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Hydro-geochemical characterization and modeling of groundwater in Chikun Local Government Area of Kaduna state, Nigeria

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ABSTRACT

This study assessed groundwater quality in Chikun Local Government Area of Kaduna State and how it can be harnessed as a useful resource for water supply and to improve the management of water resources. The field survey methods adopted with the collection of water samples in the field were employed in collecting data. The study randomly collected fifty water samples from wells and boreholes in the peak of wet and dry seasons for 2 years (2021–2022) in the five selected wards within the Chikun Local Government Area and a range of water quality parameters were measured and compared with WHO standards for drinking water. The laboratory analysis results revealed that with the exception of magnesium, mercury, iron, lead and calcium, all other physicochemical parameters measured fell within the maximum permissible limit. The presence of some of these pollutants at varying degrees was found. Groundwater models showed groundwater flow in the North-Western direction and significant vertical movement of contaminants up to depths of about 60 m. This calls for regulations on the handling of wastes and pollutants that affect groundwater, which is best done through strict enforcement of laws and advocacy through all the appropriate institutions involved in water management.

Key words: anthropogenic activities, groundwater samples, hydrochemical investigation, hydrogeology, water quality

HIGHLIGHTS

- The spatiotemporal patterns of groundwater quality parameters were investigated in Chikun Local Government Area of Kaduna State, Nigeria.
- Water Quality Index (WQI) was employed to determine the suitability of groundwater quality parameters.
- The key water pollution indicators were identified through the MODFLOW model.
- Results were presented and discussed.
- The deterioration of certain water quality indicators indicates that more attention should be paid to groundwater quality management.

GRAPHICAL ABSTRACT

1. INTRODUCTION

Water is a unique resource, having no substitute and of a fixed amount, though its quantity and quality vary over space and time. There has been a continued increase in population, particularly in the developing world, and consequently the demand for water for various uses. This increase in demand has led to water shortage in many parts of the world and water shortage has remained an endemic problem anytime anywhere. Apart from the domestic need for water, other human activities such as fishing and farming are dependent on water (Lapworth *et al.* 2016).

In recent times, groundwater has become one of the most important natural resources in many countries of the world. In its natural state, it is generally of excellent quality and an essential natural resource since water is naturally purified when it is slowly percolating through soil. Compared to surface water, groundwater has a number of essential advantages: higher quality, well protected from surface contaminants, less susceptible to drought, and much more evenly spread over large regions than surface water, these advantages have resulted in wide use of groundwater for water supply. In some countries in the world such as Denmark, Malta, and Saudi Arabia, groundwater is the only source of water supply while in other countries, it is the most important part of total water resources. For example, groundwater in Tunisia is 95% of the country's total water resources, 83% in Belgium, and 75% in the Netherlands, Germany, and Morocco (Dhakar & Bhaskar 2017).

Nigeria's groundwater resources have been under increasing threat of declining water levels and pollution in recent years due to rapid demographic changes, which have coincided with the establishment of human settlements lacking appropriate water supply and sanitation infrastructure. This applies especially to peri-urban areas like Chikun Local Government Area, the study area, which surrounds the larger metropolitan towns in the country (Abubakar *et al.* 2017). Chikun Local Government Area has developed with no proper water supply network, in spite of the efforts of Kaduna State government to provide portable water for the residents. The problem now is that with the increase in demand for water for various uses in the area, it is impossible to meet the whole demand from a single source; besides, relying heavily on one single source of water supply in the face of existing unfavourable and fickle climatic conditions is very precarious. Coupled with the fact that groundwater level in several parts of Chikun Local Government Area has been falling rapidly and the quality deteriorating due to an increase in abstraction and the number of wells and boreholes drilled for domestic water use has rapidly and indiscriminately increased due to rapidly rising population and changing lifestyles (Samira *et al.* 2015).

A World Bank-sponsored study of the pollution case of surface and groundwater in the Chikun Local Government Area with emphasis on Mararaban Rido, Kakau, Nassarawa and Sabon Tasha wards as well as river Kaduna in 1988 was the first empirical evidence reported that groundwater in the Chikun Local Government Area is being polluted (World Health Organization [WHO] 2017). The result indicated that out of the sampling sites studied, the point at which River Romi entered into the Kaduna River is the one having the highest pollution load, which was attributed to the effluents being discharged from the refinery through the Romi River and River Romi is known to be recharging groundwater of most parts of Chikun Local Government Area. Since then, there has been limited academic research on the pollution of groundwater in the Chikun Local Government Area. A climax of these academic researches was a study by Samira *et al.* (2015) that focused on water quality from hand-dug wells in Bayan Dutse, Narayi in Chikun local government with emphasis on the physicochemical paramaters of the samples taken. The study found that due to the location, water in hand-dug wells is polluted by runoff from the sewage system.

From the available literature on groundwater prospecting in the study area, there is no study on the use of the Water Quality Index (WQI) technique to assess groundwater quality in the Chikun Local Government Area of Kaduna State. Using the WQI technique to assess groundwater conditions in the Chikun Local Government Area would assist in reducing water shortage from unsafe sources and from health problems leading to death.

Therefore, assessment of groundwater quality is necessary to protect groundwater sources in the Chikun Local Government Area since the resource is being threatened by contamination.

2. THE STUDY AREA

Chikun Local Government area lies geographically between Latitude 10° N and 10° 50″ North of the equator and Longitude 6° 4″ E and 7° 5″ East of the Greenwich Meridian, as shown in Figure 1. It is located in the Southern part of Kaduna State and shares common boundaries with Kaduna North Local Government and Igabi in the North. In the Southwestern part, it shares a border with Niger State and in the East and with Kajuru and Kachia Local Government Area. At present Chikun Local Government Area has Kujama as its administrative

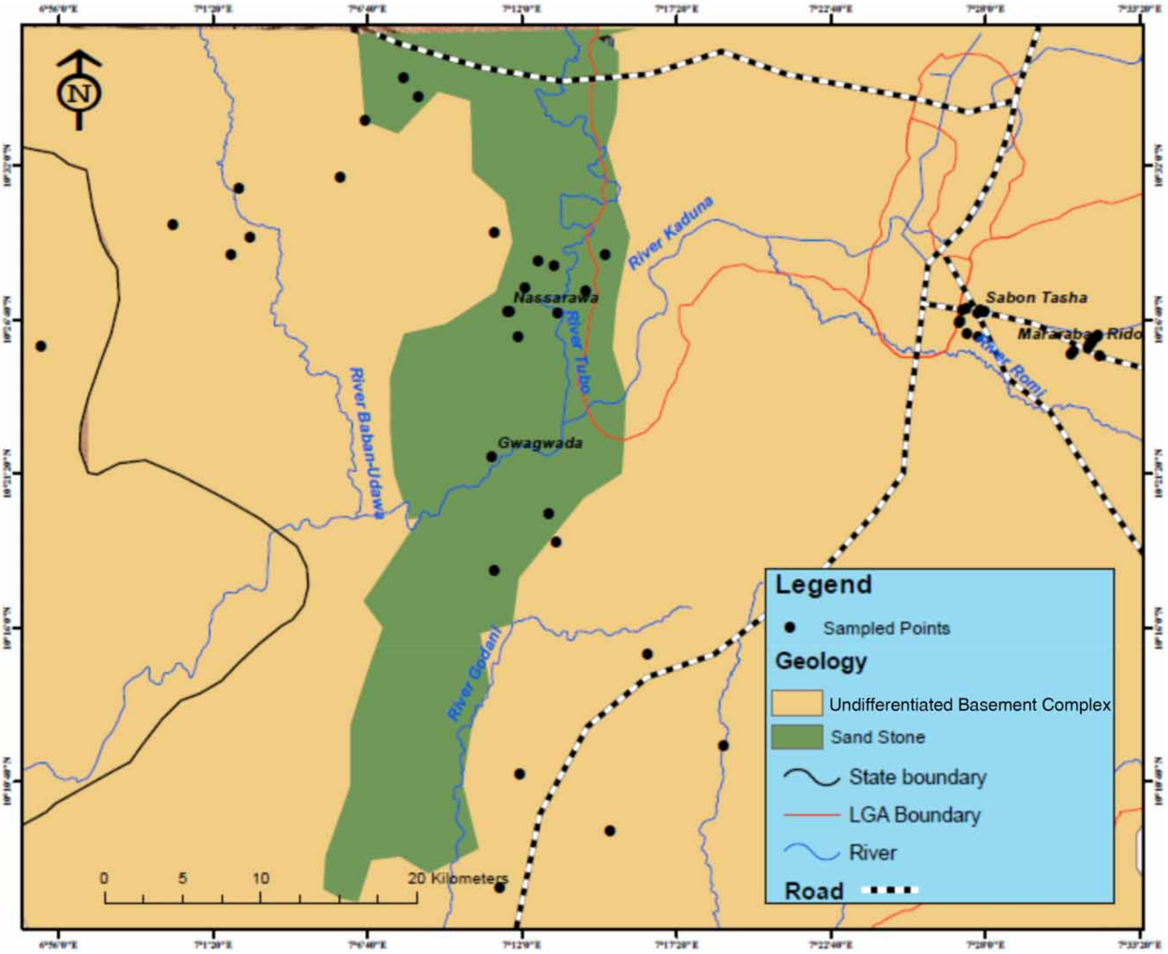

Figure 1 | Geology of Chikun Local Government. *Source:* GIS Lab. Department of Environmental Management, Kaduna State University (2021).

headquarters, Gonin Gora, Narayi, Nassarawa, Trikania, Sabon Tasha, Ungwar Romi, Ungwar Sunday, Ungwar Yelwa, Karatudu and part of Barnawa as it component area covering a total land size of 4,801 km^2 (Danjuma 2015).

According to Danjuma (2015), Chikun Local Government Area is under the influence of two major trade winds, which are the tropical continental air mass (cT) blowing from the North-East through the Sahara desert, and bringing about dry season and the tropical maritime air mass (mT) blowing form South-East through the Atlantic Ocean and it brings about the wet season.

The study area is situated within the guinea savannah zone which is characterised by two distinct seasons, that is, the wet and dry seasons, with a climate type according to Koppen's classification as a tropical wet and dry climate. This region is said to have 6–7 months of rainfall with the onset between April and May, it has a short dry period in August called the 'August break' as presented in Table 1. Rainfall in this region sometimes exceeds the month of September though there are variations, but it peaks in July (Danjuma 2015).

The mean annual rainfall ranges from 1,397 to 1,551 mm and the dry season on the other hand begins in November and ends in March a period of 5 months. Within this period comes the Harmattan cold wind which prevails from December to February and a short but excessive heat period between March to April and sometimes the early days of May depending on when the rain commences as shown in Table 1. The temperature is high throughout the year, with the highest in March ranging between 37 and 42 °C with the lowest temperature in January ranging between 5 and 13 °C (Danjuma 2015).

Relative humidity ranges between 10 and 30% in the dry season and 70 and 90% in the wet season, in the afternoon and night or at dawn, respectively. This relative humanity is generally higher at night. It should be noted that surface and groundwater levels fluctuate in response to seasonal and diurnal climatic variations (Danjuma 2015).

3. MATERIALS AND METHODS

The assessment of groundwater quality for Chikun Local Government Area of Kaduna State was designed and carried out in stages as follows: pre-field preparation which includes preparation of maps for the study area; reconnaissance study of the area; sampling technique adopted for water sample collection from hand-dug wells and borehole across the study area (Chikun Local Government Area of Kaduna State) and data collation and analysis. Two main types of groundwater abstracting structures can be identified in Chikun Local Government Area, they are boreholes and hand-dug wells. Samples from groundwater sources from the five wards selected were collected for the years 2021 and 2022 during both the peak of dry and rainy seasons of 2021 and 2022 as shown in Tables 1–4. Groundwater sample collection was done between 7 am and 1 pm during the study period, about 2 l of water sample from each source (wells and boreholes), was collected in separate two litres of plastic cans and transported to the laboratory for analysis and stored in order to keep the composition of water samples unchanged., the analysis of parameters on the priority basis had been taken up, 14 water quality parameters were considered in the analysis of WQI representing four hazard classes (Salinity hazard, Permeability/infiltration hazard, Specific ion toxicity hazard and Miscellaneous hazard) . The choice of a well and borehole depended on its distance from a previously chosen one in the locality, and the consent of the owner to make the well or borehole available for study. Water samples from different locations within the study area were collected as per the guidelines of the random sampling technique and new two litres acid washed plastic cans were used.

Boreholes fitted with motors for water lifting were allowed to run the water for 5 min and others fitted with hand pumps were allowed to run for 15 min in order to flush out stationary water. All sample containers were flushed with several volumes of water before the samples were collected. As water is dynamic in nature and during sampling it enters the new environment from its natural environment, its chemical composition may not remain the same but may tend to adjust itself according to its new environment and its content alters at very different rates, particularly with organic materials. Before sampling from taps/hand pumps, the exit was opened and closed several times to get rid of dirt particles, the tips of the tap/hand pump were cleaned sufficiently long time to ensure sterilisation, and the water was then allowed to run free in a pencil thick stream for approximate 5 min before filling the bottle. The sample bottle is closed under sterile conditions and labelled. Immediately upon arrival, samples were refrigerated at approximately 4°C. Then, the chemical characteristics including metals were determined as per the standard methods for the examination of water and wastewater

Table 1 | Monthly rainfall (mm) data of Chikun Local Government Area (2007–2022)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	28.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.0	3.6	32.7	95.1	48.0	28.0
Apr	76.4	37.1	48.8	10.0	60.4	8.0	26.4	29.8	57.1	61.6	74.3	90.8	0.0	20.1	74.3	76.4
May	85.1	122.8	84.3	99.2	99.0	157.9	65.7	62.5	137.4	212.8	117.6	183.3	89.3	239.8	117.6	85.1
Jun	151.5	178.1	218.8	107.0	182.5	102.3	158.0	202.8	80.9	140.3	287.1	230.1	112.6	216.5	286.1	151.5
Jul	402.6	358.7	203.8	170.9	222.9	90.2	186.5	190.1	233.4	225.6	344.9	183.5	263.1	324.2	344.9	402.6
Aug	431.2	310.7	259.8	223.5	214.5	223.6	462.8	327.8	208.0	269.4	317.7	317.7	544.0	498.1	317.7	431.2
Sep	396.5	347.3	144.3	199.6	60.0	183.7	133.7	300.8	298.7	403.4	428.2	428.2	359.4	351.8	428.2	396.5
Oct	71.3	24.6	51.5	88.5	33.9	27.7	193.8	148.7	135.0	135.1	37.4	37.4	89.6	35.2	37.4	71.3
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**1,642.6**	**1,379.3**	**1,011.3**	**898.7**	**873.2**	**793.4**	**1,226.9**	**1,262.5**	**1,151.8**	**1,448.2**	**1,655.2**	**1,474.6**	**1,490.7**	**1,780.8**	**1,654.2**	**1,642.6**

Source: NIMET (2022).

Table 2 | Selected wards in Chikun Local Government Area

S/No	Ward	Selected wards
Rural wards		
1	Chikun	Gwagwada
2	Gwagwada	Kunai
3	Kakau	
4	Kunai	
5	Kuriga	
Urban wards		
6	Kujama	Mararaban Rido
7	Mararaban Rido	Nassarawa
8	Narayi	Sabon Tasha
9	Nassarawa	
10	Sabon Gari	
11	Sabon Tasha	
12	Yelwa	

Source: Field Survey, 2021.

Table 3 | Number of wells and boreholes sampled in the study area

S/No	Settlement	Number of wells sampled	Number of boreholes sampled
1	Gwagwada	5	5
2	Kunai	5	5
3	Mararaban Rido	5	5
4	Nassarawa	5	5
5	Sabon Tasha	5	5
		25	25

Source: Field Survey, 2021.

(APHA 2012). A total of 50 samples were collected, that is, ten samples (five samples from wells and the other five samples from boreholes) were collected in each of the five settlements per season per year for laboratory analysis.

These parameters were chosen based on their considerable impact on water quality (Tyagi *et al.* 2013), the intended use of the water and most widely used for the calculation of the WQI (Tyagi *et al.* 2013).

3.1. Calculation of sub-index of quality rating (Qi)

To calculate the Sub-Index Quality Rating (Qi) the following assumptions are made; let there be i water quality parameters where the quality rating or sub-index (Qi) corresponding to the nth parameter is a number reflecting the relative value of this parameter in the polluted water with respect to its standard permissible value. The value of Qi is calculated using the following expression:

$$Qi = \left[\frac{(Vn - Vi_o)}{(Si - Vi_o)}\right] \times 100 \tag{1}$$

where Qi is the quality rating for the nth water quality parameter, Vn is the estimated value of the nth parameter at a given sampling station, Si is the standard permissible value of ith parameter, and Vi_o is the ideal value of ith parameter in pure water.

All the ideal values (Vi_o) are taken as zero for drinking water except for pH is 7.0 and dissolved oxygen is 14.6 mg/l. (Tyagi *et al.* 2013).

Table 4 | Details of sampling locations in Chikun Local Government Area

		Coordinates			
Sample area (Ward)	**Sample code**	**Lat. (N)**	**Long. (E)**	**Elevation (m)**	**Depth (m)**
Gwagwada	GD(W1)	10°21′55.4″	07°10′56.9″	590.3	9.41
	GD(W2)	10°19’58.2″	07°12’54.4″	594.4	10.38
	GD(W3)	10°17’58.3″	07°11’01.7″	591.9	10.74
	GD(W4)	10°18’59.1″	07°13’10.5″	592.5	11.96
	GD(W5)	10°15’03.6″	07°16’19.7″	597.1	11.13
	GD(BH1)	10°11’53.8″	07°18’57.6″	591.6	
	GD(BH2)	10°10’56.3″	07°11’54.7″	601.3	
	GD(BH3)	10°08’56.9″	07°15’01.0″	589.6	
	GD(BH4)	10°07’00.2″	07°11’12.7″	594.8	
	GD(BH5)	10°05’15.7″	07°10’23.9″	563.7	
Kunai	KN(W1)	10°22’31.8″	06°53’33.5″	629.1	12.33
	KN(W2)	10°25’44.1″	06°55’22.4″	631.6	12.78
	KN(W3)	10°29’58.3″	06°59’55.8″	633.1	11.36
	KN(W4)	10°28’55.6″	07°01’56.3″	622.4	12.11
	KN(W5)	10°30’73.2″	07°02’12.9″	624.6	10.95
	KN(BH1)	10°29’31.6″	07°02’36.0″	621.0	
	KN(BH2)	10°31’37.8″	07°05’42.9″	627.0	
	KN(BH3)	10°33’33.4″	07°06’34.6″	630.9	
	KN(BH4)	10°35’01.1″	07°07’53.8″	627.4	
	KN(BH5)	10°34’24.6″	07°08’24.5″	622.1	
Mararaban Rido	MR(W1)	10°25’42.0″	07°31’32.2″	698.6	11.36
	MR(W2)	10°26’02.4″	07°31’42.9″	639.1	12.67
	MR(W3)	10°26’08.1″	07°31’52.5″	648.7	13.04
	MR(W4)	10°25’49.9″	07°31’34.4″	663.4	9.64
	MR(W5)	10°25’52.7″	07°31’37.5″	642.2	10.12
	MR(BH1)	10°25’34.2″	07°31’02.4″	658.3	
	MR(BH2)	10°25’23.9″	07°31’56.2″	650.6	
	MR(BH3)	10°26’06.4″	07°31’50.7″	642.4	
	MR(BH4)	10°25’54.3″	07°31’40.7″	641.2	
	MR(BH5)	10°25’30.1″	07°30’57.3″	632.3	
Nassarawa	NS(W1)	10°26’57.5″	07°11’29.4″	621.8	3.41
	NS(W2)	10°26’57.5″	07°11’34.2″	614.3	3.94
	NS(W3)	10°26’51.9″	07°13’13.8″	623.1	6.49
	NS(W4)	10°27’44.3″	07°12’06.2″	609.8	7.83
	NS(W5)	10°27’37.9″	07°14’11.4″	638.4	6.98
	NS(BH1)	10°28’55.0″	07°14’52.6″	633.7	
	NS(BH2)	10°28’31.4″	07°13’06.2″	628.5	
	NS(BH3)	10°28’40.9″	07°12’33.3″	622.1	
	NS(BH4)	10°26’05.2″	07°11’51.7″	631.9	
	NS(BH5)	10°29’41.8″	07°11’01.6″	629.3	
Sabon Tasha	ST(W1)	10°26’58.5″	07°27’48.4″	611.6	11.31
	ST(W2)	10°26’54.4″	07°27’43.9″	609.8	12.01
	ST(W3)	10°27’01.7″	07°27’20.1″	611.5	10.12
	ST(W4)	10°26’33.9″	07°27’05.3″	610.7	11.78

(*Continued.*)

Table 4 | Continued

Sample area (Ward)	Sample code	Coordinates Lat. (N)	 Long. (E)	Elevation (m)	Depth (m)
	ST(W5)	10°26’11.7″	07°27’21.8″	611.9	10.93
	ST(BH1)	10°26’56.5″	07°27’56.9″	609.5	
	ST(BH2)	10°26’05.2″	07°27’44.8″	610.2	
	ST(BH3)	10°26’37.1″	07°27’06.3″	611.9	
	ST(BH4)	10°26’55.6″	07°27’58.0″	609.4	
	ST(BH5)	10°27’01.4″	07°27’11.5″	607.1	

Source: Field Survey 2021.

To calculate the quality rating for pH, it may be considered that:

For pH the ideal value is 7.0 (for natural water) and the permissible value is 8.5 (for polluted water). Therefore, the quality rating for pH is calculated from the following relation:

$$Q_{\mathrm{pH}} = 100\left[\frac{(V_{\mathrm{pH}} - 7.0)}{(8.5 - 7.0)}\right] \tag{2}$$

Here, V_{pH} is the observed value of pH during the study period.

To calculate the Quality Rating for Dissolved Oxygen, the ideal value (VDO) for dissolved oxygen is 14.6 mg/l and the standard permitted value for drinking water is 5 mg/l. Therefore, the quality rating is calculated from the following relation:

$$Q\mathrm{DO} = 100\left[\frac{(V\mathrm{DO} - 14.6)}{(7.5 - 14.6)}\right] \tag{3}$$

where VDO is the measured value of dissolved oxygen; *Wi* is the calculation of Unit Weight; calculation of unit weight (*Wi*) for various water quality parameters is inversely proportional to the recommended standards for the corresponding parameters.

$$Wi = \frac{K}{Si} \tag{4}$$

where *Wi* is the unit weight for *n*th parameters, S*i* is the standard value for *n*th parameters, and *K* is the constant for proportionality.

3.2. Calculation of WQI

WQI is calculated from the following equation:

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n} QiWi}{\sum_{i=1}^{n} Wi} \tag{5}$$

This study adopted a weighted arithmetic method in computing the WQI.

4. RESULTS AND DISCUSSION

The results of the hydrochemical analyses are presented in Tables 5–14, highlighting the results of laboratory analysis of water samples, statistical analysis as well as comparing the concentration of the physicochemical parameters of groundwater with that of World Health Organisation (WHO) standards for portable water are discussed.

Table 5 | Mean values of pH concentration in groundwater of Chikun Local Government Area (2021–2022)

	WHO (MP)	Well				Borehole			
Ward	6.6–8.5	Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		7.073	0.29732	0.066484	0.04203	6.825	0.097899	0.021891	0.014344
Kunai		6.9485	0.142433	0.03184	0.020498	6.426	0.095278	0.021305	0.014827
Mararaban Rido		6.829	0.118495	0.026496	0.017352	6.852	0.035184	0.007867	0.005135
Nassarawa		6.476	0.176707	0.039513	0.027286	6.564	0.263986	0.059029	0.040217
Sabon Tasha		6.8255	0.172458	0.03856	0.025267	6.43	0.113025	0.025273	0.016457

Source: Field Survey and Laboratory Analysis (2021 and 2022).

Table 6 | Mean values of turbidity in groundwater of Chikun Local Government Area (2021–2022)

	WHO (MPL) 50 (NTU) mg/l	Well				Borehole			
Ward		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		48.35	6.351751	1.420295	0.13137	34.99	12.34951	2.761435	0.352944
Kunai		46.5	1.877849	0.4199	0.040384	16.8	0.756724	0.169209	0.014827
Mararaban Rido		49.35	2.796144	0.625237	0.056659	22.65	0.873951	0.195421	0.038636
Nassarawa		41.7	4.079474	0.912198	0.097829	15.63	8.14849	1.822059	0.521337
Sabon Tasha		48.1	2.125039	0.475173	0.04418	48.48	2.444241	0.546549	0.050418

Source: Field Survey and Laboratory Analysis (2021 and 2022).

Table 7 | Mean values of EC in groundwater in Chikun Local Government Area (2021–2022)

	WHO (MPL) 15,000 (μs/cm)	Well				Borehole			
Ward		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		639.165	98.74404	22.07984	0.154489	690.348	4.312581	0.965322	0.006247
Kunai		554.693	75.69895	16.9268	0.13647	596.967	4.685292	1.047663	0.007848
Mararaban Rido		570.144	12.68637	28.36759	0.222512	688.179	10.81259	2.417769	0.015712
Nassarawa		664.402	43.93596	9.82438	0.066129	572.345	6.065617	1.356313	0.010598
Sabon Tasha		694.801	8.289031	1.853484	0.01193	697.549	10.26037	2.294289	0.014709

Source: Field Survey and Laboratory Analysis (2021 and 2022).

4.1. pH

The pH value of water samples in the study area indicated a minimum statistical mean value of 6.4 in the sample collected at Nassarawa and a maximum statistical mean value of 7.07 in the sample collected at Gwagwada for wells and with a maximum statistical mean value of 6.85 in the samples collected at Mararaban Rido. A minimum value of 6.43 was observed in samples from Sabon Tasha for boreholes as presented in Table 5.

The varying pH values in the groundwater system may be attributed to the variation in photosynthetic activity, disposal of untreated wastewater, and agricultural and anthropogenic activities (Rilwanu 2017). The results of this

Table 8 | Mean values of TDS concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 100 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		85	5.129892	1.147079	0.060352	34.99	12.34951	2.761435	0.352944
Kunai		90	10.25978	2.294157	0.113998	16.8	0.756724	0.169209	0.014827
Mararaban Rido		90	10.25978	2.294157	0.113998	22.65	0.873951	0.195421	0.038636
Nassarawa		105	5.129892	0.912198	0.097829	15.63	8.14849	1.822059	0.521337
Sabon Tasha		48.1	2.125039	0.475173	0.04418	48.48	2.444241	0.546549	0.050418

Source: Field Survey and Laboratory Analysis (2021 and 2022).

Table 9 | Mean values of calcium concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 2.0 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		2.03	0.093302	0.020863	0.045962	1.899	0.097489	0.021799	0.051337
Kunai		0.404	0.106646	0.023846	0.263649	1.83	0.317714	0.070914	0.172453
Mararaban Rido		1.937	0.120092	0.026853	0.061999	1.972	0.147098	0.032892	0.074593
Nassarawa		1.532	0.135436	0.030284	0.088405	2.212	0.132012	0.029519	0.05968
Sabon Tasha		1.933	0.111596	0.024953	0.057732	1.961	0.150749	0.0337085	0.076874

Source: Field Survey and Laboratory Analysis (2021 and 2022).

Table 10 | Mean values of magnesium concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 0.5 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		0.581	0.016189	0.005808	0.027865	0.515	0.012354	0.002762	0.023989
Kunai		0.299	0.047514	0.010624	0.158646	0.698	0.070007	0.015654	0.100297
Mararaban Rido		0.524	0.041218	0.009216	0.078661	0.526	0.017888	0.004	0.034009
Nassarawa		0.486	0.030157	0.006743	0.062052	0.563	0.024730	0.005529	0.043926
Sabon Tasha		0.571	0.058873	0.013164	0103015	0.534	0.028727	0.006423	0.053797

Source: Field Survey and Laboratory Analysis (2021 and 2022).

study concur with the findings of Sadiq *et al.* (2022) who carried out a study using the WQI to evaluate the water quality of River Kaduna, Nigeria.

The standard value of pH for drinking water as per WHO is between 6.5–8.5 and 95.63% of the samples analysed from the entire study area during both rainy and dry seasons, have pH values within the permissible limits of WHO and could be classified as suitable for drinking purpose. However, pH alone cannot be taken as a criterion for determining the portability of water.

4.2. Turbidity

The turbidity values (NTU) for the groundwater samples are presented in Table 6. The values obtained for wells indicated a minimum mean value of 46.5 and a maximum mean value of 49.35 NTU and that of boreholes indicated a minimum mean value of 15.63 and a maximum mean value of 48.48 NTU in the samples collected for

Table 11 | Mean values of sulphate concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 100 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		45.665	12.317565	2.7542911	0.269738	37.85	5.6834478	1.270857	0.150157
Kunai		16.415	0.9980375	0.223168	0.0608	23.39	1.9490619	0.435823	0.083329
Mararaban Rido		28.215	6.8476869	1.5311893	0.242697	43.5	1.2354415	0.276253	0.028401
Nassarawa		28.435	0.657167	0.14497	0.023111	33.92	0.6740295	0.150717	0.019871
Sabon Tasha		35.955	2.8863517	0.6454079	0.080277	34.98	3.3516061	0.749441	0.095815

Source: Field Survey and Laboratory Analysis (2021 and 2022).

Table 12 | Mean values of iron concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 0.3 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		0.517	0.031305	0.007	0.060551	0.596	0.296832	0.066373	0.498041
Kunai		0.225	0.069772	0.015601	0.309411	0.31	0.031455	0.007033	0.101471
Mararaban Rido		0.437	0.078731	0.017604	0.179958	0.589	0.065284	0.014598	0.11084
Nassarawa		0.827	0.25701	0.056058	0.302963	0.675	0.068094	0.015226	0.100881
Sabon Tasha		1.149	0.381808	0.085375	0.332297	0.828	0.375900	0.084053	0.453986

Source: Field Survey and Laboratory Analysis (2021 and 2022).

Table 13 | Mean values of lead concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 0.01 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		0.009	0.001099	0.000246	0.110452	0.083	0.020026	0.004478	0.241281
Kunai		0.007	0.001333	0.000298	0.168835	0.009	0.000852	0.000190	0.093648
Mararaban Rido		0.056	0.051205	0.011449	0.902296	0.092	0.011964	0.002675	0.130053
Nassarawa		0.056	0.050965	0.011396	0.901254	0.098	0.051052	0.011415	0.52094
Sabon Tasha		0.069	0.064189	0.014353	0.918968	0.107	0.025975	0.005808	0.242764

Source: Field Survey and Laboratory Analysis (2021 and 2022).

both rainy and dry seasons in the study area. Furthermore, it was observed that the turbidity values of groundwater samples during the rainy season have indicated an increasing trend when compared to the dry season. However, all the samples have turbidity values falling within the permissible limits of the WHO (maximum 50 NTU). This result conforms with the results of a study by Vivan (2023) that analysed groundwater conditions in the Chikun Local Government Area of Kaduna State of Nigeria, the study found that turbidity values of groundwater samples were higher in the wet season than the dry season. This result conforms with the findings of Tay (2021) in a study titled Hydrogeochemical Framework of groundwater within the Asutifi-North District of the Brong-Ahafo Region, Ghana, with the aims of bringing to bare the factors and elements affecting groundwater quality within the study area.

Table 14 | Mean values of mercury concentration in groundwater of Chikun Local Government Area (2021–2022)

Ward	WHO (MPL) 0.001 mg/l	Well				Borehole			
		Mean	Standard deviation	Standard error mean	Coefficient of variation	Mean	Standard deviation	Standard error mean	Coefficient of variation
Gwagwada		0.0143	0.01628	0.003641	1.138741	0.00138	0.000832	0.000186	0.602899
Kunai		0.000855	0.000128	0.028505	0.14924	0.0234	0.021934	0.004905	0.937346
Mararaban Rido		0.00139	0.000827	0.000185	0.594604	0.0016	0.000821	0.000184	0.513
Nassarawa		0.002	0.000973	0.000218	0.48665	0.00127	0.000673	0.000151	0.529843
Sabon Tasha		0.00185	0.00104	0.000233	0.562162	0.00128	0.000668	0.000149	0.521719

Source: Field Survey and Laboratory Analysis (2021 and 2022).

4.3. Electrical conductivity

The statistical mean and the values of electrical conductivity (EC) (µs/cm) are presented in Table 7. The observed values of EC in the area during the study period, with a maximum statistical mean of 694.80 μs/cm and a minimum statistical mean of 554.69 μs/cm in groundwater samples collected from wells and with a maximum statistical mean of 697.54 μs/cm and a minimum statistical mean of 572.34 μs/cm in groundwater samples collected from the borehole for both seasons during the study period in the area.

It was observed that the EC values have exhibited an increasing trend in boreholes compared to wells owing to the fact that the dissolution of salts, minerals and other soil constituents increases due to an increase in the groundwater table. Most of the inorganic salts such as NaCl, are responsible for increasing the EC values of groundwater systems. The results obtained revealed that groundwater in the entire study area belongs to the permissible category. This result compares favourably with that of Vivan *et al.* (2012) who opined that the EC is a useful parameter for water quality indicating salinity hazards. In general waters with conductivity values below 750 (µs/cm) are satisfactory; conductivity values ranging between 250 and 750 (µs/cm) are widely used for crop growth. Akpoborie (2011) observed that a sudden rise in conductivity in the water indicates the addition of some pollutants to it, and that the area having higher EC also has high pH. Groundwater has normally a large amount of dissolved inorganic matter and therefore high values are not unexpected.

4.4. Total dissolved solids

The total dissolved solid (TDS) values for the groundwater samples are given in Table 8. The table indicated that TDS value varies from a minimum statistical mean value of 48 mg/l in the groundwater samples collected at Sabo Tasha ward to a maximum statistical mean value of 105 mg/l in samples collected at Nassarawa ward for wells had a maximum statistical mean of 48 mg/l and for samples collected at Sabo Tasha, while a minimum value of 15 mg/l was obtained in samples collected at Nassarwa ward for boreholes. Further TDS values have exhibited an increasing trend in concentration during the rainy season compared to the dry season. This may be due to the dissolution of more quantity of constituents of soil particles as the groundwater table increases during the rainy season. These results concur with the outcome of the study by Ulla *et al.* (2022) using a localised Geographic Information Systems (GIS)-based WQI to evaluate the groundwater quality of industrial areas in Pakistan.

4.5. Calcium

The values of calcium obtained for the five settlements from wells and boreholes in the study area with minimum and maximum mean values are presented in Table 9.

Table 8 revealed that the calcium concentration varies from a minimum statistical mean of 0.40 mg/l in the groundwater samples collected at Kunai to a maximum statistical mean of 2.03 mg/l in samples collected at Gwagwada for wells, while the concentration varies from a minimum statistical mean of 0.001 mg/l in the groundwater samples collected at Sabon Tasha to a maximum statistical mean of 1.97 mg/l in samples collected at Mararaban Rido for boreholes. It was observed that most of the samples have exhibited an increasing trend in calcium concentration boreholes compared to wells. Yusuf (2015) has expressed the opinion that the high concentrations of calcium have no health hazard. Asiwaju-Bello & Ololade (2013) attested to this as they reported that calcium is an essential macro element owing to its functions in bone structure, muscle contraction, blood clotting, etc. Excess of calcium has a teratogenic action in chicks and depresses the functioning of muscles and nerve tissues. However, it should be noted that in human beings, Hyper-Calcimea causes coma and death if serum calcium rises to 160 mg/l (Tse & Adamu 2012). Besides, it is important to note that calcium has indicated a strong significant correlation with total hardness and TDS.

4.6. Magnesium

The values of magnesium obtained for the five selected wards from wells and boreholes in the study area with minimum and maximum mean values are presented in Table 10.

The magnesium concentration varies from a minimum statistical mean of 0.05 mg/l in the groundwater samples collected in Kunai ward; to a maximum statistical mean of 0.58 mg/l in samples collected in Gwagwada ward. It was observed that most of the samples have exhibited an increasing trend in Magnesium concentration boreholes compared to wells.

Magnesium is also an essential macronutrient for human beings. It forms part of the structure of the body. It plays a critical role in cell metabolism. Magnesium toxicity in higher doses greater than 400 mg/l causes nausea, muscular weakness and paralysis in humans and mammals (Vivan *et al.* 2012). Newborn infants develop hypermagnesemia if the mother is treated with $MgSO_4$ drugs.

The results of Magnesium analysis have revealed that most of the samples have exceeded the permissible limits of 0.5 mg/l. This result is in line with a study conducted by Nwankwoala & Amachree (2020) titled The WQI and Hydrochemical Characterisation of Groundwater Resources in Hydrocarbon Polluted Sites in the Niger Delta, Nigeria, appraise the levels of Heavy metals in Khana and Gokana Local Government Areas of Rivers State, Nigeria to ascertain the suitability of the groundwater resources in the area for human domestic consumption and irrigation purpose.

4.7. Sulphate

The concentration of sulphate in groundwater in the study area is presented in Table 11. The sulphate concentration varied from a minimum statistical mean of 16.4 mg/l in the groundwater samples collected at Kunai ward to a maximum statistical mean of 45.66 mg/l in the samples collected at Nasarawa ward for wells and with a minimum statistical mean of 37.85 mg/l in Gwagwada ward for boreholes. It was noticed that the sulphate values have exhibited an increasing trend in concentration boreholes compared to wells. This may be attributed to the dissolution of more quantity sulphate minerals at increased depth due to the rise in the groundwater table by the recharge process. A considerable quantity of sulphate has also been added to the hydrologic cycle from precipitation (rainfall). Agriculture runoff and irrigation drainage carry these sulphate minerals in the soil and due to variations in the temperature conditions, the breakdown of organic substances in soil, leachable sulphates present in fertilizers and other human interferences are the expected causes for the high concentration of sulphates (Asiwaju-Bello & Ololade 2013). Generally, the concentration of sulphate in all the groundwater samples (boreholes and wells) collected falls within the permissible limits of 100 mg/l.

4.8. Iron

The dissolved iron content in the groundwater of the study area indicated a minimum statistical mean of 0.22 to a maximum statistical mean of 1.14 mg/l for wells during the study period and concentration ranged from a minimum statistical mean of 0.22 to a maximum statistical mean of 0.82 mg/l for boreholes in the same study area as presented on Table 12.

The maximum permissible limit for iron is 1.0 mg/l, beyond this limit, taste and appearance are affected and have adverse effects on domestic uses such as staining of clothes and utensils (Kahsay 2011). If the concentration of iron exceeds 0.3 mg/l, it affects water supply structures as well as promotes iron bacteria. It was observed that the concentration of iron in the samples was above permissible limits.

4.9. Lead

The distribution of concentration lead in the study area is presented in Table 13.

The concentration of lead ranged from a minimum statistical mean of 0.0024 mg/l to a maximum statistical mean of 0.05 mg/l for wells and a minimum statistical mean value of 0.97, a maximum statistical mean value of 1.91 for boreholes. Thus, the concentration of lead observed is well above the safe limit for most of the groundwater samples in the study area. As the maximum permissible limit is 0.01 mg/l.

4.10. Mercury

The concentration of mercury ranges from a minimum statistical mean of 0.008 mg/l to a maximum statistical mean of 0.0143 mg/l for wells and a minimum statistical mean value of 0.00127, a maximum statistical mean value of 0.0234 for boreholes as presented in Table 14. The concentration of mercury observed is well above the safe limit for most of the groundwater samples in the study area. The results compare favourably with the study by Kalip *et al.* (2020) titled ‘Assessment of Radon and Heavy Metals in Groundwater Sources from Kaduna and Environs, Nigeria’ the results obtained in this study indicate that the concentration ranged between 1.07 and 1.67 mg/, and 1.11 and 1.77 mg/l for borehole and hand-dug well water samples, respectively. Mean concentrations were 1.16 mg/l for boreholes and 1.76 mg/l for wells. While the average values are within the maximum permissible limits set by USEPA, but were far greater than the 0.001 mg/l WHO world average. However, several incident values from wells and boreholes exceeded the USEPA maximum permissible limits, while the annual effective doses of all samples were within the recommended limits.

The physicochemical analysis carried out for the groundwater in Chikun Local Government Area, Kaduna State revealed that the quality of most water samples investigated was poor. Thus, 45% of the overall samples (from the entire study area) are non-portable, on comparing the laboratory results obtained with that of standards prescribed by the WHO for drinking water. Among the parameters responsible for non-portability, it is seen that heavy metals, total hardness and TDS are the three parameters that stood out.

Similarly, the WQI analysis carried out for the groundwater of Chikun Local Government Area revealed that most samples exhibited poor water quality as such considered unfit for drinking, the results from WQI Tables 15–17 rates samples from boreholes as poor with a score of 106.521 and samples from wells were rated good with a score of 85.450. The findings here are in line with a study by Samira *et al.* (2015) that analysed the water quality of selected wells, the study randomly collected samples from nine different wells and concentration levels of 10 physicochemical parameters were determined to ascertain how fit groundwater in the area is for human consumption. Laboratory analysis of samples and inferential statistics were used to determine the

Table 15 | WQI of wells in Chikun Local Government Area

Parameters	Test results (Vn)	Standard permissible value (Si)	Units	Relative weight (*Wi*)	Quality rating (*Qi*)	Weighted value {(*Wi*) *(*Qi*)}
Ph	6.8	6.5–8.5		0.04000	88.4	3.54
Turbidity	46.78	50		0.11764	6.66	0.784
Total Hardness	27.32		NTU	0.03333	326.6	10.88
TDS	93		mg/l	0.00200	24	0.048
Electrical conductivity	624.7	15,000	μs/cm	0.13333	94.36	12.58
CO_2	30.52	50		1.00000	2.8	2.8
Nitrite	Nill	0.2	mg/l	0.10000	42.1	4.21
Sulphate	30.9	100	mg/l	1.00000	6	6
Copper	0.912	1.0	mg/l	0.00000	0	0
Iron	0.626	0.3	mg/l	0.02500	135	3.375
Cadium	0.502	0.01	mg/l	0.20000	70.2	14.04
Calcium	1.15	2.0	mg/l	10.0000	121	1,200
Mercury	0.004	2.0	mg/l	0.00500	4.75	0.0237
Lead	0.039	0.001	mg/l	1.00000	212	212
Magnesium	0.437	0.01	mg/l	0.20000	28.6	5.72
Coliform Bacteria	0.00	1.0	mpn/ml	0.00000	0	0
				13.8563		1,476.001

$\mathrm{WQI} = = \frac{1476.001}{13.8563} = 106.521.$

Table 16 | WQI of boreholes in Chikun Local Government Area

Parameters	Test results (Vn)	Standard permissible value (Si)	Units	Relative weight (*Wi*)	Quality rating (*Qi*)	Weighted value {(*Wi*) *(*Qi*)}
Ph	6.65	6.5–8.5		0.04000	88.4	3.54
Turbidity	23.4	50		0.11764	6.6	0.78
Total Hardness	60		NTU	0.03333	50.0	1.6
TDS	80		mg/l	0.00200	6.0	0.012
Electrical conductivity	699.8	15,000	μs/cm	0.13333	44.79	5.971
CO_2	33.0	50		1.00000	97	97
Nitrite	Nill	0.2	mg/l	0.10000	30.1	3.01
Sulphate	44.9	100	mg/l	1.00000	5	5.0
Copper	1.70	1.0	mg/l	0.00000	0	0
Iron	0.71	0.3	mg/l	0.02500	55	1.375
Cadium	0.1	0.01	mg/l	0.20000	76	15.2
Calcium	0.11	2.0	mg/l	10.0000	98	980.0
Mercury	2.13	2.0	mg/l	0.00500	0.415	0.021
Lead	0.1	0.001	mg/l	1.00000	70	70.0
Magnesium	0.5	0.01	mg/l	0.20000	2.6	0.52
Coliform Bacteria	0.0	1.0	mpn/ml	0.00000	0	0
				13.8563		1,184.029

$\text{WQI} = \frac{1,184.029}{13.8563} = 85.450.$

Table 17 | Water quality classification based on the arithmetic WQI method

WQI	Water quality value
0–50	Excellent
50–100	Good water
100–200	Poor water
200–300	Very poor water
>300	Water unsuitable for drinking

Source: Brown *et al.* (1972).

difference between the laboratory values of the samples and WHO standards for drinking water. The results revealed that there was a significant difference between the levels of concentration of the selected parameters of samples and WHO standards for drinking water. The study recommended that water from open hand-dug wells in the area should be treated before human consumption.

4.11. Groundwater modeling in Chikun Local Government Area of Kaduna State

The package used for this work is MODFLOW, developed by the United States Geological Survey (McDonald & Harbaugh 1988). MODFLOW can perform steady-state analysis based on the law of conservation of mass, which assumes that the groundwater flow rate into an aquifer equals the rate of flow out from the aquifer. The governing equation is given in the following:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - Q = S_S\frac{\partial h}{\partial t}$$

where K_x, K_y, K_z indicate the hydraulic conductivity along the *x, y, and z* axes which are assumed to be parallel to the major axes of hydraulic conductivity; *h* indicates the piezometric (hydraulic) head; *Q* indicates the volumetric flux per unit volume representing source/sink terms; S_s indicates the specific storage coefficient i.e. the volume of water released from storage per unit change in head per unit volume of porous material.

The contaminant plume in the study area was modelled for a stress period of 30 years. Transportation of solutes in the saturated zone is controlled by the advection-dispersion equation, which for a porous medium characterised by constant porosity distribution is given as follows:

$$\frac{\partial c}{\partial t} = -\frac{\partial}{\partial x_i}(cv_i) + \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial c}{\partial x_j}\right) + R_c \qquad i,\ j = 1, 2, 3$$

where c indicates the concentration of the solute; R_c indicates the sources or sinks; D_{ij} indicates the dispersion coefficient tensor; V_i indicates the velocity tensor.

4.12. Conceptual model

The conceptual model grid approach was used to produce the groundwater flow model. The model's grid consists of x, y, and z axes indicating width, length, and depth; $x = 1{,}104$ m, $y = 1{,}582$ m was estimated from the Digital Elevation Model (DEM) of the study area and $z = 80$ m from the borehole log of the area. Groundwater flow direction was determined from known hydraulic heads from wells. The DEM of the area was used as the top elevation, and the borehole log was used to assign the remaining two layers. The hydraulic conductivity values of each layer were assigned from the hydraulic conductivity values of different formations as given by Guideal *et al.* (2011). The recharge rate of 638.46 mm/year = 0.001749 m/day used for the model was estimated from the average annual rainfall of Chikun Local Government Area between 2004 and 2014 (Vivan 2023).

Dispersion, longitudinal dispersivity, transverse and vertical dispersivity as estimated by Schulze-Makuch (2005) were used in this study. Longitudinal dispersivity was taken as 8.5 m, while transversal and vertical dispersivity were taken as 0.85 and 0.085 m, respectively.

5. CONCLUSION

This study assessed groundwater quality and developd a sustainable groundwater management strategy to be implemented in the Chikun Local Government Area and the world at large. This study found that inhabitant's exclusion in the management of groundwater is a key feature of the current system. Consequently, the study used realistic evaluation to show that groundwater in Chikun Local Government Area belongs to the hard to very hard category and groundwater from a majority of the wells and boreholes of the study region is unfit for drinking purposes. The major groundwater contamination problems are mainly attributed to the impact of pit latrines, open dump sites, and other non-point sources across the study area. This study has identified and ranked the potential sources of groundwater contamination in the Chikun Local Government Area in mitigating their impact on the underlying aquifer. The groundwater quality results suggest that the water quality is presently fairly good for consumption and other domestic uses. The petrographic analyses suggest that the upper horizon of the sedimentary units of the case study area is dominated by fine-grained materials which likely provided better physicochemical barriers; due to their higher sorption capacity and relatively lower permeability than the coarse sands occurring at the base. In the case study area, it is likely that the above factors helped in minimising the amount of contaminants concentration in the groundwater. Hydrochemical investigations in addressing societal problems and in achieving sustainable management of vulnerable aquifers into the future.

6. RECOMMENDATIONS

The recommendations proffered by this study can be implemented by the various local, state, and national governments globally in collaboration with the relevant stakeholders across the world. At, the local, national, and global levels, communities can be empowered by the local authorities to participate actively in groundwater management activities. Time scales of 1–30 years, can be set as short (1–10 years), medium (16–20 years), and long (21–30 years) terms, respectively. These projections can be set to start the process of implementation. In this regard, the following recommendations need to be considered in achieving sustainable management of water resources globally:

i. Taking into consideration, the evidences presented in the study on the lack of knowledge about groundwater contamination; there is a need to educate the citizenry on issues of groundwater protection. The first step of achieving this is by educating the general public, particularly the inhabitants of the study area to create awareness among the general population on the benefits of safe, clean water and the environment. If not, the water sources needed for future development and population growth are likely going to be degraded by current waste disposal practices and the stakeholders (especially those with low capacities) need to be made aware of this to help curb contaminating practices. In this regard, the state government, through the Ministry of Education and the state primary education board, has an important role to play by reviewing the current curriculum to incorporate environmental education into the existing curriculum of education so that future actors (pupils) will recognise the importance of sustainability.

ii. The institutional stakeholders engaged through interviews opined that the current legislative framework is not very clear on the role of inhabitants of the study area in the management of groundwater resources. Also, the inhabitants of the study area suggested that the adoption of strict laws will address the current problem. Thus, federal, state, and local government authorities in Nigeria must liaise with the citizenry to introduce legislation that will define the role of stakeholders in groundwater development and legislation that will constrain the activities that might compromise groundwater quality.

iii. Lack of concern on issues of waste management was also pointed out, thus, developing a robust waste management framework that considers the ethics, beliefs and cultural norms of the people is essential. For this reason, the state and local governments, and all other relevant institutions should adopt and implement programmes that will empower local women and youth groups through beneficial waste management activities. This has multiple benefits as it will ensure the protection of groundwater resources and the environment, and this will help to prevent illnesses related to poor sanitary conditions. As a supplementary benefit, it will create employment opportunities for jobless women and youths who are typically the lowest income earners across the sub-region.

iv. The study has revealed that there is a lack of adequate sanitary and drainage facilities in the Chikun Local Government Area of Kaduna state. Replacement of damaged pipelines and lining of sewer drains is necessary to prevent the leakage of sewage pipes and seepage through unlined channels and prevent the intermixing of sewage and groundwater. Therefore, the attention of concerned authorities must be drawn to take appropriate steps in providing the necessary facilities for the supply of potable water to the people.

v. The federal, states, and local governments need to further commit their resources as contained in the national water policy to improving access to safe, clean, and affordable water in the country. Also, it is equally important, for the sake of sustainable water resource management, to ensure that there are adequate returns from cost recovery to finance data collection, monitoring of system status, and resources management.

vi. Regular groundwater quality monitoring network stations should be established through suitable observation wells. The Kaduna State Water Corporation in collaboration with The National Institute of Water Resources Mando, Kaduna can establish observation wells across the study area to enhance monitoring of groundwater quality in Chikun Local Government Area.

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All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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