Research article

Multivariate statistical and hydrochemical approaches for evaluation of groundwater quality in north Bahri city-Sudan

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ABSTRACT

Groundwater has recently been considered one of the primary sources of water supply in Sudan. However, groundwater quality is continuously degraded due to overexploitation and long-term agricultural operations. The fossilized Cretaceous Nubian sandstone is the principal aquifer in the study area. This research aims to determine the major factors influencing groundwater quality and detect the suitability of groundwater for drinking and irrigation purposes by integrating hydrochemical and multivariate statistical methods. Hydrochemical plots such as Piper, Chadha, and Durov diagrams were applied to detect the groundwater facies and hydrochemical processes controlling the groundwater quality. They indicated Ca–Mg–HCO₃ water type as a dominant groundwater facies followed by Na–HCO₃ and Na–Cl types. Gibbs plots suggested that the dissolution of the minerals is the main factor influencing the water quality. The results of the Gibbs plot were further interpreted using saturation indices (SI). The SI values indicated that aragonite, calcite, and dolomite precipitated respectively in 58.33%, 75%, and 75% of groundwater samples. Multivariate statistical analyses, including Pearson's correlation analysis, hierarchical cluster analysis (HCA), and principal component analyses (PCA), were jointly employed to identify the structure of water quality data and deduce the main factors controlling groundwater quality. The statistical analysis revealed the effect of the physical and human-induced activities as the main factors influencing groundwater chemistry. These factors are rock-water interaction, agricultural practice, and organic contamination from septic tanks. Further, the suitability of groundwater for irrigation is determined using sodium adsorption ratio (SAR) and sodium percent (Na⁺%) indices. They carefully indicated that 75% of the groundwater samples in the study area are excellent for irrigation except for some sample location where the salinity hazard is stimulated by ion exchange. This integrated approach was effective in calibrating water quality assessment methodologies. The current research concluded that the implication of a groundwater quality monitoring scheme is crucial to ensure water supply sustainability in north Bahri city.

1. Introduction

Groundwater supplies freshwater for drinking and other household needs to most people worldwide (P. Li, Qian, et al., 2018). Groundwater use for domestic and agricultural reasons has undoubtedly increased its demand worldwide. However, groundwater is susceptible to contamination from both natural and artificial sources (Singh et al., 2015). Groundwater in Sudan is a fundamental source of water supply. It is a critical component of population settlement and sustainable socio-economic activities (Hassan et al., 2017). The demand for groundwater has increased dramatically to fulfill the development plans; nevertheless, these changes have posed various issues, such as inefficient pumping, reduced dependable production, and deterioration of groundwater quality (Abdo and Salih, 2012). The primary sources of water supply in Bahri city are the Nile River and groundwater. The groundwater supplies about 52% of the total need, mainly for irrigation. The sophistication in irrigation, chemical fertilizers, and pesticides has helped sustain life for many Sudanese people. On the other hand, the widespread adoption of pesticides and chemical fertilizers damaged groundwater quality and soil permeability. Water quality degradation leads to an increase in groundwater salinity, caused mainly by natural and anthropogenic activities. Consequently, the expense of health care and irrigation is rising, while the standard of living and the agricultural economy is declining (Rishi et al., 2020). Groundwater quality is as vital

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as quantity since it determines its usefulness for drinking and irrigation. Therefore, the hydrochemical assessment of groundwater aquifers is crucial for water resource management and development. The evaluation of the groundwater offers insight into the effects of natural and human-induced disturbances on the water resources and the suitability of the groundwater for drinking and irrigation purposes.

Few studies regarding water quality were conducted in Bahri city. For example, (Elkrail et al., 2003); assessed the spatial distribution of the major chemical parameters. Their study indicated that the ion concentration appreciably increases with increasing distance from the surface water systems. Alsidig and Al-Hagaz, 2019 evidenced that the groundwater in Bahri city ranges from generally acceptable to good for domestic uses. Kudoda and Abdalla, 2015 indicated that three factors are affecting groundwater quality in Khartoum state. These factors are mineral dissolution and weathering, carbonate system, and anthropogenic effect. Abdo and Salih, 2012 assessed the drinking water quality in north Bahri city. They reported that 55% of the investigated water samples are affected by coliform bacteria. Abdelsalam et al., 2016 discussed the factors retard the groundwater consumption in Khartoum state. They noted that the groundwater quality is affected by faulty groundwater well design and seepage of contamination from septic tanks and latrines. However, almost all the explored studies rely on identifying the chemical parameters and comparing them to a given quality standard without providing due account to delineating the contamination sources. The factors affecting the groundwater quality and hydrochemical properties of the groundwater have been widely documented in recent years, for example (Adimalla, 2019; Ben Brahim et al., 2021; Ismail et al., 2021; Kaur et al., 2019; Khalid, 2019; P. Li, Qian, et al., 2018; Rafa Trigui et al., 2021; Sunkari et al., 2020; Zhang et al., 2021). These investigations aided in developing hydrochemical studies, making them a dependent tool in water quality control and prediction. Multivariate statistical approaches are utilized to efficiently analyze and appraise the physicochemical properties of groundwater (Bhimanagouda et al., 2020; Dlamini and Demile, 2020; Duan et al., 2022; Elumalai et al., 2022; Enyegue A Nyam et al., 2020; Ibrahim et al., 2019; Lu et al., 2012; Osialwan et al., 2021; Ren et al., 2021; Ziani et al., 2021). Multivariate statistical
techniques are used to acquire information about similarities between groundwater samples, the variables that determine groundwater quality, and the hidden components that affect the data structure (Bhakar and Singh, 2019; Gulgundi and Shetty, 2018; Sheikhi et al., 2021). Hydrochemical and multivariate statistical analyses effectively understand the aquifer's characteristics and behavior concerning groundwater contamination (Ma et al., 2014; Masoud and Ali, 2020). The specific properties and the key groups of groundwater quality can be conveniently presented and categorized using multivariate statistical methods (Abdelaziz et al., 2020; Lu et al., 2012). Irrigation indices such as sodium adsorption ration and sodium percent have been widely used for assessing groundwater quality for irrigation purposes (Asadi et al., 2020; Kaur et al., 2021; P. Li et al., 2019; Masoud and Ali, 2020; Othman et al., 2019; Wilcox, 1948). Such indices are particularly useful for informing the public and relevant agencies about the quality of groundwater for different water management scenarios.

The study area is densely populated agricultural land with few water sources. On the other hand, anthropogenic pollution, namely agricultural activities, produce both point sources and diffuse contamination observed in scattered localities. This study aims to assess groundwater quality for irrigation and household uses in the north Bahri locality using hydrochemical and multivariate statistics methods. This integrated approach is efficient in detecting the chemical characteristics of groundwater and determining the vertical and horizontal variation in the groundwater facies. This study is considered the most comprehensive study to assess groundwater quality in the central Sudan hydrogeologic system. It can be used as a guide for future groundwater quality studies in similar regions in Sudan.

2. Materials and methods

2.1. The study area

The research area is in north Bahri city, Khartoum state, Sudan. It covers about 250 km², and the Nile River confines it from the west (Figure 1). The area is located in the northern part of the Savanna belt, which is characterized by a hot climate. The average annual rainfall ranges from 100 to 200 mm/year. Topographically, the study area is a flat peneplain. These plains rise gradually from ground 340 m (MSL) in the middle of the site to 600 m towards the eastern part. About 80% of the population lives along the Nile River, and the density of the population drops rapidly away from the Nile. The study area consists of three geological units; the Precambrian basement rocks are the oldest in the study area. They are composed of gneisses, schists, and granites, which appear on the surface outside the region, primarily on the northern and eastern sides. The Precambrian rocks are overlain unconformably by the Nubian formation of the Cretaceous age, which is considered the prime aquifer (Awad, 1994; Kheiralla, 1966; Saeed, 1974; Whiteman, 1971). This formation consists of conglomerates, sandstone, and mudstone. They are intruded on by basaltic rocks. The recent deposits encountered in the study area include windblown sands and alluvium wadi deposits (Figure 2). Groundwater is found in the Nubian formation's poorly cemented sandstone strata in confined to semiconfined conditions. This is due to silts and clays in thick to thin aquitards and aquicludes (Abdelsalam et al., 2016). Nubian sandstone forms two aquifers (Farah et al., 1997). An upper aquifer of thicknesses ranges from 10 to 300 m, and a lower one with a thickness of more than 400 m. The groundwater

Figure 3. Potentiometric surface map showing the diverse direction of groundwater flow in the study area.
levels vary from 10 to 15 m near the Nile River and reach up to 45 m in the eastern and northern parts of the study area. The drainage system is dominated by the Nile River and local systems of ephemeral streams (e.g., Wadis and Khors), which trend mostly east-west. The flow of groundwater shows diverse directions but mostly flows from the Nile River to the east and southern part of the area (Figure 3). In the research area, there are two main groups of the recharged groundwater that can be identified depending on their source and expected time of recharging: Nilotic and Meteoric waters. Nilotic groundwater infiltrated from the Nile after the middle Holocene and retained in upper and lower aquifers within a 12-kilometer radius from the Nile River. Meteoric palo groundwater that recharged between the Pleistocene and middle Holocene and exists in the regions outside the Nile influence. The recent recharge from rainfall is minimal, with the exception of regions close to ephemeral streams, wadis, and depressions (Farah et al., 2000).

2.2. Groundwater sampling

In 2018, a total of 12 samples is taken during the post-monsoon season. The groundwater samples were taken from bore wells installed in the north Bahri city that were privately owned and ranged in depth from 100 to 150 m. The geographical distribution of the samples is shown in Figure 1. Groundwater samples were collected based on the well’s accessibility and reliability, and the collected samples were kept in previously cleaned plastic bottles. Groundwater samples were analyzed for physicochemical parameters by Khartoum State Water Corporation (KWSW). These parameters are total alkalinity (TA), total hardness (TH), magnesium (Mg²⁺), nitrate (NO₃⁻), chloride (Cl⁻), sulfate (SO₄²⁻), bicarbonate (HCO₃⁻), fluoride (F⁻), and Ammonia (NH₃). Electrical conductivity (EC), total dissolved solids (TDS), and pH were measured using a multi-parameter portable instrument immediately after the sample collection. The accuracy of the physicochemical analysis was examined by the electrical balance (EB) between the cations and anions using the formula (equation (1)) suggested by (Appelo and Postma, 2005)

\[
(EB\%) = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100
\]

(1)

All anions and cations were in milliequivalents per liter. In this research, the EB% was within ±5%, which indicates good accuracy.

2.3. Hydrochemical and statistical analysis

Hydrochemical tests were performed to define the groundwater facies, detect the geographical distribution of chemical parameters, and demonstrate the physiochemical mechanisms that influence groundwater chemistry using different hydrochemical plots (Chadha, 1999; Durov, 1948; Gibbs, 1970; Piper, 1944).

Multivariate statistical techniques were employed to investigate the primary factors influencing the quality of groundwater in the north Bahri locality. The statistical methods such as correlation, cluster, and principal component analyses are useful techniques for understanding the sources of groundwater contamination (Wu et al., 2020). First, the correlation between the physicochemical parameters is applied to study the degree of associations between them and detect the role of each parameter in the overall quality. The correlation analysis aids in monitoring the chemical parameters and understanding the interrelation between the various water quality variables (Rishi et al., 2020). Pearson correlation coefficient (r) is utilized in this study. It can be computed using Eq. (2) as

\[
r = \frac{\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{\sum x_i^2 - \sum x_i^2} \sqrt{\sum y_i^2 - \sum y_i^2}}
\]

(2)

where r represents the values of the variables x and y, and \(\bar{x}\) and \(\bar{y}\) symbolize the means of these values.

Secondly, hierarchical cluster analysis (HCA) is performed to categorized the groundwater samples and their ions according to their chemical characteristics. It organizes the items into clusters according to a predetermined selection criterion, with each variable being comparable to the others in each cluster. Thus generated clusters exhibit both high internal homogeneity and substantial interclass variability (Daughney et al., 2012; Kaur et al., 2020). The most popular technique is hierarchical clustering, which provides inherent similarity correlations
between any variable and the complete collection of data (Shrestha and Kazama, 2007). The result of the cluster analysis is visualized in dendrograms. The dendrogram reduces the complexity of the original data and offers a graphical representation of clusters and their proximity.

Finally, principal components (PCs) were obtained through principal component analysis (PCA) to detect the major components controlling the quality of groundwater in the study area. PCA is employed to reduce the dimensionality of the data for analyzing the interrelationships between a wide range of variables and explaining their common underlying factors (Kumar et al., 2011). The degree of connection between variables and their effect on the analyzed samples can be determined using PCA (Bhimanagouda et al., 2020). The variances extracted from the PCs are called eigenvalues. The remaining variables determine how much of the residual variability (Behera and Das, 2018). The PCs ($\Psi$) are expressed using Eq. (3)

$$\psi = \psi_1 x_1 + \psi_2 x_2 + \cdots + \psi_p x_p,$$

where $p$ is the total number of variables, $i$ is the component number, which varies from 1 to $p$, $w$ is the component loading, and $x$ is the original variable.

### 2.4. Irrigation indices

Sodium adsorption ratio (SAR) and sodium percent ($\text{Na}^+$%) were employed to assess the suitability of groundwater for irrigation. The quality of irrigation water directly affects plant growth, which may cause a decline in crop production (P. Li et al., 2019). Therefore, using high-quality water for irrigation is crucial for agricultural development. The most generally used metric to evaluate irrigation water is SAR, which is a proportional balance of $\text{Na}^+$ ions to $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ ions in the water sample. The following formula (Eq. (4)) can be used to estimate SAR

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}}$$

where $\text{Na}^+$, $\text{Ca}^{2+}$, and $\text{Mg}^{2+}$ are in meq/L. On the SAR basis, water is classified into four categories: excellent category where SAR <10, in a good category SAR range from 10 to 18, doubtful is between 18 and 26, and SAR >26 for unsuitable water.

$\text{Na}^+$% is one of the frequently used indices to determine the suitability of groundwater for irrigation purposes (Wilcox, 1948). Crop growth is affected by an excessive $\text{Na}^+$ concentration since it impacts the permeability of the soil (Todd and Mays, 2004). $\text{Na}^+$% is computed using eq. (5)

$$\text{Na}^+\% = \frac{\text{Na}^+}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + K^+}$$

where all the ion concentrations are expressed in meq/L. According to $\text{Na}^+$%, water is classified to excellent (less than 20%), good (20–40 %), permissible (40–60 %), doubtful (60–80 %), and unsuitable (more than 80 %) (Khodapanah et al., 2009).

### 3. Results and discussion

#### 3.1. General hydrochemistry

In this research, 14 physiochemical parameters are used to evaluate the groundwater quality in north Bahri city. The result of the hydrochemical analysis is shown in Table 1. The descriptive statistics such as
The mean, minimum, and maximum for the analyzed parameters are given in Table 2 to reveal the deviation of the Physiochemical parameters from the permissible concentration limits prescribed by the World Health Organization (WHO) (Edition, 2011). Almost all the parameters are within the acceptable range prescribed by WHO. In this study, the analyzed physiochemical parameters are EC, TDS, TH, pH, Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\), SO\(_4\)\(^{-2}\), NO\(_3\)\(^-\), F\(^-\), HCO\(_3\)\(^-\) and NH\(_3\). These parameters are subject to alteration depending on the surrounding environment (P. Li et al., 2016). The pH of the groundwater samples is between 7.2 and 8.3, indicating a neutral to alkaline water type. The spatial distribution of pH (Figure 4a) revealed the highest values in the southeastern part and the lowest values in the southwestern part of the study area. The EC of groundwater samples varies between 357.3 and 1500 \(\mu\)S/cm. Almost all the samples show EC values less than 1500 \(\mu\)S/cm. EC of the groundwater is directly related to the dissolved solids. The most important indicator of the overall mineral concentration in groundwater is TDS. In this study, TDS ranges from 214.4 to 1050 mg/L. The highest record is observed in the east, while the lowest is in the western part (Figure 4b). The rock-water interaction is the possible reason for the variation in the total dissolved solids. TH concentrations are below the WHO standard (Edition, 2011) and range from 134 to 380. TH of the groundwater is connected to the presence of Ca\(^{2+}\) and Mg\(^{2+}\) (Hailu et al., 2019). The content of Mg\(^{2+}\) fluctuates between 5.8 and 82.6 mg/L. Dolomite dissolution and silicate weathering are two common sources of Mg\(^{2+}\). Since TH is mainly controlled by Mg\(^{2+}\), therefore, the geographical variation of TH (Figure 4c) and Mg\(^{2+}\) (Figure 4d) shows a similar trend. The calcium concentration in the groundwater samples ranges from 16 to 66.4 mg/L. The highest Ca\(^{2+}\) concentration (66.4) is found in location 9 in the central part of the study area (Figure 4e). Calcium may have come via the dissolution of carbonates. In groundwater chemistry, Na\(^+\) is the most critical ion. Its concentration in the investigated area gradually rises from west to east (Figure 4f). Site 5 in the eastern part of the research area has the highest concentration (332.8 mg/L), while location 7 has the lowest (17.6 mg/L). Silicate weathering and halite dissolution might explain the high concentration of Na\(^+\) (Hem, 1985). The concentration of the HCO\(_3\) varies between 142 and 414.8 mg/L. The major anion in the research region is HCO\(_3\). Locations 5 and 7 have the highest concentration. The areal distribution of HCO\(_3\) is shown in Figure 4g. Calcite and dolomite dissolution or ion exchange are the sources of HCO\(_3\). The HCO\(_3\) level rises in concordance with the mineral content. The concentration of SO\(_4\)\(^{-2}\) in groundwater ranges from 4 to 320.5 mg/L and gradually increases from the west to the eastern part of the study area (Figure 4h). It might result from soil leaching or groundwater discharge (Yidana et al., 2018). Cl\(^-\) concentrations range from 8 to 193.12 mg/L. The highest concentration of Cl\(^-\) is 193.12 mg/L. The highest concentration is detected in sample 5, while the lowest is recorded in sample 3. The geographical distribution of Cl\(^-\) is shown in Figure 4i. The maximum concentration of F\(^-\) is 1.23 mg/L which is considered a high value According to WHO (Edition, 2011). The highest NH\(_3\) concentration
Figure 6. Chadha diagram showing the water facies in the study area.

Figure 7. Durov diagram showing the dominant chemical processes affecting groundwater chemistry.
3.2. Hydrochemical facies

Hydrochemical facies are defined as distinct chemical compositions of groundwater that result from the interaction of water with different geological formations. The classification of groundwater types is crucial for understanding the quality and origin of the water and for managing its use. Hydrochemical facies are usually represented using plots such as Piper, Chadha, and Durov diagrams, which allow for the interpretation of the chemical composition of groundwater samples.

In the study area, the groundwater quality is influenced by various factors, including geology, climate, and human activities. The chemical composition of groundwater samples (75%) fall in the Ca²⁺ mode, indicating that the groundwater quality is influenced by the recharged water from the Nile River or perhaps by mixing of fresh water with saline water (Adams et al., 2001). Na–Cl type dominates 16.66% of the samples. Na–Cl water type might be produced by the mixing of fresh water with saline water (Adams et al., 2001) or by reverse ion exchange (Yadav et al., 2018). The concentration of sodium increases from recharge to discharge area while the bicarbonate, on the other hand, decreases. This can be visualized as the cation exchange stimulated along the flow path.

Chadha diagram is a modified version of Piper diagram (Chadha, 1999). Groundwater cations and anions were determined at the same time step. As a result, the water chemistry data were shown as percentile difference between HCO₃⁻(SO₄²⁻ + Cl⁻) and (Ca²⁺ + Mg²⁺)-(Na⁺ + K⁺) concentrations in meq/L. Chadha diagram reveals the association between cations and anions of groundwater (Rafique et al., 2015). Four different types of water facies may be identified using the Chadha diagram: Ca–Mg–HCO₃, Na–HCO₃, Ca–Mg–SO₄/Cl, and Na–Cl. Consequently, four hydrochemical processes result in the production of these water facies (Figure 6).

Field 1 depicts the Ca–Mg–HCO₃ water type. This type reflects the influence of weathering and recharging processes on the groundwater. 75% of the water samples in the research area are projected in this field. Ca–Mg–SO₄/Cl water type plotted in field 2 and indicates reverse ion exchange activities and no samples is plotted in this field. Field 3 shows the NaCl water type, indicating that evaporation and mixing with saltwater have influenced water samples in this field. This zone contains 16.66% of the water samples. The water type of Na–HCO₃ is shown in Field 4. This class contributes 8.33% to the total hydrochemical facies.

Durov diagram (1948) has been used to indicate the hydrochemical processes controlling groundwater chemistry. Durov diagram is a plot that combines two triangles and a central rectangular shape in which the milliequivalent percentage of cations against anions is projected (Figure 7). Most of the groundwater samples with TDS less than 500 mg/L are located in the field of ion exchange, whereas samples with TDS higher than 500 mg/l are located in the dissolution and mixing zone. Durov diagram helped in the interpretation of Piper and Chadha diagrams. It showed that most of the samples are plotted in dissolution and ion exchange regions. According to (Lloyd and Heathcote, 1985), the mixing of groundwater with newly recharged water with no noticeable major anion or cation can explain this pattern.

Figure 8. Gibb's plot shows the impact of rock weathering, evaporation, and precipitation on the groundwater samples.
3.3. **Saturation index**

Gibbs diagrams are frequently used to understand how natural activities affect groundwater chemistry. In this study, the influence of several mechanisms, such as weathering of rocks, precipitation, and evaporation, was detected using Gibbs (1970) scatter plot. The ratio of Cl⁻/(Cl⁻ + HCO₃⁻) and (Na⁺/Na⁺ + Ca²⁺) is projected versus TDS concentration (Figure 8). Except for two samples that occurred in the evaporation and precipitation zone, the Na⁺/(Na⁺ + Ca²⁺) versus TDS plot revealed that the majority of the groundwater samples were affected by rock-water interaction. Chemical weathering, dissolution of carbonate minerals, and ion exchange are the main component affecting the rock-water interaction process (Boateng et al., 2016). Mineral dissolution is likely the primary natural mechanism influencing the primary salts in

**Figure 9.** Saturation indices for (a) anhydrite (b) aragonite (d) calcite (c) dolomite (e) Gypsum (f) halite.
groundwater. TDS with \( \frac{\text{Cl}^-}{(\text{Cl}^- + \text{HCO}_3^-)} \) plot confirmed that those two samples of shallow depth which were affected by evaporation are also influenced by saline water intrusion. This shows that shallow aquifers in dry and semi-arid regions often experience higher rates of evaporation than deeper subterranean water sources. (Li et al., 2018b). Accordingly, it is clear that significant rock weathering and minimal evaporation together influence groundwater chemistry in the research area. To evaluate the product of the rock-water interaction, the saturation indices (SI) for major minerals such as gypsum, aragonite, dolomite, anhydrite, halite, and calcite were calculated. The calculation results are illustrated in Figure 9. The SI values of aragonite, calcite, and dolomite are higher than zero in 41.6%, 58.3%, and 75% of groundwater samples, respectively (Figure 9b, c, and d). It means the precipitation of these minerals in the majority of the groundwater samples. In contrast, the SI values of gypsum, anhydrite, and halite for all groundwater samples are less than zero (Figure 9a, e and f), indicating that groundwater might dissolve these minerals along the flow path. Groundwater in the recharge zones is unsaturated in gypsum, anhydrite, halite, aragonite, dolomite, and...
calcite since the contact period between the rocks and groundwater is limited. In discharge zones, groundwater achieves equilibrium with these minerals as many water-rock interactions occur. As a result of gradual mineral dissolution from recharge to discharge zones, the TDS in groundwater will rise along the groundwater flow path. The SI values of calcite and dolomite range from $0.28$ to $0.68$ and $0.96$ to $1.63$, respectively, suggesting no substantial connections between them and TDS. Therefore, Calcite and dolomite do not dissolve further along the flow path (Figure 10). On the other hand, gypsum and halite are associated with SI values less than zero and a significant positive relationship with TDS, suggesting that these minerals continue to dissolve along the flow path. The decomposition of anhydrite and gypsum raises the concentration of Ca$^{2+}$ in groundwater, which raises the SI values of calcite and dolomite and may soon precipitate them in the groundwater.

3.4. Multivariate statistical analysis

3.4.1. Correlation analysis

The correlation matrix is an effective statistical tool. It reveals the linear correlation between different physical and chemical variables and the influence of each parameter on the overall hydrochemical data (Figure 11). Two variables are entirely connected if the correlation coefficient ($r$) values are $+1$ or $-1$, which are regarded as a whole correlation coefficient value (Y. Singh & Kumar, 2011). In this study, if ($r$) is higher than $0.7$, it was described as strongly correlated, while $0.4$ to $0.7$ value is moderately correlated. TDS shows a strong relationship with SO$_4^{2-}$, TH, Mg$^{2+}$, and Na’, suggesting a high contribution of these ions to the groundwater salinity. TH is highly correlated with SO$_4^{2-}$, Mg$^{2+}$ and Na’ and moderately correlated with HCO$_3^-$ and Cl$^-$, suggesting the temporary hardness predominance (Arumugam, 2010). Cl$^-$ has high correlations with Na’. Na’ to Cl-ratio in millimole per liter is equal to 1 if Na’ and Cl$^-$ are produced entirely from halite disintegration (P. P. Li et al., 2013). In this work, most of the samples are projected below the 1:1 line (Figure 12a). According to (Meybeck, 1987) if the Na’/Cl$^-$ ratio in water is not 1, silicate weathering is the source of Na’, but a ratio of about 1 implies halite dissolution. The average Na’/Cl$^-$ ratio in groundwater samples reported in the current investigation is less than 1:1, indicating that weathering of rocks or human activity may have added to the sodium concentration. NO$_3^-$ has a moderate correlation with Ca$^{2+}$, and it always indicates contamination from agricultural practice (Sabo and Christopher, 2014). As shown in Figure 12c, Ca$^{2+}$ is positively associated with SO$_4^{2-}$. More than 75% of the samples are plotted under
the 2:1 line, which indicates that the calcium in groundwater is not only from calcium sulfate minerals but also from other sources such as weathering of carbonate rocks. Mg$^{2+}$ has a high correlation with SO$_4^{2-}$ and a low with HCO$_3^-$ (Figure 12d), which indicates calcareous magnesium materials which contribute Mg$^{2+}$ and SO$_4^{2-}$ to the groundwater.

Carbonate mineral dissolution undoubtedly had a significant role in regional groundwater development, particularly in terms of the origins of Ca$^{2+}$, Mg$^{2+}$, and HCO$_3^-$. If the sources of Ca$^{2+}$ and HCO$_3^-$ can be traced back to carbonate dissolution, the Ca$^{2+}$/HCO$_3^-$ samples in mmol/L scatter plot should lie between 1:1 and 1:2. In this work, the concentration of
Ca\textsuperscript{2+} shows a positive trend with HCO\textsubscript{3}\textsuperscript{–}. Most samples are plotted below the line of 1:2 (Figure 12/b) demonstrating that carbonate dissolution isn’t the primary source of HCO\textsubscript{3}\textsuperscript{–}. It can be concluded from correlation analysis that the groundwater in the study area is mainly influenced by mineral dissolution and agricultural practice.

### 3.4.2. Hierarchical cluster analysis (HCA)

HCA can potentially classify groundwater samples into different water quality groups or hydrochemical facies (Daughney et al., 2012). HCA applies the Euclidean separation technique as a similarity measure to distinguish between groundwater samples based on their hydrochemical characteristics. The dendrogram in Figure 13 obtained for chemical parameters showed three clusters (C1, C2, and C3). Due to the role of the sampling sites in the establishment of clusters, Water sample sites that are geographically close are mostly in the same cluster. C1 includes pH and NH\textsubscript{3} with a high degree of similarity (77%). The occurrence of NH\textsubscript{3} in groundwater results from the degradation of the organic materials by bacteria (X. X. Li et al., 2013); therefore, in this study, the first cluster might indicate anthropogenic contamination such as seepage from septic tanks. This cluster may also reflect the effect of organic pollution on the pH of the groundwater. C2 involves EC, TDS, Na\textsuperscript{+}, SO\textsubscript{4}\textsuperscript{2–}, TH, Cl\textsuperscript{–}, F\textsuperscript{–}, HCO\textsubscript{3}–, Mg\textsuperscript{2+}. The salinity of groundwater is mostly influenced by these parameters. This cluster could possibly show the effect of rock-water interaction on groundwater samples (Sharma et al., 2022). C3 includes NO\textsubscript{3} and Ca\textsuperscript{2+}. A high concentration of NO\textsubscript{3} is due to irrigation return flow (Nethononda et al., 2019). The main source of Ca\textsuperscript{2+} in groundwater in the study area is the dissolution of carbonate rocks, as suggested by the interionic interactions. Thus, the parameters in the third cluster may indicate carbonate weathering and agricultural contamination (Sabo and Christopher, 2014). The dendrogram of Figure 14 illustrates the general clustering of the groundwater samples in the study area. According to their chemical compositions, groundwater samples are clustered into three groups. The first group includes sample locations of 1,2,3,4,6,7,8,10,11, the second cluster is 9,12, and the third cluster is sample number 5. The samples of the first cluster are associated with low chemical contents, and the maximum values of the parameters are below the standard prescribed by WHO (Edition, 2011). Groundwater samples of cluster 2 have higher chemical content than cluster 1, and some parameters exceed the permissible limit. Samples in cluster 3 are considered highly mineralized due to the high values of many parameters such as TDS and Na\textsuperscript{+}. According to Piper and Chadha diagrams, the groundwater samples in C1 are of Ca–Mg–HCO\textsubscript{3} water type, C2 represented in Na–HCO\textsubscript{3} water type, and C3 is Na–Cl water type. The geochemistry of C2 and C3 show high similarity as they are projected near to each other in the hydrochemical plots. Groundwater quality varies smoothly throughout the region, as evidenced by the spatial distribution of the clustered samples. This variation could be attributed to the equally dominant hydrogeological environment in the study area.

### 3.4.3. Principal component analysis (PCA)

PCA is a pattern recognition method that reduces data dimensionality to facilitate visualization and analysis. The extracted principal components are orthogonal to one another. 12 PCs were extracted in this study, but only PCs with eigenvalues greater than one were selected. In this study, according to (C. W. Liu et al., 2003), variables loading higher than 0.3 are considered for the interpretation of the result as they strongly influence the principal component. Table 3 shows the results of the PCA based on the correlation matrix between the chemical and physical components. In this study, three PCs were extracted, describing 86.1% of total variances. PC1 accounted for most of the total variance (52.52%) and is associated with high loading of EC, TDS, TH, Cl\textsuperscript{–}, F\textsuperscript{–}, SO\textsubscript{4}\textsuperscript{2–}, Mg\textsuperscript{2+}, and Na\textsuperscript{+}. PC1 contains the major cations and anions that seem to be

| Parameter | PC 1 (52.52%) | PC 2 (21.86%) | PC 3 (11.72%) |
|-----------|---------------|---------------|---------------|
| pH        | 0.09066       | -0.33266      | 0.53685       |
| EC        | 0.35198       | 0.02946       | -0.00328      |
| TDS       | 0.35344       | 0.05078       | 0.06696       |
| TH        | 0.33024       | 0.10771       | -0.12109      |
| Cl\textsuperscript{–} | 0.30754 | -0.17669 | 0.2745 |
| F\textsuperscript{–} | 0.247 | -0.18365 | 0.31462 |
| SO\textsubscript{4}\textsuperscript{2–} | 0.35529 | 0.04195 | -0.03717 |
| NH\textsubscript{3} | 0.07518 | -0.31972 | 0.54168 |
| NO\textsubscript{3} | -0.07459 | 0.39158 | 0.22308 |
| Ca\textsuperscript{2+} | -0.10032 | 0.44295 | 0.28406 |
| Mg\textsuperscript{2+} | 0.31335 | -0.12771 | -0.23247 |
| Na\textsuperscript{+} | 0.36097 | 0.01431 | -0.003 |
| HCO\textsubscript{3}– | 0.22527 | 0.41359 | 0.11369 |
related to the dissolution of the geological component from rock-water interaction. This was also interpreted by (Gopinath et al., 2018). This PC depicts the second cluster of HCA and suggests that high values of TDS are affected by Na\(^+\), Cl\(^-\), Mg\(^{2+}\), SO\(_4\)\(^{2-}\), and F\(^-\) (P. Liu et al., 2017). suggested that the strong positive PC coefficient of Mg\(^{2+}\) and Ca\(^{2+}\) indicates that these ions are derived from weathering of carbonate minerals. This component also represented the salinity of water since TDS, Na\(^+\), and Cl\(^-\) showed the highest loading as the main cause of salinization. The concentration of F\(^-\) is relatively low, which contributed less to salinity. PC2 accounted for 21.86% of variance and is associated with medium to high positive loading of NO3\(^-\), Ca\(^{2+}\) and HCO3\(^-\). The presence of NO3\(^-\) in groundwater suggests contamination from agricultural activities. High coefficients of and NO3\(^-\) are due to infiltration of wastewater and irrigation return flow (Nethononda et al., 2019). PC2 may also indicate carbonate dissolution. PC3 shows high positive loading of pH and NH3\(^+\) and accounted for 11.72% of the total variance. PC3 suggests that the pH of groundwater is influenced by NH3\(^+\). This component represents the influence of anthropogenic activities such as organic contamination on the pH of water and it reflects C1 of HCA. Figure 15 shows the biplot of PC1 (52.52% variance) versus PC2 (21.86% variance), which illustrates the orientation of different parameters towards the plotted components and the influence of the two components on the groundwater samples. The chemical variables in the PC1 effects three water samples in this study: samples 9, 12, and 5. These samples are highly mineralized and influenced by the minerals dissolution process. Samples 1, 2, 6, 10, and 11 are impacted by PC2 while the remaining samples fall in the transition zone, which means they are controlled by ions in the PC1 and PC2, simultaneously. According to the principal component analysis, the water chemistry in the study area is mostly influenced by mineral dissolution and anthropogenic activities such as agricultural practices and septic tank.

3.5. Irrigation indices

Groundwater is mostly used for agricultural purposes in the Bahri area since farming is the principal profession of the residents. On the other hand, irrigation water poses the greatest harm to the groundwater quality in the study area. The quality of the irrigation water is determined by the concentration of dissolved sodium relative to the other major cations and the presence of toxic elements in the groundwater. The incorporation of Na\(^+\) into clay particles accelerates the base-exchange process by eliminating Ca\(^{2+}\) and Mg\(^{2+}\) ions. Sodium adsorption ratio (SAR) and sodium percent (Na\(^+\) %) are employed in this study to assess the appropriateness of groundwater for irrigation. SAR is the most widely used index to assess groundwater quality for irrigation. The sodium concentration is one of the major components in evaluating water quality for irrigation since high sodium concentration potentially affects soil permeability (Sadashivaiah et al., 2008). The soil becomes unusable for agriculture after prolonged exposure to groundwater with a high content of Na\(^+\) (Younger and Casey, 2003). Figure 16 shows the United States salinity laboratory (USSL) diagram (Richards, 1954), which takes the EC of the water samples as the main component for evaluation. EC is typically regarded as a crucial factor in understanding whether water is suitable for irrigation purposes. Any water's EC is dependent on the amount of salts present, which in turn has an impact on crop production. In this study, the values of SAR range from 0.56 to 7.42. About 75% of the samples fell under the excellent category with low sodium and salinity hazard. This category can be used safely for crop irrigation. 16.6% of the samples fell under the C3S1 class with low alkali, and medium salinity hazard and 8.3% of the samples represented the good category and plotted in C3S2 class. The C2S1, C3S1, and C3S2 classes respectively reflect Cluster 1, Cluster 2, and Cluster 3 obtained from hierarchical cluster analysis.

![Figure 17. Wilcoxon diagram.](image-url)
Na⁺ % index is widely used to indicate sodium hazards. High Na⁺ concentration reduces the soil permeability and, thus, reduces the capacity of the water movement (Ayers et al., 1985). Alkaline soils are formed when Na⁺ reacts with HCO₃⁻, whereas saline soils are formed when Na⁺ reacts with Cl⁻. The observed Na⁺ % ranges from 17 to 65.6. Wilcox's (1948) diagram in Figure 17 relates EC to Na⁺ % to categorize the groundwater samples. In the present work, 75% of the water samples are plotted in the excellent category, 16.66% are located in the good to permissible class, and 8.33% are projected in the permissible to doubtful class. The doubtfulness is due to the high salinity in the groundwater samples. As in SAR, the categories of Na⁺ % can be read in the light of the hierarchical cluster analysis. The groundwater in the study area is suitable for irrigation, and no threats to soil structure and crop yield are posed. However, two samples (5 and 9) are associated with high salinity, and the ongoing use of these samples in irrigation may induce salinity hazards.

4. Conclusions

The study evaluated the quality of the groundwater for domestic and agricultural usage in north Bahri city, Sudan, using hydrochemical and multivariate statistical methods. The main conclusions are summarized:

- The primary hydrochemical analysis for the measured parameters demonstrated that the composition of the groundwater is fresh to alkaline. The spatial distribution of major ions except for Ca²⁺ and HCO₃⁻ showed that the water samples in the eastern part are highly mineralized compared to the west. This reflects the chemical nature of the Nile River, which considers the main source of recharge.
- Hydrochemical plots such as Piper, Chadha, and Durov diagrams revealed the dominant groundwater facies. Ca-Mg–HCO₃ water type is prevailing, followed by Na–HCO₃ and Na–Cl water types.
- Based Gibbs plot, mineral dissolution and precipitation are the main natural factors influencing the groundwater chemistry in the study area. The mineral content of anhydrite, dolomite, aragonite, calcite, gypsum, and halite was calculated using saturation indices (SI). SI indicated the precipitation of aragonite, calcite, and dolomite in 41.6%, 58.33%, and 75% of groundwater samples, respectively.
- Multivariate statistical techniques have been demonstrated to be an effective tool in groundwater quality assessment. Correlation analysis is applied to identify the interrelationship between the measured variables and the role of each variable on the overall quality. HCA has been used to group the major ions and groundwater samples based on their physico-chemical similarities. The clustering for major ions reveals two factors controlling water quality: mineral dissolution and to less degree, anthropogenic activities. Additionally, sample clustering classifies groundwater into three groups as low, medium, and highly mineralized groundwater. Three Principal components (PCs) explained 86.1 % of the total variance, indicating that groundwater quality is affected by water-rock interaction, agricultural practice, and septic tanks.
- Sodium adsorption ratio (SAR) and sodium percent (Na⁺ %) were utilized to assess the irrigation compatibility of groundwater. According to USLI and Wilcox diagrams, more than 75% of ground- water samples are excellent for irrigation.
- The integrated approaches proved to be robust and efficient in highlighting and evaluating groundwater quality characteristics in the north Bahri locality. This study recommended the installation of groundwater quality monitoring scheme to ensure water supply sustainability.

Declarations

Author contribution statement

Musaab A.A. Mohammed: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Norbert P. Szabo; Péter Szics: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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