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Hydrogeology And Ground Water Potentials Of The Pre-Cambrian Basement Rocks Of Tabe And Environs In Gwagwalada Area, Abuja North Central, Nigeria

Chukwunenyoke Amos-Uhegbu, Mmaduabuchi Uche Uzoegbu, Okwuchukwu Peter Odoh and Chukwudike Dandy Akoma

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Abstract: *The hydrogeology and groundwater potentials of Tabe and Environs in Gwagwalada Abuja Nigeria were carried out using lithologic logs of 7 boreholes, field measurement data, stream flow / meteorological data and hydrogeochemical data. 17 sampling points (7 boreholes and 10 hand-dug wells) were evaluated to establish the potential of groundwater in the area. Annual rainfall in the area is 800mm and 80%of it is lost through surface runoff and evapotranspiration while about 20% recharges the groundwater system. The area exhibits four aquifer systems from four distinct geologic lithologies - weathered layer aquifer, weathered/fractured or partly weathered aquifer; fractured aquifer and the Quaternary alluvium. Groundwater from the hand-dug wells is mainly from the upper unconfined aquifer with a maximum depth of about 25m, while the boreholes are completed either within the middle semi-confined aquifer 25 -45m or the lower confined aquifer 45-65m (depth range of 0-65m). The computed aquifer parameters gave a mean hydraulic conductivity of 5.60 x10^{-1}m/day, a transmissivity of 28.32m^2/day groundwater velocity of 2.43m/yr, groundwater discharge of 612.69m^3/yr, a groundwater reserve of 1.01x$10^{10}$$m^3$which is capable of supporting a population of 1.4m for one year on an average of 220/l/day/head and a mean borehole yield of 20 m^3/hr. Results of the hydrogeochemical analysis indicate that most of the water samples are within the WHO (2006) and the NIS (2007) drinking water quality standards. However isolated samples especially from the upper unconfined aquifer tested moderately hard to very hard (106-421mg/l); with a few cases of high NO_3^-(88-132mg/l), high Fe^{2+} (1-2mg/l). The area has two dominant water types, the Ca^{2+}-HCO_3^- and the Na^++K^+-HCO_3^-. The study reveals that the Gwagwalada area (Tabe and environs) could be considered as a potential source of sustainable groundwater supply and also as a good alternative to the existing sources of supply. It would however require an improved waste management system and proper well completion methods to avoid surface contaminant migration to the groundwater.*

Keywords: *Stream flow/meteorological data, weathered/fractured aquifer, surface contaminant migration, aquifer parameters and hydrogeochemistry*

Chukwunenyoke Amos-Uhegbu*
Department of Geology, Michael Okpara University of Agriculture, Umudike, PMB 7267 Umuahia, Abia-State, Nigeria.
Email:
amos-hegbu.chukwunenyoke@mouau.edu.ng
Orcid id: 0000000321137834

Mmaduabuchi Uche Uzoegbu
Department of Geology, Michael Okpara University of Agriculture, Umudike, PMB 7267 Umuahia, Abia-State, Nigeria.
Email: **mu.uzoegbu@mouau.edu.ng**

Okwuchukwu Peter Odoh
Department of Geology, Michael Okpara University of Agriculture, Umudike, PMB 7267 Umuahia, Abia-State, Nigeria.
Email: : op.odoh@mouau.edu.ng

Chukwudike Dandy Akoma
Department of Geology, Michael Okpara University of Agriculture, Umudike, PMB 7267 Umuahia, Abia-State, Nigeria.
Email: **akoma.chukwudike@mouau.edu.ng**

1.0 Introduction

The study area is a metamorphic terrain that forms part of the north-central Nigerian Basement Complex (Fig. 1). The Nigerian Basement Complex is part of the reactivated Dahomeyan rocks known as the Pan-African mobile belt situated between the West African and Congo cratons.

The rocks within this study area are mostly metasediments and granitic rocks of pan-African origin. The Pan African mobile belt continues into the Boborema Province of northeast Brazil and composed of the migmatite-gneiss complex, the metasedimentary and metavolcanic schist belts that have been subjected to series of polycyclic metamorphism, tectonism and magmatic deformations that resulted in the emplacement of igneous rocks called the Pan African Older Granites of Nigeria (Dada *et al*., 1999; Wright et al., 1985). These older granites are intrusive into the migmatite gneiss and schist belts though generally regarded as syn to post-tectonic with the Pan African event (Fitches *et al.*, 1985). These rocks all make up the Precambrian to Lower Palaeozoic Basement Complex.

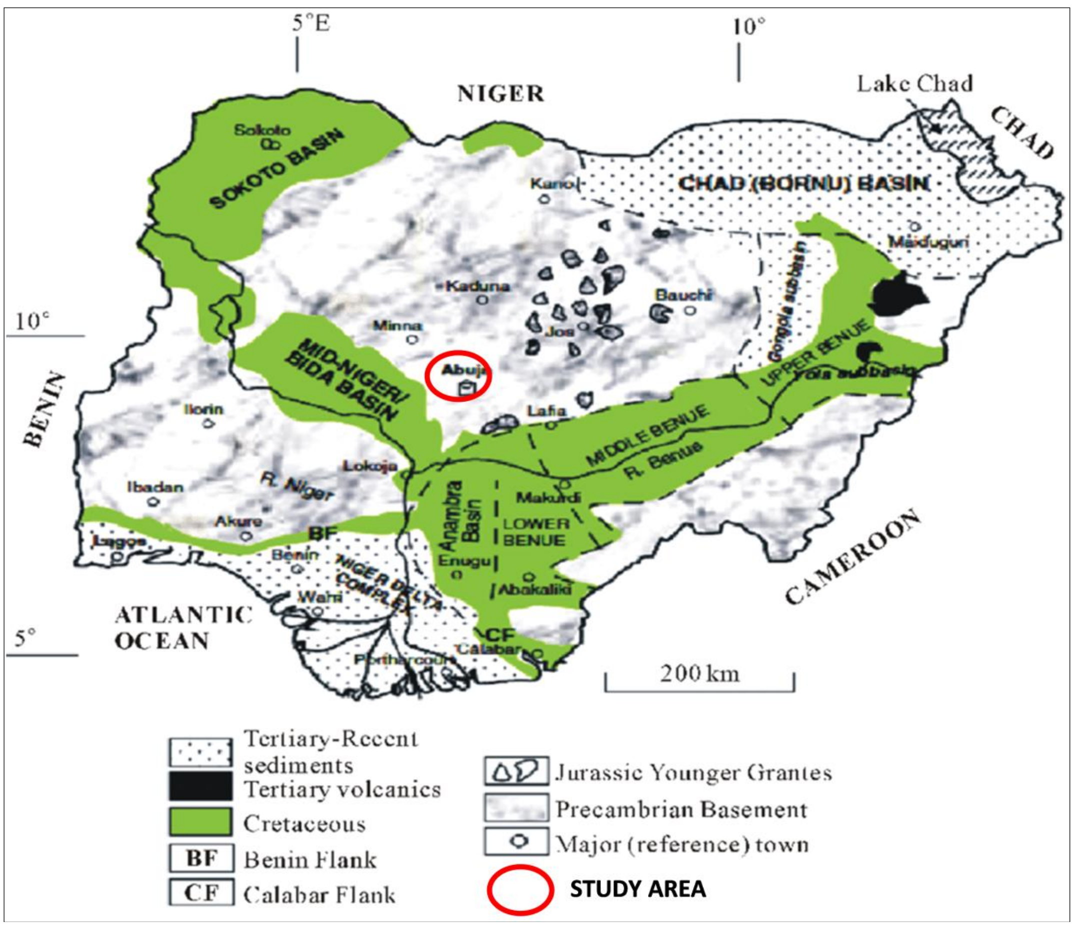

Fig. 1: Outline geologic map of Nigeria with the study area in-set (Source: Nigerian Geological Survey Agency, 2001).

The study area is situated in the southern part of north central Nigerian Basement Complex dominated by metamorphic and igneous rocks with minor pegmatite and granitic intrusions (Fig. 2). Several workers including Oyawoye (1964), Mc Curry (1976), Rahman, (1976a), Annor (1986), Rahman et al. (1988a), Ekwueme, (1989) and Dada, (1999) have studied and described several aspects and axes of the Basement Complex of Nigeria in the past.

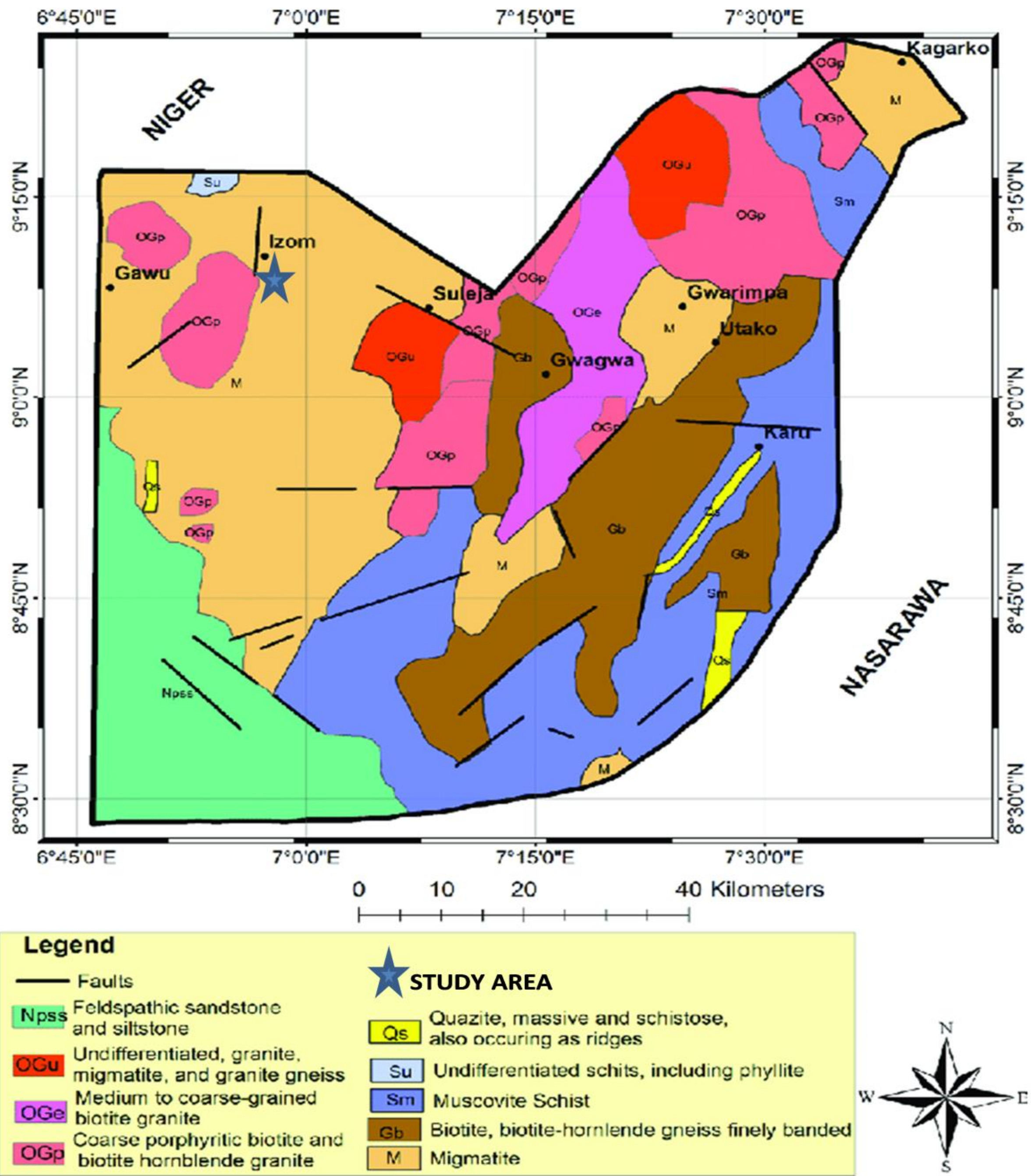

Fig. 2: Geological Map of Abuja showing the Study area

Workers like Oyinloye, (2002, 2007, 2011); Obiora, (2006); Dada, (2006); Obaje, (2009); Akindele, (2011); Opara, et al., (2014); Ayodele, (2015); (Adeoti and Okonkwo, 2016); Haruna, (2017); Lawal *et al*., (2017); (Muhammad and Saad, 2018); (Bassey and Udinmwen, 2019)and **A**bdulkarim *et al*.,(2021), Ekeleme et al., 2023a-c, have also studied and classified most axes of the Basement Complex of Nigeria. Some aspects of the geology and geochemistry of the basement rocks of parts of north-central Nigeria have been studied by Onyeagocha, (1984, 1986), and Obiora and Ukaegbu, (2009).

Groundwater is a vital resource because a significant proportion of the world's population depends on groundwater, either directly or indirectly for several applications such as domestic, agricultural, and livelihoods (Callist, 2006); Sanjay, (2010); Mbiimbe *et al*.,(2008). Much of the groundwater can be said to be meteoric in origin, which is originating from the atmosphere. Also, a small percentage is known to enter the hydrologic cycle from subterranean sources and is described as juvenile water. This water includes water from magmatic and volcanic sources, while connate water is entrapped between the interstices of sedimentary formations.

The quality of groundwater can be affected or degraded as a result of human activities that introduce contaminants into the environment. It can also be affected by natural processes that result in elevated concentrations of certain constituents in the groundwater. Recently, groundwater quality has become a matter of concern due to the discharge of industrial and domestic effluents directly into both surface and underground, the use of agricultural chemicals, land use and cover changes. Thus water quality is influenced by many factors, including atmospheric chemistry, the underlying geology, climate change and anthropogenic activities. The quality of water should satisfy the requirements or standards set for specific uses, such as drinking, domestic, agricultural, industrial and recreational purposes. However, available literature has shown that objectional quality (based on physicochemical, nutrient, heavy metals and other quality parameters) has been reported for some groundwater, suggesting that public health may be at severe risk if the current trend is not checked. The availability of information on the quality of groundwater can therefore provide a reference point in deciding on best remediation approaches. Therefore, the present study is aimed at determining the occurrence and distribution of groundwater in the study area, and the provision of information on the quantity and quality of groundwater in the area and suggesting options for a more sustainable development and management of groundwater in the area.

1.1 Geology

A detailed geologic mapping of various rock units around Tabe in Gwagwalada area council of Abuja (Nigeria) was carried out on a scale of 1: 12,500. The area lies 9º06'30" to 9º08'24"N and longitudes 6º55'30" to 6º59'30"E of Paiko sheet 185 SE (Fig. 3).

Tabe area is underlain by rocks of the Nigerian basement complex comprising migmatites-gneiss complex, younger metasediments, older and younger granites (Bala *et al*., 2011); Ekeleme *et al*.,(2023 a-c). MacDonald *et al*., (1986) established that it is dominantly underlain by undifferentiated metamorphic suite, older granite, coarse pink granite and porphyritic biotite granite. The predominant rock type is older granite. The older granite is composed of coarse-grained granite, granodiorite, diorite and aplite. The lithological varieties are less common than in the metamorphic suite, which was emplaced during the Pan-African orogeny and was dated about 650-850 ma (Geological Survey of Nigeria, 1994).

The most abundant and typical member of the older granite suite is a coarse porphyritic granite (Oyawoye, 1972). It is typified by the abundant large feldspar set in a groundmass rich in biotite or hornblende. The feldspar may be white, purple, pink, yellowish brown and dark grey (Fig. 3).

The schists are considered to be Upper Proterozoic supracrustal rocks which have been in folded into the migmatites-gneiss-quartzite complex (Obaje, 2009). They occupy an area within the ''walled city'' to the central part of the Federal Capital Territory (FCT). They are reddish to greenish-grey in colour and highly weathered. They are found to be associated with diorite. This association indicates that schists have been intruded by small dioritic bodies, and are considered older than diorites in the area.

1.2 *Hydrogeology*

In the study area, groundwater occurs within the weathered mantle or in the joint and fracture systems of the unweathered or partly weathered rocks (MacDonald *et al.*, 1986); Mbiimbe *et al.*, (2008); Tahir *et al.*, (2015). Du Preez and Barber (1965) proposed that the aquifer is located in the weathered mantle and fractured rock where permeability and porosity are sufficient to allow appreciable amount of water to accumulate in storage. The high groundwater yield in the area is found where thick overburden overlies fractured zones. The aquifer types described by Olorunfemi and Fasuyi (1993) from the study area include:-

- Weathered layer aquifer;
- Weathered/ fractured or partly weathered aquifer; and
- Fractured aquifer.

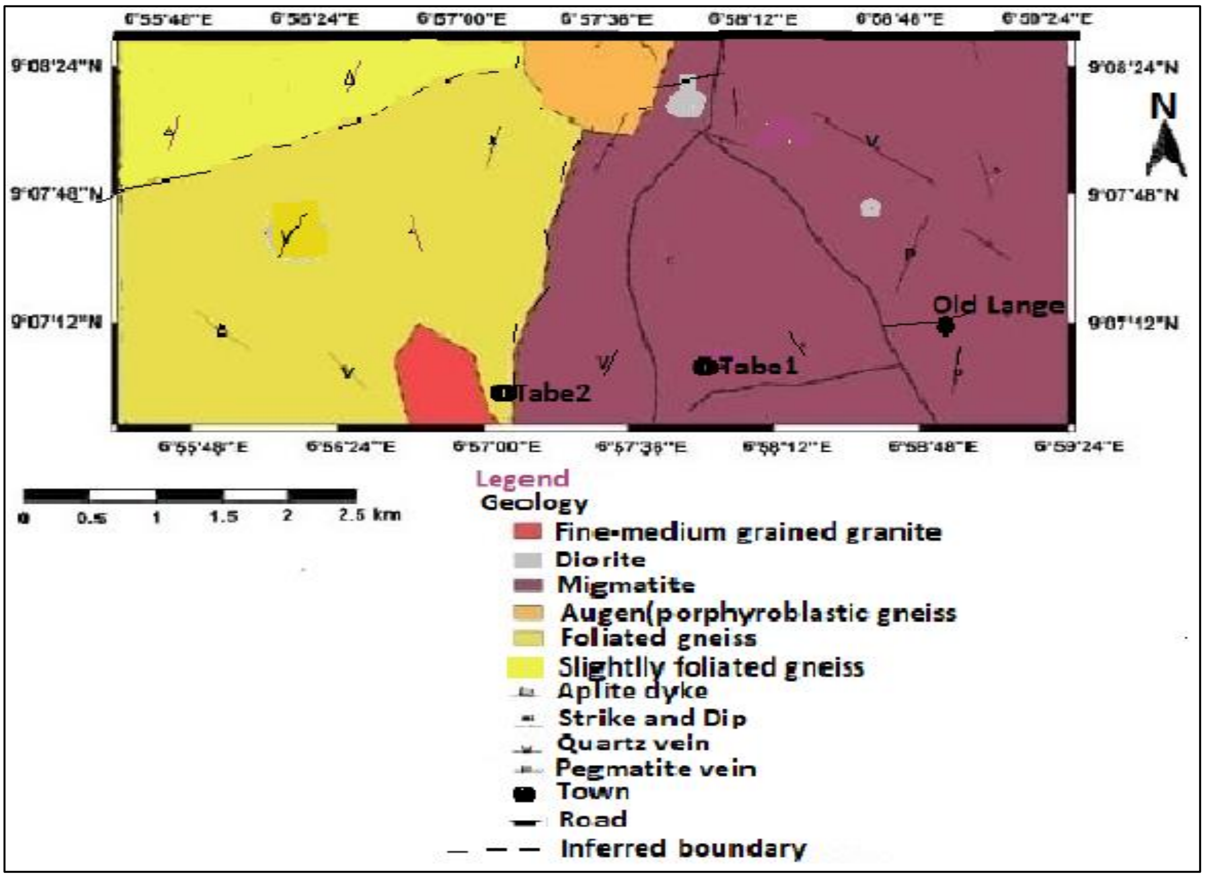

Fig.3: Geological Map of Tabe area (after Ekeleme *et al.*, 2023a).

The older granite has been subjected to many tectonic movements and pressure through geologic history such that they often have several fracture lines (Ekeleme *et al*., 2023a-c). However, the Basement Complex of the study area has received little or no attention in the general literature of the Nigerian basement rocks. Much of the existing records of the geology of the Abuja area and environs have been in the form of Geological maps as produced and updated by the Nigerian Geological Survey Agency (NGSA) in the early millennium (NGSA, 2001 Figure 1). Oluwatosin *et al*., (2017) studied the underground water distribution systems of four streams in the Gwagwalada area council of Abuja using the resistivity method and only made a regional description of the geology. The only close record on the geology of the area under study is that of the NGSA, which at the beginning of the millennium embarked on an exploration drive in search of potentially mineralized areas in northwestern Nigeria. They recorded the general geology of the BabbanTsauni area to which Tabe is adjoining, concerning rock types, base metal sulphides and gold mineralization (MMSD, 2010); Ekeleme *et al*.,(2023a-c).

2.0 Materials and Methods

The area lies between latitudes 9º06'30" to 9º08'24"N and longitudes 6º55'30" to 6º59'30"E of Paiko sheet 185 SW. Lithologic logs used for this study were obtained from FCT Water Resource, Abuja, Rural Water Supply and Sanitation Agency (RUWASSA) Abuja, stream flow and meteorological data were provided by the Upper Niger River Basin Development Authority (UNRBDA) Abuja, while the hydrogeochemical data used was generated from field sampling and laboratory analysis of water samples from 7 boreholes and 10 hand-dug wells.

In this study, six (6) major parameters were considered; hydraulic conductivity (K), Transmissivity (T), groundwater velocity (V), groundwater discharge (Q), groundwater reserve (Qa) and aquifer thickness (b).

Groundwater velocity was calculated using Todd (1980) equation while the groundwater discharge was obtained using Guisti (1978) relation (Q =10kit where k is hydraulic conductivity, I the hydraulic gradient and t the aquifer thickness). An estimate of the groundwater reserve was determined from Brassington (1990) formula (Qa= b x sy x area; where b=average saturated thickness of the aquifer, sy =the specific yield). The available driller's record is incomplete so Storativity and specific yield could not be evaluated. Available pumping test data for six boreholes were used in computing aquifer parameters. A summary of the computed results is presented in Table 1.

2.1 Hydrogeochemistry and groundwater quality

Water samples were collected from all the available groundwater sources in the area for analysis. Using field measuring kits pH reading, hydraulic head for hand-dug wells, temperature and TDS were measured right in the field. A total of seven deep boreholes and ten hand-dug wells were sampled for analysis. The ten (10) hand-dug wells include HW-1, 3, 4, 6, 8, 9, 10, 11, 13, and HW- 14. The collected samples were analyzed in the Nigerian Geological Survey chemistry laboratories, in Kaduna, northwestern Nigeria.

The cations were analyzed using an adsorption flame photometer and atomic absorption spectrophotometer (AAS) Spectronic 20D while the anions were analyzed using general volumetric titrimetric methods with EDTA and Phenolphthalein as the indicators. Results of the chemical analysis were interpreted using the hydrochem computer software and are presented in the Piper trilinear diagram (Fig. 4) Water quality is commonly defined by a multitude of chemical, physical and biological properties which determine the suitability of the water for domestic, industrial or agricultural use (Bachmat *et al.*, 1980).

Groundwater quality generally depends on the quality of water recharging the source, the length of the flow path, the mineralogy of the soils and aquifer materials, the residence time in the groundwater flow system and human activities (Thomas *et al*., 1993). To establish the quality of groundwater in the study area four parameters were considered and the results were compared with WHO (2006) standards and the Nigerian industrial standard for drinking water, (NIS, 2007), (Table 2). The parameters chosen are Cl^-, NO_3^- , HCO_3^- and hardness. These parameters in addition to being used as pollution indicators can also be used as indices to check on-site sanitation (Mike et al., 1999). The results of the hydrogeochemical analysis are presented in Table 3.

3.0 Results and Discussion

The analysis of the stream flow data and other meteorological data for the streams shows that there is effluent hydraulic connectivity between the river and the adjoining groundwater system. The mean annual discharge of streams is about $1.35x\ 10^{10}m^3$/year the mean runoff in the streams is about $1.24\ x10^{10}m^3$ per annum. The base flow from the adjoining aquifers into the river is $1.12x10^{10}m^3$and this represents about 6.8% of the total flow. Gwagwalada receives about 800mm ($5.12x10^8m^3$/yr) of rainfall per year about 65% ($3.30x10^8$m) of this is lost through evapotranspiration while 15% ($7.70x10^7m^3$) constitutes runoff and the remaining 20% is considered to be the main recharge into the groundwater systems.

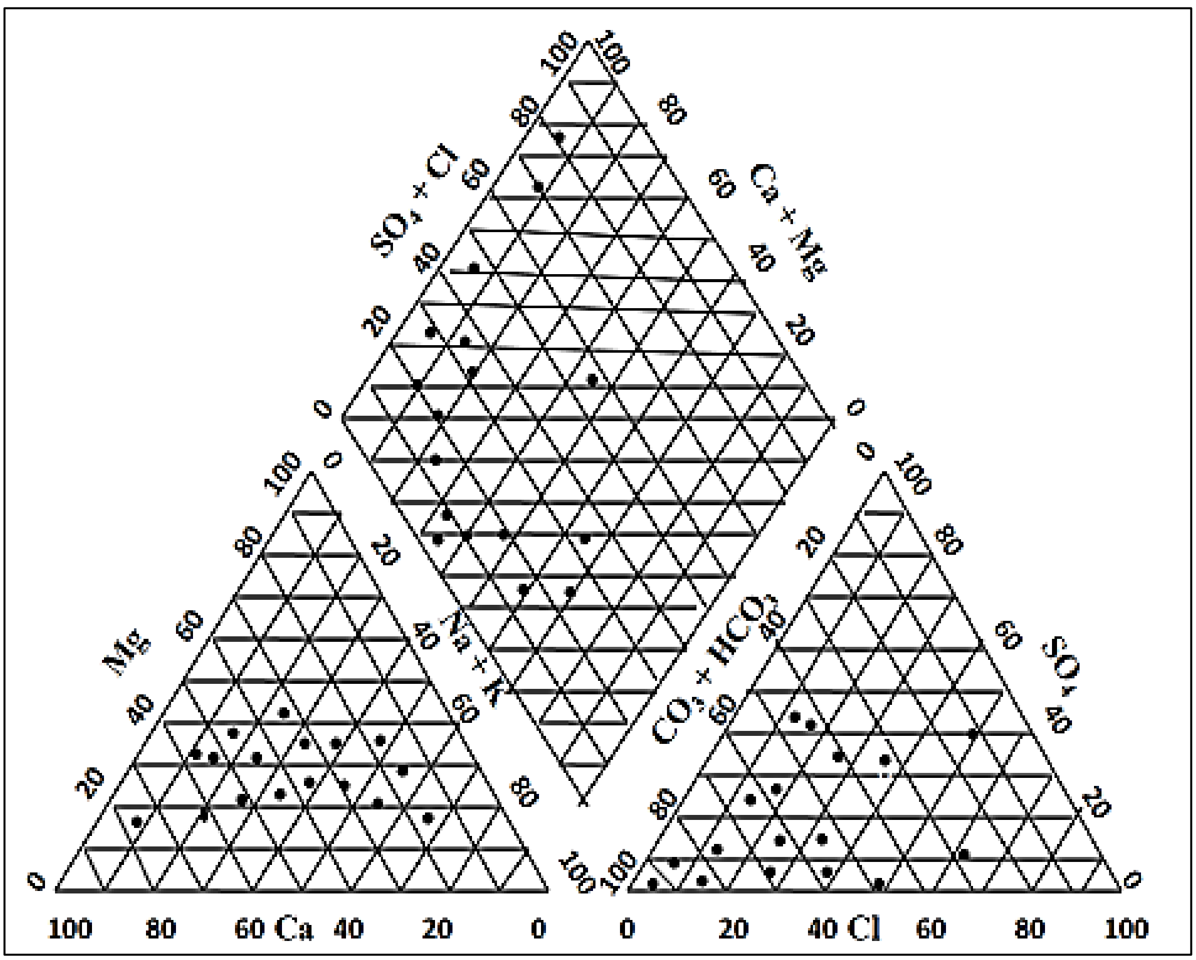

Fig. 4: Piper diagram for water samples from the study area (major cations and anions for water samples from the study area.

3.2 Aquifer Parameters

Granulometric analysis of available lithologic logs from six boreholes (BHG-1, BHG-3, BHG-4, BHG-6, BHG-7, and BHG-9) and driller's data from pumping test were used in computing aquifer thickness and hydraulic conductivity while Cooper-Jacobs (1946) method was used to determine the transmissivity for the 6 boreholes in the study area (Table 1). The method relates (T, K and b): T=Kb where T= transmissivity, K = hydraulic conductivity and b= aquifer thickness or the screen length.

The area receives a moderate amount of rainfall (800mm) annually 65% of this is lost through evapotranspiration, 15% constitutes direct surface runoff while 20% goes to recharge the groundwater system. The high percent evapotranspiration is probably due to the high maximum daily temperature experienced in the area for most of the year as well as poor vegetation cover.

Table 1: Summary of aquifer parameters from the study area using pumping test data from single wells

Bore-hole number	Saturated aquifer thickness (m)	Drawdown (m)	Transmissivity (T) (m^2/day)	Hydraulic conductivity (*k*)(m/day)
BHG -1	33.20	21.50	26.09	$4.11*10^{-1}$
BHG -3	35.30	16.50	17.25	$2.30*10^{-1}$
BHG -4	44.00	7.00	37.05	$6.50*10^{-1}$
BHG -6	39.00	26.00	4.95	$3.30*10^{-2}$
BHG -7	50.00	21.00	51.80	$1.60*10^{-1}$
BHG -9	63.00	10.15	32.76	$4.20*10^{-1}$
Mean	44.08	17.03	28.32	$3.17*10^{-1}$

Table 2: WHO and NIS standards for drinking water quality

Parameter	Units	WHO (2006) limit	NIS (2007) limit
Aluminium (Al^{3+})	mg/l	0.20	0.20
Chloride (Cl^-)	mg/l	250	250
Colour	TCU	15	15
Odour	Threshold numbers	3.00	NA
Copper (Cu^{2+})	mg/l	1.00	1.00
Corrosivity		Non-corrosive	NA
Fluoride (F^-)	mg/l	2.00	1.50
Iron (Fe^{3+})	mg/l	0.30	0.30
Magnesium (Mg^{2+})	mg/l	0.05	0.20

Mercury (Hg+)	mg/l	0.002	0.001
pH		6.50 – 8.50	6.50 – 8.50
Arsenic (As^{2+})	mg/l	NA	0.01
Barium (Ba^{2+})	mg/l	NA	0.70
Chromium (Cr^{6+})	mg/l	NA	0.05
Cyanide (CN)	mg/l	NA	0.01
Conductivity	µs/cm	NA	1000
Hardness (CaCo3)	mg/l	NA	150
Lead (Pb^{2+})	mg/l	0.015	0.01
Nickel (Ni^{2+})	mg/l	NA	0.02
Nitrate(NO_3)	mg/l	10	50
Sodium (Na^{2+})	mg/l	30-60	200
Silver	mg/l	0.10	NA
Sulphate (SO_4^{2})	mg/l	250	100
Total Dissolved Solids (TDS)	mg/l	500	500
Zinc (Zn^{2+})	mg/l	5.00	3.00

Table 3: Results of chemical analysis of groundwater samples from the study area

No	**Source**	**Location**	**Temp (°C)**	**Conductivity (µs/cm)**	**TDS (mg/l)**	**pH**	**Ca2+ (mg/l)**	**Mg2+ (mg/l)**	**Na+ (mg/l)**	**K+ (mg/l)**	**SO42- (mg/l)**	**Cl- (mg/l)**	**HCO3- (mg/l)**	**NO3- (mg/l)**	**F (r**
1	BH- 1	Tabe	33.00	350	224	6.50	36.00	11.20	13.00	6.00	10.00	16.00	133	13.70	0.
2	BH- 2	Pagadna	33.00	340	218	6.50	32.00	11.40	15.00	6.00	0.00	40.00	112	0.00	0.
3	BH- 4	Babban	35.00	210	135	6.00	28.00	13.40	18.00	6.00	0.00	16.00	212	0.00	0.
4	BH- 5	Tsauni	31.50	370	237	6.50	16.00	6.00	17.00	6.00	10.00	8.00	100	8.80	1.
5	BH- 8	Maji	30.00	70	45	6.50	6.00	2.70	9.00	5.00	12.00	16.00	180	17.60	0.
6	BH- 9	Jigbodo	33.80	300	192	6.50	27.20	9.20	12.00	6.00	5.00	12.00	106	4.40	0.
7	BH-10	Tunga	35.00	250	167	6.50	32.80	7.80	17.00	6.00	0.00	2.00	80	4.40	0.
8	HW -1	Doba	32.20	60	38	6.30	4.00	2.20	13.00	5.00	20.00	20.00	84	13.20	2.
9	HW -3	Lange	33.00	220	141	6.70	12.00	9.30	29.00	6.00	5.00	48.00	60	8.80	1.
10	HW -4	Abuchi	32.40	1320	846	6.90	120.00	30.00	29.00	6.00	80.00	28.00	168	17.60	0.
11	HW -6	Ikka	32.90	880	564	7.10	54.00	17.00	15.00	3.40	70.00	52.00	100	88.00	0.
12	HW -8	Koro	34.40	1070	686	6.90	60.00	20.00	15.00	4.00	45.00	16.00	204	44.00	0.
13	HW -9	Chizako	33.80	110	71	6.80	8.00	2.00	16.00	4.00	7.00	36.00	200	35.20	0.
14	HW -10	Kwamba	32.40	334	214	6.30	72.00	17.00	22.00	6.00	26.00	8.00	53.00	88.00	0.
15	HW -11	Diko	-	1400	897	6.00	140.00	16.00	18.00	6.00	40.00	28.00	22.00	132.00	0.
16	HW -13	Rafin Madugu	31.80	300	192	6.30	26.00	10.00	18.00	6.00	12.00	32.00	120	22.00	0.
17	HW -14	Ibo	30.30	220	141	6.00	28.00	10.00	20.00	6.00	10.00	8.00	250	22.00	0.

While the surface runoff is favoured by urban development through the pavementnt of roads and other drainage systems, the recharge into the groundwater system is supported by highly permeable loose sand of the Quaternarriverer course alluvium (Obiefuna *et. al.*,1999).

Correlation of bore logs in SW-NE directiorevealsal that there are three aquifer systems- the upper unconfined (0-25m) mostly tapped by hand-dug wells, the middle semi-confined aquifer (25-45m) that serves some boreholes

(BH-3, 4, 5, 6 and 7) and the lower confined aquifer (45-65m) The borehole yields range from 9.0 m^3/hr to 31.7 m^3 /hr with an average of 20 m^3 /hr. The mean hydraulic conductivity (K) determined from the available pumping test data is 5.6 x10 -1m/day and a Transmissivity of 28.32m^2/day, these results agree witBrassington'son's (1990) moderate yielding aquifers. The calculated groundwater velocity of 2.42m/yr is moderate to allow sustainable infiltration /percolation into the groundwater regime. The groundwater reserve of $1.01x10^{10}m^3$ is capable of supporting a population of 1.4m for one year on an average of 220/l/day/head and a mean borehole yield of 20 m^3/hr is sufficient for sustainable development of groundwater.

The hydrogeochemical results show that most samples are withithemaximumum permissible limits for drinking water quality of WHO (2006) and the NIS (2007). The hardness of 150 mg/L and above was recorded in Hw-3, 6, 8, 1and 1111. NO_3^- concentration of 50mg/L and above was recorded in 3 samples (Hw-6, 10, 11), these same samples also recorded high concentrations of TDS, electrical conductivity (EC) and are among those samples with Fe^{2+} concentrationononon of 0.6 and above. For hardness, NO_3^-, TDS and EC in high concentration it is most likely to be due to input from domestic effluents into wells closer to waste disposal sites. A plot of the major cations and anions in the Piper trilinear diagram (Fig. 3) reveals that there are two dominant water types in the study area; Ca^{2+}- HCO_3^- type and Na^+ +K^+ – HCO_3^-type, (Table 5). The Ca^{2+}- HCO_3 is associated with areas with a temporary hardness which agrees with results in Table 4 (hardness of 106-136 mg/L).

Table 4: Hardness of individual groundwater sources from the study area

Sample No	Location	Hardness (mg/l)	Water Type
BH -1	Tabe	136	Slightly hard
BH -2	Pagadna	127	Slightly hard
BH -4	Babban	125	Slightly hard
BH -5	Tsauni	67.00	Slightly hard
BH -8	Maji	26.00	Soft
BH -9	Jigbodo	106	Slightly hard
BH -10	Tunga	144	Slightly hard
HW -1	Doki	19.00	Soft
HW -3	Lange	68.00	Moderately soft
HW -4	Abuchi	421	Hard
HW -6	Ikka	199	Moderately hard
HW -8	Koro	231	Moderately hard
HW -9	Chizako	28.00	Soft
HW -10	Kwamba	250	Moderately hard
HW -11	Diko	415	Hard
HW -13	Rafin Madugu	105	Slightly hard
HW -14	Ibo	109	Slightly hard

This was recorded in four out of the seven boreholes sampled. The second water type recorded in seven out of the ten hand-dug wells is mostly associated with an influx of domestic effluents rich in sodium and bicarbonate which gives the water similar characteristics as those originating from alkali carbonate rocks (Arthur, 1995). Additional bicarbonate could also be released from the breakdown of weak carbonic acid formed by rainwater and carbon dioxide recharging these aquifers.

Table 5: Summary of water chemistry data

Sample No	Na^+ mg/l meq/l	K^+ mg/l meq/l	Ca^{2+} mg/l meq/l	Mg^{2+} mg/l meq/l	Cl- mg/l meq/l	HCO_3- mg/l meq/l	SO_4^2- mg/l meq/l	TDS mg/l	Cations/ Anions	Comments
BH -1	13.0	6.0	36.0	11.2	16.0	133.0	10.0	225.2	1.20	Ca^{2+} -HCO_3-
	0.57	0.15	1.80	0.92	0.45	2.18	0.21			
BH -2	15.0	6.0	32.0	11.4	40.0	112.0	0.0	216.4	1.10	Ca^{2+} -Cl^-
	0.65	0.15	1.60	0.94	1.13	1.84	0.00			
BH -4	18.0	6.0	28.0	13.4	16.0	212.0	0.0	293.4	0.50	Ca^{2+} -HCO_3-
	0.78	0.15	1.40	1.10	0.45	3.47	0.00			
BH -5	17.0	6.0	16.0	6.0	8.0	100.0	10.0	163.0	1.10	Ca^{2+} -HCO_3-
	0.74	0.15	0.80	0.49	0.23	1.64	0.21			
BH -8	9.0	5.0	6.0	2.7	16.0	180.0	12.0	230.7	0.30	Na^+ +K^+-HCO_3-
	0.39	0.13	0.30	0.22	0.45	2.95	0.25			
BH -9	12.0	6.0	27.2	9.2	12.0	106.0	5.0	177.4	1.30	Na^+ +K^+-HCO_3-
	0.52	0.15	1.36	0.76	0.34	1.74	0.10			
BH -10	17.0	6.0	32.8	7.8	2.0	80.0	0.0	145.6	2.30	Ca^{2+} -HCO_3-
	0.74	0.15	1.64	0.64	0.06	1.31	0.00			
HW -1	13.0	5.0	4.0	2.2	20.0	84.0	20.0	148.2	0.50	Na^+ +K^+-HCO_3-
	0.57	0.13	0.20	0.18	0.56	1.38	0.42			
HW -3	29.0	6.0	12.0	9.3	48.0	60.0	5.0	169.3	1.10	Na^+ +K^+-HCO_3-
	1.26	0.15	0.60	0.77	1.35	0.98	0.10			
HW -4	29.0	6.0	120.0	30.0	28.0	168.0	80.0	461.0	1.90	Ca^{2+} -HCO_3-
	1.26	0.15	5.99	2.47	0.79	2.75	1.67			
HW -6	15.0	3.4	54.0	17.0	52.0	100.0	70.0	311.4	1.10	Ca^{2+} -HCO_3-
	0.65	0.09	2.69	1.40	1.47	1.64	1.46			
HW -8	15.0	4.0	60.0	20.0	16.0	204.0	45.0	364.0	1.10	Ca^{2+} -HCO_3-
	0.65	0.10	2.99	1.65	0.45	3.34	0.94			
HW -9	16.0	4.0	8.0	2.00	36.0	200.0	7.0	273.0	0.30	Na^+ +K^+-HCO_3-
	0.70	0.10	0.40	0.16	1.02	3.28	0.15			

HW -10	22.0	6.0	72.0	17.0	8.0	53.0	26.0	204.0	3.70	Ca^{2+} -HCO_3-
	0.96	0.15	3.59	1.40	0.23	0.87	0.54			
HW -11	18.0	6.0	140.0	16.0	28.0	22.0	40.0	270.0	4.70	Ca^{2+} -HCO_3-
	0.78	0.15	6.99	1.32	0.79	0.36	0.83			
HW -13	18.0	6.0	26.0	10.0	32.0	120.0	12.0	234.0	1.00	Ca^{2+} -HCO_3-
	0.78	0.15	1.30	0.82	0.90	1.97	0.25			
HW -14	20.0	6.0	28.0	10.0	8.0	260.0	10.0	342.0	0.70	Ca^{2+} -HCO_3-
	0.87	0.15	1.40	0.82	0.73	4.26	0.21			

4.0 Conclusion

The study has identified three aquifer systems in the area within the depth bracket of 0-65m. The upper unconfined aquifer receives recharge from direct rainfall and is tapped mainly by the hand-dug wells (0-25m total depth). This aquifer is presently under the threat of surface-generated pollution mostly associated with domestic/household waste. The middle semi-confined aquifer occurs at a depth below 40m and is a source of supply to boreholes completed within 25-45m. The quality of water from this aquifer is still within the limits for drinking water quality of WHO (2006) and NIS (2007).

The lower confined aquifer is tapped by very few boreholes 45-65m. Groundwater chemistry suggests that the upper aquifer has isolated cases of high concentrations of NO_3^-, (88-132mg/L), high TDS (546-897 mg/L) Fe^{2+} (0.5-2 mg/L), moderately hard to very hard (144 -421 mg/L). The quality of the water from the middle and the lower aquifers is generally acceptable as it falls within the maximum permissible limits of WHO (2006) and NIS (2007). Two dominant water types are identified from the Piper diagram – Na^++K^+-$HCO_3^-$and the Ca^{2+} - HCO_3^- water types. The study area therefore has high potential for sustainable groundwater development to meet the needs of the populace. It is however suggested that the development of groundwater through hand-dug wells should ensure high protective aprons and well points should be sited at good safety distances from waste disposal sites.

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Compliance with Ethical Standards Declarations

The authors declare that they have no conflict of interest.

Data availability

All data used in this study will be readily available to the public.

Consent for publication

Not Applicable

Availability of data and materials

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CAinitiateded the process, MUU led in the field work and drafted the initial manuscript, CAU reviewed the manuscript, OPO and CDA collaborated in making the (work) manuscript a success. All the authors were involved in the final presentation of the manuscript.