Review Paper

Quality reassessment using water quality indices and hydrochemistry of groundwater from the Basement Complex section of Kaduna Basin, NW Nigeria

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Abstract
Water quality indices allow for defining the acceptable limits for water usage. This paper evaluates the suitability of water for industrial and domestic uses. Hydrogeochemical data were derived from previous studies and exposed to an internal consistency test. Groundwater was classified using physicochemical parameters and water quality indices. Multivariate analysis (factor and clustering analyses) was applied to identify the sources of ions and classify groundwater. Similarly, regression analysis was used to model the hydrochemistry of the study area. Results indicated groundwater of varying quality based on hardness, TDS, EC, chloride, and nitrate. Groundwater classification based on the Chadha diagram revealed a Na–HCO_3 water type in the Kudenda–Nassarawa area. Kaduna South and Kakuri and its Environs have a Ca–Mg–Cl water type. Calcium, Mg, Na, and TDS constituted the major elements influencing the hydrochemistry of groundwater based on regression analysis. Factor analysis showed that aquifers are strongly influenced by rock weathering. Also, cluster analysis revealed different types of water sources based on their hydrogeochemical characteristics. The results of multivariate analysis concurred with Gibb's model. However, groundwater is unsuitable for industrial use since it is undersaturated with calcium carbonate. Thus, water treatment is required to avoid serious corrosion.

Keywords Basement Complex rocks · Scale formation · Water quality index · Multivariate analysis · Regression analysis · Gibbs diagram

1 Introduction

Groundwater quality appraisal using water quality indices (WQIs) is essential for managing water quality [1–6]. The use of WQIs for appraisal of groundwater aptness for drinking and industrial uses in developing countries is required. There is an unprecedented increase in anthropogenic activities that are harmful to water quality. These include urbanization, industrialization, and irrigation farming. The WQIs were established for a rating of sources of water supply in a user-friendly format and easily understandable design. It allows for defining the acceptable limits for water usage. By design, WQIs reduce information on hydrochemical data and provide a summary of hydrochemical data that failed to comply with a certain index. Thus, water quality indices are typically beneficial for comparative analysis and overall inquiries relating to water quality and population vulnerability [7]. Concerns about different hydrochemical characteristics consequent of variation in geology and geography are possible and require the application of WQIs [8]. Water quality comprises the esthetic, radiological, biological, chemical, and physical qualities of the water [9, 10]. The evaluation of groundwater quality is beneficial owing to increasing demand and

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degradation of groundwater aquifers in emerging economies and pollutant generation from multiple sources such as industry, agriculture, and urban discharges. The water quality of aquifers can be weighed using individual water quality parameters. It is currently declining since it involves computations of a lot of concentrations of hydrochemical parameters. Many countries prefer the application of a WQI. This enables the appraisal of water quality status. It is easy to comprehend as a single rated parameter [10].

Individual countries and agencies have incorporated various parameters of water quality to create local WQI. Most of the indices created are built on the American National Sanitation Foundation index [10]. Hydrochemical analysis of groundwater using WQI is widely conducted in many parts of the world. The evaluation of nitrate pollution in groundwater and its impending health hazards indicate that 61% of groundwater sources have NO_3 concentrations exceeding WHO reference guidelines in the Nagpur region of southern India [11]. Sources of drinking water were slightly alkaline. The values of WQI vary between 92 and 295. Also, 86% of groundwater sources fall in poor water quality class [11]. Weathering of bedrock and anthropogenic activities have rendered shallow aquifers near Kaduna Refinery unsuitable for drinking, due to the migration of effluents from petrochemicals and landfills [12]. Leaching of HCO_3 was the major mechanism aiding arsenic mobilization in HCO_3 assertive aquifers in Bangladesh [13]. Hydrochemical analysis of shallow groundwater in Kakuri and its Environs by Anudu, Obrike [14] discovered water of good quality for drinking.

Seasonal assessment of WQI from the River Kolong, India, by Bora and Goswami [15], revealed more deterioration of water quality during monsoon. Mean WQI varied between 85.73 and 80.75 in pre- and post-monsoon, respectively. Significant temporal variability with high concentrations of NO_3, SO_4, and Ca was reported from the Pocheon spa region of South Korea [16]. It suggested the impact of surface processes. The evaluation of groundwater quality during post-monsoon indicates that 90% of water sources are appropriate for drinking. In contrast, the percentage declined to 60% during monsoon [17]. Water quality appraisal from Kaduna, Kafancan, and Zaria indicate no radium and thorium could be trace from the study area. However, Cd, Ni, COD, and pH concentrations were above the WHO reference guidelines [18]. Groundwater quality assessment from some villages in northern India indicates the unsuitability of groundwater due to high levels of hardness, F, Ca, and Mg [19]. The content of calcium carbonate renders aquifers unsuitable for industrial use since $CaCO_3$ precipitates easily. In Kanavi Halla basin India, two-third of groundwater sources fall in poor to very poor class based on WQI [20]. The heavy metal pollution index (HPI) revealed severe pollution from a gold mine in east Cameroon [21]. A good water based on WQI was revealed from Karacaoren Dam. Poor and very poor water quality occurred in the northern and southern portions of the basin. Water quality in the study area was impacted by the diffusion of in situ pollutants in the Aksu River Basin SW Turkey [22]. Groundwater contaminants were derived primarily from anthropogenic activities in the Lower Yangtze Delta in China. Groundwater suitability for industrial and domestic uses can be guaranteed after the removal of high ions and toxic metals [23]. The water of better quality occurred during post-monsoon compared to pre-monsoon as a result of groundwater recharge in the Bay of Bengal, India [24].

Despite the tremendous research works on groundwater quality in Kaduna Basin [25–30], these studies are characterized by reports on individual physicochemical elements of water quality, instead of the application of WQI for the appraisal of the quality status of aquifers. Studies around the world are increasingly employing water quality indices [10, 11, 15, 20, 22, 31–36], for the evaluation of groundwater suitability for drinking. Appraisal of the quality status of groundwater using WQI helps to classify groundwater sources and became an essential topic in third world nations; hence, continuous monitoring of sources of drinking water is important. This is due to anthropological activities (mainly effluents from industry, agriculture, and municipal sources) that are harmful to groundwater quality. This study seeks to evaluate the hydrochemistry of groundwater using WQIs in the Kaduna Basin.

2 The study area

2.1 2.1. Location and climate

Kaduna Basin is situated between latitude 9°30N–11° 45N and longitude 7°03E–8°30E (Fig. 1). It covers a total area of 21,065 sq km. It is drained by Rivers Galma, Kubanni, and Tubo which formed the major tributaries to River Kaduna [37]. Kaduna Basin rests on the '*High Plains*' of northern Nigeria reaching up to 670 m above sea level at some locations. The basin is in Guinea Savannah Zone, with both wet and dry seasons. Rainfall season prevails from May to October. The average annual precipitation is above 2000 mm. During the dryer years, it can be as low as 300 mm (Fig. 2a). The difference between the wettest and driest month in terms of precipitation is 279 mm. The long-term average is 1000 mm [37]. The annual variation of temperature is 3.8 °C (Fig. 2b). The dry spells last from November to April. It is characterized by low temperatures during Harmattan (December–February). Very dry and hot weather is prevalent from March to April. Mean diurnal temperature can

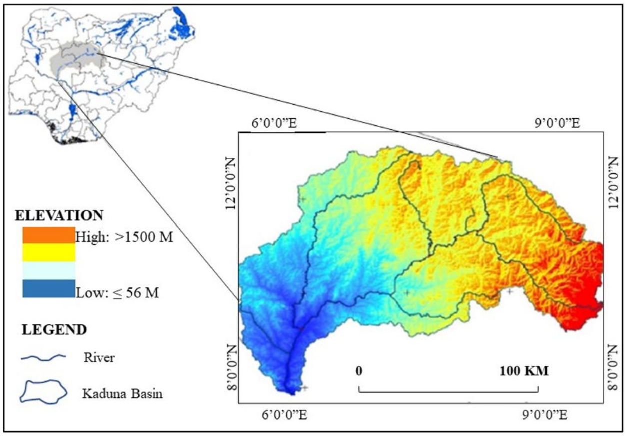


Fig. 1 Map of the Kaduna Basin. After Okafor and Ogbu [38]

attain 27 °C. The relative humidity is high throughout the rainy season. It decreases during the dry spells.

2.2 Geology and hydrogeology

Kaduna Basin consists of crystalline basement complex (CBC) rocks. These are mainly of granitic gneisses, migmatites, and biotite types. Rebooted metasediments formed the magnetite gneiss complex. It is characterized by various structures and textures. Batholiths and younger granites are noticeable southwestwards. Severe chemical weathering and fluvial erosion shaped by the environmental bioclimatic scenery of the region have formed a conspicuous high-pitched undulating flatland as well as soothing interfluves. Weathered or metamorphic rocks are dominant. The normal rock type is a gneiss–migmatite complex that outcropped along the Kaduna–Zaria axis [37]. Metasedimentary rock series consisting of interchangeable rocks including gneiss, pegmatites, schist, and quartz are noticeable (Fig. 3), mainly comprised of decayed sedimentary and metavolcanics rocks. Marvelous boulders of well-outlined migmatites in the northeast–southwest bloc and west of the Kaduna area are noticeable. The ubiquitous batholiths in the southern parts of Kaduna are characterized by exposed plutonic rocks [37]. These batholiths

Fig. 2 **a** Temperature and **b** rainfall (Climate-Data.Org: https://en.climate-data.org/africa/nigeria/taraba/kaduna-lissam-385152/. Retrieved on 12/02/2020)

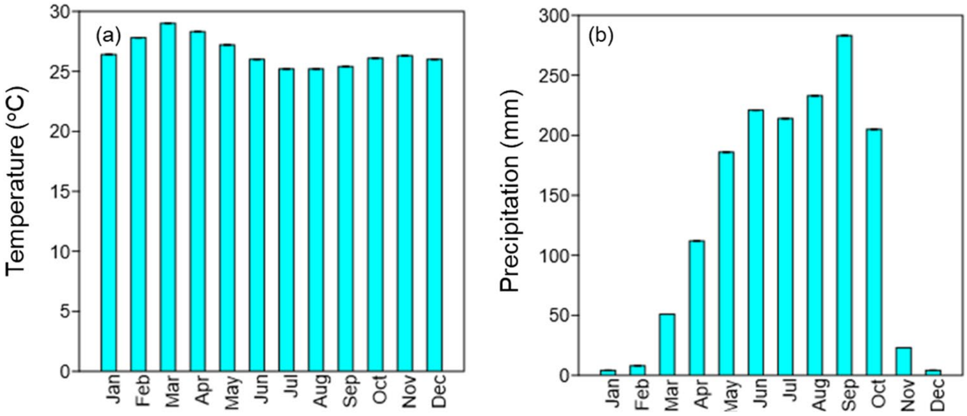
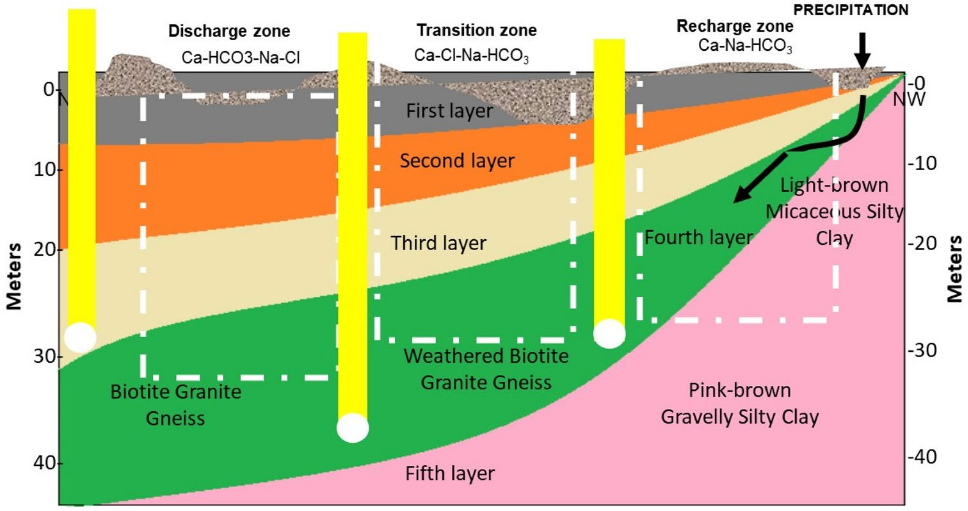


Fig. 3 Theorized geological cross section of the groundwater flow in the Kaduna Basin



mainly comprise of granodiorites, charnockites, granites, monthonites, diorites, and leucocratic-porphyritic granites. Some sections are coated by laterites that are sporadically fused especially the battered exteriors into lateritic knobs pied with silty and sandy clays [37].

Over 80% of the study area is enclosed by the CBC. The fresh alluvium of the River Niger and Nupe Sandstone make up 20% [39]. The hydrogeological specifications of the basin are characteristic of Nigeria's Basement Complex areas [40–42]. Previous assessment of hydrogeological conditions in the basin showed that at least 30% of boreholes were not productive. Borehole yields varied between 0.2 and 1lit/sec. Although a 30% borehole failure was documented, even the productive wells were not promising, thus illustrating the gratuitous hydrogeological condition of Nigeria's Basement Complex [39]. Ten percent of the Kaduna Basin is covered by sedimentary formations of the Nupe Sandstone. The '*Newer basalt*' is evident throughout Manchok and Kafanchan areas. It adjoined the western peripheries of the north–central plateau. The basalt was formed when the plateau attained its current topography. It is marginally influenced by erosion, consequently overlaying alluvial sediments [43]. The areas of severe erosion and sandy riverbeds also rise. These are squeezed in between specific basalt deluges.

The prospect of the fluvio-volcanic aquifer shows a great water yield (370–500 m^3/day). At Tum Village (Borehole No. GWR/21/1) in the '*Newer Basalt*' a great quantity of water was recorded (12.6 m^3/h). An extremely productive spring appears in the '*Newer Basalt*' producing about 11,000 m^3/day at Manchok, throughout the dry season. It established the headwater of an offshoot of the Kaduna River [43]. Potential sources of pollutants like landfills ought to be located far away from probable recharge regions, consequent to the superficial depth of shallow groundwater [25]. Seasonal assessment of spring water, shallow and deep aquifers by Obada and Olaniyan [43], discovered that the superficial aquifers were polluted from anthropologic activities. Sources of pollutants include inappropriate waste disposal, seepage by septic reservoirs, and urban effluents. Although the hydrochemistry and the hydrogeology of the Kaduna Basin are detailed in the literature [12, 18, 44–47], there is a need for further analysis of groundwater quality based on WQI.

3 Materials and methods

3.1 Review procedure and data sources

Hydrochemical data were derived from the literature following the procedure summarized in Fig. 4 and Table 1. A total of 1754 potentially important articles were identified, from Google Scholar, reducing to 3 based on extractable data on pH, temperature, TDS, EC, Na, Fe, K, Cl, NO_3, HCO_3, and SO_4. This was based on the defined criteria summarized in Fig. 2. The search was limited to studies published from the year 2000 (Table 2). Data on physicochemical parameters were adopted from 52 sites [14, 26, 43]. The electrical conductivity (EC) values were not measured by Obada and Olaniyan [43]. So, the EC values were calculated using the *LENNTECH* converter for EC values (https://www.lenntech.com/calculators/conductivity/tdsengels.htm).

3.2 Internal consistency test

The internal consistency of data was tested using the chemical balance error (CBE) equation [48]. The CBE is defined thus:

$$\mathrm{CBE} = \frac{\sum \mathrm{Cations} - \sum \mathrm{Anions}}{\sum \mathrm{Cations} + \sum \mathrm{Anions}} \times 100 \tag{1}$$

where the concentration of individual elements is stated in meq/l. The sums of cations (6893.09) and anions (7829.92) were substituted, Eq. 2 and 3:

$$\mathrm{CBE} = \frac{\sum \mathrm{cations}(6893.09) - \sum \mathrm{Anions}(7829.92)}{\sum \mathrm{Cations}(6893.09) + \sum \mathrm{Anions}(7829.92)} \text{ x } 100 \tag{2}$$

$$\mathrm{CBE} = \frac{6893.09 - 7829.92}{6893.09 + 7829.92} = \frac{-936.83}{14723.00} = -0.064 \times 100 = \pm - 6.40 \tag{3}$$

where the cationic and anionic concentration is fully measured, and the variance should not be more than 5%. However, there are slight but more negative values greater than 5% ($\pm - 6.40$), as a result of the lack of NO_3 measurements from Kudenda–Nassarawa area. Despite the slight variance, the hydrochemical data were employed for further analysis due to the irregularity of sampling periods and locations, which may interfere with the results.

3.3 Computation of WQI

The WQI is a remarkable technique that offers a broader outlining of water quality conditions [10, 20, 21, 49, 50]. It represents the magnitude that reflects the collective consequence of various physicochemical parameters. It is computed by assigning discrete weights (*wi*) over a scale of 1 which represents the lowest effect. The greatest impact on water quality is presented by 5. It is built on their expected impacts on human health. Elements having serious health consequences and whose concentrations exceeding the essential limits can hamper the usability of groundwater are ranked high. High intensities of elements such as NO_3, Cl, and TDS were given a high-ranking weight

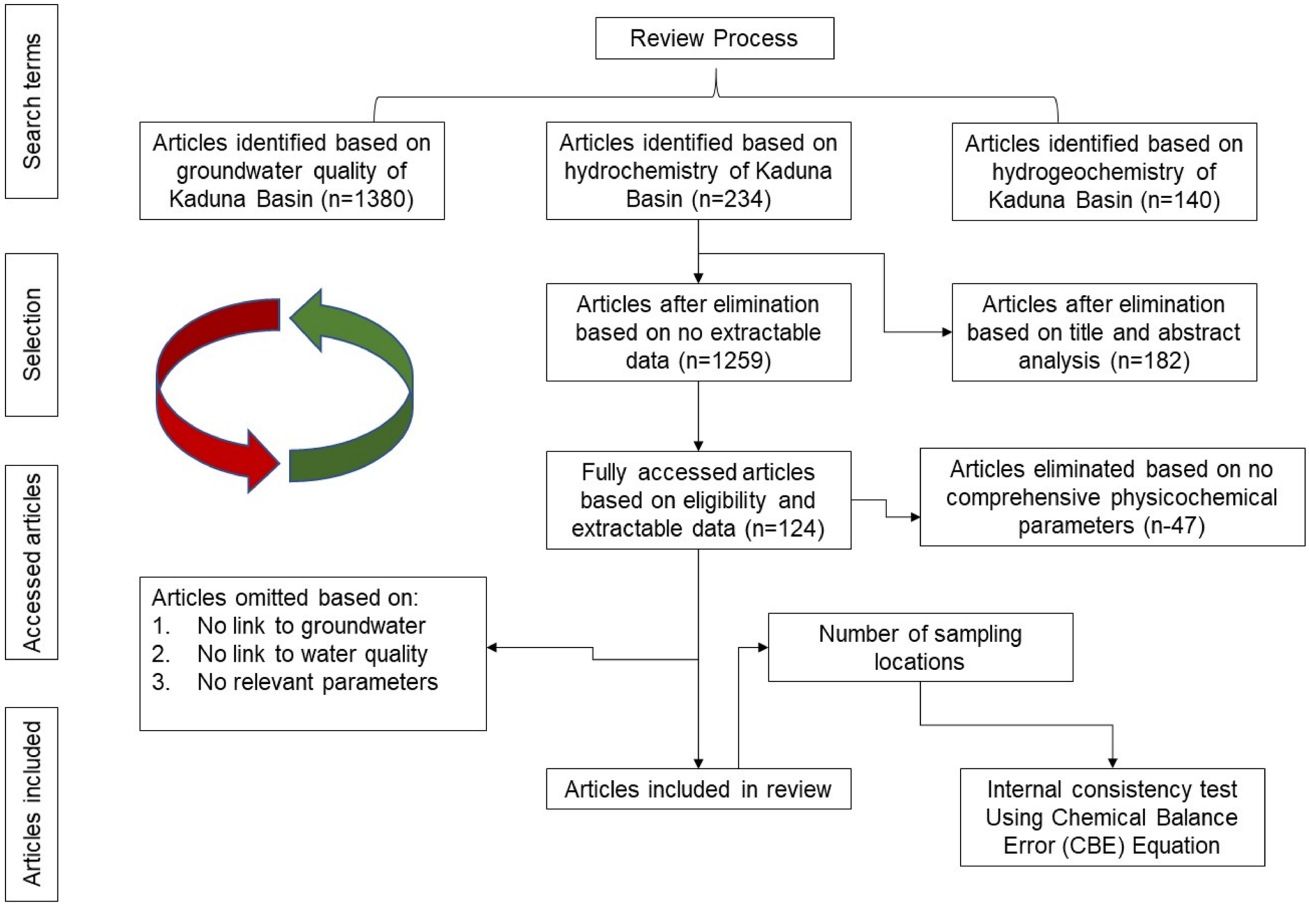


Fig. 4 Review methodology adopted for this study

Table 1 Search terms used in exploring the database and the related parameters

S/no	Term classification	Search terms	Articles identified
1	Groundwater quality Kaduna Basin	Groundwater, aquifers, physicochemical parameters, water quality elements (pH, temperature, TDS, EC, Na, Fe, Mg, Ca, K, Cl, HCO_3, NO_3, and SO_4)	1380
2	Hydrochemistry Kaduna Basin	Groundwater, aquifers, physicochemical parameters, water quality elements (pH, temperature, TDS, EC, Na, Fe, Mg, Ca, K, Cl, HCO_3, NO_3, and SO_4)	234
3	Hydrogeochemistry Kaduna Basin	Groundwater, aquifers, physicochemical parameters, water quality elements (pH, temperature, TDS, EC, Na, Fe, Mg, Ca, K, Cl, HCO_3, NO_3, and SO_4)	140

of 5 (Table 3). Elevated NO_3 concentration in drinking water is related to the blue baby syndrome. High chloride can affect the palatable taste and is injurious to plants. Variation in TDS can be an indicator of anthropogenic inputs. The intermediate elements such as Ca, Mg, SO_4, sodium, bicarbonate, and potassium were assigned weights varying from 2 to 4. Those that have negligible impacts like potassium were assigned the lowest weight of 1 (Table 3). The relative weight of physicochemical parameters, as summarized in Table 3, is estimated using Eq. 4:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

where $\boldsymbol{W}_1$ represents the relative weight, w_i is the weight of individual elements and n is the sum of the analyzed elements. The estimated W_i values of respective elements are summarized in Table 3.

The quality ranking (q_i) for discrete elements is given by dividing its absorption value(s) by its standard value specified by the WHO (2011). The outcome is transformed into

Table 2 Sources of data employed for review

S/no	Study	Study area	Type of data	No. of samples	Study period	Source type	References
1	Assessment of sub-surface water in Southern Sections of Kaduna, Nigeria	Southern Kaduna	List of evaluated physical and chemical parameters	$N=31$	Not specified	Deep groundwater	[43]
2	Hydrogeochemical assessment of subsurface water from shallow wells across Kakuri and its surroundings, Kaduna, Nigeria	Kakuri and its surroundings	"	$N=15$	"	Superficial subsurface water	[14]
3	Contamination of groundwater from septic reservoirs in designated areas, Kaduna, Nigeria	Kudenda–Nassarawa zone	"	$N=6$	"	"	[26]

Table 3 Relative weight of chemical parameters

Elements	WHO (2011)	w_i	W_1
pH	6.5–8.5	4	0.093
Temperature	Ambient	1	0.023
EC	1000	5	0.116
TDS	500	5	0.116
Ca	75	2	0.047
Mg	125	2	0.047
Na	200	2	0.047
K	12	1	0.023
HCO_3	250	3	0.070
Cl	250	5	0.116
SO_4	250	4	0.093
Fe	2	4	0.093
NO_3	50	5	0.116
		$\Sigma w_i=43.000$	$\Sigma w_i=1.000$

All absorptions are in mg/l, except pH (unit), temperature (°C), and EC (μS/cm)

a fraction (mainly percentage) through multiplying by 100. This is computed using Eq. 5:

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{5}$$

where the quality rating is q_i, C_i is the intensity of different elements in groundwater samples (mg/l) and the reference value for the individual parameter (mg/l) is S_i built on the WHO (2011) reference value. It represents SI_i value determined initially using Eq. 5, before computation of water quality index:

$$SI_i = W_i \times q_i \tag{6}$$

$$WQI = \sum_{i=1}^{n} SI \tag{7}$$

where the subindex is SI_i of the ith element and the quality rating built on the intensities of ith elements is q_i. The computed values of WQI are categorized into five classes: WQI = ≤ 50 (excellent), WQI = 50–100 (good), WQ1 = 100–200 (poor), WQI = 200–300 (very poor), and WQI = > 300 (unsuitable) [11, 15, 20, 31–33, 35, 51]. However, groundwater sources that are suitable for drinking may not necessarily be suitable for industrial use(s).

3.4 Suitability for industrial use

Water quality requirements vary with types of industry. Industries, such as thermal plants, boiler feed water, and beverages, require a substantial quantity of water. Good water quality capable of averting scale formation and corrosion is required by certain industries. Beverages, dairy, and brewing industries require guidelines for drinking water quality. In heavy industries, scale formation constitutes a major problem. Consequently, Langelier (1936) proposed a saturation index to determine the extent of scale formation by water. The Langelier Saturation Index (LSI) predicts the stability of $CaCO_3$ in water and shows whether water can dissolve, precipitate, or will be stable with $CaCO_3$ [10, 52]. The LSI is computed (Eq. 8), as the variance between calcium bicarbonate-saturated pH (pHs) and the actual pH (Eq. 9).

$$LSI = pH\ (measured) - pHs \tag{8}$$

where

$$pHs = A + B - C - D \tag{9}$$

The pHs, *A*, *B*, *C*, and *D* are computed following the Langelier technique. The LSI tends to be negative if the pH level of water is below the saturation pH. Thus, water is expected to have low scale formation potential. The LSI tends to be positive if the initial pH of water is above the pHs, indicating $CaCO_3$-supersaturated water that has a high potential for scale formation. The greater the LSI values, the more its potential for scale formation [10, 52]. Also, a different index for quantifying $CaCO_3$ scale formation was later developed by Ryznar [53]. The Ryznar Stability Index (RSI) helps to avoid confusion of positive saturation indices that are typically classified as non-scale forming or non-corrosive. The RSI is calculated:

$$\mathrm{RSI} = 2\mathrm{pH_s} - \mathrm{pH} \tag{10}$$

where pH represents the estimated pH value of water and the $\mathrm{pH_s}$ represents the pH at saturation point, computed using Langelier's technique. The RSI for all water types is constantly positive. The character of both treated and natural water having RSI values of 5.5 or below can have high potentials for scale formation. Water having RSI values of 9.5 tend to have a low scale formation potential, though might have acute corrosivity under high temperature [10, 52–54]. The LSI was calculated using the LSI Calculator (https://www.lenntech.com/calculators/langelier/inex/langelier.htm).

3.5 Statistical analysis

3.5.1 Factor analysis

Factor analysis (FA) is applied to classify data for an easy explanation [55, 56]. It is used to obtained proper evidence concerning the link between hydrogeochemical parameters and sampling spots [57]. The central objective of FA in the hydrogeochemical analysis is the classification of the hydrochemical data [48]. It involved two steps: (a) data standardization and (b) removal of factors [56, 58]. Even though some related hydrogeochemical data are lost during the analysis, the depiction of the method is significantly reduced [56]. It is used to obtain proper evidence concerning the link between hydrogeochemical parameters and sampling spots [57]. The FA bilinear model is typically reorganized using a matrix decomposition equation:

$$X = TP^T + E \tag{11}$$

where the matrix of data is represented by *X* which is reduced into *T* (matrix score) and *PT* (loadings matrix), plus (residual matrix(*E*)).

3.5.2 Hierarchical clustering analysis

Hierarchical clustering analysis (HCA) is used to categorize groundwater sources based on a raw hydrochemical data matrix in individual clusters devoid of any prior supposition. This study used the Ward's algorithmic clustering process subsequent to the Euclidean distance method. It is deemed a potent clustering procedure [58, 113]. Before the clustering, the hydrogeochemical data x_{ji} were harmonized by *Z*-scale translation as:

$$Z = \frac{X_{ji} - \dot{x}_j}{S_j} \tag{12}$$

where x_{ji} = value of the *j*th hydrochemical factor calculated at the *i*th location, $\dot{x}_j$ = mean (spatial) value of the *j*th parameter and S_j = standard deviation (spatial) of the *j*th parameter.

This verification allowed for the formation of a dendrogram as a function of the sampling locations and hydrogeochemical parameters. So, employing the hydrogeochemical data into HCA is an incomparable approach. HCA simplifies data grouping assembled on similarities of the studied physicochemical parameters [59, 60]. The FA and HCA were performed on 13 subsets of hydrogeochemical parameters. The entire analyses were performed using PAST3 (version 3.14), SPSS (version 16) and Minitab (mbt 16) statistical software packages.

3.5.3 Regression analysis

Regression analysis enables an understanding of the relationship between hydrochemical elements by fitting a linear equation to the hydrochemical data. Values of the separate elements *x* are connected to a value of *y* (i.e., dependent variable). The regression model of hydrochemical data for *p* experimental elements $x_1, x_2, x_3, \ldots x_p$ is expressed:

$$\mu_\gamma = \beta_o + \beta_1 + x_1 + \beta_2 x_2 + \cdots + \beta_p x_p \tag{13}$$

How the mean reaction μ_γ varies with experimental elements is defined by the regression model. The detected *y* values tend to vary with their means μ_γ and are believed to have a similar standard deviation σ. The fitted values $b_0 b_1, \ldots, b_p$ approximate the elements $\beta_0, \beta_1, \ldots, \beta_p$ of the regression model. Meanwhile, the detected *y* value(s) differ with their mean, and the regression model contains an expression for this difference. It is defined as Data = fit + residual. The term 'fit' is expressed:

$$\mu_\gamma = \beta_o + \beta_1 + x_1 + \beta_2 x_2 + \cdots + \beta_p x_p \tag{14}$$

The term 'RESIDUAL' is the deviation of the detected y value(s) from the means μ_Y. It is typically distributed with mean 0 and the variance σ. The symbol of the model is ε. The regression model for formally given n observations is:

$$y_i = \beta_o + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip} + \varepsilon_i \quad \text{for } i = 1, 2, \ldots n \tag{15}$$

The best-fit line and least-squares models for the hydrochemical data are computed by lessening the sum of squares of the perpendicular deviations from individual data point to the line. If a point lies exactly on the fitted line, then its perpendicular deviations = 0. Since the aberrations are initially squared, then calculated, there are no annulments between negative and positive values. The least-squares values $b_0 b_1, \ldots, b_p$ are typically calculated using the statistical software package(s). The fitted values using the equation $b_0 b_1 x_{i1} + \cdots + b_p x_{ip}$ expressed as $\hat{y}_i$, and the residuals e_i are equal to $y_i - \hat{y}_i$, the variance between the fitted and observed value(s). The summation of the residuals = 0. The variance σ_2 maybe computed:

$$S^2 = \frac{\sum e_i^2}{n - p - 1} \tag{16}$$

It is identified as MSE, i.e., mean squared error. The computed standard error is given as $s = \sqrt{\text{MSE}}$. The statistical analysis was conducted using MINITAB (mbt 16) statistical package.

3.6 Groundwater evolution

The basis of dissolved ionic substances and the processes for the evolution of groundwater are revealed by the graphical procedure as an interface of TDS versus Cl/(Cl + HCO_3) and Na/(Na + Ca) ratios [21, 61, 62]. Precipitation is the preliminary process since the chemical compositions of aquifers are affected by the volume of suspended salts/ions generated by precipitation [21, 61–64]. Naturally, the volume of precipitation is consistently high surpassing the low quantity of dissolved elements resulting from the rock mineral. Aquifers in this group occur naturally in hot and dry regions. The contrary end member to precipitation sequence consists of freshwaters obtaining their main source of suspended elements from the soils and rock mineral of their basins. This assembly specifies the successive mechanism which affects groundwater chemistry as rock dominance. The last mechanism is consisting of evaporation–fractional definition. This process produces an order of series extending from the calcium-rich water type resultant from rock weathering, to the sodium-rich high-salinity end member which is the opposing process. The mechanism shaping world water chemistry can be measured by plotting the TDS mass ratio against the [Na + K]/Na + K + Ca] and [Cl]/[Cl + HCO_3] ratios for anions and cations [61, 64]. Further, the Chadha diagram was used to classify groundwater [65–67].

4 Results and discussion

Table 3 and Fig. 5 present a statistical summary of hydrochemical data. Groundwater rating built on WHO (2011) reference guidelines indicated that TDS, Ca, Mg, and K concentrations are above the defined reference values for drinking water in the Kudenda–Nassarawa area. Though TDS is not commonly viewed as an essential pollutant; it is used as a mark of palatable attributes of drinking water and as an overall indicator of the chemical contaminants. Essential sources of TDS in aquifers include overflow from irrigated fields and private (or urban) spillover, effluent-rich mountain waters, filtering of soil sullying, and point source water contamination release from modern or polluted water treatment facilities [58, 68–73]. The most recognized chemical constituents are Ca, PO_4, NO_3, Na, K, and Cl, which are found in overland flow, general stormwater spillover, and overflow from street deicing salts [74–78]. Vibrant and destructive components of TDS are pesticides and other contaminants emerging from overland flow [79–81]. Elevated concentrations of Ca and Mg in aquifers are normally associated with hardness [82]. However, significant positive correlations between hardness and sodium were reported from Texas aquifers [83]. Calcium and Mg are particularly derived from dolomite, gypsum, and limestone. Calcium and Mg occur in vast amounts in saltwater [84, 85].

Magnesium is the primary cause of the hardness and scale-forming properties of water. It is imperative to understand that other factors including pH, temperature, supersaturation, and flow velocity can influence scale formation [86]. Groundwater sources that have low Ca and Mg are required in manufacturing, coloring, tanning, and electroplating [86–88]. Calcium functions as a stabilizer for pH, owing to its buffering properties. Calcium can react with water even at a room temperature based on the mechanism defined in Eq. 17.

$$\text{Ca(s)} + 2\text{H}_2\text{O(g)} \rightarrow \text{Ca(OH)}_2\text{(aq)} + \text{H}_2\text{(g)} \tag{17}$$

Consequently, dissolved calcium hydroxide in the form of hydrogen gas and soda is formed. Erosion reaction is another critical reaction mechanism. It is triggered by the presence of CO_2, resulting in the formation of carbonic acid. This can alter Ca compounds. Carbon weathering reaction mechanism is:

$$\text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{H}_2\text{CO}_3 \text{ and } \text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{CaH(CO}_3)_2 \tag{18}$$

Calcium and Mg are the major cause of scale formation in pipes, water radiators, and boilers and to the horrible

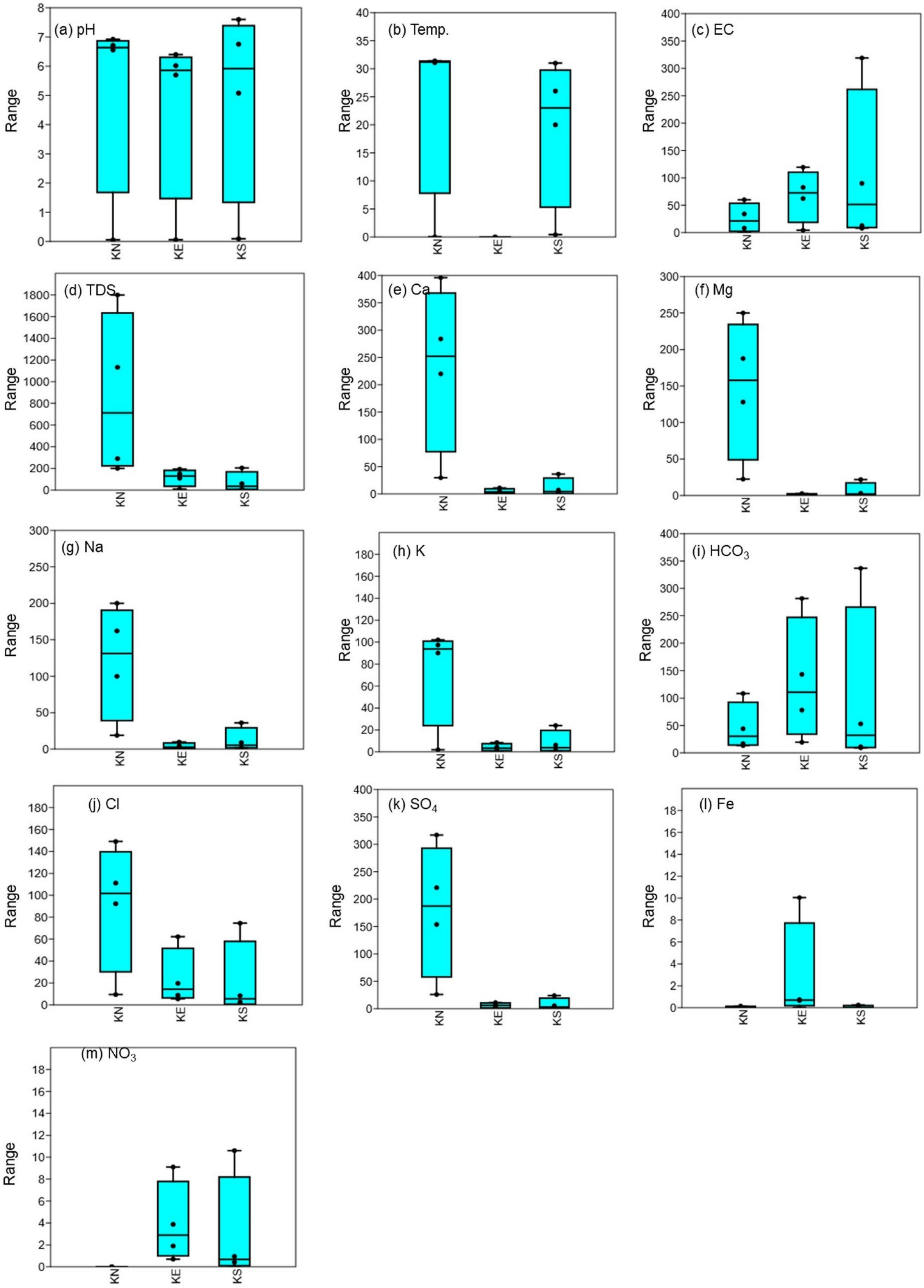


Fig. 5 Box and jitter plot of physicochemical elements of water quality in the Kaduna Basin. *Note*: All absorptions are in mg/l, except pH (unit), EC (µS/cm) and temperature (°C)

curd within the sight of cleanser. The total reaction mechanism is:

$$CaCO_3(s) + CO_2(g) + 2H_2O(l) \rightarrow Ca^{2+}(aq) + 2HCO_3^-(aq) \tag{19}$$

Sulfate concentrations are below the WHO guidelines as indicated in Table 4. Sulfide mineral oxidation is the primary source of SO_4 in groundwater. Equally, sulfate can originate from calcium sulfate, sodium sulfate, and magnesium sulfate minerals [89, 90]. Conversely, sulfate ions originate from industrial effluents and shales [89, 90]. Sulfate is found in all types of aquifers because SO_4 is one of the major dissolved components of precipitation. High-level SO_4 in aquifers tends to be correlated with the emetic effect, chiefly if combined with Mg or Na [91, 92].

4.1 Groundwater evolution

4.1.1 Chadha diagram

Groundwater classification based on the Chadha diagram (Fig. 6) showed that 11.54% (n = 6) fall in field 4 representing Na–HCO_3 water type. Groundwater samples in field 4 are derived from the Kudenda–Nassarawa area. Na–Cl water type occurred at one location representing 1.92%. The location is in Kaduna South. The remaining locations (*n* = 45; 86.53%) fall in field 2, indicating a Ca–Mg–Cl water type. Water samples in this field are comprised of the locations from Kakuri and its Environs (*n* = 15) and Kaduna South (*n* = 30). Results concur with the previous classifications of groundwater in the Kaduna Basin [12, 43, 93] and elsewhere in Nigeria's Basement Complex areas [94–97].

4.1.2 Gibbs diagram

The processes influencing the hydrogeochemistry of aquifers can also be revealed by Gibbs plot. It helps explains visibly, the pattern of groundwater sources producing a rebound-shaped cloud on a graph. Groundwater is not in a state of equilibrium with aquifer rock mineral, consequent of their mingling with recharged waters with distinct transport periods and often having higher Ca and HCO_3 concentrations when compared with Cl and Na [64]. The hydrochemistry of aquifers in the study area is controlled by rock weathering, as depicted in Fig. 7. This symbolizes the inverse end member to precipitation sequence. It consisted of freshwaters drawing their main source of liquefied components from the rock minerals and soils from their basins. The compendium is classified as a rock weathering process as portrayed in Fig. 7. Results are concurrent with multivariate analysis.

4.2 Suitability for drinking

Table 5 presents groundwater classification based on nitrate (NO_3), chloride (Cl), total hardness (TH), electrical conductivity (EC), and total dissolved solids (TDS). Kudenda–Nassarawa area had TH above 300 mg/l, indicating very hard water. The TH values were less than 75 mg/l in Kakuri and its Environs, indicating soft water. Likewise, 93.55% of sampling locations in Kaduna South had TH values less than 75 mg/l (soft water), 3.23% (moderately hard water), and 3.23% (hard water). Hardness is influenced by several factors including soil/rock composition, the evolution of groundwater chemistry, and outflow from adjoining aquifers. Possible human controls on TH comprised

Table 4 Statistical summary of hydrochemical data derived from the literature

Parameter	Kaduna South (*n* = 31)				Kakuri and Its Environs (*n* = 15)				Kudenda–Nassarawa area (*n* = 8)				WHO (2011)
	Min	Max	Mean	SE	Min	Max	Mean	SE	Min	Max	Mean	SE	
pH	5.0	7.60	6.75	0.09	5.70	6.40	**6.02**	0.06	6.56	6.92	6.71	0.05	6.6–8.5
Temp	20.00	31.00	26.03	0.42	ND	ND	ND	ND	31.10	31.40	31.28	0.05	Ambient
EC	8.00	319.00	90.09	12.99	62.37	119.43	82.74	4.25	0.47	60.00	34.08	8.27	1000
TDS	5.12	204.00	59.60	8.98	109.60	192.90	149.51	9.02	200.00	1800.00	**1133.33**	290.59	500
Ca	0.24	36.30	7.17	1.45	2.40	11.00	4.91	0.79	220.00	396.00	**284.00**	29.72	75
Mg	0.22	21.89	3.06	0.85	0.50	2.60	1.43	0.22	128.00	250.00	**187.67**	22.39	125
Na	1.61	36.09	8.91	1.62	0.70	9.70	4.40	0.87	100.00	200.00	162.00	18.90	200
K	1.44	24.00	6.07	0.80	2.20	8.40	4.35	0.51	90.00	102.00	**97.33**	1.84	12
Fe	0.00	0.25	0.04	0.01	0.03	10.05	0.74	0.66	0.02	0.15	0.09	0.02	2
HCO_3	9.15	336.79	53.01	11.29	78.20	281.50	143.51	19.41	16.80	108.40	44.07	13.25	250
Cl	0.00	74.50	8.37	2.63	8.80	62.20	19.65	5.47	92.30	149.10	111.13	9.45	250
SO_4	0.00	23.90	5.46	1.01	3.90	11.20	8.23	0.63	153.70	316.90	220.87	26.00	250
NO_3	0.00	10.60	0.95	0.42	1.90	9.10	3.87	0.70	ND	ND	ND	ND	50

ND no data (i.e., no NO_3 measurements from Kudenda–Nassarawa area)

Fig. 6 Chadha plot showing groundwater classification in Kaduna Basin

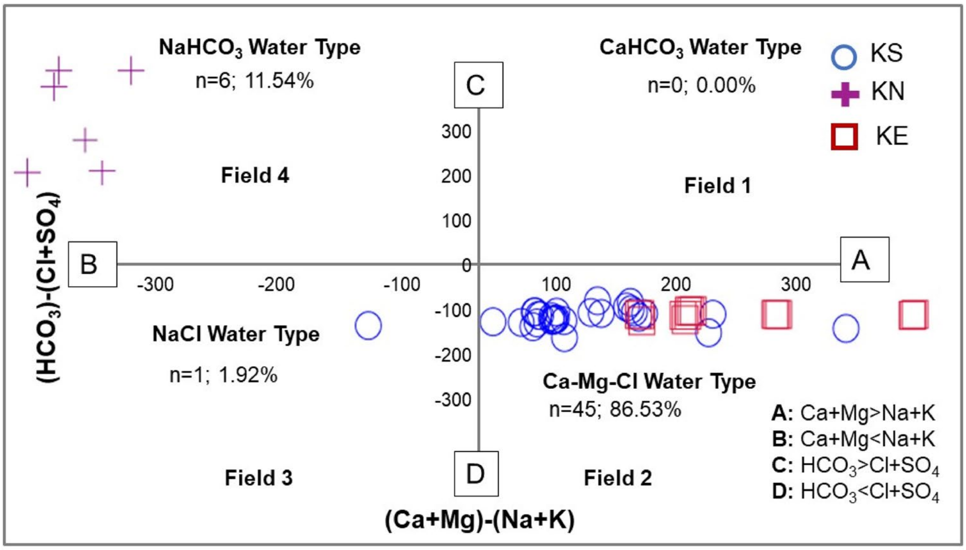
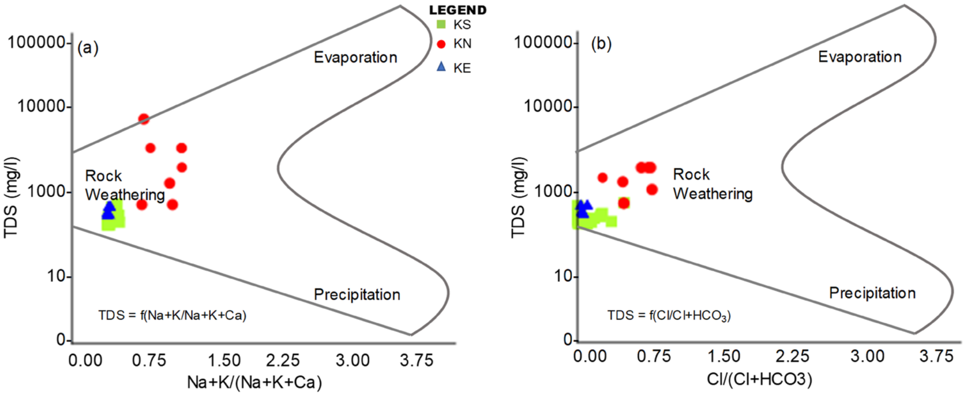


Fig. 7 A plot of ratio weight of TDS vs. Na + K/(Na + K + Ca) and Cl/(Cl + HCO_3) for anions and cations. *KN* Kudenda–Nassarawa, *KE* Kakuri and Environs, *KS* Kaduna South



of flow from irrigation return and intrusion of saltwater induced by pumping [83].

The TDS level is generally low in the study area. TDS less than 500 mg/l denote excellent water. Kaduna South and Kakuri and its Environs had TDS less than 500 mg/l [6, 24, 62, 98, 99]. In the Kudenda–Nassarawa area, 33.33% fall in excellent class, 16.67% are suitable (500–1000 mg/l TDS) and 33.33% are acceptable (1000–3000 mg/l TDS). The significance of TDS is that high ingestion may be connected to the strength of the joints, gallstones, kidney stones, inurement, or blockage of veins [100]. Based on chloride, 100% of water sources in the Kudenda–Nassarawa area are in the brackish salt class. Similarly, 80% are brackish and 20% are brackish salt in Kakuri and its Environs. In Kaduna South, the composition of groundwater varied from very fresh to brackish salt (Table 5). Chloride (Cl) is important to humans as it plays a significant role in the structure of the cell. Littoral aquifers can have high Cl level consequent of seawater invasion [101, 102]. At concentrations above 250 mg/l, water taste can be influenced [62, 103].

Nitrate pollution is generally low. In Kakuri and its Environs, 80% of groundwater had NO_3 concentrations less than 5 mg/l. Water in this category is acceptable for drinking. Twenty percent (20%) had NO_3 concentration ranging from 5–30 mg/l. In Kaduna South, 93.55% of groundwater had NO_3 level of less than 5 mg/l. The implication of high NO_3 in drinking water is its harmful effects on children (*blue baby syndrome*). Nitrate in aquifers is derived from many sources such as soil organic matter, urban runoff, landfill, septic tanks, municipal sewage, and animal wastes [103]. Thus, it is expected that current contaminating activities will continuously impact the nitrate levels for many decades to come. If the groundwater abstraction is high, NO_3 transport can be accelerated within the zone of saturation (Fig. 8). Therefore, a higher NO_3 level in groundwater is a sign of previous anthropogenic pollution.

Table 5 Water classification based on physicochemical parameters

Range	Classification	Kudenda–Nassarawa		Kakuri and its Environs		Kaduna South	
		No. of samples	% of samples	No. of samples	% of samples	No. of samples	% of samples
Hardness (mg/l)							
Less than 75	Soft	0	0	15	100	29	93.55
75–150	Moderately hard	0	0	0	0	1	3.23
150–300	Hard	0	0	0	0	1	3.23
Above 300	Very hard	6	100	0	0	0	0
TDS (mg/l)							
Less than 500	Excellent	2	33.33	15	100	31	100
500–1000	Acceptable	1	16.67	0	0	0	0
1000–3000	Suitable	2	33.33	0	0	0	0
Above 3000	Unsuitable	0	0	0	0	0	0
EC (μS/cm)							
Less than 250	Excellent	6	100	15	100	31	100
250–750	Good	0	0	0	0	0	0
750–2000	Permissible	0	0	0	0	0	0
2000–3000	Doubtful	0	0	0	0	0	0
Above 3000	Unsuitable	0	0	0	0	0	0
Chloride (mg/l)							
Less than 0.14	Awfully fresh	0	0	0	0	4	12.90
0.14–0.85	Very fresh	0	0	0	0	1	3.23
0.85–4.23	Fresh	0	0	0	0	14	45.16
4.23–8.46	Fresh brackish	0	0	0	0	5	16.13
8.46–28.21	Brackish	0	0	12	80	6	19.35
28.21–546.13	Brackish salt	6	100	3	20	1	3.23
Above 564.13	Hypersaline	0	0	0	0	0	0
Nitrate (mg/l)							
Less than 5	Acceptable	ND	0	12	80	29	93.55
5–30	Moderate	ND	0	3	20	2	6.45
Above 30	Severe	ND	0	0	0	0	0

4.3 Water quality index

The water quality index (WQI) of Kaduna Basin (mean ± standard error) was 8.387 ± 1.088 in Kudenda–Nassarawa area, 2.062 ± 0.376 in Kakuri and its Environs, and 1.204 ± 0.109 in Kaduna South, respectively (Fig. 9). The computed WQI revealed that the overall WQI was 13.46 in the Kudenda–Nassarawa area, 7.64 in Kakuri and its Environs, and 10.26 in Kaduna South. The study area holds groundwater of excellent quality based on WQI (Table 6). Calcium, potassium, and TDS are the primary elements controlling water quality in the Kudenda–Nassarawa area. Iron is the major element influencing water quality in Kakuri and its Environs. In contrast, pH was the major element controlling water quality in Kaduna South. The pH values indicated an alkaline condition. High pH in aquifers means that the water can buffer acidic solution having elevated levels of hydrogen ions. The high dissolution of carbon-based minerals is the primary source of high pH in aquifers. Alkaline water tends to be hard. The major mineral compound triggering high pH (or alkalinity) in aquifers is calcium carbonate. It is chiefly derived from mineral rocks including limestone, dolomite, and calcite [105–109].

4.4 Groundwater classification based on LSI and RSI

The Langelier Saturation Index (LSI) (mean ± standard error) was – 2.71 ± 0.18 and ranged from – 5.30 to – 1.00 in Kaduna South, – 2.03 ± 0.27 and ranged from – 5.30 to 0.18, in the Kudenda–Nassarawa. The LSI was – 3.00 ± 0.39 and ranged from – 5.30 to 0.27 in Kakuri and its environs (Table 7; Fig. 10a). Table 7 presents the groundwater classification based on LSI. In Kaduna South, 74.19% of groundwater samples fall in very aggressive class, and 25.81% fall in moderately aggressive class. In the Kudenda–Nassarawa area, 16.67% are very aggressive, 66.67% are moderately aggressive and 16.67% are non-aggressive. Very aggressive

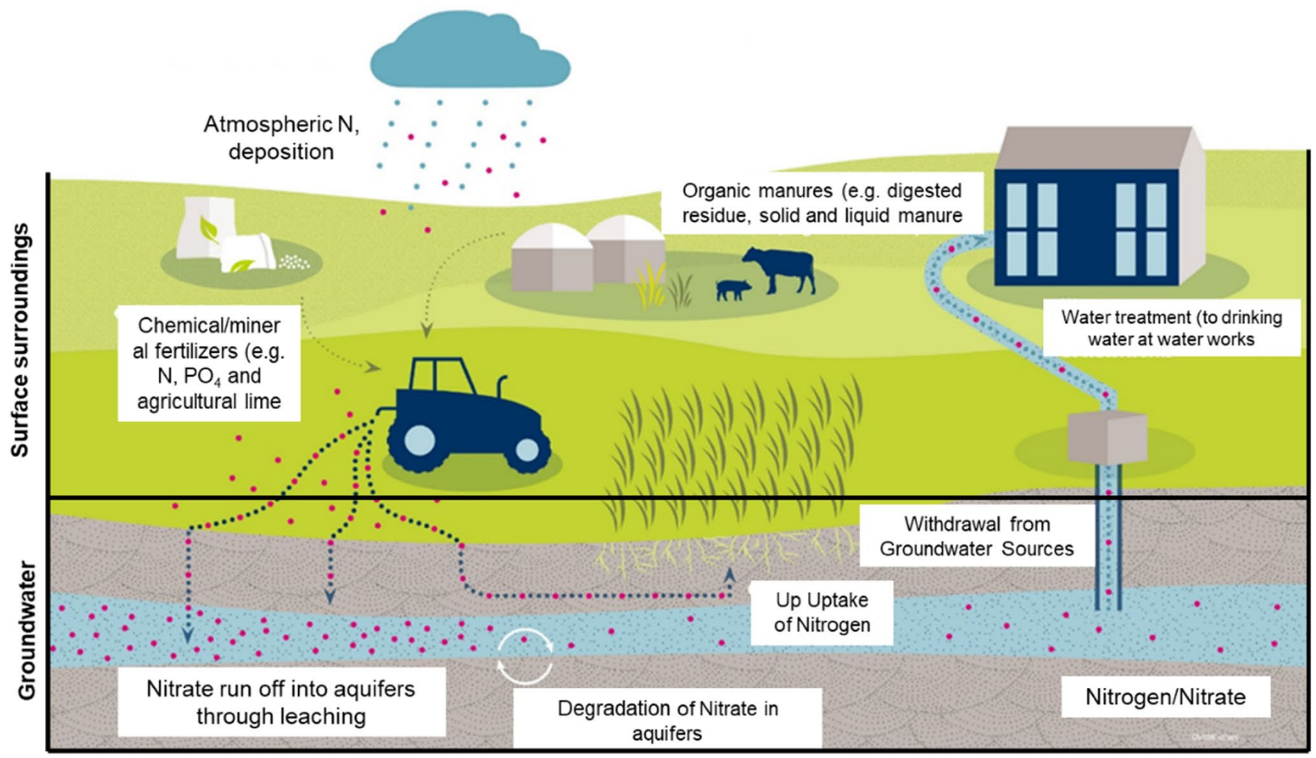


Fig. 8 Conceptual model of NO_3 occurrence in groundwater. After DVGW [104]

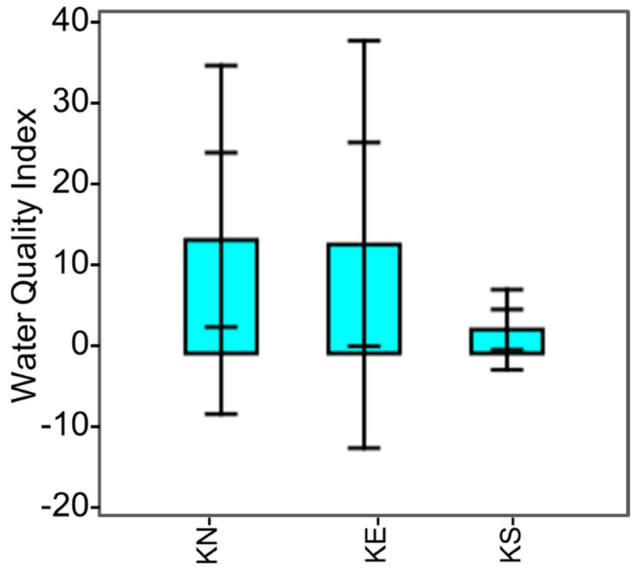


Fig. 9 Box and jitter plot showing calculated water quality index

Table 6 Groundwater classification based on WQI

Range	Classification	Kudenda–Nassarawa	Kakuri and its Environs	Kaduna South
Less than 50	Excellent	13.4628	7.64	10.26
50–100	Good	0	0	0
100–200	Poor	0	0	0
200–300	Very poor	0	0	0

water occurred in the Kakuri and its Environs. Non-aggressive water is ideal for industrial uses [10, 52].

Table 8 and Fig. 10b summarize the groundwater classification based on the Ryznar Stability Index (RSI). The RSI values were above 8.5 in Kaduna South and Kakuri and its Environs, indicative of extremely aggressive water. Similarly, 83.33% of RSI values in Kudenda–Nassarawa are between 6.2 and 8.5, indicative of aggressive water. However, 16.67% is acceptable for industrial use. Saturation index is essential for rating the extent of precipitation by water running through pipes or the extent of the dissolution of calcium carbonate. Groundwater in Kaduna Basin is unsuitable for industrial use.

4.5 Statistical application

4.5.1 Factor analysis

Factor analysis (FA) is a widely applied statistical method in hydrogeochemical analysis. It is used to classify

Table 7 Groundwater classification based on Langelier Saturation Index

Range	Kaduna South		Kudenda–Nassarawa		Kakuri and its Environs		Classification
	No. of samples	% of samples	No. of water samples	% of water samples	No. of water samples	% of water samples	
Less than – 2.0	23	74.19	1	16.67	15	100.00	Very aggressive
– 2.0 to 0.0	8	25.81	4	66.67	0	0.00	Moderate
Above 0.0	0	0.00	1	16.67	0	0.00	Non-aggressive

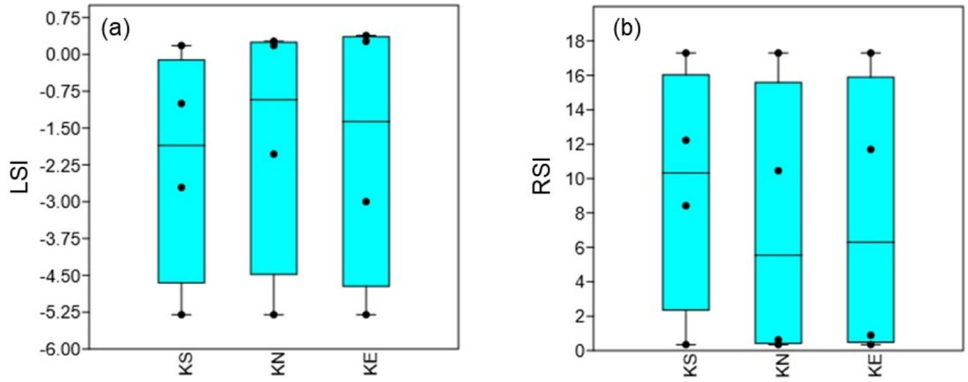


Fig. 10 Box and jitter plot: **a** Langelier Saturation Index and **b** Ryznar Stability Index

Table 8 Groundwater classification based on the Ryznar Stability Index

Range	Kaduna South		Kudenda–Nassarawa		Kakuri and its Environs		Classification
	No. of water samples	% of water samples	No. of water samples	% of water samples	No. of water samples	% of water samples	
Below 5.5	0.00	0.00	0.00	0.00	0.00	0.00	Heavy scale
5.5–6.2	0.00	0.00	0.00	0.00	0.00	0.00	Moderate scale
6.2–6.8	0.00	0.00	1.00	16.67	0.00	0.00	Acceptable
6.8–8.5	0.00	0.00	5.00	83.33	0.00	0.00	Aggressive water
Above 8.5	31.00	100.00	0.00	0.00	15.00	100.00	Extremely aggressive

hydrogeochemical data and relates it to the origin of ions in aquifers. Factor analysis was conducted on 13 subsets of parameters (Table 9). Factor 1 had high positive correlations on pH, EC, TDS, temperature HCO_3, SO_4, and K in Kudenda–Nassarawa (KN), HCO_3, NO_3, Na, Ca, and K in Kakuri and its Environs (KE), TDS, EC, and Cl in Kaduna South (KS). Factor 1 correlated with the rock weathering process. However, a high positive correlation on NO_3 is suggestive of anthropogenic contributions because NO_3 is continuously added from the N-rich fertilizers, oxidation of ammonia, and macrobiotic waste. Chloride is gradually increased in the environment by human activities [110–112]. Factor 2 had positive correlations on Na, Mg Fe, and Ca in KN; EC, TDS, and SO_4, in KE; and HCO_3, Mg, and Ca in KS. Factor 2 is exclusively correlated with rock weathering.

Factor 3 had high positive loading on Cl and Mg in KN; Mg in KE, SO_4, and K in KS. Factor 3 can be correlated with rock weathering. Insignificant correlation on Ca and Mg in Factor 1 from KN is pleasing since pH regularly attains an opposite relationship with ions of carbonate source [62, 113]. Figure 11 demonstrates the biplot of the extracted factors. The three factors accounted for 83.539% of the total variance in KN, 86.653% in KE, and 59.866% in KS, respectively. These factors have the highest eigenvalues.

4.5.2 Hierarchical clustering analysis

The use of hierarchical clustering analysis (HCA) in hydrogeochemical analysis aids the classification of aquifers by separating hydrogeochemical data that acts contrarywise. Groundwater sources with comparable hydrogeochemical

Table 9 Rotated (varimax) factor scores of hydrochemical data

Parameter	Kudenda–Nassarawa			Kakuri and Environs			Kaduna South		
	1	2	3	1	2	3	1	2	3
pH	**0.892**	−0.19	0.286	0.42	0.77	−0.093	−0.143	−0.171	0.275
Temp	**0.801**	0.219	0.161	ND	ND	ND	0.345	0.167	−0.124
EC	**0.912**	0.221	−0.299	−0.116	**0.976**	−0.014	**0.914**	0.111	−0.254
TDS	**0.719**	0.335	0.08	0.28	**0.841**	0.325	**0.876**	0.127	−0.304
Ca	0.07	**0.926**	−0.079	**0.787**	0.579	0.178	−0.096	**0.817**	0.041
Mg	0.071	**0.66**	**0.674**	0.503	0.066	**0.702**	0.407	**0.808**	0.192
Na	−0.135	**0.901**	0.391	**0.718**	0.581	−0.19	0.503	**0.757**	0.026
K	**0.787**	0.297	−0.416	**0.737**	−0.22	−0.417	0.116	0.01	**0.726**
Fe	0.212	**0.861**	−0.055	0.077	−0.03	−0.816	0.132	−0.039	−0.469
HCO_3	**0.78**	−0.064	0.286	**0.747**	0.566	0.327	−0.011	**0.963**	−0.051
Cl	0.268	0.06	**0.895**	**0.907**	0.339	0.236	**0.788**	−0.053	0.308
SO_4	**0.839**	−0.218	0.217	0.318	**0.794**	0.111	0.581	0.026	**0.682**
NO_3	ND	ND	ND	**0.949**	0.223	0.155	0.103	−0.087	−0.312
% of variance	43.287	25.721	14.53	57.741	16.362	12.55	30.304	16.633	12.929
Eigenvalue	5.194	3.087	1.744	6.929	1.963	1.506	3.939	2.162	1.681
Cumulative %	43.287	69.008	83.539	57.741	74.103	86.653	30.304	46.937	59.866

Values in bold indicated a significant correlation (≥ 0.65). *ND* no data (i.e., data not observed)

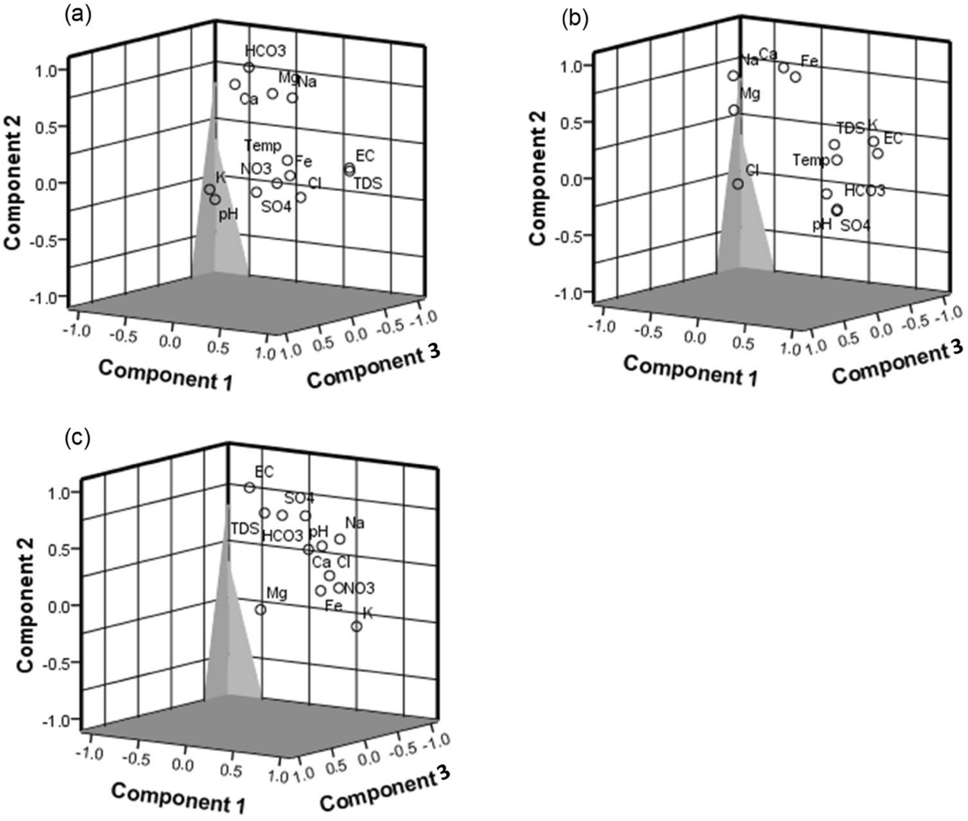


Fig. 11 Factor analysis (biplot) showing the variability of hydrogeochemical elements **a** Kaduna South, **b** Kudenda–Nassarawa, and **c** Kakuri and its Environs

characteristics tend to produce a discrete cluster. The graphical image of the grouping procedure is given as a dendrogram (Fig. 12). Cluster 1 is consisting of wells in the Kudenda–Nassarawa area and is having analogous concentrations of temperature and pH. So, it can be correlated with physical/external control (i.e., extreme temperatures), with its consequential effect on chemical reactions within aquifers. Inconsistency of temperature (5–10 °C) in

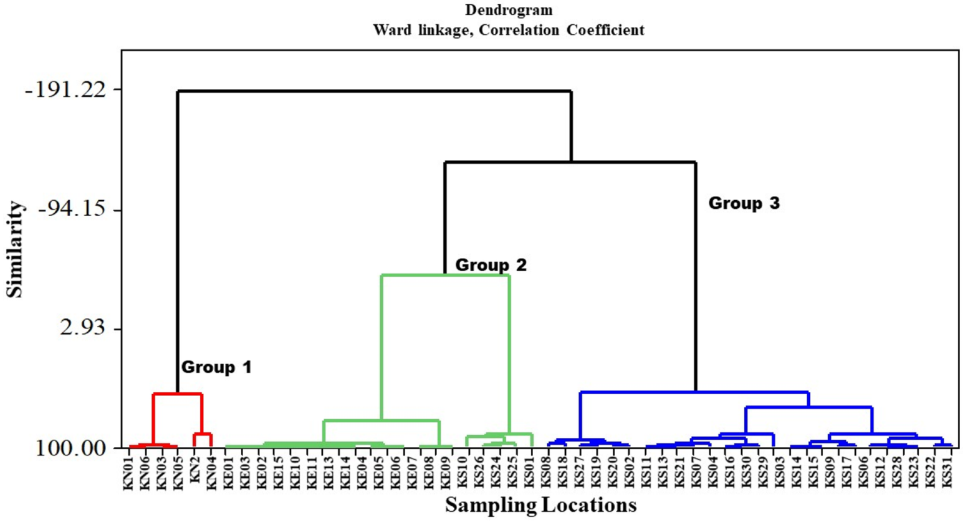


Fig. 12 Hydrogeochemical characteristics of groundwater based on hierarchical cluster analysis

groundwater influences TDS concentration, which eventually disturbs complexation, ion exchange, the solubility of gasses, redox reaction, sorption process, speciation process, and pH level [62, 114–118]. Cluster 2 comprises of wells in Kakuri and Environs and some wells (KS10, KS26, KS24, KS25 and KS01). It is characterized by analogous concentrations of SO_4, Cl, Mg, Ca, K, Na, and TDS. Cluster 3 is comprised of wells in Kaduna South and are having parallel concentrations of NO_3, HCO_3, Fe, and EC. Cluster 2 and 3 can be correlated with the rock weathering. However, NO_3 and SO_4 concentrations in groundwater are increasing consequent of agriculture and household chemicals [62, 116–120].

4.5.3 Generalized regression model

A general regression model was generated using MINITAB (mbt 16) statistical software, to identify the major hydrochemical parameter(s) influencing the hydrochemistry of aquifers in the Kaduna Basin. Electrical conductivity (EC) was choosing to be a response variable, while the remaining 12 parameters were predictors. Although EC cannot be associated with any specific chemical parameter; it is an excellent indicator of the overall ionic concentrations of water. It informs the range into which ionic concentrations are likely to fall. Consequently, it enables a water quality analyst to take suitable decisions relating to water usage. A significant relationship between EC and certain ions is an indicator of major ionic effect on the hydrochemistry of aquifers. The regression equation is thus: $EC = 123.553 - 11.2206\ pH - 1.71577\ Ca - 4.41477\ Mg + 5.99857\ Na + 0.929561\ K - 0.178372\ HCO_3 + 0.903213\ Cl - 0.16986\ SO_4 - 3.40888\ Fe + 0.162469\ TDS + 0.582821\ NO_3$.

The model as summarized in Table 10 showed that Ca, Mg, Na, and TDS are the most important hydrochemical variables influencing EC levels. The residual plots are summarized in Fig. 13. It was used to verify the hypothesis that residuals are normally distributed. The normal probability plot of the residuals approximately follows a straight line (Fig. 13a). The overall *P* value is < 0.001. The observed relative normality in this analysis, confirmed the accuracy of the model used. The hydrochemical parameters with *P* value < 0.005 are considered significant. Calcium, Mg, Na, and TDS have *P* value < 0.001. These elements represented the most important parameters affecting the hydrochemical composition of aquifers in the study area. Further, the model output had clearly shown no significant anthropogenic inputs (*P* value > 0.005, NO_3; Cl) in the study area.

5 Conclusion

With increasing industrial activities and urbanization, more groundwater is harnessed. Kaduna Basin has a semiarid tropical climate. This coupled with changes in land use posed a threat to water quality. While human activities can alter the hydrochemistry of aquifers, understanding the natural processes influencing the hydrochemistry of aquifers is also important. Kaduna–Kano zone represents the most urbanized and industrialized section of northern Nigeria. Thus, the appraisal of subsurface water by rating its quality for domestic and industrial uses is important. The use of WQIs to classify groundwater has demonstrated the effectiveness of these techniques for rating the quality of groundwater aquifers. Results obtained from this review lead to the following remarks:

Table 10 Summary of the general regression model

Model summary				*S*	R-Sq%	Rsq (Adj)%
				44.6605	55.33	43.05
Analysis of variance						
Source	*DF*	Seq SS	Adj SS	Adj MS	*F*	*P*
Regression	11	98,839	98,839.2	8985.4	4.5049	**0.000202**
pH	1	427	1459.5	1459.5	0.7318	0.397409
Ca	1	13,985	22,274.1	22,274.1	11.1674	**0.001814**
Mg	1	279	62,534.2	62,534.2	31.3523	**0.000002**
Na	1	27,336	50,780.8	50,780.8	25.4596	**0.00001**
K	1	6424	583	583	0.2923	0.59175
HCO_3	1	87	5530.9	5530.9	2.773	0.103681
Cl	1	5755	7195.8	7195.8	3.6077	0.06474
SO_4	1	0	384.1	384.1	0.1926	0.663138
Fe	1	445	1083.9	1083.9	0.5434	0.465324
TDS	1	44,032	43,626.5	43,626.5	21.8727	**0.000033**
NO_3	1	69	69.2	69.2	0.0347	0.85318
Error	40	79,782	79,782.5	1994.6		
Total	51	178,622				

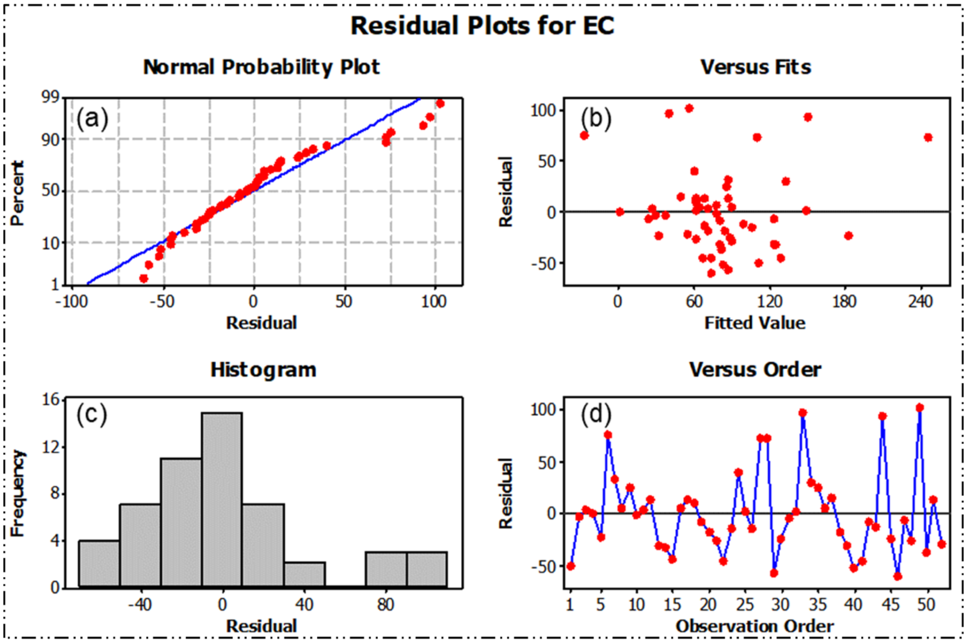


Fig. 13 Summary of regression analysis

1. Mean concentration of TDS, Ca, Mg, and K is above WHO (2011) reference guidelines for drinking water in Kudenda–Nassarawa area;
2. Groundwater classification based on the Chadha diagram showed that the Kudenda–Nassarawa area had a Na–HCO_3 water type. Na–Mg–Cl water type occurred in Kaduna South and Kakuri and its Environs;
3. Groundwater sources in the Kudenda–Nassarawa area had TH above 300 mg/l, indicating very hard water. The TH values are less than 75 mg/l in Kakuri and its environs, indicating soft water;
4. Likewise, 93.55% of groundwater in Kaduna South had TH values less than 75 mg/l, indicating soft water;

5. The TDS level was less than 500 mg/l in Kaduna South and Kakuri and its Environs, indicative of excellent water for drinking;
6. Based on chloride, 100% of water sources in the Kudenda–Nassarawa area fell in brackish salt class;
7. Similarly, 80% are brackish and 20% are brackish salt in Kakuri and its Environs. Kaduna South had very fresh to brackish saltwater type;
8. Nitrate pollution is generally low. In Kakuri and its Environs, 80% of water samples have NO_3 concentrations less than 5 mg/l and 20% had NO_3 levels ranging from 5–30 mg/l;
9. In Kaduna South, 93.55% of groundwater sources have NO_3 level below 5 mg/l;
10. The computed WQI revealed that the overall WQI was 13.46 in the Kudenda–Nassarawa area, 7.64 in Kakuri and its Environs, and 10.26 in Kaduna South;
11. Based on LSI and RSI, 16.67% was very aggressive, 66.67% was moderately aggressive and 16.67% was non-aggressive in the Kudenda–Nassarawa area. Very aggressive water occurred under Kakuri and its Environs;
12. Groundwater is primarily controlled by rock weathering as indicated by multivariate analysis and Gibb's model; and
13. Regression analysis revealed the hydrochemical parameters with P-value < 0.005 are Ca, Mg, Na, and NO_3. These elements represented the most significant elements controlling the hydrochemistry of aquifers in the Kaduna Basin.

Based on these revelations, it can be inferred that groundwater in Kaduna Basin is unsuitable for industrial use. It is undersaturated with $CaCO_3$. Undersaturated water can take off existing $CaCO_3$ protecting shells within equipment and pipelines. Classification of water using WQIs and saturation indices presented a user-friendly tool for rating sources of water supply. It helps to figure out the suitability of water for domestic and industrial uses. We hope that this review will stimulate other researchers to a similar method in an upcoming investigation on water quality.

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Compliance with ethical standards

Conflict of interest There is no conflicting interest associated with this review.

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