, 2005). The reaction results in displacement of the Ca^{2+}, Mg^{2+}, K^{+} which percolate through the soil and altering the geochemistry of the groundwater. Thus, both percolation and capillary movement of water through the soil have either or both chemical and physical effects on the soil and/or groundwater especially in cases where it is the water-bearing lithology (aquifer) that also formed the soil.

As common factors contribute to both the groundwater geochemistry and soil geotechnical behaviour, there should be a relationship between the groundwater geochemistry and the soil geotechnical characteristics. The present work is aimed at evaluating such relationship. A work prompted by the incessant failure of some major road portions and shallow water tables occurring in an area within North-central Nigeria. Results of this work could be relevant in relating the variations of groundwater depths and cationic concentrations with the geotechnical behaviour of the residual soils of the lithology bearing the water.

2. Regional geology and hydrogeology

The study area, located between latitudes 9°05′N and 9°36'N and longitudes 6°01′E and 7°00′E of North-central Nigeria, is underlain by gneiss, schist and granites of the Pan-African Nigerian Basement Complex and Campanian Bida Sandstone of the Bida Basin (Fig. 1a). Pan-African Basement Complex formed as a result of the global Pan-African tectaonic event giving rise mostly to gneiss, schists and granites (Ofoegbu, 1983; Rahaman, 1988; Obaje, 2009a,b). The gneiss and schist, which were reconstructed as having formed simultaneously, co-occur and are separate from the granite. Consequently, gneiss and schist are regarded as one unit in the present work. These Basement Complex rocks (gneiss/schist and granite) host groundwater within their fractured (joints and faults) and weathered zones.

Mineralogically, the Basement Complex gneiss is composed mostly of orthoclase, biotite, quartz, microcline and andesine/oligoclase; the schist is composed mostly of biotite, muscovite, quartz, hornblende and chlorite while the granite is composed mostly of quartz, muscovite, biotite and plagioclase (Obiora, 2005). Amongst these Basement rocks, gneiss and schist, which contains less stable minerals and foliated in texture, are more susceptible to chemical/mechanical breakdown and dissociation of their minerals than the granites, which contains more stable minerals and graphic in texture. Gneiss/schist being low-high grade regional metamorphosed rocks of pelitic/mudrock protoliths, contains lower stable minerals that are more susceptible to chemical weathering than granite that are acidic igneous rock composed of mostly stable minerals that have low susceptibility to chemical weathering (Goldich, 1938; Ekwueme, 1993; Obiora, 2005; Railsback, 2006). Also, considering that foliation is an aspect of rock anisotropy (variations in rock physic-mechanical properties), it (foliation) plays important role in the development of weathering profile and subsequent advancement in chemical weathering of rocks (Dobereiner et al., 1993; Marques et al., 2010; Dobereiner et al., 1990). In other words, foliation enhances the gradual permeation of weathering agent (water) into the rock unlike in the case of non-foliated rocks such as granite. In addition, foliated schist, which is low-medium grade metamorphic rock and lower mechanical strength, is more susceptible to mechanical weathering than granite, which is an acidic igneous rock and of higher mechanical strength (Brown, 1981; Hoek and Brown, 1997; Nasseri et al., 2003; Ukaegbe, 2011; Ozbek et al., 2018). By implication, in the Basement Complex containing schist and granite, schist is expected to weather faster to residual soil than granite.

Bida Basin is a NW-SE trending Basin which is regarded as the Northwest extension of the Anambra Basin (western part of Lower Benue Trough, see Fig. 1a). Both Bida and Anambra Basins were major depocentres of the Benue Trough. The Benue Trough evolved as third failed arm of a triple rift system in the Neocomian/early Gallic Epoch during the separation of South American plate from African plate; which also gave rise to the Gulf of Guinea and South Atlantic (Grant, 1971; Burke et al., 1971; Adeleye, 1974). The rift formed due to violent mantle plume upwelling that resulted in stretching, uplift, faulting and subsidence of the major crustal blocks in Aptian/early Albian Stage (Olade, 1975). The Benue Trough experienced a Santonian tectonic event that resulted in fracturing, uplifting, folding and eventual formation of the Anambra and Bida Basins (Nwachukwu, 1972; Ofoegbu, 1983). In the Campanian-Maastrichtian Stage, the Bida Basin received its first phase sediments - Bida Sandstone, which has Mamu Formation (of Anambra Basin) as its lateral equivalent (Ojo and Akande, 2003). Obaje et al. (2011) and Ojo (2012) reported that the Bida Sandstone is composed mostly of poorly-sorted pebbly arkosic and quartzose friable sandstone with little claystone and siltstone. This friable nature of the sandstone makes it a good aquifer of high primary porosity and good permeability. Works by Shekwolo (1990), Olaniyan and Oyeyemi (2008), Olabode et al. (2012) and Idris-Nda et al. (2013) reveals that the Bida Sandstone aquifer, underlying the study area, is in unconfined/semi-confined condition. Bida Sandstone hosts groundwater in its connected pores. As Bida Sandstone is sedimentary rock of Basement Complex protolith, it (Bida Sandstone) is composed of mostly minerals that are more chemically stable than minerals of the Basement Complex rocks.

3. Climate

According to Koppen's climatic classification system, North-central Nigeria is located in the tropical savanna climatic region which is characterized by dry and wet seasons (Kottek et al., 2006; Peel et al., 2007). The dry season occurs from October to March with daily temperatures ranging from 19 °C to 37.5 °C and daily precipitation ranging from 0 mm to 1 mm while the wet season occurs from April to September with daily temperatures ranging from 21 °C to 35.7 °C and daily precipitation ranging from 4 mm to 17 mm. It is conventional that, owing to reduced infiltration during the dry season; the groundwater depth increase (water table decreases) more during the dry season than during the wet season.

4. Study methodology

4.1. Sampling

Twenty-nine (29) water wells consisting of twenty-three (23) hand-dug wells and six (6) boreholes were mapped in the three lithologic terrains viz: gneiss/schist, granite and sandstone terrains. These terrains coincide with the Pan-African Nigeria Basement Complex gneiss/schist and granite and Campanian Bida Sandstone. Nine (9) hand-dug wells and two (2) boreholes were mapped in the gneiss/schist terrain; eight (8) hand-dug wells and one (1) borehole were mapped in the granite terrain while six (6) hand-dug wells and three (3) boreholes were mapped in the sandstone terrain. The wells mapped border a road. Some portions of the road are characterized by incessant failure while other portions are stable over long period; an observation that eventually led to the present work. Care was taken that water wells occurring close to dumpsite, mechanic workshops or rivers were not mapped as such wells are susceptible to contamination from dumpsite leachate and/or domestic/industrial effluents. Seasonal groundwater depths were determined from the twenty-three (23) hand-dug wells using a water level meter and water samples were collected from each of the twenty-nine (29) water wells. The groundwater depths were determined in the months of January and July that are the peak periods of the dry and wet seasons respectively. The measurements and collection of water samples were done early in the morning when there is maximum recharge, zero abstraction and minimum contamination of the groundwater due to abstraction. Each of the water samples was collected using a clean labelled 1-L plastic water bottle which was double-rinsed with the same sampled water before the collection to avoid contamination from the bottle. The bottled samples were transported to the laboratory within 24 h for assessment of relevant cationic concentrations and physiochemical properties.

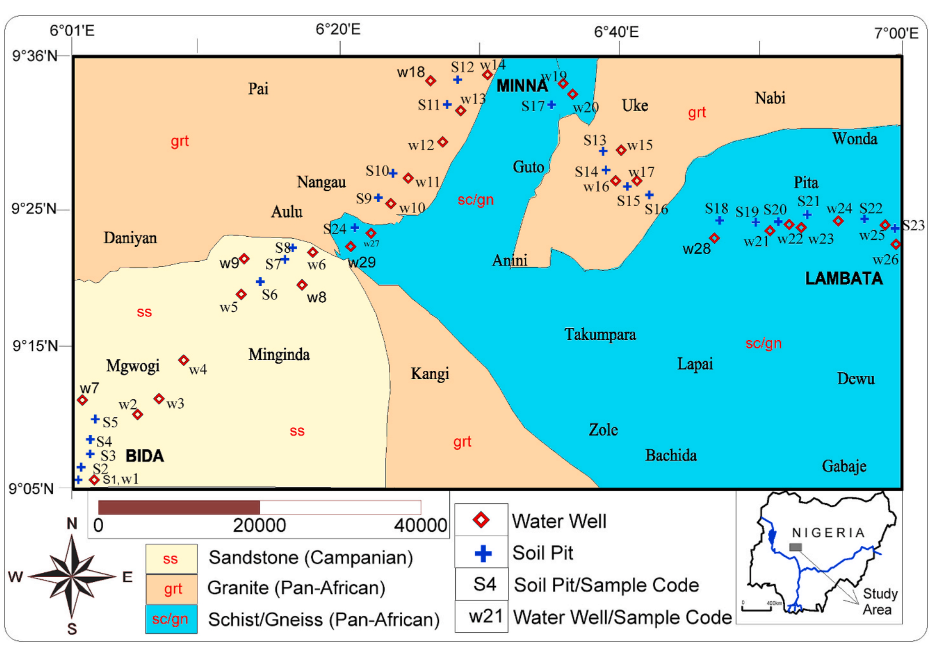

Fig. 1b. Spatial distribution of the water wells and soil pits from where the water and soil samples were taken.

Table 1
Ground elevation, seasonal water tables of the water wells and cation concentrations of the water samples.

s/n	Terrain	Well type	Sample code	Ground Elevation (m)	Water Table (m)		Cationic Conc. (mg/l)			
					Wet season	Dry season	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
1	Schist/gneiss	BH	w29	NA	NA	NA	13.2	8.1	6.0	2.00
2	Schist/gneiss	BH	w28	NA	NA	NA	36.9	8.8	17.0	6.00
3	Schist/gneiss	HDW	w27	131	128.2	126.2	18.1	6.6	15.0	6.03
4	Schist/gneiss	HDW	w26	446	443.5	440.6	27.3	13.7	11.5	2.01
5	Schist/gneiss	HDW	w25	472	470.8	467.4	26.1	15.6	21.0	7.37
6	Schist/gneiss	HDW	w24	399	395.0	390.2	32.9	23.9	14.5	5.36
7	Schist/gneiss	HDW	w23	359	355.0	352.1	45.3	17.3	22.5	7.37
8	Schist/gneiss	HDW	w22	369	359.0	355.2	18.1	11.2	8.0	1.34
9	Schist/gneiss	HDW	w21	362	352.9	348.2	11.2	1.5	13.5	0.67
10	Schist/gneiss	HDW	w20	202	200.5	197.5	13.2	6.1	7.5	2.01
11	Schist/gneiss	HDW	w19	241	239.3	235.9	33.7	7.3	8.0	2.70
	Mean						**25.09**	**10.92**	**13.14**	**3.90**
12	Granitic	BH	w18	NA	NA	NA	18.1	5.37	1.5	6.80
13	Granitic	HDW	w17	302	299.4	298.0	10.8	2.9	6.5	0.70
14	Granitic	HDW	w16	304	301.5	299.8	19.7	0.7	7.5	2.00
15	Granitic	HDW	w15	303	302.9	300.6	18.1	4.2	3.5	3.40
16	Granitic	HDW	w14	237	229.0	228.1	12.8	16.4	6.5	2.00
17	Granitic	HDW	w13	239	236.3	233.5	9.6	7.1	7.0	2.70
18	Granitic	HDW	w12	224	221.8	219.1	15.2	2.9	8.0	2.70
19	Granitic	HDW	w11	189	181.4	180.0	10.4	6.1	9.5	3.40
20	Granitic	HDW	w10	180	174.0	173.3	8.4	3.4	7.5	1.30
	Mean						**13.68**	**5.45**	**6.39**	**2.78**
21	Sandstone	BH	w9	NA	NA	NA	3.2	1.2	2.0	3.40
22	Sandstone	BH	w8	NA	NA	NA	15.6	2.7	1.5	0.70
23	Sandstone	BH	w7	NA	NA	NA	5.2	0.2	1.5	4.70
24	Sandstone	HDW	w6	155	149.8	149.3	13.2	3.2	2.0	1.34
25	Sandstone	HDW	w5	131	117.9	116.7	5.2	1.0	2.0	1.30
26	Sandstone	HDW	w4	108	94.6	94.0	5.6	1.2	2.5	3.40
27	Sandstone	HDW	w3	105	94.6	93.9	7.6	0.2	1.0	1.30
28	Sandstone	HDW	w2	119	108.9	107.2	8.8	2.0	1.0	1.30
29	Sandstone	HDW	w1	201	196.3	195.9	6.0	1.0	1.0	2.00
	Mean						**7.82**	**1.41**	**1.61**	**2.16**

HDW=Hand-dug well, BH=Borehole, NA=Not Applicable.

Twenty-four (24) pits, evenly distributed within the three lithologic terrains, were dug to a depth range of 50–70 cm from which soil samples were collected. The pits were dug to this depth range to ensure that the soil samples to be collected were in situ residual soil. Caution was taken to dig the pits at close lateral range to the water wells. However, any pit containing up to 50% of grains greater than 76.2 mm (gravel) was abandoned and another pit dug in its replacement from which the soil sample was collected. It means that some of the pits were not close to any water well. The soil samples were preserved in labelled plastic bag for analyses. Spatial distribution of the water wells and soil pits from where the water and soil samples were taken is shown in Fig. 1b.

4.2. Laboratory analyses

The cations determined for the water samples are calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}) ions while the physiochemical properties determined are total hardness, alkalinity and electrical conductivity. The concentration of the cations were determined with Perkin – Elemer AAS 3110 following the Atomic Absorption Spectrophotometery (AAS) method described in SMEWW (1980) and Smith (1983). The total hardness (TH) was determined with Hach digital titrator; the alkalinity was determined following ASTM (1982) and electrical conductivity was measured using EC meter.

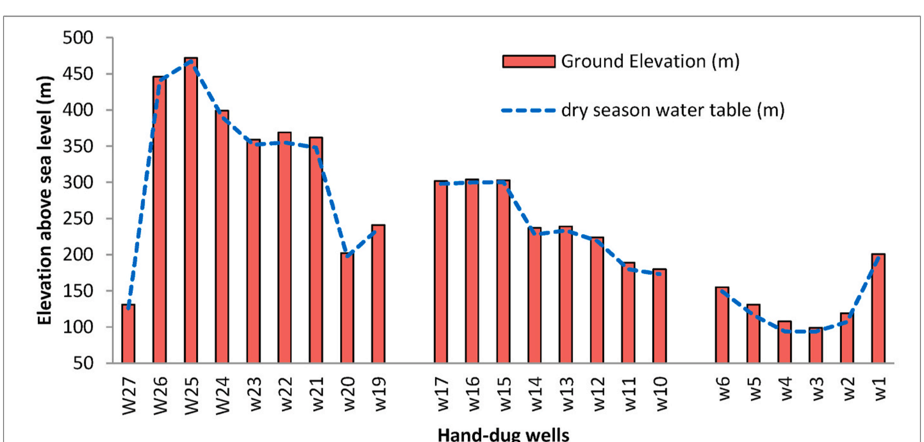

Fig. 2. Ground elevation and dry season water table of the hand-dug wells (note: w1-w6 occur in sandstone terrain; w10-w17 occur in granite terrain; w19-w27 occur in gneiss/schist terrain).

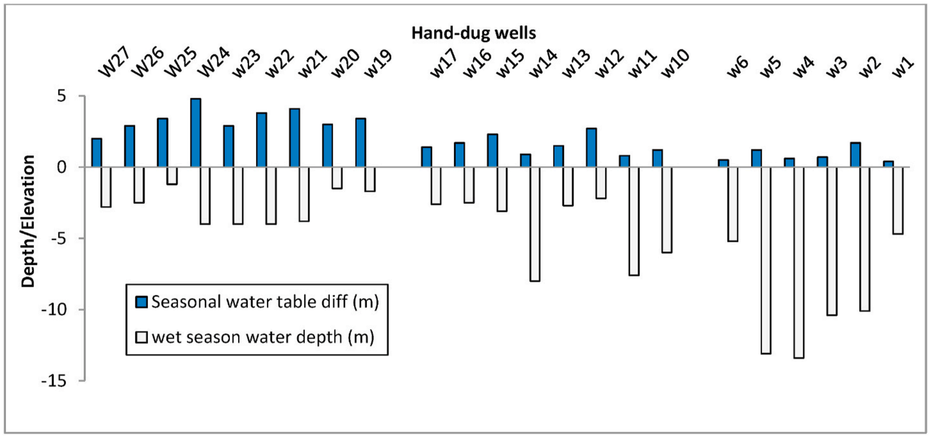

Fig. 3. Seasons' water table difference (SWTD) and wet season water depth of the hand-dug wells (w1-w6 occur in sandstone terrain; w10-w17 occur in granite terrain; w19-w27 occur in gneiss/schist terrain).

Table 2
Correlation Matrix of the soil CBRs and the groundwater parameters.

Properties	Correlation Parameters	Soil CBRs		WSWD	SWTD	Cation Concentrations				Physiochemical Properties		
		Soaked CBR	Unsoaked CBR			Ca^{2+}	Na^{+}	Mg^{2+}	K^{+}	Alkalinity	Hardness	EC
Soaked CBR	Correlation	1	.868**	-.792**	-.791**	-.670**	-.689**	-.590**	-.139	-.724**	-.684**	-.652**
	N	24	24	23	23	24	24	24	24	24	24	24
Unsoaked CBR	Correlation	.868**	1	-.641**	-.747**	-.706**	-.700**	-.611**	-.209	-.734**	-.719**	-.702**
	N	24	24	23	23	24	24	24	24	24	24	24
Wet season water depth (WSWD)	Correlation	-.792**	-.641**	1	.560**	.523*	.527**	.317	.263	.624**	.447*	.522*
	N	23	23	23	23	23	23	23	23	23	23	23
Seasons' water table difference (SWTD)	Correlation	-.791**	-.747**	.560**	1	.658**	.642**	.567**	.331	.678**	.655**	.725**
	N	23	23	23	23	23	23	23	23	23	23	23
Ca^{2+}	Correlation	-.670**	-.706**	.523*	.658**	1	.755**	.709**	.566**	.690**	.834**	.888**
	N	24	24	23	23	29	29	29	29	29	29	29
Na^{+}	Correlation	-.689**	-.700**	.527**	.642**	.755**	1	.687**	.574**	.589**	.797**	.891**
	N	24	24	23	23	29	29	29	29	29	29	29
Mg^{2+}	Correlation	-.590**	-.611**	.317	.567**	.709**	.687**	1	.481**	.548**	.916**	.791**
	N	24	24	23	23	29	29	29	29	29	29	29
K^{+}	Correlation	-.139	-.209	.263	.331	.566**	.574**	.481**	1	.495**	.593**	.675**
	N	24	24	23	23	29	29	29	29	29	29	29
Alkalinity	Correlation	-.724**	-.734**	.624**	.678**	.690**	.589**	.548**	.495**	1	.607**	.753**
	N	24	24	23	23	29	29	29	29	29	29	29
Hardness	Correlation	-.684**	-.719**	.447*	.655**	.834**	.797**	.916**	.593**	.607**	1	.884**
	N	24	24	23	23	29	29	29	29	29	29	29
Electrical Conductivity (EC)	Correlation	-.652**	-.702**	.522*	.725**	.888**	.891**	.791**	.675**	.753**	.884**	1
	N	24	24	23	23	29	29	29	29	29	29	29

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

The soil samples were subjected to sieve analysis following the ASTM C136/C136M (2014) standard (samples with significant fines 'i.e. >12%' were also subjected to Atterberg limit tests) and subsequently classified following the Unified Soil Classification System (ASTM D2487, 2017) to ascertain the soil types. The soil samples were further subjected to three-point method California bearing ratio (CBR) test following ASTM D1883 (2016) standard to determine the soaked and unsoaked CBRs of the soils.

The studied groundwater parameters (groundwater depth/table, cationic concentration and physiochemical properties) and soil CBRs were subjected to correlation analysis using Statistical Package for the Social Sciences (SPSS) to ascertain the extent of relationship amongst the groundwater parameters and the relationship between the groundwater parameters and the soil CBRs.

5. Results and discussion

5.1. Water table and depth parameters

The ground elevation and seasons' water table of the hand dug wells are shown in Table 1. For clear comparison, the ground elevation and dry season water table are shown as chart in Fig. 2 while the seasons' water table difference (SWTD) and wet season water depths (WSWD) are shown in Fig. 3. Correlation matrix of the groundwater parameters and

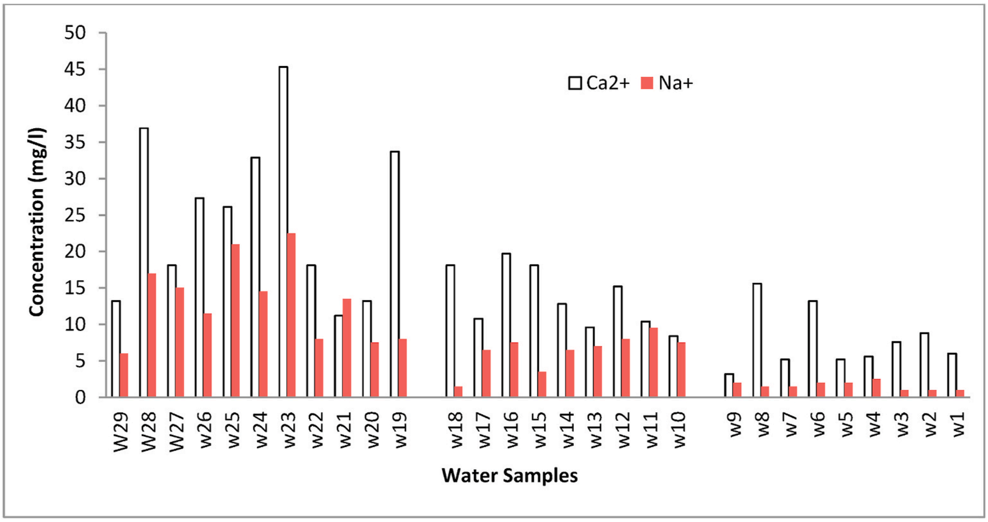

Fig. 4a. Concentration of Ca^{2+} and Na^{+} in the water samples collected from the three terrains (w1-w9 = Sandstone; w10-w18 = Granite; w19-w29 = Gneiss/schist).

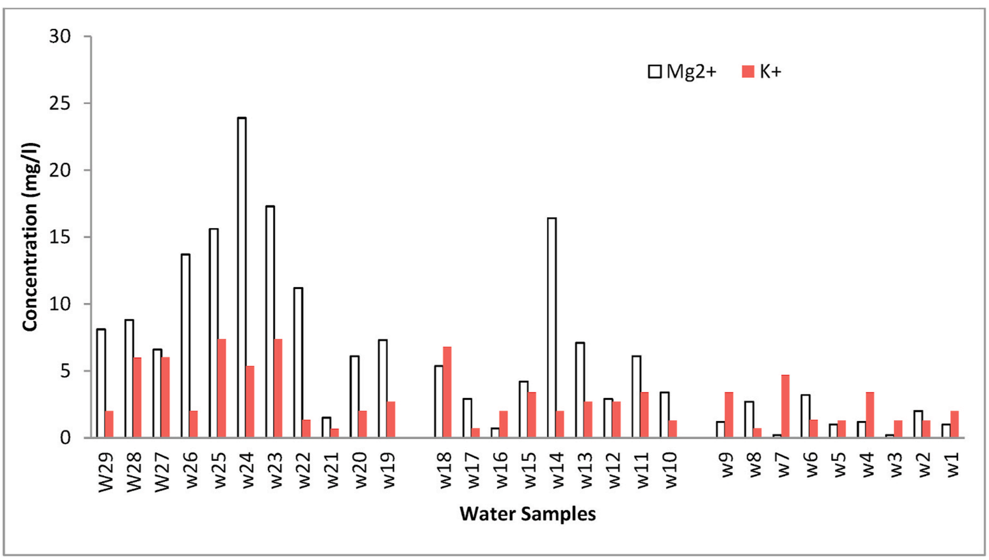

Fig. 4b. Concentration of Mg^{2+} and K^{+} in the water samples collected from the three terrains (w1-w9 = Sandstone; w10-w18 = Granite; w19-w29 = Gneiss/schist).

soil CBRs is shown in Table 2.

Fig. 2 clearly shows that the water table follows the same trend as the ground elevation; wells located in high elevation have high water tables and vice versa. Comparing Fig. 2 with Fig. 1b reveals that elevation of the study area increases from the west to the east. Coincidentally, wells mapped in sandstone terrain occur in the western part while wells mapped in granite terrain occur at the central part. Most wells sampled in gneiss/schist terrain occur in the eastern part except wells W19, W20 and W27. This observation agrees with Tóth (1963) and Haitjema and Mitchell-Bruker (2005) that water table is the subdued replica of the ground surface elevation especially in low-permeable and/or anisotropic aquifers.

Fig. 3 shows that wells occurring in gneiss/schist terrain have SWTD and WSWD ranging from 2.0 to 4.8 m and from −1.2 to −4.0 m respectively; wells occurring in granite terrain have SWTD and WSWD ranging from 0.8 to 2.7 m and from −2.2 to −8.0 m respectively while wells occurring in sandstone terrain have SWTD and WSWD ranging from 0.4 to 1.7 m and from −4.4 to −13.4 m respectively. This suggests two things. Firstly, the two parameter viz: seasons' water table difference (SWTD) and the wet season water depth (WSWD) vary with the aquifer lithology. Secondly, SWTD of the studied wells has an inverse relationship with the WSWD. This relationship is evidenced in the significant correlation between SWTD and WSWD shown in Table 2 and also implies that either the aquifer lithology controls both parameters (SWTD and WSWD) or that the two parameters affect each other. The friable and unconfined nature of the Bida Sandstone aquifer gives it good permeability that permits infiltration of water to great depths (Shekwolo, 1990; Olaniyan and Olabaniyi, 1996; Obaje et al., 2011; Olabode et al., 2012; Idris-Nda et al., 2013). This good permeability also promotes the quick recharge of the wells which manifests more during dry seasons characterized by reduced infiltration. This explains why wells occurring in the sandstone terrain have deeper water table and smaller SWTD than wells occurring in granite and gneiss/schist terrains. It suggests that, considering the SWTD and WSWD of wells in granite terrain relative to those of gneiss/schist terrain, the granite aquifer has deeper and more connected fractures/weathered zones than the gneiss/schist aquifer. Therefore, seasons' water table difference (SWTD) and water depth can serve as a tentative check for assessing the relative permeabilities of aquifers of different lithologies.

5.2. Geochemical and phyiosochemical properties of the water samples

Concentrations of Ca^{2+}, Na^{+}, Mg^{2+} and K^{+} in the water samples collected from the three lithologic terrains are shown in Fig. 4a and b while the total hardness, alkalinity and electrical conductivity are shown in Fig. 5.

Fig. 4a and b reveal that, generally, the concentrations of the cations are relatively high in water collected from wells of gneiss/schist terrain; relatively intermediate in water collected from wells of granite terrain and relatively low in water collected from wells of sandstone terrain.

This variation in groundwater cations according to the aquifer lithology is based on mineralogy and weatherability of the aquifers. Gneiss/schist and granite of the Nigerian Basement complex contain more minerals than the Bida Sandstone (Obiora, 2005; Okunlola et al., 2009; Obaje et al., 2011). In the presence of water, these minerals (of gneiss/schist and granite) hydrolyze yielding more ions than in the case of sandstone. Secondly, the low stable mineralogy and foliated texture of the gneiss/schist aquifer promotes its weathering and hydrolysis of its mineral components to more ions than in the case of granite aquifer which has less weatherability due to its high stable mineralogy and graphic texture (Goldich, 1938; Ekwueme, 1993; Railsback, 2006 Dobereiner et al., 1993; Marques et al., 2010; Dobereiner et al., 1990). This finding corroborates with Garrels (1976), Hanshaw and Back (1979), Datta and Tyagi (1996) that geochemistry of groundwater is a reflection of mineralogy and weatherability of the aquifer.

A closer look at Fig. 4a and b reveals that the variations in concentrations of Ca^{2+}, Na^{+}, Mg^{2+} in the water samples, according to the lithologic terrain, is more certain than the variations in concentration of K^{+}. Furthermore, for water samples collected from gneiss/schist and granite terrains, the mean order of cationic concentrations is: $Ca^{2+}>Na^{+}>Mg^{2+}> K^{+}$ in which K^{+} concentration is very much lower than that of the other three cations; while for water samples collected from sandstone terrain, the mean order of cationic concentrations is: $Ca^{2+}> K^{+}>Na^{+}>Mg^{2+}$ (Table 1). These variations are also attributed to the mineralogy of the aquifers. Amongst the major minerals that make up the Nigerian Basement Complex gneiss/schist and granite, hornblende ($Na_{0.5}Ca_2(Fe_{1.5}Mg_{2.6}Al_{1.1})(Al_{1.6}Si_{6.4})O_{22}(OH)_2$) and plagioclase ($NaCaAl_3Si_5O_{16}$) are more susceptible to chemical weathering and subsequent dissociation into their component ions than muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), biotite ($K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$) and microcline ($KAlSi_3O_4$) (Goldich, 1938; Onyeagocha, 1984; Obiora, 2005; Railsback et al., 1996 and Railsback, 2006). The hydrolysis and dissociation of plagioclase and hornblende yielding Ca^{2+}, Na^{+} and/or Mg^{2+} follow Equations (1) and (2) respectively (Helms et al., 1987; Appelo and Postma, 1999).

$$\underset{\text{(Plagioclase)}}{2NaCaAl_3Si_5O_{16}} + 8CO_2 + 9H_2O \rightarrow 2Ca^{2+} + 2Na^{+} + 6HCO_3^{-} + 4SiO_2 + \underset{\text{(clay mineral)}}{Al_2Si_2O_5(OH)_4} + 2CO \tag{1}$$

$$\underset{\text{(Hornblende)}}{Na_{0.5}Ca_2(Fe_{1.5}Mg_{2.6}Al_{1.1})(Al_{1.6}Si_{6.4})O_{22}(OH)_2} + 15H^{+} + H_2O \rightarrow 0.5Na^{+} + 2Ca^{2+} + 2.6Mg^{2+} + 1.3Fe^{2+} + 2.7Al(OH)_2 + 6.4H_4SiO_{4(aq)} \tag{2}$$

Thus, the high concentrations of Ca^{2+}, Na^{+} and Mg^{2+} relative to K^{+} in samples collected from gneiss/schist and granite terrains are due to the weatherability of the minerals making up the aquifer lithology. Significant amount of these Ca^{2+}, Na^{+} and Mg^{2+}-rich minerals (like plagioclase and hornblende) contained in the sandstone protolith weathered and dissociated into their component ions during its (sandstone) sedimentation and diagenetic processes remaining mostly the K^{+}-rich minerals which dissociates gradually; a process which results in a higher concentration K^{+} in groundwater contained in the sandstone

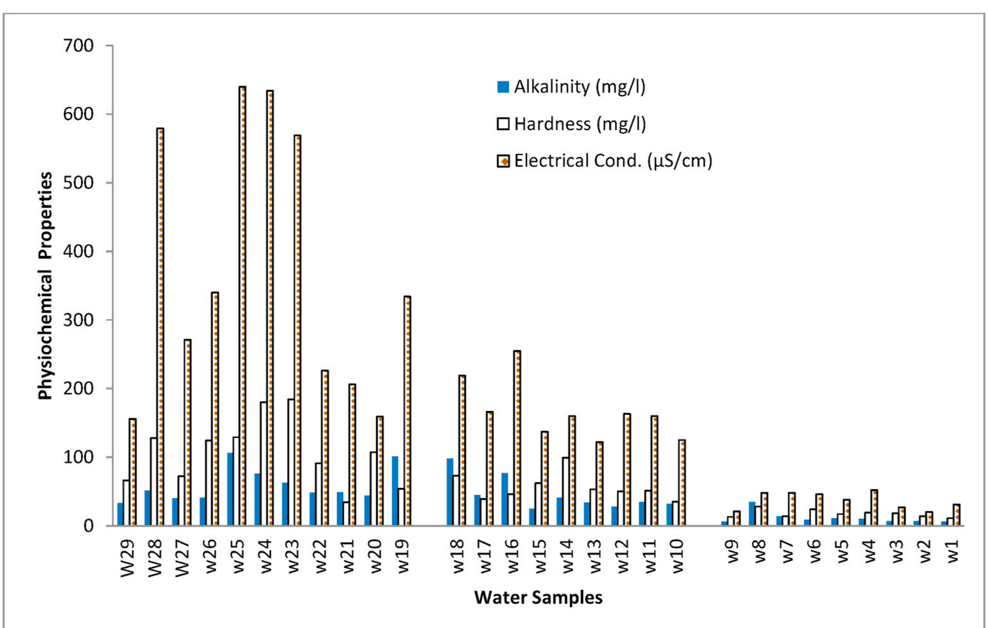

Fig. 5. Alkalinity, hardness and electrical conductivity of the water samples collected from the three terrains (w1-w9 = Sandstone; w10-w18 = Granite; w19-w29 = Gneiss/schist).

Table 3
The grain size percentages, Atterberg limits and Description of the soil samples.

s/n	Terrain	Sample code	Grain Size (%)			Atterberg Limits (%)			Unified Soil Classification System (USCS)	
			Gravel	Sand	Fine	LL	PL	PI	Symbol	Description
1	Schist/gneiss	S24	20.98	61.88	17.20	31.50	25.80	5.70	SM	Silty sands, silt sand mixtures
2	Schist/gneiss	S23	43.20	54.50	2.30	NA	NA	NA	SW	Well-graded sands, gravelly sands with little or no fines
3	Schist/gneiss	S22	43.00	51.90	5.10	NA	NA	NA	SW-SM	Well-graded sands with silt binder
4	Schist/gneiss	S21	46.30	44.47	9.22	NA	NA	NA	GW-GM	Well-graded gravels with silt binder
5	Schist/gneiss	S20	48.36	44.47	7.08	NA	NA	NA	GW-GM	Well-graded gravels with silt binder
6	Schist/gneiss	S19	76.20	19.24	4.21	NA	NA	NA	GP	Poorly-graded gravels, sandy gravel with little or no fines
7	Schist/gneiss	S18	50.16	36.05	13.59	40.00	27.00	13.00	GM	Silty gravels, silty sandy gravels
8	Schist/gneiss	S17	54.69	24.11	20.99	38.50	5.40	23.10	GC	Clayey gravels, clayey sandy gravels
	Mean		**47.86**	**42.08**	**9.96**					
9	Granitic	S16	56.74	42.25	0.70	NA	NA	NA	GP	Poorly-graded gravels, sandy gravel with little or no fines
10	Granitic	S15	19.24	70.03	10.56	NA	NA	NA	SP-SM	Poorly-graded sands with silt binder
11	Granitic	S14	22.35	67.86	9.70	NA	NA	NA	SW-SM	Well-graded sands with silt binder
12	Granitic	S13	64.08	30.87	4.87	NA	NA	NA	GW	Well-graded gravels, sandy gravels with little or no fines
13	Granitic	S12	50.60	41.10	7.90	NA	NA	NA	GW-GC	Well-graded gravels with clay binder
14	Granitic	S11	80.70	10.45	8.60	NA	NA	NA	GP-GM	Poorly-graded gravel with silt binder
15	Granitic	S10	40.70	54.40	4.60	NA	NA	NA	SW	Well-graded sands, gravelly sands, with little or no fines
16	Granitic	S9	53.93	41.10	4.97	NA	NA	NA	GW	Well-graded gravels, sandy gravels, with little or no fines
	Mean		**48.54**	**44.76**	**6.49**					
17	Sandstone	S8	11.56	83.87	4.56	NA	NA	NA	SP	Poorly-graded sands, gravelly sands, with little or no fines
18	Sandstone	S7	16.04	80.97	2.89	NA	NA	NA	SP	Poorly-graded sands, gravelly sands, with little or no fines
19	Sandstone	S6	6.51	88.05	5.43	NA	NA	NA	SP-SC	poorly-graded sands with clay binder
20	Sandstone	S5	10.42	84.69	4.89	NA	NA	NA	SW	Well-graded sands, gravelly sands, with little or no fines
21	Sandstone	S4	25.44	71.29	3.25	NA	NA	NA	SW	Well-graded sands, gravelly sands, with little or no fines
22	Sandstone	S3	13.42	78.38	7.79	NA	NA	NA	SP-SM	poorly-graded sands with silt binder
23	Sandstone	S2	13.21	76.87	8.70	NA	NA	NA	SP-SM	poorly-graded sands with silt binder
24	Sandstone	S1	14.69	80.20	5.11	NA	NA	NA	SP-SM	poorly-graded sands with silt binder
	Mean		**13.91**	**80.54**	**5.33**					

Gravel = 76.2–4.75 mm; Sand = 4.75–0.075 mm; Fine (silt and clay) = ≤0.075 mm; LL = Liquid limit; PL = Plastic limit; PI = Plasticity Index; NA = Not Applicable.

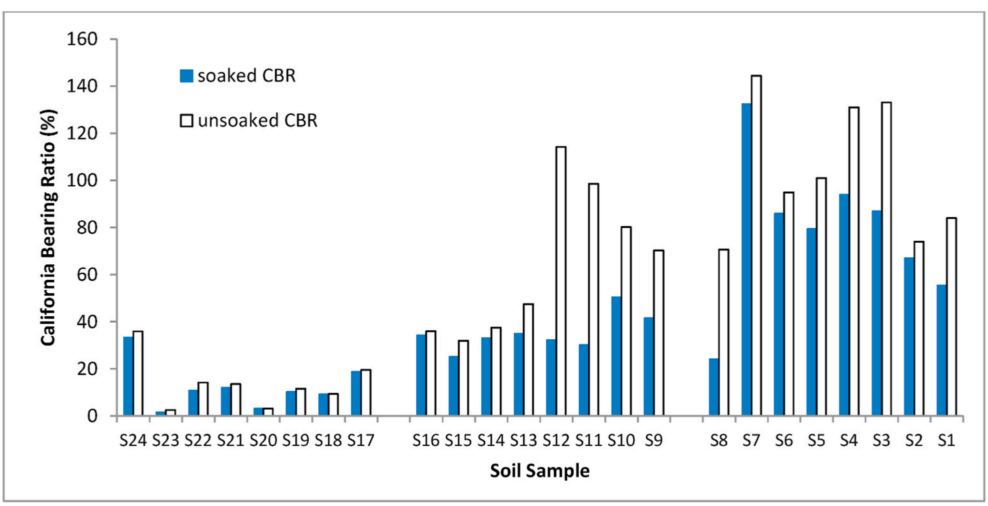

Fig. 6. Variation of soaked and unsoaked CBR amongst soil from the three terrains (S1–S8=Sandstone; S9–S16 = Granite; S17–S24 = Gneiss/Schist).

aquifer than concentration of other cations. This result further validates the generally low concentrations of cations as well the higher concentration of K^+ than concentrations of Na^+ and Mg^{2+} in the water samples collected from the sandstone terrain. Therefore, the cationic concentration of the groundwater samples is primarily controlled by the mineralogy of the water-bearing lithology (aquifer).

Comparing Fig. 4a and b with 5, reveals that results of present work agrees with Bhattacharya et al. (2008) that the physiochemical properties (alkalinity, total hardness and electrical conductivity) of t\he water samples follow the same trend as the cation concentrations. It is generally known that water hardness is proportional to the concentrations of Ca^{2+} and Mg^{2+}. The electrical conductivity is controlled by both concentration and mobility of cations contained in the water; mobility of cations in water follows the order: $\mu Rb^+ > \mu Cs^+ > \mu K^+ > \mu Ca^{2+} > \mu Mg^{2+} > \mu Na^+ > \mu Li^+$ where μ is cationic mobility (Atkins and de Paula, 2006).

5.3. Geotechnical properties of the soil samples

The grain size fractions, Atterberg limits and derived soil types of residual soils occurring in the three lithologic terrains are shown in Table 3 while the California Bearing Ratios (CRBs) are Fig. 6. Table 3 shows that the soils occurring in the three terrains are coarse-grained - sandy and gravelly soils. Soils occurring in the sandstone terrain are totally sandy soils while soils occurring in the gneiss/schist and granite are sandy and gravelly soils. These variations in soil types stem from the protolith texture. Friable sandstone weathers to sandy soils while the harder gneiss/schist and granites weather to gravelly soils and subsequently to sandy soils. It is expected that the soil types should control the soil CBRs. That is, gravelly soils are expected to have higher CBRs than sandy soils. On the contrary, results of the present work reveal that the gravely and sandy soils, which occur in gneiss/schist terrain, have the low CBRs while the sandy soils, which occur in the sandstone terrain, have the high CBRs. This implies that, besides texture, other petrologic property affect the CBRs of soils.

CBR, which is a check of mechanical stability of soil, is largely controlled by the intrinsic petrologic properties of the soil protolith. The Bida Sandstone, composed mostly of relatively stable minerals (quartz and k-feldspars), has higher mechanical and chemical stability than gneiss/schist and granite composed of relatively low stable minerals (plagioclase, chlorite and hornblendes). Consequently, the soils that formed from the Bida Sandstone have higher mechanical stability (CBRs) than the soils that formed from the Basement Complex gneiss/ schist and granite. On the second hand, gneiss/schist, having foliated texture, is more susceptible to both chemical and mechanical weathering than granite, which has graphic texture (Brown, 1981; Dobereiner et al., 1993; Hoek and Brown, 1997; Nasseri et al., 2003; Marques et al., 2010; Ozbek et al, 2018). In other words, gneiss/schist weathers to soil faster than granite. A closer look at Fig. 6 reveals that sample S24 has CBRs higher than others collected from gneiss/schist terrain while sample S8 has CBR lower than others collected from sandstone terrain. This is because these two samples occurred close to lithologic boundaries; S24 occurred close to gneiss/schist-granite boundary while S8 occurred close to sandstone-granite boundary (Fig. 1b). Each of these two soil samples may have formed from the two different lithologies occurring at the stated boundaries. That is, S24 formed from both gneiss/schist and granite; while S8 formed from both sandstone and granite. Thus, the influence of granite manifested in the CBR of the two soils. This is additional evidence buttressing the inference that the CBRs of soils are controlled by the intrinsic petrologic properties of the soil protolith.

5.4. Variation of the hydrogeological parameters with soil CBRs

Comparing Figs. 3–5 with Fig. 6, it can be seen that each of the hydrogeological parameters viz: depth, cationic concentrations and physiochemical properties varies with the CBRs of the soil according to the lithologic terrain on which they are formed. In gneiss/schist terrain, the groundwater occurs at shallow level and the soils have relatively low CBRs. In sandstone terrain, the groundwater occurs at deeper level and the soils have relatively high CBRs. Groundwater may have affected the CBRs of the soils especially soils occurring at the gneiss/schist terrain, where groundwater occurs at very shallow depth (1.2–4.0 m). Groundwater in this terrain rises by capillary action to a height that affects the overlying soil thereby degrading the CBRs of the soil; a process enhanced by the significant amount of fines contained in the soils (see Table 3). The constant saturation of soils in gneiss/schist by such capillary water, perhaps, makes it (the soil) to be in a state of 'hydrological fatigue'; a situation that manifests as minimal difference between the unsoaked CBR and soaked CBR. This may explain the smaller difference between unsoaked CBR and soaked CBR of soils occurring in gneiss/schist terrain than those of soils occurring in sandstone and granite terrains (Fig. 6). Capillary rise is of little or no effect on the soils occurring in granite and sandstone terrains due to the deep water depths in these terrains. Therefore, soils constantly saturated by water have smaller unsoaked CBR and soaked CBR difference than soils seldom saturated by water.

On aspects of geochemistry, it has been discussed earlier that the cationic concentration of the groundwater is, primarily, a reflection of mineralogy of the water-bearing lithology (aquifer). This same lithology bearing the water can also weather to the soils. For instance, water collected from the gneiss/schist terrain contains high concentrations of Ca^{2+}, Na^{+}, Mg^{2+} because the Nigerian Basement gneiss/schist are composed of relatively low stable Ca^{2+}-, Na^{+}-, Mg^{2+}-rich minerals like plagioclase and hornblende. Parts of this same gneiss/schist, containing minerals of low stability, weathers to soils of low CBRs. On the other hand, water collected from the sandstone terrain contains low concentration of Ca^{2+}, Na^{+}, Mg^{2+} because the Bida Sandstone is composed of relatively stable $Si^{2+}$and K^{+}-rich minerals like quartz and K-feldspar. Parts of this same sandstone, containing minerals of high stability, weathers to soils of high CBRs. Hence, lithology/aquifer that is composed of lower stability minerals results in high concentrations of cations in its groundwater which also weathers to soils of low CBRs and vice versa. Understandably, the physiochemical properties (alkalinity, hardness and electrical conductivity) controlled by the cations (Ca^{2+}, Na^{+}, Mg^{2+} and K^{+}) also have the variation with the soils' CBRs as the cations. The significant correlation existing between the CBRs and each of these hydrogeological parameters (water depth, cationic concentration and physiochemical properties) as shown in Table 2 further validates these assertions.

6. Conclusions

The following conclusions can be drawn from the present work.

1. Aquifers made up of minerals of low stability contain groundwater of high cationic concentrations and also weathers into soils of low CBRs. Conversely, aquifers made up minerals of high stability contain groundwater of low cationic concentrations and also weathers into soils of high CBRs.
2. The cationic concentrations of the groundwater samples vary according to the aquifer lithology. Groundwater contained in gneiss/ schist aquifer has relatively high concentrations of Ca^{2+}, Na^{+}, Mg^{2+} and K^{+}; groundwater contained in granite aquifer has relatively intermediate concentration of Ca^{2+}, Na^{+}, Mg^{2+} and K^{+} while groundwater contained in sandstone aquifer has relatively low concentrations of Ca^{2+}, Na^{+}, Mg^{2+} and K^{+}. The mineralogy of the aquifer is the intrinsic property controlling the cationic concentrations.
3. CBRs of soils are largely dependent on the intrinsic petrologic properties of the lithology from which the soils were formed. These properties include the mineralogy and texture.
4. Soils frequently saturated by water have smaller differences between their unsoaked CBR and soaked CBR than soils scarcely saturated by water. In the present study, soils occurring in the gneiss/schist terrains are being saturated by capillary water emanating from groundwater.
5. Seasons' water table difference (SWTD) and water depth can be used for tentative assessment of the relative permeabilities of different aquifers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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