



Application of water quality index and statistical-hydrochemical techniques in groundwater assessment of the Quaternary aquifer, southwest Nile Delta of Egypt

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Received: 19 June 2023 / Accepted: 22 April 2024 / Published online: 28 May 2024
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Abstract

The objective of the current study is to investigate the hydrogeochemistry of the Quaternary groundwater and evaluating its suitability for drinking and irrigation needs using statistical analysis, water quality indicators and physicochemical parameters, in west of the Nile Delta, Egypt. The study area has high population growth and agricultural activities, which require groundwater protection, and predicting probable environmental problems. For these reasons, 54 groundwater samples were collected during April 2021. Hierarchical cluster analysis, Pearson, and factor analysis used for statistical analysis. Biplots, Gibbs and Piper diagrams were used to infer the geochemical processes controlling groundwater chemistry. The groundwater is affected by silicate weathering, reverses ion exchange, dissolution of CO₂, and recharge from the Nile. According to the WQI_{CCME} drinking value, the groundwater ranged between fair to marginal water quality. The distribution of integrated-weight water quality index of the samples, showed that it is excellent for irrigation (<25). The nine physicochemical parameters sodium percent (Na%), permeability index, sodium adsorption ratio, Kelley Index, residual sodium carbonate, magnesium hazard, Potential Salinity, Corrosive Ratio and Chloro-alkaline Indices revealed that most of the groundwater are of good quality and can be safely used for agricultural activities, albeit few samples due the west needs some treatment. It is recommended to minimize the fertilizers and nutrients use to decrease the anthropogenic impact on the groundwater. The reuse of irrigation water without treatment should be limited. As well, the pumping rates should be controlled to avoid aquifer salinization.

Keywords Factor analysis · Cluster analysis · Hydrogeochemistry · Water quality · Quaternary aquifer · West Nile Delta

Introduction

Water is one of the most important natural resources for all living organisms. It is considered as an important source for sustainable economic growth in society, especially in arid regions. Due to the high consumption of water by the increased population, urbanization and anthropogenic activities, water may be subjected to depletion. This requires appropriate management and assessment of this precious resource.

More than 85% of the total water budget of Egypt is consumed in agricultural uses (MWRI 2016). Lately, Egypt needs of water increased because of increasing population and introducing new strategic land reclamation projects and industrial development. These projects depend mainly on surface water for agricultural purposes; but recently, groundwater has been used to meet the agricultural requirements.

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The chemistry of groundwater is affected by the hydrogeochemical reactions with the surrounding rocks (e.g. dissociation of minerals, cation exchange, precipitation of secondary minerals, evaporation, oxidation–reduction reactions, waters mixing, leaching of pesticides, fertilizers and manure, and contamination processes). Investigating the hydrogeochemical processes will help in elucidating the influencing factors on groundwater quality and the spatial variations of the groundwater chemistry (Matthess 1982, Kumar et al. 2006, Mohamed et al. 2015, Gad et al. 2021, Abu Salem et al. 2021 and 2022, Mohammed et al. 2022a, Nosair et al. 2022). As well, these processes provide important evidence for the nature of groundwater recharge and discharge, and interpreting the origin of groundwater components (Walton 1970).

In order to categorize the quality of water, water quality index (WQI) has been applied to groundwater results of the area of study. This methodology is useful to infer the quality of water to the people and policy makers in the concerned area. WQI is a mathematical relationship benefited to convert large batch of water data into one number (Stambuck-Giljanovic 1999; Stigter et al. 2006), which assesses the overall quality of water. This has the advantage of distinguishing between clean and contaminated waters with respect to location and time (Todd 1980; Tyagi et al. 2013). As well, the drinking water quality index (DWQI) is useful technique for evaluating water for drinking use (Bora and Goswami 2017).

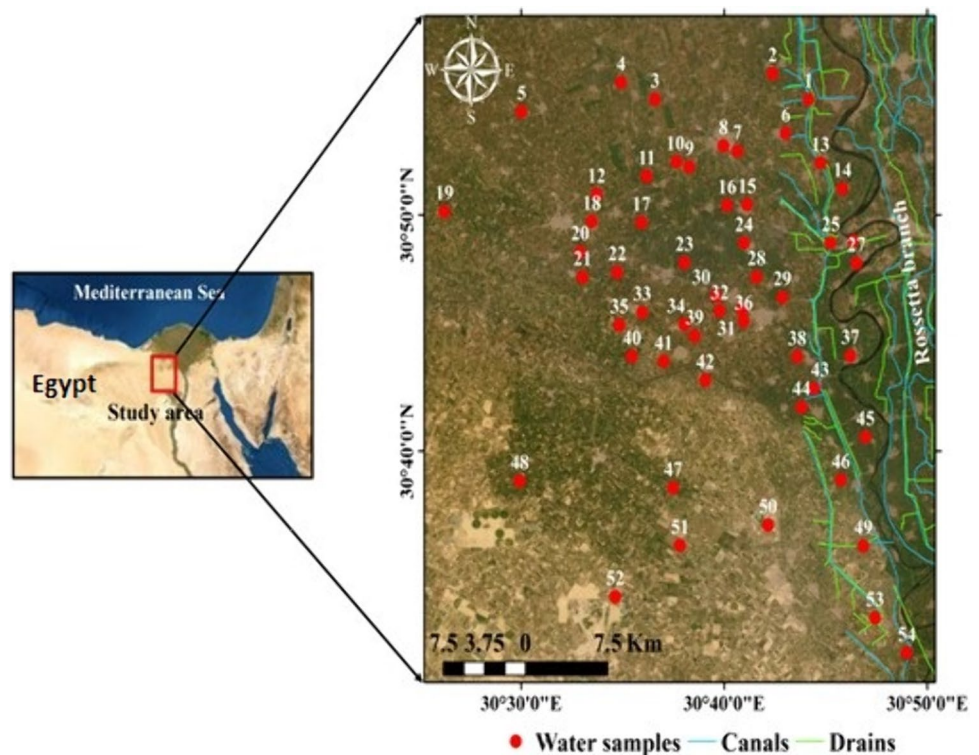
In addition, the physicochemical parameters are used to assess the quality of water, and connecting information about water quality and water liability to contamination (Mondal et al. 2016). Many authors investigated the groundwater suitability to drinking, irrigation and industrial purposes through the hydrogeochemistry and water quality (Ekenta et al. 2015, Naaz and Anshumali 2015, Manoj et al. 2017, Sakram and Adimalla 2018, Egbueri 2019, Egbueri et al. 2019, Rajesh et al. 2019, Egbueri et al. 2020, Egbueri et al. 2021, Hussein et al. 2021 and Gad et al. 2023).

In the southwest of the Nile Delta water, which is available from the River Nile, irrigation canals and groundwater, is used to fulfill the needs of different uses. The aim of the current study is to investigate hydrogeochemistry of the Quaternary groundwater and evaluating its suitability for the drinking and irrigation purposes using water quality indicators and physicochemical parameters.

Study area

The area of the study is located to the west of the Rosetta Branch of the Nile River between latitudes $30^{\circ} 31' 26''$ – $30^{\circ} 56' 06''$ N and longitudes $30^{\circ} 26' 04''$ – $30^{\circ} 49' 08''$ E (Fig. 1). It is characterized by a desert arid climate (Nashwan et al. 2019). It has a warm winter season with rainfall falling in

Fig. 1 Location map of the groundwater wells in the area of west of Rosetta Branch



the coastal parts and a dry summer season. Day temperatures differ by season and alter with the dominant winds.

The area of investigation is dominated by agricultural activities, which is dependent on the groundwater tapping the Quaternary aquifer. The water-table ranges from 1 to 6 m. Pesticides and fertilizers are used extensively to increase the productivity of the agricultural crops. Hence, the pollution of groundwater is possible owing to geogenic activities and anthropogenic influences. The effect of applying compost and insecticides for agriculture have harmful bearings on the health of human. Furthermore, the anthropogenic aspects are exemplified by waste disposal in unsuitably designed septic cisterns. The present study investigates the hydrogeochemical status and the class of groundwater to evaluate it for drinking besides agricultural uses. Also, this work is of great importance for the strategic controlling of water resources and for protection of local inhabitants besides agricultural practices.

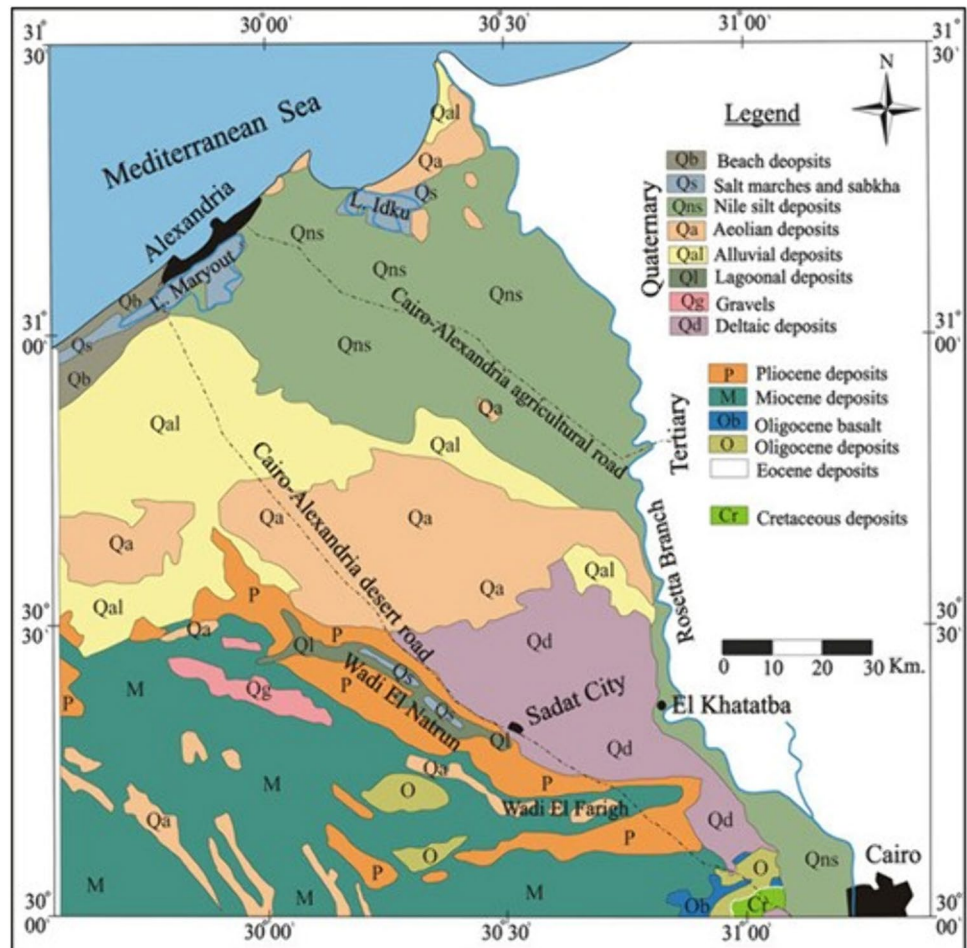
Hydrogeological setting

Geologically, sedimentary layers constitute the western Nile Delta succession, which belongs to Cenozoic Era (Fig. 2). The area of research is distinguished by a plain topography with little heights. The essential geomorphic units are the alluvial plains, which can be differentiated into young and old alluvial plains. Maryuit plain appears and attains about 110 m elevation to the west of old alluvial plains.

Stratigraphically, the sediments of Quaternary comprise the principal aquifer of the study area. The sedimentary column of the Delta attains ~4000 m thickness, where it unconformably overlay the basement.

The majority of the yearly recharge to the Quaternary aquifer is obtained from the direct infiltration from the surface canals and agricultural practices. The aquifer receives about 6.70 km³ of water yearly (Sherif et al. 2012; Salem et al. 2016). The surface canals run through highly porous Holocene sands and gravels. Consequently, the groundwater can be polluted from surface sources, which might contain excessive amounts of farming and anthropogenic wastes.

Fig. 2 Geological map of the western Nile Delta (modified after Geologic survey and Mining Authority of Egypt 1981; CONOCO 1987)



The Quaternary aquifer is of semi-confined nature (Mabrouk et al. 2013), and is occupying the whole Nile Delta, with thickness ranges between 200 m due south and 1000 m due north. The water table depth ranged from 1 to 2 m due north, 3–4 m due the middle, and ~5 m due the south (Morsy 2009; Mabrouk et al. 2013).

The aquifers of the Quaternary times could be distinguished into Mit-Ghamr and Bilqas Formations. Mit-Ghamr Formation forms the essential aquifer of the Delta (Rizzini et al. 1978; Mabrouk et al. 2013; Salem et al. 2016). It is composed of sand and gravel with existence of tiny clay interbeds. Mit-Ghamr Formation is capped by Holocene Bilqas formation, which is composed of fine detrital materials ranging between clay and silt with traces of sand.

Hydraulically, the Quaternary aquifer is unconnected with the formations found below which act as an aquiclude formation. The groundwater flows towards the northwest (Emara et al. 2007, Nasr et al. 2023).

Material and methods

Water sample collection and physicochemical parameters

In the current study, 54 samples were collected from different drilled groundwater wells distributed in the southwest area of Nile Delta in April 2021 (Fig. 1). The location of each water well was taken by Garmin GPS MAP 86sci. The collected groundwater samples were chemically examined for major and minor ions in agreement with the guidelines of US Environmental Protection Agency (USEPA 2018), and the American Public Health Association (APHA 1995). The physicochemical results of the analyzed samples of the study area are given in Table 1.

Before sampling, the used polyethylene containers were washed with 0.1% HNO₃, and then rinsed with distilled water to avoid interferences with the parameters being sampled. From an operating well for at least 15 min, two samples from each wellhead were collected. The first one is taken at its normal pH after washing the container with the

Table 1 Statistical results of the analyzed samples of the Quaternary groundwater

Parameters	Units	Minimum	Maximum	Average	Std. deviation	Drinking guideline		
						EHA (2007)	WHO (2011)	EPA (2014)
pH		7.1	8.1	7.53	0.26	6.5–8.5	6.5–8.5	6.5–8.5
EC	mmhos/cm	551	1602	910.76	239.94	–	–	–
TDS	mg/L	353	1026	582.89	153.56	1000	1000	500
Ca ²⁺	mg/L	35.14	126.51	69.37	20.09	–	–	–
Mg ²⁺	mg/L	12.30	86.12	28.82	12.08	–	–	–
Na ⁺	mg/L	32.00	251.38	76.89	43.01	200	200*	200
K ⁺	mg/L	3	9	4.91	1.91	–	–	–
HCO ₃ [–]	mg/L	219.31	621.94	330.97	81.89	–	–	–
SO ₄ ^{2–}	mg/L	11	386	69.59	61.54	250	500**	250
Cl [–]	mg/L	28.23	177.22	82.73	40.85	250	250*	250
Fe ²⁺	mg/L	0.04	1.63	0.37	0.30	0.300	0.300	0.300
Mn ²⁺	mg/L	0.02	0.95	0.43	0.27	0.400	0.400	0.050
Pb ²⁺	mg/L	0.007	0.941	0.20	0.20	0.010	0.010	0.015
Cu ²⁺	mg/L	0.01	0.21	0.07	0.06	2.0	2.0	1.3
Cd ²⁺	mg/L	0.01	0.04	0.02	0.01	0.003	0.003	0.005
Cr ²⁺	mg/L	0.01	0.08	0.02	0.01	0.050	0.050	0.100
Ni ²⁺	mg/L	ND	0.32	0.07	0.08	0.020	0.070	0.02
Zn ²⁺	mg/L	0.01	0.21	0.03	0.04	3	3	5
B ²⁺	mg/L	0.01	0.68	0.05	0.10	0.500	2.400	–
SiO ₂	mg/L	10	43	15.19	4.87	–	–	–
NH ₄ ⁺	mg/L	ND	1.75	0.24	0.29	–	–	–
NO ₃ [–]	mg/L	1	351	28.69	65.83	45	50	10
PO ₄ ^{3–}	mg/L	0.020	18.800	4.01	4.86	–	–	–

ND: not detected

*No guideline, but a taste limit exist, ** No guideline for SO₄^{2–}, the limit is for taste, gastrointestinal effects and corrosion

well water then well preserved (~at 4 °C) for the analysis of anions. The second sample was acidified (after filtration through 0.45 µm membrane filters) by adding 2 ml of HNO₃ to pH < 2 for the analysis of cations and metals. Acidification was performed to minimize adsorption, hydrolysis, and precipitation effects. In situ, pH and electrical conductivity (EC) were measured by portable HI 991300 Hanna Instruments.

Analysis of major ions (Ca²⁺, Mg²⁺, Na⁺, K⁺, HCO₃⁻, SO₄²⁻, Cl⁻ and NO₃⁻) and minor ions (Fe, Mn, Pb, Cu, Cd, Cr, Ni, Zn, B, SiO₂, NH₄⁺, NO₃⁻, and PO₄³⁻) were achieved on the water samples with the usual known techniques. All the analyses were done in the Central Lab of the Faculty of Science, University of Alexandria.

The ion balance errors calculation was used to ensure the precision of the analysis, using the following formula (1):

$$\text{Error of ion balance} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100 \quad (1)$$

The results of chemical analysis were observed to be within the standard edge of ±5% (Appelo and Postma 1999).

Titration methods were used to determine Ca²⁺ and Mg²⁺, HCO₃⁻ and Cl⁻ concentrations. DR4000 HACH Spectrophotometer was used to determine SO₄²⁻ concentration. Na⁺ and K⁺ were specified using PFP7 Flame Photometer. SiO₂, NH₄⁺, NO₃⁻, and PO₄³⁻ were measured using Hach DR 3900 Spectrophotometer.

Fe, Mn, Pb, Cu, Cd, Cr, Ni, Zn and B were measured using analytikjena contrAA 300 Atomic Absorption Spectrophotometer.

Statistical analysis

The statistical analysis of the analytical data (Descriptive statistics, Pearson correlation, Q-mode cluster analysis and factor analysis) was performed using SPSS[®] 17.0 software.

Groundwater categorization

The chemical character of the groundwater samples was studied using Piper diagram generated by AquaChem v 4.0.264 software. The hydrogeochemical processes, water types, concentrations of major ions and the relationship and ionic ratios were also investigated.

Water quality assessment

Drinking water quality index (DWQICME)

This index is based on three factors that represent time, water type, and variables (EPA 2003):

F1 represents the scope that signifies the extent of water quality guideline non-compliance in the studied time interval (2).

$$F1 = \frac{\text{Number of failed variables}}{\text{Total number of variables}} \times 100 \quad (2)$$

F2 represents the frequency where the individual tests percentage do not fulfill objectives (tests that fail) (3).

$$F2 = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100 \quad (3)$$

F3 represents the amplitude denoting the amount where the failed tests do not fulfill their objectives. *F3* is calculated through Eqs. 4, 5, 6, 7. Excursion represents how many times a particular concentration is less than (when the objective is a minimum) or greater than the objective (4).

$$\text{Excursion}_i = \frac{\text{Failed test value } i}{\text{Guideline } j} - 1 \quad (4)$$

As the test value should not fall below the objective (5):

$$\text{Excursion}_i = \frac{\text{Guideline } j}{\text{Failed test value } i} - 1 \quad (5)$$

Finally, the normalized sum of excursions (*nse*) represents the total amount by which individual tests are far of guidelines. It is determined by the sum of excursions of individual tests divided by the total number of tests (6) (Tests that meet and do not meet the objectives).

$$nse = \frac{\sum \text{excursions}}{\text{Total number of tests}} \quad (6)$$

F3 is computed via a function (asymptotic) that scales the *nse* from objectives to produce a range from 0 to 100 (7).

$$F3 = \frac{nse}{0.01 nse + 0.01} \quad (7)$$

The *WQI* is finally estimated as (8):

$$WQI = 100 - \frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732} \quad (8)$$

Integrated-weight water quality index (IWQI)

The quality index of water represents one of the good indicators that is useful in groundwater quality management (Pei-Yue et al. 2010, Hameed et al. 2015). The weighted arithmetic water quality index is calculated for eleven parameters. *IWQI* is calculated using the following Eqs. (9–11) (Călmuc et al. 2018; Gao et al. 2020 and Zhang et al. 2021):

$$IWQI = \frac{\sum WiQi}{\sum Wi} \tag{9}$$

where Wi represents the unit weight that reflects the significance of a parameter in the WQI calculation, Qi is the quality relative value of i^{th} parameters. Qi and Wi are calculated using the following equations:

$$Qi = \frac{Vi - Vo}{Si - Vo} \times 100 \tag{10}$$

$$Wi = \frac{K}{Si} \tag{11}$$

where Vi is the measured concentration of the parameter, Vo is the ideal value of the parameter. All parameters have an ideal value of 0 except pH has a value of 7. Si is the agriculture water quality guideline standard (Ayers and Westcot 1994) and K is a proportionality constant that is calculated according to the formula:

$$K = 1 / \sum \left(\frac{1}{Si} \right) \tag{12}$$

Water quality can be categorized into different grades depending on $IWQI$ (Bora and Goswami 2017) as indicated in Table 2.

Table 2 Water quality classification according to IWQI Grade

Grade	<25	26–50	51–75	76–100	> 100
IWQI class	Excellent	Good	Poor	Very poor	Unsuitable

Table 3 Calculated physicochemical parameters of groundwater in the study area

Parameter	Unit	Equation	Eq. no	Reference
Na	%	$Na\% = \frac{Na^+ + K^+}{Na^+ + K^+ + Ca^{2+} + Mg^{2+}} \times 100$	(13)	Wilcox (1955), Todd (1980)
PI	%	$PI = \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100$	(14)	Doneen (1964)
SAR	meq/L	$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}}$	(15)	Richards (1954)
KI	meq/L	$KI = \frac{Na^+}{(Ca^{2+} + Mg^{2+})}$	(16)	Kelley (1940)
RSC	meq/L	$RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$	(17)	Eaton (1950)
MH	%	$MH = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100$	(18)	Szabolcs and Darab (1964)
PS	meq/L	$PS = Cl^- + \frac{1}{2}SO_4^{2-}$	(19)	Doneen (1964)
CR	mg/L	$CR = \frac{\frac{Cl^-}{35.5} + 2\left(\frac{SO_4^{2-}}{96}\right)}{2\left(\frac{HCO_3^- + CO_3^{2-}}{100}\right)}$	(20)	Ryner (1944)
CAI	meq/L	$CAI1 = \frac{Cl^- - (Na^+ + K^+)}{Cl^-}$	(21)	Schöeller (1965)
		$CAI2 = \frac{Cl^- - (Na^+ + K^+)}{SO_4^{2-} + HCO_3^- + NO_3^-}$	(22)	

Assessment of water for irrigation

Nine physicochemical parameters are used to assess groundwater quality for irrigation, they are Na%, PI, KI, SAR, MH, RSC, PS, CR and CAI (Table 3).

Results and discussion

Statistical analysis

Descriptive statistics of the physicochemical parameters

The minima, maxima, and standard deviations of the groundwater from the Quaternary aquifer were calculated and compared to some standard guidelines (World Health Organization (WHO 2011), Environmental Protection Agency (EPA 2014), and the Egyptian Health Authority (EHA 2007)) (Table 1).

The groundwater salinity of the collected water samples varies from 353 (fresh) to 1026 (slightly saline) (Mayer et al. 2005). The values of pH of the Quaternary groundwater vary from 7.1 to 8.1, showing slight alkaline water, which shows normal ranges for drinking water according to the guidelines (Table 1). The EC values vary from 551 to 1602 μ mhos/cm, which indicate slight to moderate water salinity. High EC reflects slow soil–water ion exchange, high solute dissolution and soluble minerals. The maximum concentrations of Na^+ , SO_4^{2-} , B, Cr, Mn, Fe, NO_3^- , Cd, Ni, and Pb increase by ~ 1.3, ~ 1.5, ~ 1.4, 1.6, 2.4, 5.4, 7.8, 13.3, 16, and 94 folds the EHA (2007) guidelines for drinking water (Table 1).

Conversely, Cu, Cl^- , and Zn maximum concentrations are less than the EHA (2007). Regarding anions concentrations, alkalinity values vary from ~ 219 to 621 mg/L revealing the

dominance of this anion followed by SO_4^{2-} that changed from 11 to 386 mg/L that is in the normal limit for irrigation depending on (FAO 1985).

Pearson correlation

The application of Pearson bivariate correlation to the studied variables shows strong positive correlation of TDS and HCO_3^- (0.791), Na^+ (0.757), SO_4^{2-} (0.7), and K^+ (0.634) indicating that the salinity is attributed to these ions (Table 4). In addition, strong positive correlation exists between Na^+ and SO_4^{2-} (0.760) (Table 4).

Moderate positive correlations found between Mg^{2+} and HCO_3^- (0.627), Na^+ and K^+ (0.665), B and NO_3^- (0.534), K^+ and SO_4^{2-} (0.526), K^+ and NO_3^- (0.502), and B and NO_3^- (0.560) (Table 4).

These correlations could be attributed to the use of secondary nutrients (Mg^{2+} and S) and micronutrients (B, Na^+ , and Mn) in cultivation processes. In addition, anthropogenic impact is evidenced by NO_3^- . Weak positive correlations found between TDS and Mg^{2+} (0.473), NO_3^- (0.418), and B (0.401) (Table 4).

Factor analysis (FA)

According to Kaiser (1958), statistical factor analysis is a familiar method to reduce large variables into significant factors using a satisfactory rotation of loadings. Factor analysis was applied to the Quaternary groundwater samples where the Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity tests were first used to check the reliability of applying the factor analysis (Field 2009; Abu Salem et al. 2017). After that, a varimax rotation with Principal Component Analysis (PCA) extraction was made (Table 5). The best adequacy results were obtained using 13 variables (Na^+ , B, SO_4^{2-} , NO_3^- , Cd, Mn, Mg^{2+} , PO_4^{3-} , Cu, Cr, Fe, Ca^{2+} , and Pb). The KMO equals 0.615 implying the feasibility of factor analysis using these variables. Moreover, Bartlett's sphericity results (Chi-Square ~ 196, degree of freedom = 78, and $p = \text{zero}$) prove that variance is shared among the examined variables. To extract factors, eigenvalue more than one was used giving five factors with total cumulative variance of ~69% (Table 5).

The first factor represents ~23% of the variance where a strong positive loadings exist on Na^+ (0.908), B (0.822), SO_4^{2-} (0.806), and NO_3^- (0.715). The second factor represents ~15% of the variance and provides strong positive loading on Cd (0.794), Mn (0.792), and Mg^{2+} (0.671). The first and second factors possibly could be related to anthropogenic impacts. The third factor represents ~11% of the variance and shows strong positive loading on PO_4^{3-} (0.81), and moderate positive loading on Cu (0.552). This factor could be named the fertilizers factor. The fourth factor represents ~11% of

the variance and shows strong positive loading on Cr (0.74), moderate positive loading on Ca^{2+} (0.565), and strong negative loading on Fe (−0.645). This factor could be named the geogenic factor. The fifth factor represents ~9% of the variance and shows strong positive loading on Pb (0.903). This factor could be termed the lead factor.

Hierarchical cluster analysis (Q-mode) (HCA)

One of the well-known methods for identifying various classes and groupings within the data under investigation is the HCA which can display the findings with a dendrogram representation (Davis and Sampson 1986; Jia et al. 2020; Gao et al. 2022,).

To eliminate mistakes caused by the orders of magnitude and the variance of the variable, the dataset was normalized before performing HCA to the Z scores. HCA was applied to the Quaternary groundwater samples through the variables (pH, TDS, Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , SO_4^{2-} , Cl^- , Fe, Mn, Pb, Cu, Cd, Cr, Ni, Zn, B, SiO_2 , NH_4^+ , NO_3^- , and PO_4^{3-}) (Fig. 3a). The HCA was represented by a dendrogram where the pheon line was chosen at distance 10 (Fig. 3a) where five main clusters were distinguished (Fig. 3b). The minima, maxima and means of the different clusters and their representation were given in Table 6 and Fig. 4. Samples of cluster 1 (C1, 33 samples) have the lowest salinity while those of cluster 5 (C5, 2 samples) have the highest salinity as well as SO_4^{2-} , Na^+ , Cu and NO_3^- . This reflects the proximity of C1 samples to the sources of recharge (seepage from irrigation canals and the River Nile). Since the groundwater flow is due northwest, C5 samples lie far west of the delta reflecting the decrease of freshwater recharge from the River Nile and seepage from irrigation canals as well as the effect of lithologic variation (Table 6 and Fig. 3b). Cluster 2 (C2, 10 samples) show the highest Fe and NH_4^+ contents (Table 6) explaining the effect of lithology as a source of iron (Abdelhameed et al. 2019) and the anthropogenic outputs from cultivation that increase NH_4^+ (Nasr and Abdel-Motelib 2023). Additionally, cluster 3 (C3, 2 samples) show the highest Cl^- , Pb, Cr and B (Table 6), while cluster 4 (C4, 7 samples) show the highest HCO_3^- , Mn, Ni, and PO_4^{3-} (Table 6) explain the proximity to the River Nile and irrigation canals and their role in the bicarbonate facies of the groundwater. The higher Mn, Ni, and PO_4^{3-} in C4 samples could be attributed to local anthropogenic sources in these localities.

Hydrogeochemical facies

Ionic dominance and water types

The ionic concentrations of the groundwater samples have the sequence $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$ and

Table 4 Pearson correlation between the variables of the water samples of the Quaternary aquifer

	pH	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	Fe ²⁺	Mn ²⁺	Pb ²⁺	Cu ²⁺	Cd ²⁺	Cr ²⁺	Ni ²⁺	Zn ²⁺	B ²⁺	SiO ₂	NH ₄ ⁺	NO ₃ ⁻	PO ₄ ³⁻	
pH	1																						
TDS	-0.036	1																					
Ca ²⁺	0.221	0.300*	1																				
Mg ²⁺	-0.176	0.473**	0.270*	1																			
Na ⁺	0.023	0.757**	-0.136	-0.023	1																		
K ⁺	-0.032	0.634**	0.024	0.179	0.665**	1																	
HCO ₃ ⁻	-0.104	0.791**	0.365**	0.627**	0.340*	0.386**	1																
SO ₄ ²⁻	-0.008	0.700**	-0.032	0.067	0.760**	0.149	1																
Cl ⁻	0.161	0.192	0.454**	0.276*	0.248	0.242	0.074	-0.022	1														
Fe ²⁺	0.100	-0.164	-0.088	-0.079	-0.171	-0.155	-0.148	-0.041	-0.226	1													
Mn ²⁺	-0.115	-0.021	0.101	0.481**	-0.223	-0.141	0.079	-0.127	0.196	0.205	1												
Pb ²⁺	0.158	-0.279*	-0.075	0.006	-0.188	-0.151	-0.190	-0.286*	0.203	-0.066	0.162	1											
Cu ²⁺	0.027	0.214	-0.011	-0.066	0.277*	0.171	0.035	0.306*	-0.009	0.066	0.463**	0.069	-0.201	1									
Cd ²⁺	-0.090	-0.063	0.060	0.278*	-0.108	-0.158	-0.122	0.007	0.251	0.066	0.463**	0.069	-0.201	0.032	1								
Cr ²⁺	-0.039	-0.039	0.238	0.032	-0.104	-0.070	-0.004	-0.105	0.181	-0.174	-0.089	0.153	-0.116	0.032	0.242	1							
Ni ²⁺	0.180	-0.064	0.183	0.248	-0.174	-0.117	0.006	-0.154	0.239	0.381**	0.150	0.005	0.130	0.043	0.338*	0.253	1						
Zn ²⁺	-0.013	0.180	0.255	0.082	0.062	0.072	0.236	-0.013	0.102	0.036	-0.013	-0.024	0.205	0.043	0.338*	0.253	0.140	1					
B ²⁺	0.243	0.401**	-0.142	-0.217	0.684**	0.368**	0.080	0.493**	0.131	-0.168	-0.190	0.046	0.225	-0.032	0.011	-0.118	0.140	0.140	1				
SiO ₂	0.079	-0.185	0.158	-0.159	-0.176	-0.299*	-0.171	-0.123	0.047	0.058	0.171	0.003	-0.116	0.184	0.029	-0.050	-0.025	-0.021	0.029	1			
NH ₄ ⁺	-0.028	-0.038	0.091	-0.068	0.024	0.127	-0.037	-0.087	0.227	-0.115	-0.266	0.302*	-0.215	0.000	0.454**	-0.050	0.236	0.148	-0.128	0.148	1		
NO ₃ ⁻	0.028	0.418**	-0.143	-0.019	0.534**	0.502**	0.207	0.430**	-0.030	-0.087	-0.142	-0.202	0.276*	-0.219	-0.235	-0.134	-0.116	0.560**	-0.147	-0.173	0.148	1	
PO ₄ ³⁻	0.269*	0.126	0.237	0.341*	-0.146	0.076	0.151	0.068	-0.022	0.157	0.257	-0.172	0.181	0.006	-0.019	0.405**	-0.021	-0.057	-0.164	-0.282*	0.114	0.114	1

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

Table 5 The KMO, Bartlett's sphericity tests and the factor analysis for the examined samples of Quaternary groundwater

KMO and Bartlett's test						
Kaiser–Meyer–Olkin Measure of Sampling Adequacy						0.615
Bartlett's test of Sphericity						195.610
						df
						78
						Sig
						0.000
Rotation Sums of Squared Loadings	Total	2.960	1.936	1.485	1.430	1.175
% of Variance	22.768	14.893	11.424	11.003	9.037	
Cumulative %	22.768	37.660	49.084	60.087	69.123	
	1	2	3	4	5	
Na ⁺	0.908	-0.048	-0.106	0.045	-0.120	
B ²⁺	0.822	-0.088	-0.093	0.077	0.215	
SO ₄ ²⁻	0.806	0.077	0.066	-0.004	-0.294	
NO ₃ ⁻	0.715	-0.160	0.215	-0.177	-0.031	
Cd ²⁺	-0.019	0.794	-0.234	-0.009	0.015	
Mn ²⁺	-0.161	0.792	0.221	-0.204	0.184	
Mg ²⁺	-0.005	0.671	0.407	0.191	-0.091	
PO ₄ ³⁻	-0.045	0.179	0.810	-0.068	-0.139	
Cu ²⁺	0.380	-0.330	0.552	-0.091	0.210	
Cr ²⁺	-0.148	-0.007	-0.051	0.740	0.102	
Fe ²⁺	-0.227	0.096	0.117	-0.645	-0.109	
Ca ²⁺	-0.182	0.164	0.403	0.565	-0.289	
Pb ²⁺	-0.142	0.107	-0.076	0.133	0.903	

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization

Rotation converged in 11 iterations

Bold italic value indicates negative loadings

df: degree of freedom, Sig: significance

alkalinity > SO₄²⁻ > Cl⁻. High concentration of Na⁺ ions is possibly because of the ion exchange with Ca²⁺ in the aquifer sediments and possibly due to the leaching of clay minerals and silicate weathering (El Osta et al. 2020). Elevated values of alkalinity might be related to carbonate dissolution and silicate weathering (Obeidatt and Alawneh 2019). Regarding the concentration of NO₃⁻, its concentration ranges from 1 to 351 mg/L, indicating a very high concentration with a possible effect of contamination due to the use of fertilizers.

The occurrence of trace elements is in the following sequence: Fe > Mn > Pb > B > Ni > Cu = Zn > Cr > Cd. No obvious effects on the suitability of agricultural water due to the low values of trace constituents (Gad et al. 2020).

Geochemical controlling mechanism

The diagram of Gibbs (Gibbs 1970) is a relation between TDS and the ratios (Na⁺ + K⁺)/(Na⁺ + K⁺ + Ca²⁺) and Cl⁻/(Cl⁻ + alkalinity). The plot of groundwater samples shows the essential processes that affect the groundwater chemistry are that the rock dominance and weathering

(Fig. 5) where all the investigated samples lie between the range of TDS from 100 to ~ 1000 mg/L.

Piper diagram

The diagram of Piper was used to represent the compositional change of the groundwater samples (Piper 1944). Most of the groundwater samples (~ 76%) plotted on the secondary alkalinity zone that is dominated by weak acidic anions and alkaline earths (Fig. 6) reflecting the recharge water of the River Nile (most samples of clusters 1 and 4 as well as some samples of cluster 2). The remaining samples plotted in the mixed zone (~ 22%, the rest of samples of cluster 2 and the samples of cluster 3), while only one sample (~ 2%) plotted in the primary salinity zone that is dominated by alkali metals and strong acidic anions (Fig. 6, cluster 5). The mixed zone samples reflect the effect of interference of different waters and anthropogenic impacts.

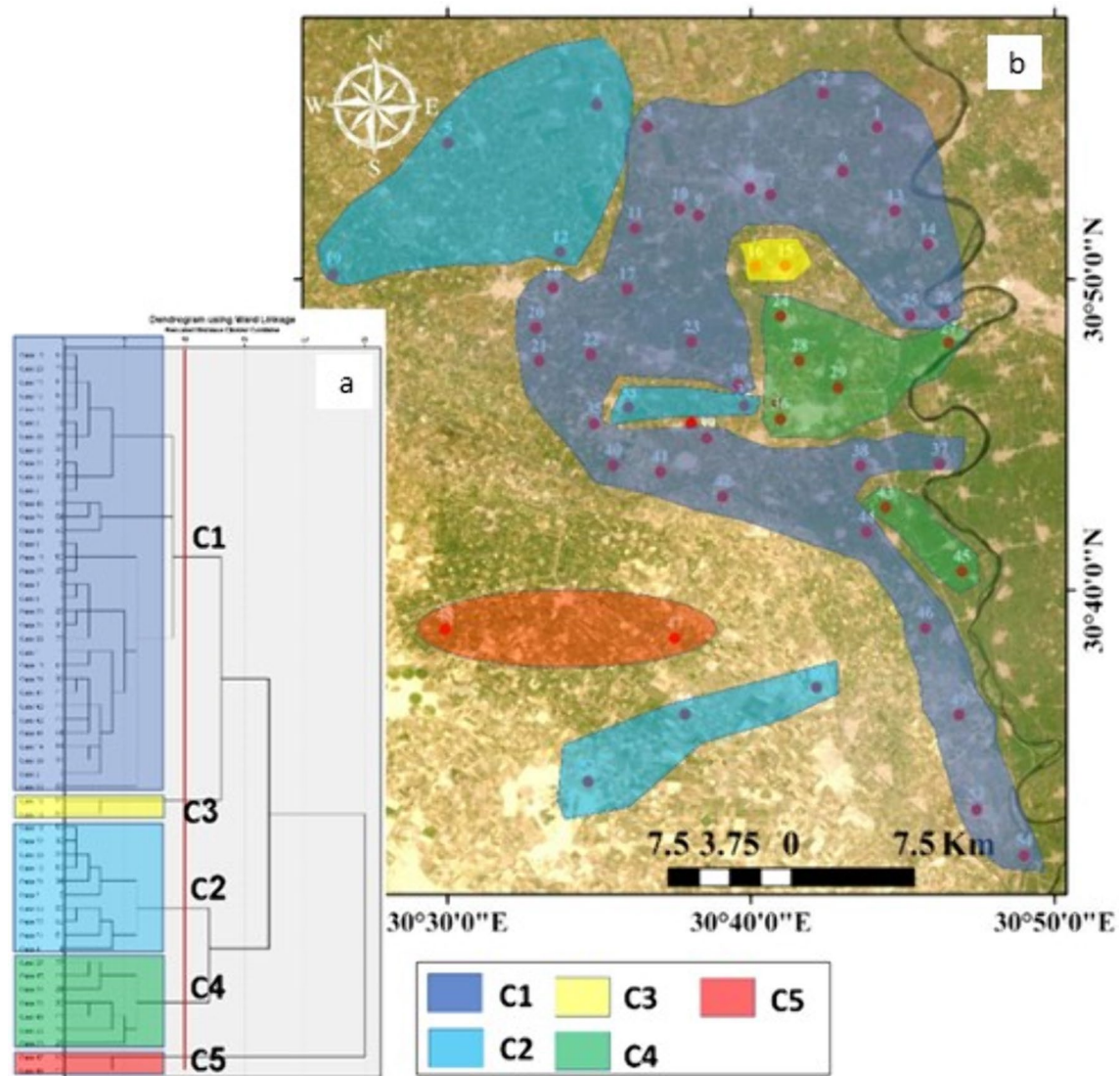


Fig. 3 **a** Dendrogram of the Quaternary groundwater samples based on HCA. The "phenon line" is defined by the dashed red line, **b** Clusters distribution for the samples of Quaternary groundwater

Ionic relationship of groundwater samples

The groundwater composition and the origin of solutes can be indicated by the ionic relations (Mohamed et al. 2015; Hussein et al. 2017; Abu Salem et al. 2021, Mohammed et al. 2022a). The relation between Na^+ and Cl^- shows that most of the studied water from C1, C4, and C3 and all samples from C2 and C5 fall above the halite dissolution line reflecting the silicate weathering process (Fig. 7a, reactions 13 and 14), while the rest of the studied samples of C1, C4, and C3 could be controlled by the reuse of irrigation water and/or reverse ion exchange due to the proximity of these samples to the irrigation canals. The $(\text{Ca}^{2+} + \text{Mg}^{2+}) - (\text{SO}_4^{2-} - \text{HCO}_3^-)$ against $\text{Na}^+ - \text{Cl}^-$ relationship was defined by (Fisher and Mullican 1997) and represented in (Fig. 7b). If the dominant

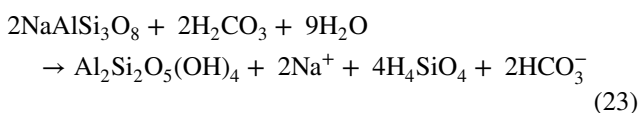
process is ion exchange, this relation must be linear with a slope of -1. The plot of the studied samples shows that the process of ion exchange is not an effective one in the controlling processes on water chemistry. The relationship between $\text{SO}_4^{2-} + \text{HCO}_3^-$ against $\text{Ca}^{2+} + \text{Mg}^{2+}$ indicates that the majority of water samples of C1, C4, and C3 and all samples from C2 and C5 plot above the equimolar line suggesting silicate weathering (Fig. 7c). The Na^+ against $\text{Ca}^{2+} + \text{Mg}^{2+}$ relationship indicates that majority of the samples of C1, C3, and C4 and some samples of C2 plot below the equimolar line reflecting the reverse ion exchange process that could have a role in the water chemistry of the groundwater (Fig. 7d, reactions 15 to 18). The rest of C2 samples and all the C5 samples plot above the equimolar line indicating a slight increase in the sodium content in these

Table 6 Descriptive statistics of the main distinguished clusters for the analyzed Quaternary groundwater samples

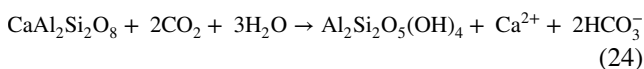
Parameters	Units	C1			C2			C3			C4			C5		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
pH		7.2	8.1	7.61	7.2	7.6	7.35	7.5	7.6	7.55	7.1	7.8	7.39	7.6	7.8	7.7
EC	mmhos/cm	551	1025	774	932	1565	1062	885	904	895	878	1347	1152	1543	1602	1573
TDS	mg/L	353	656	496	597	1002	680	567	578	573	562	862	737	988	1026	1007
K ⁺	mg/L	3	9	3.94	4	8	6.3	5	9	7	4	9	5.43	9	9	9
Na ⁺	mg/L	32.0	94.0	59.6	68.0	162.0	104.4	76.0	98.0	87.0	45.0	86.7	67.1	247.5	251.4	249.4
Mg ²⁺	mg/L	12.3	38.15	24.60	17.87	51.76	30.22	26.91	27.19	27.05	35.76	86.12	50.05	16.7	21.3	19
Ca ²⁺	mg/L	42.5	106.2	67.9	35.1	78.4	59.7	72.3	87.4	79.8	40.9	126.5	91.8	40.4	65.4	52.9
Cl ⁻	mg/L	28.2	161.7	81.0	33.0	177.2	64.8	128.3	141.3	134.8	51.7	159.3	99.7	62.9	117.0	90.0
SO ₄ ²⁻	mg/L	11	129	45.03	51	160	105.4	58	61	59.5	48	86	66.00	251	386	318.5
HCO ₃ ⁻	mg/L	219	385	292	269	622	372	298	318	308	349	531	454	289	421	355
Fe ²⁺	mg/L	0.040	1.630	0.390	0.070	1.030	0.398	0.140	0.270	0.205	0.130	0.560	0.321	0.100	0.160	0.130
Mn ²⁺	mg/L	0.020	0.770	0.416	0.020	0.920	0.417	0.100	0.180	0.140	0.100	0.950	0.669	0.080	0.230	0.155
Pb ²⁺	mg/L	0.007	0.941	0.223	0.053	0.319	0.109	0.493	0.552	0.523	0.047	0.462	0.206	0.037	0.045	0.041
Cu ²⁺	mg/L	0.010	0.210	0.066	0.010	0.170	0.045	0.010	0.030	0.020	0.020	0.170	0.083	0.180	0.190	0.185
Cd ²⁺	mg/L	0.010	0.040	0.025	0.010	0.030	0.021	0.020	0.030	0.025	0.010	0.040	0.023	0.020	0.020	0.020
Cr ²⁺	mg/L	0.010	0.050	0.022	0.010	0.030	0.017	0.030	0.080	0.055	0.010	0.060	0.026	0.010	0.020	0.015
Ni ²⁺	mg/L	0.000	0.320	0.081	0.000	0.040	0.010	0.010	0.180	0.095	0.020	0.220	0.131	0.010	0.020	0.015
Zn ²⁺	mg/L	0.010	0.140	0.027	0.010	0.050	0.022	0.020	0.170	0.095	0.010	0.210	0.059	0.020	0.030	0.025
B ²⁺	mg/L	0.010	0.180	0.034	0.010	0.030	0.019	0.090	0.200	0.145	0.010	0.040	0.017	0.250	0.680	0.465
SiO ₂	mg/L	10.0	43.0	16.5	11.0	21.0	13.4	12.0	13.0	12.5	11.0	16.0	13.1	13.0	13.0	13.0
NH ₄ ⁺	mg/L	0.000	0.400	0.191	0.100	0.400	0.250	1.450	1.750	1.600	0.100	0.300	0.143	0.100	0.100	0.100
NO ₃ ⁻	mg/L	1.00	24.00	8.70	2.00	297.00	46.00	4.00	5.00	4.50	1.00	151.00	54.43	61.00	351.00	206.00
PO ₄ ³⁻	mg/L	0.020	18.800	3.805	0.020	4.130	0.553	0.150	0.150	0.150	6.170	12.150	10.441	5.920	6.190	6.055
n		33			10			2			2			7		

samples. Additionally, the plot of the samples on the Ca²⁺ against HCO₃⁻ and Ca²⁺ against SO₄²⁻ precluded gypsum-carbonate dissolution (Fig. 7e and f) and suggested the dissolution of CO₂ as a possible process that leads to increase in bicarbonate content (Fig. 7f, reaction 19).

Silicate weathering

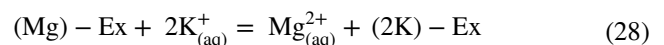
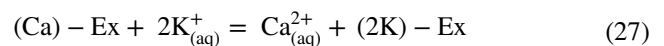
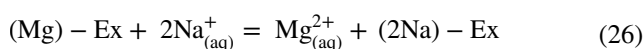
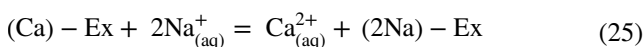


Albite Kaolinite silicic acid

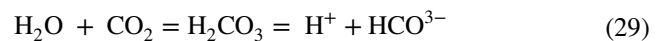


Anorthite Kaolinite

Reverse ion exchange



Dissolution of CO₂ gas



Water quality assessment

Drinking water quality index (DWQI)

Water quality index (WQI) is used for water quality assessment through the determination of physicochemical parameters of water. It can act as indicator of water contamination due the effect of natural and anthropogenic sources (WHO 1997, Mohammed et al. 2022b, Abu Salem et al. 2023), so it represents an efficient tool to assess water quality for the policy makers and environmentalists (USEPA 2008).

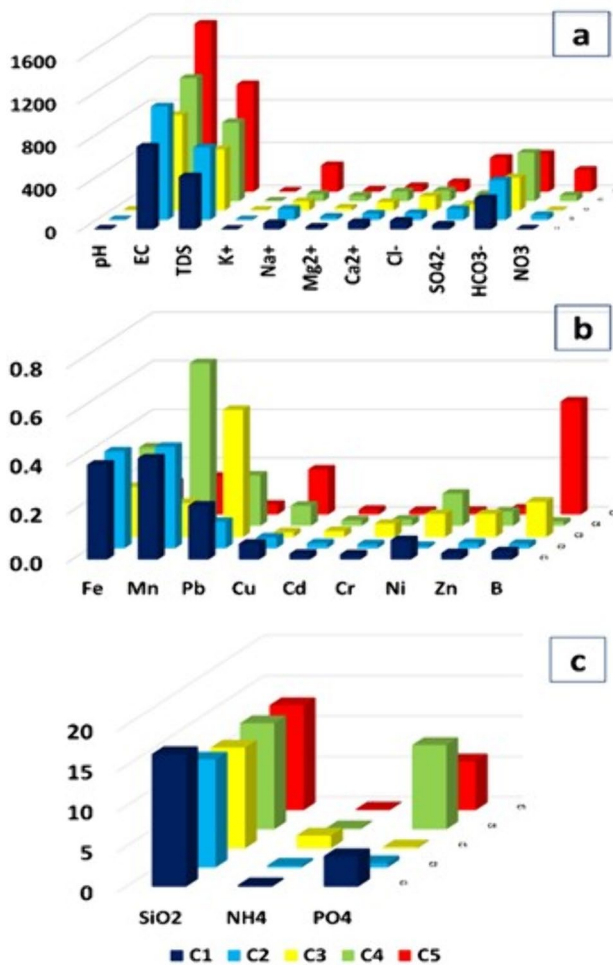


Fig. 4 Graphical comparison between means of clusters

Therefore, this index has a number that expresses the overall water quality of a certain location and time (EPA 2014).

There are several indices with many variations and limitations based on several water quality variables being used. WQI_{CCME} is selected to assess water quality in relation to contamination characterization and water classification according to the guidelines of the (EHA 2007). This index varies from 0 (poor quality) to 100 (excellent quality).

The studied groundwater samples range in quality from fair to marginal. The water seems to be threatened due the east of the area of study, because of the extensive agricultural activities and the vast distribution of the canals and drains (Fig. 8).

Integrated-weight water quality index (IWQI)

Calculation of IWQI comprises many known steps; the first step is calculation of the unit weight to each parameter. The greatest unit weight is 0.29 for K^+ and PO_4^{3-} followed by

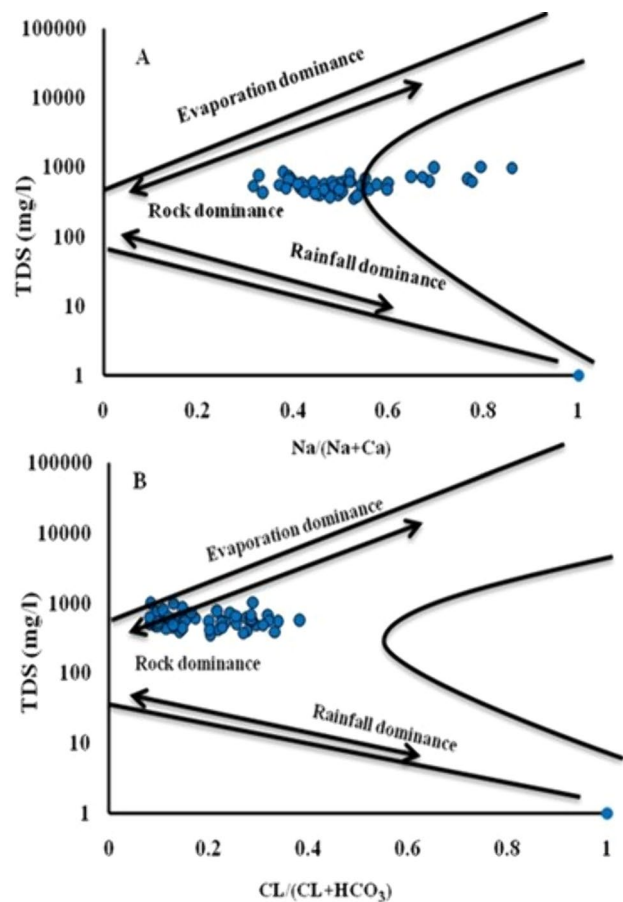


Fig. 5 The geochemical controlling mechanisms according to Gibbs diagram

0.11 for Mg^{2+} and 0.08 for pH reflecting the importance of these parameters in calculating IWQI. The standard values of different parameters that are taken in calculating the IWQI and the unit weight are illustrated in Table 7.

IWQI values for groundwater samples ranged from 0.709 to 4.65 (Table 2) revealing that the IWQI for the studied samples is considered excellent (<25) (Table 8) (Fig. 9). This may be attributed to the continuous recharge from irrigation water and infiltrated water from irrigation canals.

Suitability of water for irrigation purposes

Nine hydrochemical parameters have been used to evaluate the validity of water for use in irrigation, they are: Na%, PI, SAR, KI, RSC, MH, PS, CR and CAI.

Sodium percentage (Na%)

The Na% is usually benefited for identifying the validity of groundwater for agricultural needs. High Na^+

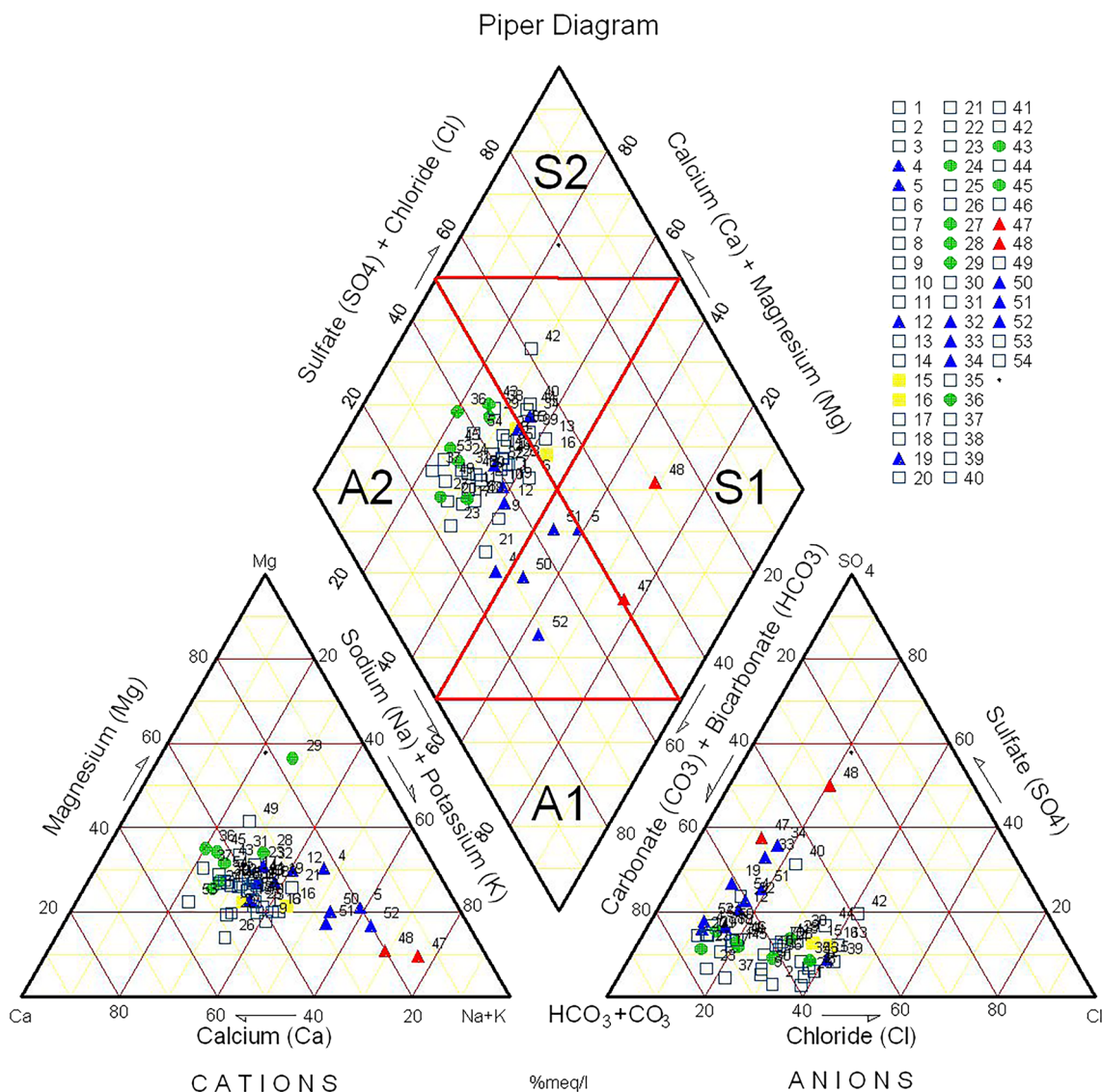


Fig. 6 The diagram of Piper of the studied samples, A1, A2, S1 and S2, stands for primary alkalinity, secondary alkalinity, primary salinity, and secondary salinity; respectively. Samples of clusters 1, 2, 3,

4, and 5 are represented by hollow squares, blue triangles, yellow squares, green diamonds, and red triangles

concentration comparing to Ca^{2+} and Mg^{2+} concentrations decrease the permeability of soil causing soil structure deterioration leading to the development of stunting plant (Doneen 1964, Todd 1980, Saleh et al. 1999, Sundaray et al. 2009, Purushothman et al. 2012).

In the groundwater samples, Na% ranges from 20.15 to 76.43 with an average value of 36.26 and standard deviation of 11.28 (Table 9). Most of the groundwater samples are of good class for irrigation (76%), about (19%) of the samples are of permissible water class and the remaining

(5%) fall in the doubtful water class (Table 9). The distribution contour map of Na% reflects an increase in value from eastern to western parts of the study area (Fig. 10a).

Results of chemical analysis of the samples of the area of study were plotted on Wilcox diagram (Wilcox 1948) (Fig. 11), reveal that about (61%) of the samples fell in the good water to permissible water class, (37%) of the samples fell in the doubtful to unsuitable water class, and (2%) fell in the permissible to doubtful water class. According

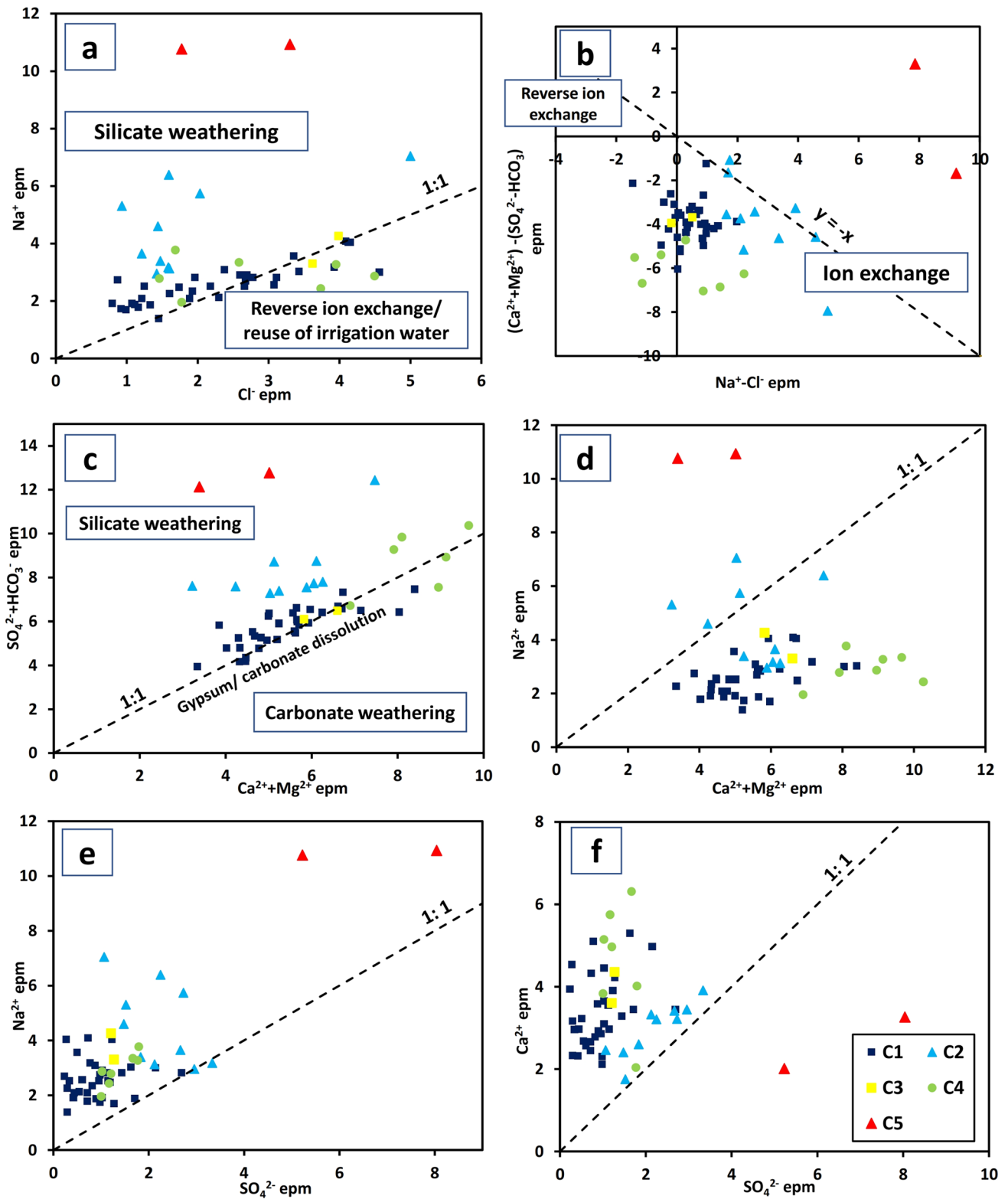


Fig. 7 Different relationships between cations and anions in the groundwater samples

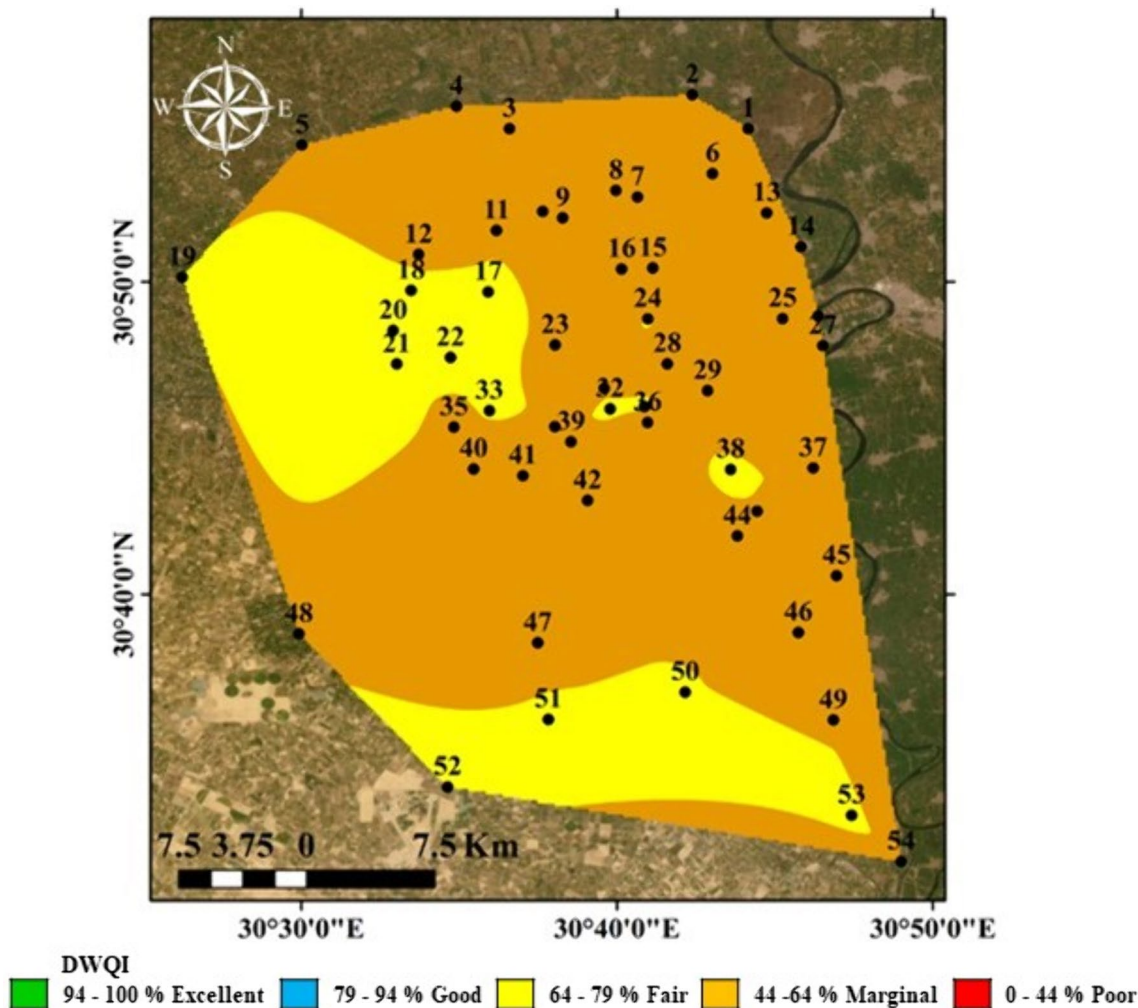


Fig. 8 Distribution of WQICMME for the groundwater samples in the study area

Table 7 Integrated-weight -quality standards and parameters unit weights

Parameters	Units	Standard Ayers and Westcot (1994)	Unit weights (Wi)
pH	–	7.25	0.081290624
Total dissolved solid (TDS)	mg/L	2000	0.000294679
Potassium (K ⁺)	mg/L	2	0.294678513
Sodium (Na ⁺)	meq/L	40	0.014733926
Magnesium (Mg ²⁺)	meq/L	5	0.117871405
Calcium (Ca ²⁺)	meq/L	20	0.029467851
Chloride (Cl ⁻)	meq/L	30	0.019645234
Sulfate (SO ₄ ²⁻)	meq/L	20	0.029467851
Bicarbonate (HCO ₃ ⁻)	meq/L	10	0.058935703
Phosphate-P (PO ₄ -P)	mg/L	2	0.294678513
Nitrate-N (NO ₃ -N)	mg/L	10	0.058935703

to these results, the investigated samples are suitable for irrigation.

Permeability index (PI)

Suitability of irrigation water is assessed using the PI, where it is affected by the long period of contact with elevated concentration of Ca²⁺, Mg²⁺, Na⁺ and alkalinity ions (Ravikumar et al. 2011).

In the groundwater samples, PI ranges from 41.96 to 94.70 with an average value of 62.13 and standard deviation of 10.54 (Table 9). The investigated samples were grouped into: (1) suitable class (I) which represents 13% of the total samples, and (2) good class (II) which represents 87% of the total samples (Table 9). The distribution contour map of PI reflects an increase in value from eastern to western parts of the study area following the same pattern as Na% (Fig. 10b). According to these results, the investigated samples are suitable for agricultural uses.

Table 8 Results of IWQI for the groundwater samples of the area of study

Sample no	IWQI	Sample no	IWQI	Sample no	IWQI	Sample no	IWQI
1	0.852	15	1.040	29	2.386	43	4.124
2	0.759	16	1.665	30	1.701	44	1.714
3	0.982	17	1.601	31	1.977	45	3.482
4	1.425	18	0.709	32	0.801	46	1.927
5	1.091	19	1.011	33	1.704	47	4.655
6	1.182	20	0.987	34	1.071	48	2.845
7	0.744	21	0.815	35	0.709	49	3.892
8	0.830	22	3.756	36	3.165	50	1.862
9	0.715	23	1.847	37	1.744	51	3.259
10	1.052	24	1.835	38	1.238	52	1.816
11	0.732	25	0.885	39	1.637	53	0.832
12	1.252	26	1.886	40	2.643	54	2.853
13	1.134	27	2.611	41	1.513	Min	0.709
14	0.766	28	2.956	42	2.015	Max	4.655

Sodium adsorption ratio (SAR)

The sodium hazard in groundwater (Subramani et al. 2005; Srinivasamoorthy et al. 2014) can be assessed using the SAR. SAR has a strong relation to the soil's exchangeable sodium percentages (Suarez et al. 2006). Values of SAR of the studied samples varied from 0.88 to 8.26 with an average value of 2.02 and standard deviation of 1.32 (Table 9). All the groundwater samples have SAR less than 10, indicating excellent water for irrigation depending on the SAR classification (Table 9). The distribution contour map of SAR reflects an increase in value from eastern to western parts of the study area (Fig. 10c).

Elevated concentration of Ca^{2+} and Mg^{2+} in water used in irrigation decreases the permeability of soil (Kelley 1951; Tiwari and Manzoor 1988; Kumar et al. 2007; Arumugam and Elangovan 2009). The EC values are plotted against the SAR to rate irrigation water (USSL 1954). Most groundwater samples (74%) fell into the C3–S1 group while the rest (26%) fell into the C2–S1 group indicating high salinity and low sodium content of the samples (Fig. 12). Depending on the USSL Classification, the studied samples are plotted in the low salinity field (< 2250 mmhos/cm), so, the groundwater samples are suitable for agricultural practices.

Kelley index (KI)

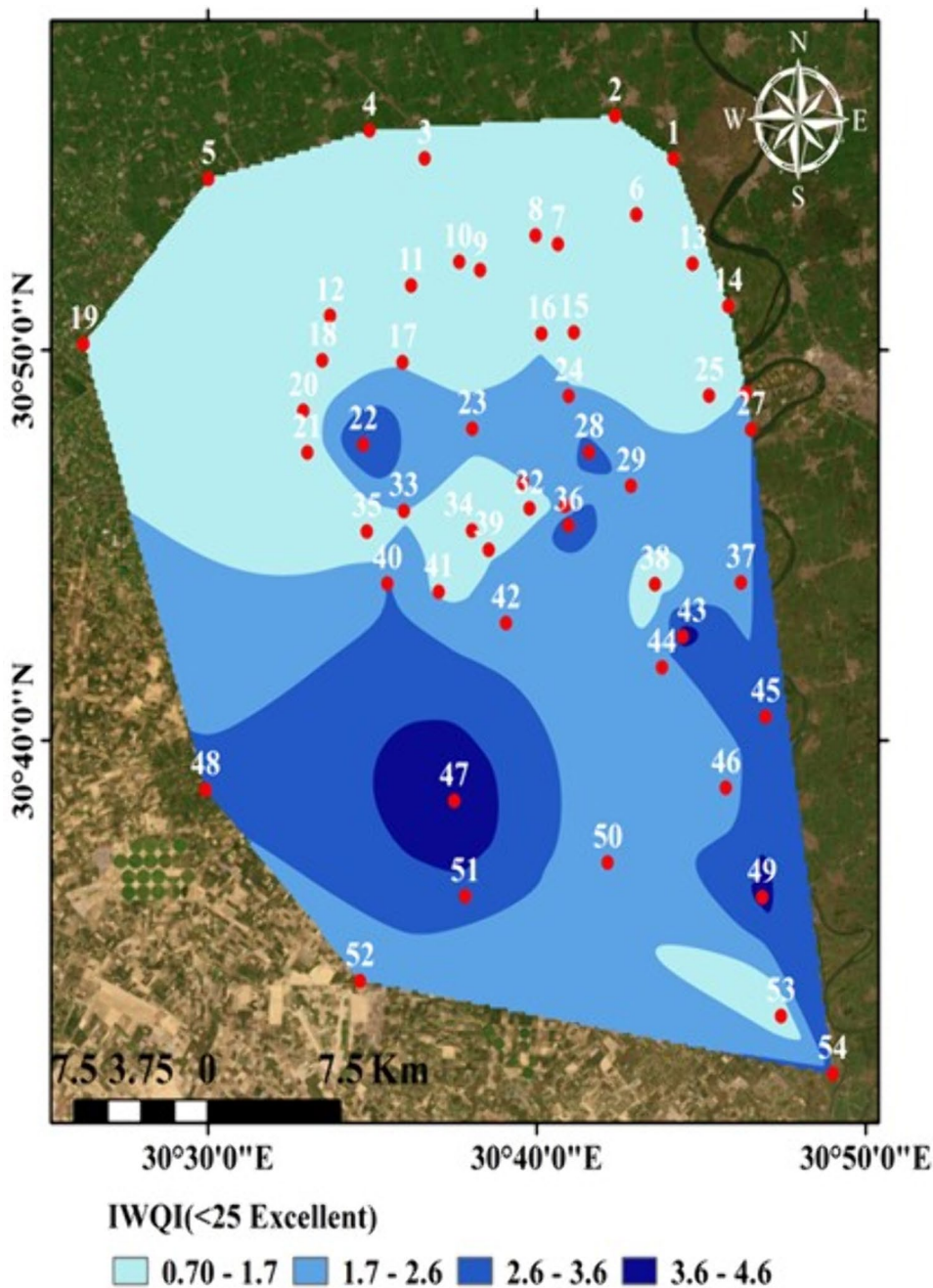
KI is another parameter for assessing the water suitability for agricultural practices reflecting the sodium excess in water (Sudhakar and Narsimha 2013). Water with a $\text{KI} > 1$ is considered unsuitable for irrigation, whereas that of $\text{KI} < 1$ is suitable for irrigation. Values of KI in the area of research

vary from 0.24 to 3.17 with an average value of 0.63 and standard deviation of 0.49 (Table 9). According to the results of KI, it is found that 89% of the studied samples have ($\text{KI} < 1$) indicating good water class for irrigation, whereas 11% of the samples are unsuitable (Table 9). The distribution contour map of KI reflects an increase in value from eastern to western parts of the study area (Fig. 10d).

Residual sodium carbonate (RSC)

RSC reflects the excess in alkaline earth metals (Ca^{2+} , Mg^{2+}) in water (Kelley 1951; Hem 1995; Subramani et al. 2005; Suarez et al. 2006; Kumar et al. 2007; Arumugam and Elangovan 2009; Sundaray et al. 2009; Ravikumar et al. 2011; Sudhakar and Narsimha 2013; Srinivasamoorthy et al. 2014). The applicability of groundwater for agricultural practices is affected mainly by the alkalinity content in the studied groundwater samples. In the area of study, the RSC values vary between -3.76 and 3.52 meq/l with an average value of -0.41 meq/l and standard deviation of 1.29 (Table 9). The RSC results revealed that 94% of the samples are less than 1.25 meq/l and located in the good class and desirable for agricultural practices, while 2% of the water samples located in the marginal class and 4% of the water samples located in the unsuitable class for irrigation (Table 9). The distribution contour map of RSC reflects an increase in value from eastern to western parts of the study area reflecting the effect of the reverse ion exchange processes in the groundwater quality (Fig. 10e).

Fig. 9 Spatial distribution of IWQI for the water samples in the area of study



Magnesium hazard (MH)

When water with high Mg^{2+} is applied for agricultural needs, it can cause damage to soil structure and high salinity. High magnesium concentration in groundwater will exchange with Na^+ causing the soil to become alkaline and decreasing the yield of crops (Anim-Gyampo et al. 2019, Zhao et al. 2021). MH values in the water samples varied between 21.37 and 77.62 with an average value of 40.21 and standard deviation of 8.43 (Table 9). About 91% of the

water samples have MH values < 50%, which reflect a valid water for agricultural practices. The rest 9% of the water samples reflect unsuitable water for irrigation (Table 9). The spatial distribution of MH reflects no specific trend indicating that the increase in magnesium content could be due to the use of Mg rich fertilizers (Todd et al. 1976, Fig. 10f).

Table 9 Statistical description and classification of the water parameters of groundwater samples of the investigated area for irrigation purposes

Parameters	Units	Minimum	Maximum	Average	Standard deviation	Range	Water class	Samples%
Na%	%	20.15	76.43	36.26	+ 11.28	<20	Excellent	Nil
						20–40	Good	76
						40–60	Permissible	19
						60–80	Doubtful	5
						> 80	Unsuitable	Nil
PI	%	41.96	94.70	62.13	+ 10.54	>75	Suitable—Class I	13
						25–75	Good—Class II	87
						<25%	Unsuitable – Class III	Nil
SAR	meq/L	0.88	8.26	2.02	+ 1.32	<10	Excellent	100
						10–18	Good	Nil
						18–26	Doubtful	Nil
						>26	Unsuitable	Nil
KI	meq/L	0.24	3.17	0.63	+ 0.49	<1	Good	89
						>1	Unsuitable	11
RSC	meq/L	– 3.76	3.52	– 0.41	+ 1.29	<1.25	Good	94
						1.25–2.5	Doubtful	2
						>2.5	Unsuitable	4
MH	%	21.37	77.62	40.21	+ 8.43	<50	Suitable	91
						>50	Unsuitable	9
PS	meq/L	– 0.83	4.46	1.61	+ 1.33	<3	good	100
						3–15	Moderate	Nil
						>15	Not recommended	Nil
CR	mg/L	0.25	1.96	0.59	+ 0.29	<1	Noncorrosive	94
						>1	Corrosive	6
CAI	mg/L	– 5.19	0.32	– 0.77	+ 1.16	Positive	Softened water	16
						Negative	Hardened water	84ss
USSL	N/A	N/A	N/A	N/A	N/A	C3-S1 group	High salinity and low sodium	74
						C2-S1 group	Medium salinity and low sodium	26

N/A means not applicable

Potential salinity (PS)

PS is another water quality parameter-based index for classifying irrigation water (Doneen 1964). It has been reported that the less soluble salts precipitate and accumulate in the soil, whereas highly soluble salts increase the salinity of the soil (Gholami and Srikantaswamy 2009). The PS ranged from – 0.838 to 4.46 meq/l with an average value of 1.61 meq/l and standard deviation of 1.33 (Table 9). According to Delgado et al. (2010), all the water samples are of good class for agricultural practices (Table 9). The spatial distribution of PS shows several trends suggesting the effect of localized anthropogenic impact promoted by the increase in chloride and sulfate contents (Fig. 10g).

Corrosivity ratio (CR)

CR value should be < 1 for the transportation of groundwater through pipes (Ryner 1944). CR of the studied water samples range from 0.25 to 1.96 with an average value of 0.59 and standard deviation of 0.29 (Table 9). It was found that 94% of the studied samples are less than 1 and are non-corrosive while 6% of the samples are corrosive (Table 9). The distribution contour map of CR shows no specific trend of increase and decrease (Fig. 10h).

Chloro alkaline indices (CAI)

The CAI are usually applied to determine the reactions of ion exchange between water and the bearing

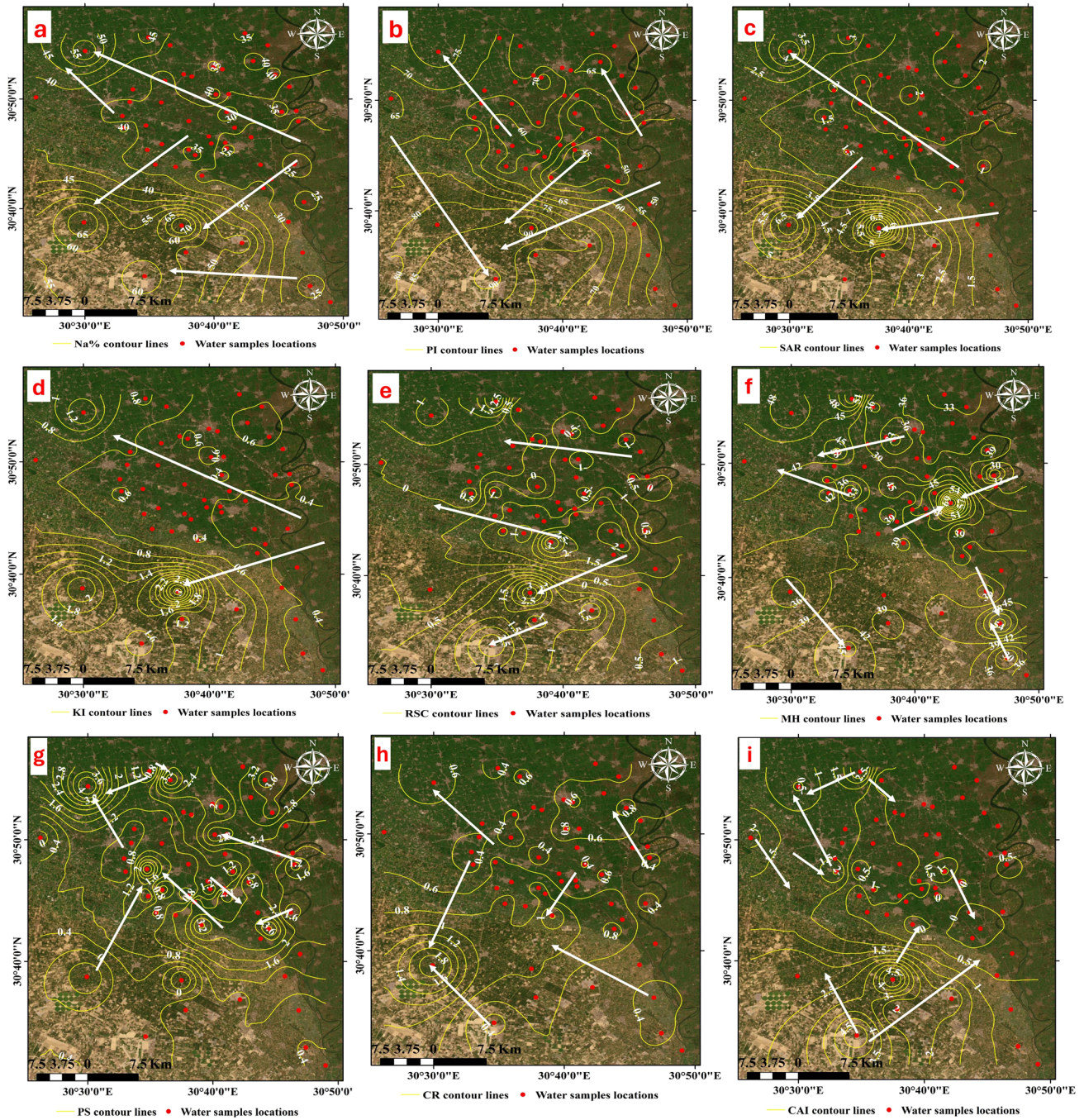


Fig. 10 Maps show the spatial distribution of the water parameters in the area of study

rock (Schöeller 1965). The values CAI in groundwater of the area of study range from -5.19 to 0.32 with an average value of -0.77 and standard deviation of 1.16 (Table 9). These negative values (about 84%) of the samples reflect the chloro-alkaline disequilibrium or indirect

base-exchange reaction, which means that the host rocks are not considered to be the main source of dissolved solids in the water (Table 9). The distribution contour map reflects CAI increase from southern parts to northern

Fig. 11 Wilcox diagram for determining groundwater quality for irrigation

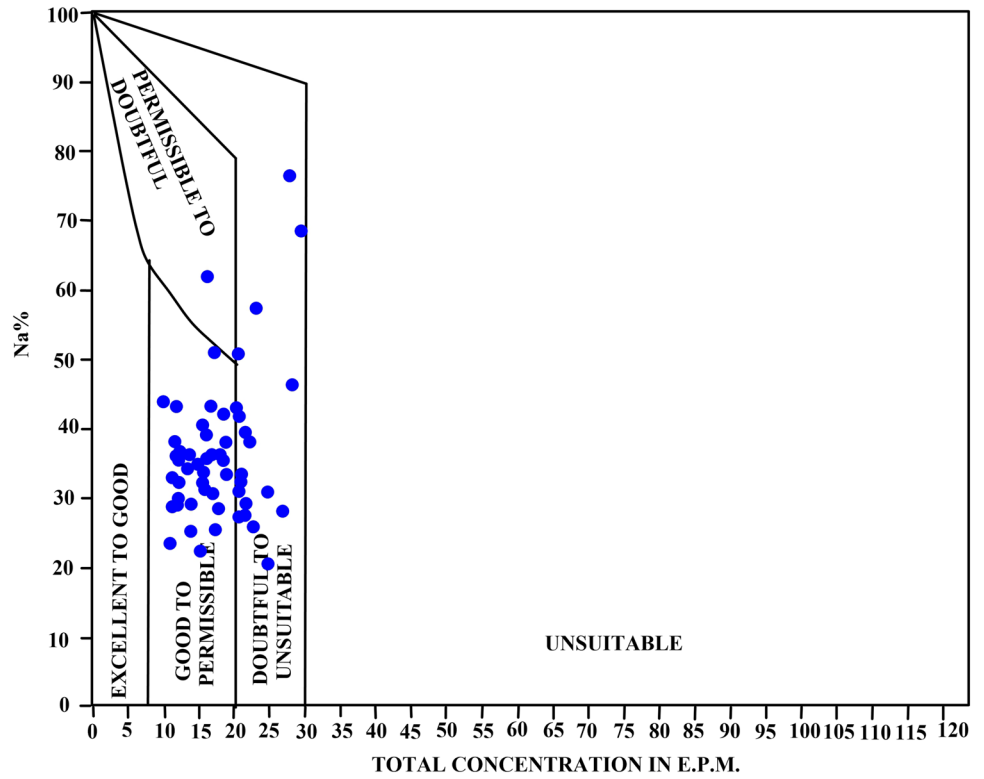
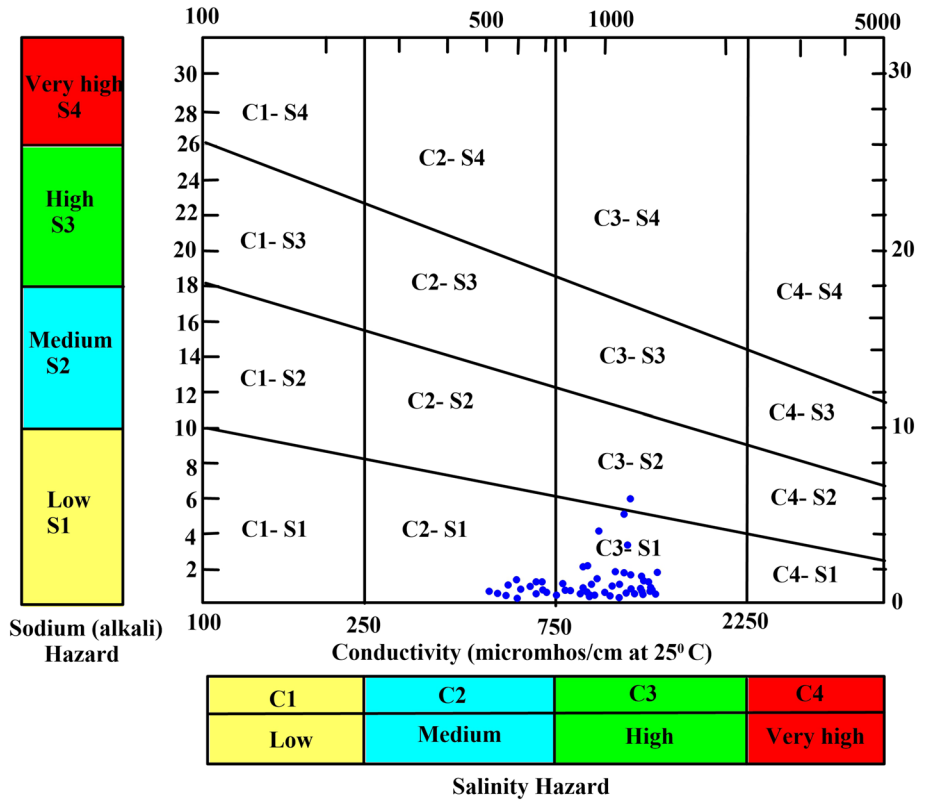


Fig. 12 USSL diagram for assessing groundwater quality for irrigation



fringes with some limited abnormalities in some parts of the area of study (Fig. 10i).

Conclusions

The groundwater salinity varies from fresh to slightly brackish and the pH values show normal ranges for drinking water. Among the studied parameters, Na^+ , SO_4^{2-} , B, Cr, Mn, NO_3^- , Fe, Cd, and Ni maximum concentrations are higher than the standard limits for drinking. Additionally, Pb^{2+} maximum concentration far exceeds the guidelines by 94 folds.

HCA distinguishes five main clusters showing variable salinities and element concentrations. The spatial distribution of clusters shows good coordination with the hydrogeologic setting and the proximity of the lower salinity samples to the River Nile. The Pearson bivariate correlation revealed the effect of using secondary nutrients (Mg^{2+} and S) as well as micronutrients (B, Na^+ , and Mn^{2+}) in cultivation process, in addition to anthropogenic impacts as evidenced by higher NO_3^- . Additionally, factor analysis gave five factors with total cumulative variance of ~69% showing the anthropogenic, geogenic, and fertilizer effects on the groundwater.

The use of biplots of ionic ratios indicates that the possible reactions affecting the groundwater chemistry are silicate weathering, reverse ion exchange, dissolution of CO_2 gas and the reuse of irrigation water. ~76% of the water samples located in the secondary alkalinity zone on Piper diagram reflecting the recharge water of the River Nile. The other water samples were located in the mixed zone (~22%), while only one sample (~2%) plotted in the primary salinity zone. The mixed zone samples reflect the effect of interference of different waters and anthropogenic impacts.

The WQI_{CCME} values for the groundwater samples range from fair to marginal water quality. The water seems to be threatened due to extensive agricultural activities to the east of the study area. IWQI values for samples show excellent water for irrigation that could be used without any cautions on soil or crops. This may be attributed to the continuous recharge of River Nile water and the infiltrated water from irrigation canals.

The suitability of water for irrigation was assessed using several parameters e.g., Na%, PI, SAR, KI, RSC, and MH where the majority of groundwater samples are suitable for irrigation.

Based on the results of this study, it can be recommended to use the minimum limit of fertilizers and nutrients to decrease the anthropogenic impact on the groundwater. The reuse of irrigation water without treatment imposes impacts on the water quality so, it is recommended to minimize this usage. The groundwater in the west of the study area shows higher salinities than in the east, so, the pumping rates should be controlled to avoid aquifer salinization.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by all authors. The first draft of the manuscript was written by all authors commenting on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors received no specific funding for this work.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article.

Human and animal participants There is no Human Participants and/or Animals in this research.

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