



Hydrogeochemical Processes and Groundwater Quality Assessment of the Nubian Sandstone Aquifer System in El Farafra Oasis, Egypt

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DESPITE its arid climate, the Egyptian Western Desert is a promising area for development depending on the groundwater, especially the water of the Nubian Sandstone Aquifer System. This article focused on the hydrogeochemical setting of the north-eastern portion of El Farafra Oasis. Groundwater samples from the shallow and the deep zones of the Nubian System were collected and analyzed. A hydrogeochemical evaluation was carried out depending on statistical analyses and bivariate plots. Additionally, Piper, Durov, and Stiff diagrams were also used. The results of factor analysis of the groundwater of the deep zone revealed five factors representing most of the variability of the samples (about 86% variance). Mostly geogenic factors control the ionic compositions of the groundwater, with minor interference of anthropogenic effects. On another side, the hydrogeochemical diagrams of the shallow and deep groundwater indicate that the dominant processes controlling the water chemistry are silicate weathering and possible dissolution of post-Nubian carbonate formations. In terms of water quality, the groundwater needs treatment to be suitable for drinking as a result of high iron concentration, but it showed high suitability for irrigation, livestock, and poultry.

Keywords: Hydrogeochemical processes, Water quality, Nubian Sandstone Aquifer System, El Farafra Oasis, Egypt.

Introduction

In arid and semi-arid regions, groundwater represents the main water resource used for household, agricultural, and industrial operations (Keesari et al. 2014). Groundwater has been widely utilised in recent decades as a result of drought, economic and population growth around the world (Llamas and Martínez-Santos 2005). Accordingly, the United Nations goal for sustainable development is safe drinking water, however in many countries, this goal remains a long way off (Radelyuk et al. 2021). In Egypt, there is a wide gap between the population (that exceeds 100 million) and the available water resources where the long-term exploitation of groundwater resources causes quantity and quality challenges. These challenges are represented by groundwater

salinization and pollution. Accordingly, changes in groundwater compositions result from reactions occurring along flow path (e.g., water-rock interaction and/ or mixing with other sources and leaching of surficial salts) (Sami 1992). Numerous studies related to the effect of the geogenic and anthropogenic factors on the groundwater composition were done (Hidalgo and Cruz-Sanjulián 2001; Londoño et al. 2008; Srivastava et al. 2012; Eissa et al. 2013; Mohamed et al. 2015; Panagopoulos et al. 2016; Abu Salem et al. 2017, 2021). These studies meant primarily to infer the controls on the groundwater chemistry to confirm or exclude other processes (e.g., anthropogenic impacts, geogenic effects, etc.).

In this article, we will spotlight on the groundwater, which is needed for development

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activities, especially agriculture in the Egyptian Western Desert. The main aquifer in the study area is the Nubian Sandstone Aquifer System (NSAS). A comprehensive hydrogeochemical, statistical, and water quality evaluation were carried out on the studied groundwater samples.

Location

The study area is located in the Farafra oasis, North-western Desert, Egypt, between longitudes 27°49' and 28°37'; and latitudes 26°59' and 27°14', with total area of about 2212 km². The study area consists of some development activities, including Sahl Qaraween, Sahl Baraka, Qasr El Farafra, Abu El Nuss and Lowa Sobieh.

Geomorphology

El Farafra Oasis comprises five major features characterizing the study area, e.g., depressions, plateaus, scarps, pediments and sand dunes. *The Depressions* cover most of the study area, while there are three major *plateaus*, including the Nagb Plateau with ground elevation reaching ~200 m a.s.l. at the north and northeastern part, El Quss Abu Said Plateau with ground elevation reaching ~325 m a.s.l. at the western part, and the Kharafish Plateau of ground elevation reaching ~400 m a.s.l. at the southeastern portion of the oasis (Ali, 2004). *The Scarps* represent the boundaries of the plateaus (e.g., scarp appears in the northwestern side of the study area), while *the Pediments* represents a plane with moderate height near the scarps' feet (appear in the northwestern side of the study area). *Sand dunes and sand sheets* cover wide areas, especially to the east of the study area.

Geological and hydrogeological setting

The geological units covering the surface of the study area vary from Quaternary to Upper Cretaceous (Fig. 3). The geological units are arranged from top to bottom as follows (Ali, 2004; CONOCO Coral, 1987): Quaternary surface cover (sand dunes, sand sheets and playa deposits), Farafra limestone, Esna shale and Tarawan chalk belonging to the Tertiary and Khoman Formation (Upper Cretaceous). The subsurface geological formations include the Upper Cretaceous and Paleozoic sediments representing the Nubian Sandstone succession which are underlain by basement rocks (RIGW/ASRT, 2016).

From the hydrogeological perspective, the area is characterized by the presence of two aquifer systems represented by the Post Nubian Aquifer System (PNAS) and the Nubian Sandstone Aquifer System (NSAS). The NSAS could be divided into two main productive zones, the shallow and deep Nubian aquifers that are separated by an aquiclude. The thickness of the PNAS ranges between 115 and 205 m. On the other hand, the thickness of the NSAS ranges between 1725 and 1875 m. A hydraulic connection between the shallow and the deep aquifer zones is reported due to the presence of faults (El-Ghamrawy *et al.*, 2021).

It is worth mentioning that the water level ranges between +80 m a.s.l. in the western part of the study area to +120 m a.s.l. in the east. Accordingly, the groundwater flow direction is from east to west, indicating local flow direction which differs from the main regional flow direction in the

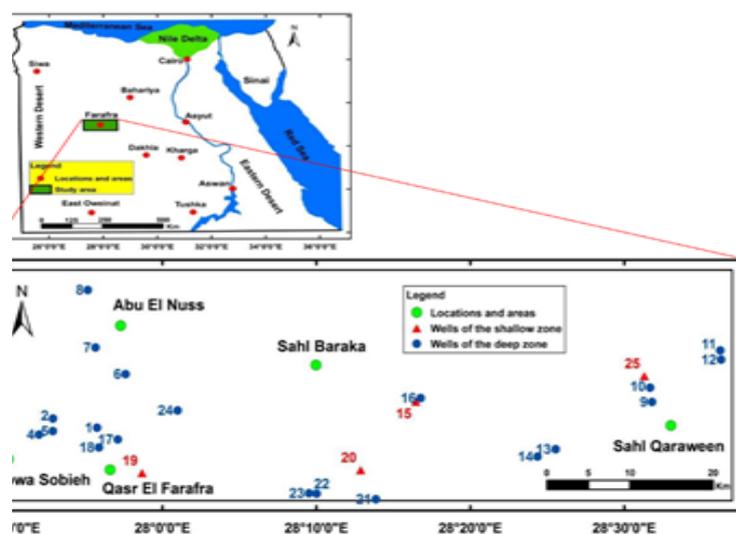


Fig. 1. Location map of study area in El Farafra Oasis including the collected groundwater samples.

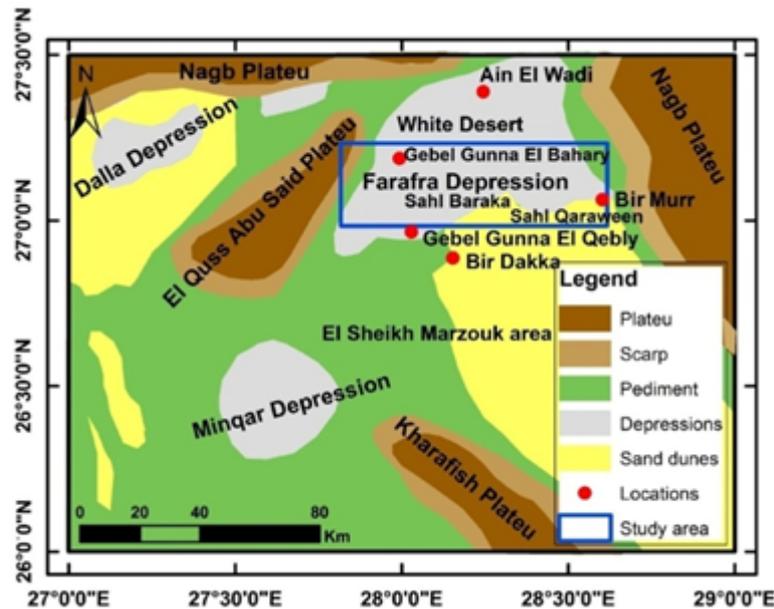


Fig. 2. General geomorphic features of El Farafra Depression and its surroundings (modified after Ali, 2004).

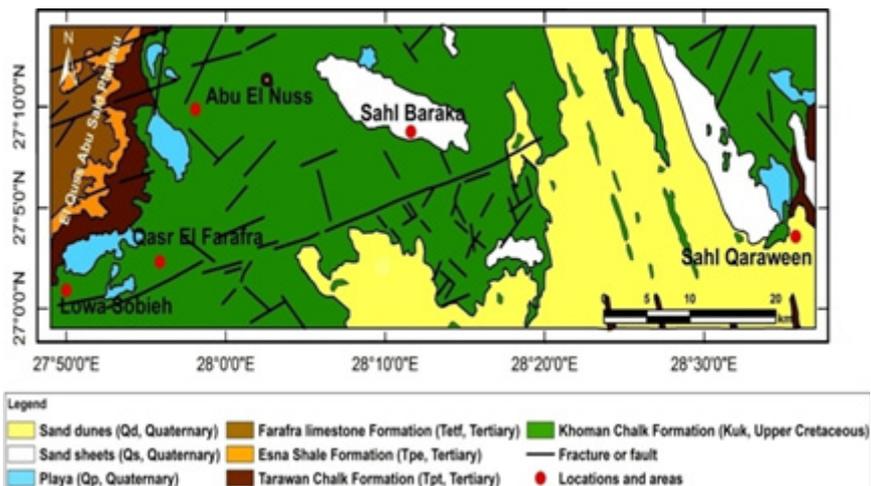


Fig. 3. Geological map of the study area (after CONOCO Coral, 1987).

Nubian aquifer in the Egyptian Western Desert (southwest-northeast). The intensive groundwater extraction rates in the western portion of the study area represents the main reason for the local different flow direction.

The main hydraulic properties (hydraulic conductivity 'K', transmissivity 'T', and storativity 'S') of the NSAS were estimated. The average hydraulic conductivity of the NSAS in the study area reaches about 7.1 m/day, while the average transmissivity reaches about 2704 m²/day. The storativity was estimated as 0.0002 (El-Ghamrawy et al., 2021).

Methodology

Duplicate sets of twenty-five groundwater samples were collected from Lowa Sobieh, Qasr El Farafra, Sahl Baraka and Sahl Qaraween areas. One set was acidized with ultra-pure conc. HNO₃, while the other set was kept as it is. Four samples were collected from the shallow zone, while twenty-one samples were collected from the deep zone. The samples were analysed for major ions and trace elements in the Central laboratories for Environmental Monitoring (National Water Research Centre 'NWRC').

Statistical analysis, major hydrogeochemical processes, origin of water, hypothetical salt assemblages and abundance of major cations and anions were studied to achieve the hydrogeochemical evaluation of the aquifer system. The evaluation of water quality and the suitability of groundwater for the different purposes was carried out as well.

Results and Discussion

Physicochemical parameters

The pH values vary from 6.9 to 7.41 with an average of 7.15 in the shallow zone (Table 1), while they vary between 6.49 and 7.42 in the deep zone (average ~6.69, Table 2). The pH values are within the accepted limits according to drinking water quality standards (Tables 1 and 2). The measured temperature ranges between 28.6 and 34.1°C in shallow zone samples, while it varies from 34.5 to 43 °C in the deep zone samples (Tables 1 and 2). The Electrical Conductivity (EC) varies from 0.243 to 0.722 mmhos/cm in the shallow zone, while it varies from 0.16 to 0.68

mmhos/cm with average of 0.3 mmhos/cm for the deep zone. There is high similarity between EC values in the two zones (Tables 1 and 2). The TDS varies from 155 to 460 mg/l in the shallow zone, while it varies from 105 to 433 mg/l with average of 167 mg/l in the deep zone (Tables 1 and 2). The TDS distribution in both shallow and deep zones indicates fresh groundwater.

Major ions

Potassium concentrations vary from 5 to 20 mg/l in shallow zone samples, but they vary from 5 to 22 mg/l in the deep zone. Potassium rich clay minerals could be considered the main source of high potassium concentration. Sodium concentrations range between 20 and 80 mg/l in shallow zone samples, while it ranges between 15 and 67 mg/l in the deep zone. Based on World Health Organization WHO (2011) Guidelines, all samples are below the maximum permissible limit (200 mg/l). Calcium concentrations in the shallow and deep zones are comparable (range between 12 and 42 mg/l). Similarly, magnesium concentrations range between 6 and 15 mg/l, and

TABLE 1. Descriptive statistics of the samples from the shallow aquifer, element concentrations and TDS (in mg/l), EC (in mmhos/cm) and temperature (in degree Celsius). Water quality guidelines of drinking water of EPA (2018) and WHO (2011) were used.

Parameter	Minimum	Maximum	Mean	Std. Deviation	EPA, 2018	WHO, 2011
T	28.6	34.1	31.68	2.28	–	–
pH	6.9	7.41	7.15	0.27	6.5-8.5	6.5-8.5
EC	0.243	0.722	0.38	0.23	–	–
TDS	155	460	245.00	144.80	500	1000
K ⁺	5	20	11.75	6.24	–	–
Na ⁺	20	80	35.75	29.51	200	200*
Mg ²⁺	6	15	9.00	4.08	–	–
Ca ²⁺	17	42	26.39	11.24	–	–
NO ₃ ⁻	0.1	1.54	0.70	0.62	10	50
Cl ⁻	26.74	108	47.69	40.21	250	250*
SO ₄ ²⁻	23	81	39.25	27.96	250	500**
HCO ₃ ⁻	65	134	93.50	31.33	–	–
Al	0.008	0.083	0.044	0.039	0.2	0.2
Ba	0.074	0.222	0.167	0.066	2	0.7
Co	0.0015	0.007	0.004	0.003	–	–
Cu	0.007	0.324	0.131	0.142	1.3	2
Fe	0.48	16.8	4.904	7.939	0.3	0.3
Mn	0.072	0.395	0.199	0.146	0.05	0.4
Ni	0.015	0.034	0.021	0.009	0.02	0.07
Zn	0.0025	0.072	0.036	0.032	5	3

from 1.46 to 15 mg/l in the shallow and deep zones; respectively. Chloride ranges between 27 and 108 mg/l in the shallow zone, while it ranges between 19 and 89 mg/l in the deep zone (Tables 1 and 2). All values in the two productive zones are less than the maximum permissible limits for drinking (WHO, 2011; EPA, 2018). In the shallow zone, sulfate concentrations range between 23 and 81 mg/l, while they range between 16 and 86 mg/l in the deep zone. All samples are below the maximum permissible limits of the EPA (2018) and WHO (2011). Bicarbonate concentrations vary from 65 to 134 mg/l and from 52 to 128 mg/l in the shallow and deep zones, respectively. Generally, the concentrations of major ions could be considered homogeneous in the shallow zone except (well 20) (Figs. 1 and 4). In the deep zone, the concentrations of ions could be considered homogeneous except well (3) which shows higher concentrations (Figs. 4 and 5). Generally, the slight increase in major ion's concentration to the

west of the study area could be related to over-pumping (El-Ghamrawy et al., 2021).

Trace metals

All the studied samples have nitrate, zinc, and nickel concentrations below the maximum permissible limits. For Aluminium, there are five samples (2, 4, 10, 22 and 24) with slightly higher concentrations above the permissible limits. Barium concentrations are below the drinking permissible limits except one sample. Likewise, cobalt and copper concentrations in all samples are within the accepted limits. However, iron concentrations in all samples exceed the maximum permissible limit (WHO, 2011) in drinking water while manganese concentrations exceed the permissible limits in only five samples (samples 1, 10, 12, 22 and 24).

The source of trace metals could be either natural or anthropogenic source (Mondal et al., 2010). The standard limits of drinking water are inserted in Tables 1 and 2.

TABLE 2. Descriptive statistics of the samples from the deep aquifer, element concentrations and TDS (in mg/l), EC (in mmhos/cm) and temperature (in degree Celsius). Water quality guidelines of drinking water of EPA (2018) and WHO (2011) were used.

Parameter	Minimum	Maximum	Mean	Std. Deviation	EPA, 2018	WHO, 2011
T	34.5	43	37.68	2.50	–	–
pH	6.49	7.42	6.69	0.2	6.5-8.5	6.5-8.5
EC	0.16	0.68	0.26	0.10	–	–
TDS	105	433	167.38	64.26	500	1000
K ⁺	5	22	8.10	3.66	–	–
Na ⁺	15	67	24.24	10.71	200	200*
Mg ²⁺	1.46	15	6.16	2.37	–	–
Ca ²⁺	12	42	17.86	5.98	–	–
NO ₃ ⁻	0.1	1.53	0.73	0.47	10	50
Cl ⁻	18.84	89	30.29	14.42	250	250*
SO ₄ ²⁻	16	86	27.06	14.13	250	500**
HCO ₃ ⁻	52	128	65.05	16.25	–	–
Al	0.055	0.338	0.13	0.09	0.2	0.2
Ba	0.094	0.811	0.21	0.14	2	0.7
Co	0.0015	0.009	0.01	0.002	–	–
Cu	0.006	0.592	0.19	0.18	1.3	2
Fe	1.77	28.4	6.36	5.59	0.3	0.3
Mn	0.181	0.546	0.33	0.09	0.05	0.4
Ni	0.012	0.029	0.02	0.005	0.02	0.07
Zn	0.0025	0.398	0.08	0.09	5	3

TABLE 3. Classification of water based on TDS values (Todd, 1980).

Water Class	(TDS (mg/l
Freshwater	1000>
Brackish water	1000-10000
Saline water	10000-100000
Brine water	100000<

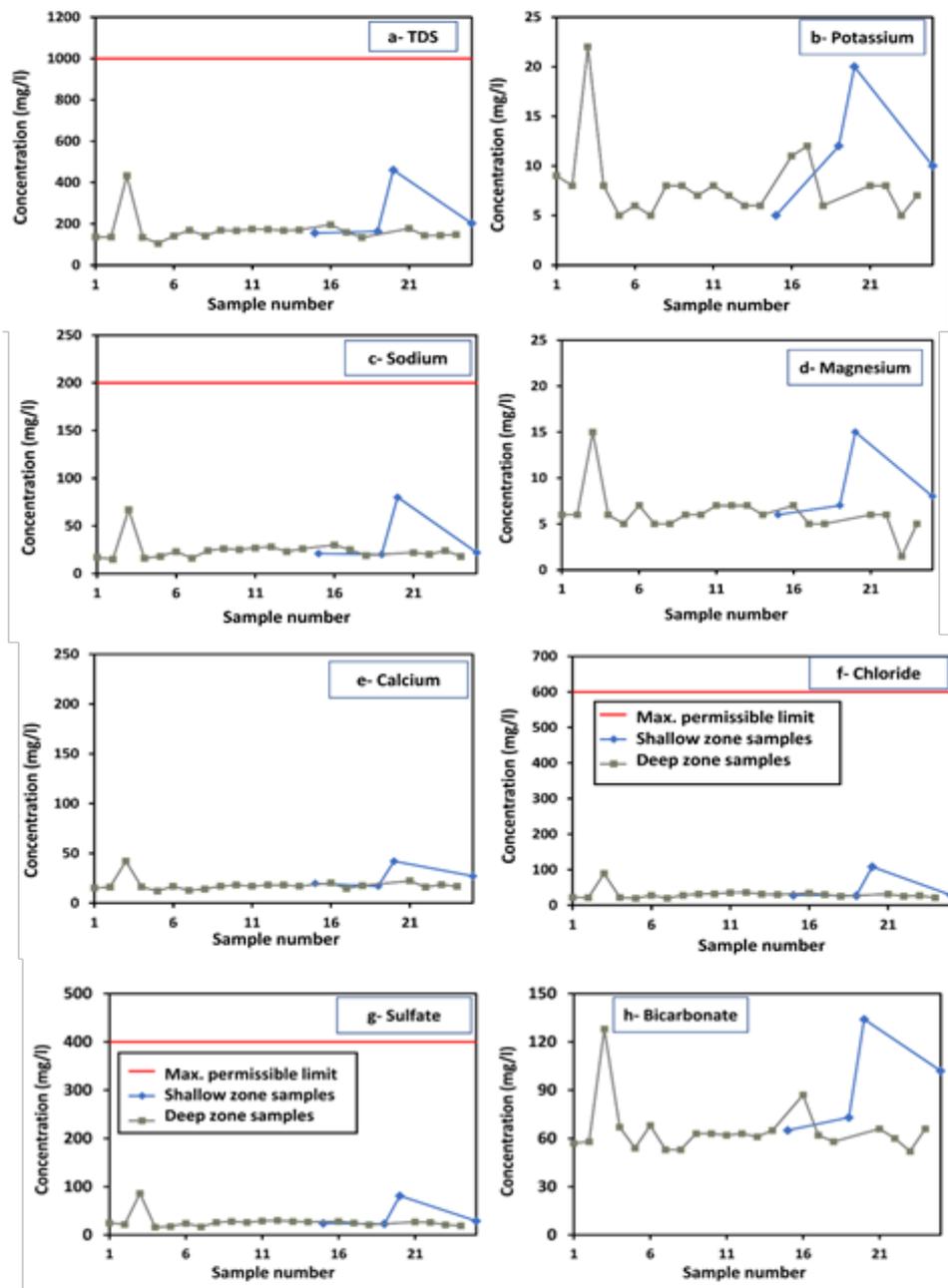


Fig. 4. Concentrations of a) TDS, b) potassium, c) sodium, d) magnesium, e) calcium, f) chloride, g) sulfate, and h) bicarbonate, of the groundwater samples from the shallow and deep zones of the NSAS. Red horizontal lines refer to the maximum permissible limit (WHO, 2011).

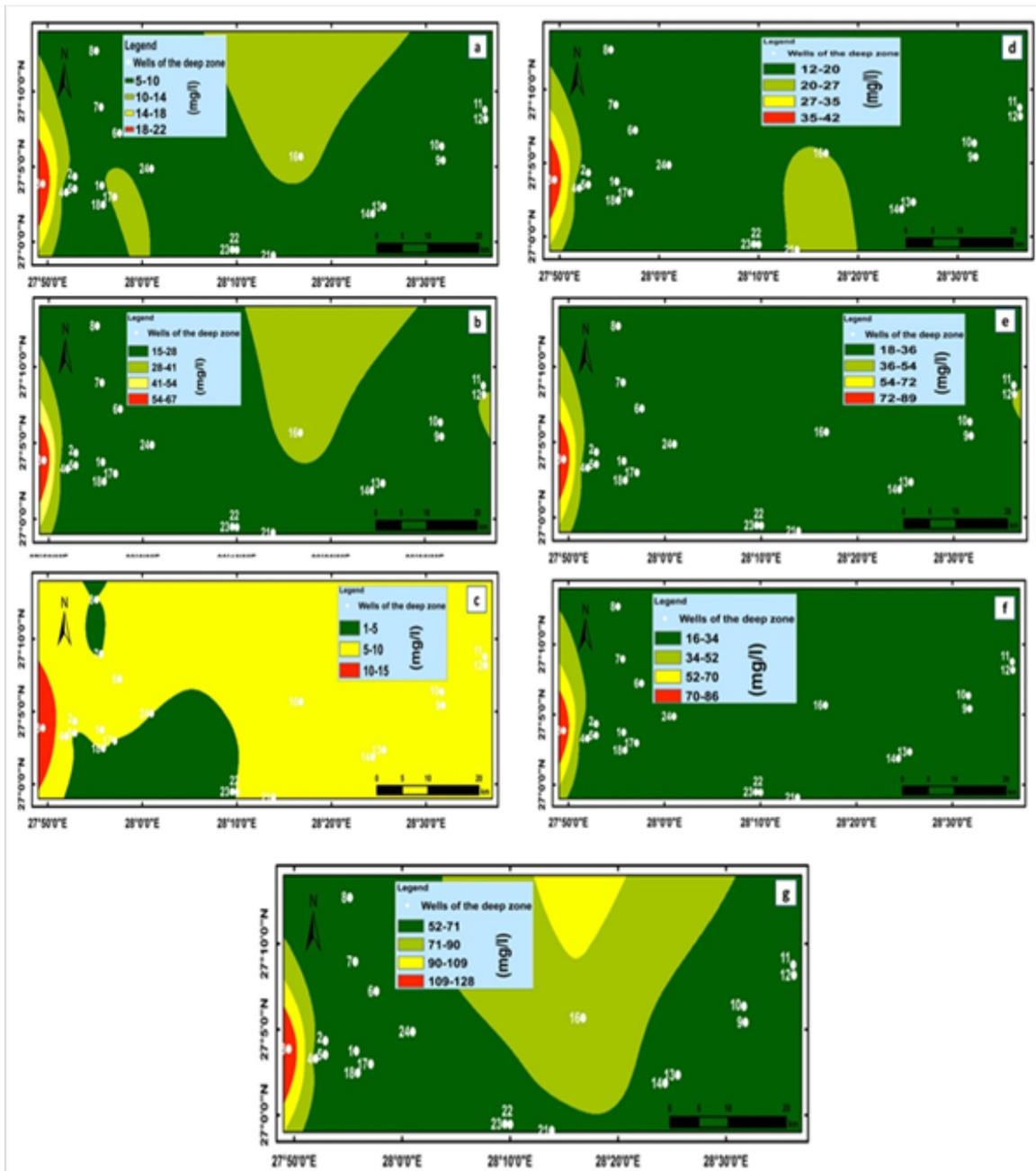


Fig. 5. Spatial distribution of major ions in the study area, where a) potassium, b) sodium, c) magnesium, d) calcium, e) chloride, f) sulfate, and g) bicarbonate, of the groundwater samples from deep zone of the NSAS.

Statistical analysis

Pearson Correlation

Pearson Correlation Coefficient “r” is used to calculate the bivariate correlation for the groundwater samples of the deep zone (Table 4). This analysis is applied only for the samples of the deep aquifer. The analysis shows the presence of strong positive correlations between a) cations and anions, and between b) cations and anions

with both TDS and EC (Table 4), representing the correlation of these elements with salinity. On other side, there is strong positive correlation between aluminium and zinc (0.7), while zinc has a moderate positive correlation with nickel (0.54) and copper (0.6). The analysis also shows the presence of very weak correlation between nitrate and major ions as well as trace elements, showing possible anthropogenic effect.

It could be concluded that geogenic processes represent the controlling factor affecting the hydrogeochemical characteristics of groundwater of the NSAS with very limited anthropogenic effects which might be caused because of fractures and/or faults in the study area.

Factor analysis

To study the most effective parameters controlling the ionic compositions in groundwater, factor analysis is applied based on the principal component analysis (PCA). In this technique, the relationships between variables are divided into limited number of factors with a minimum loss of information (Hair *et al.*, 1992). The feasibility of applying the PCA and sampling adequacy are determined by the application of the Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests (Field, 2009).

The test was applied for the samples of the deep zone where the best adequacy results were obtained depending on 18 variables, including TDS, EC, pH, K⁺, Na⁺, Mg²⁺, Ca²⁺, Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻, Al, Co, Cu, Fe, Mn, Ba, and Ni. The result of KMO test is 0.512 indicating the feasibility of applying PCA. Also, the Bartlett's sphericity test results indicate the presence of common variance among the studied variables (where Chi-Square = 496.622; degree of freedom = 153; and p < 0.001 "zero"). Five factors (based on eigenvalues more than one and varimax rotation) were extracted indicating most of the variability with total cumulative variance reaching about 86% for the groundwater samples (Table 5).

Factor 1: This factor represents the salinity factor and accounts for ~47% of the total variance. It shows strong positive loading on EC, Cl⁻, SO₄²⁻, TDS, Na⁺, Ca²⁺, HCO₃⁻, K⁺, and Mg²⁺ which are (0.99), (0.99), (0.99), (0.98), (0.97), (0.96), (0.95), (0.91) and (0.91); respectively (Table 5).

Factor 2: This factor could be named the geogenic/ anthropogenic factor that accounts for about 10% of the total variance, in which a strong positive loading on Ba (0.8) and Cu (0.72) and moderate negative loading on NO₃⁻ (-0.52).

Factor 3: accounts for about 10% of the total variance. It is associated with strong positive loading on Fe (0.85) and Co (0.72), moderate positive loading on Al (0.54) (Table 5). It could be considered the iron factor.

Factor 4: indicates a strong positive loadings on Mn (0.86) and Al (0.62) and also moderate positive loading on Cu (0.57) as shown in Table (5). This factor could be named the geogenic factor. It accounts for about 9% of the total variance.

Factor 5: shows a strong positive loading on Ni (0.83) and pH (0.8) and accounts for about 9% of the total variance (Table 5).

Major ions' chemistry

The hydrogeochemical reactions operating in an aquifer could be inferred using bivariate diagrams. Garrels (1976) attributed the presence of high concentrations of sodium, calcium, and magnesium in groundwater to weathering of clay minerals. Also, he considered that leaching of limestone, dolomite, gypsum, and anhydrite is another important source of calcium and magnesium in groundwater. On other side, several studies used ionic relations to understand factors controlling water chemistry (e.g., Stallard and Edmond, 1983; Sarin *et al.*, 1989; Datta and Tyagi 1996; Lakshmanan *et al.*, 2003; Kumar *et al.*, 2009). According to Kumar *et al.* (2009), the plotting of calcium + magnesium versus sulfate + bicarbonate indicates the presence of carbonate and silicate dissolution if the samples plot along equiline, silicate weathering if samples plot below the equiline, and carbonate weathering if samples plot above the equiline. The plot of the samples from the shallow and deep zones below the equiline indicates the effect of silicate weathering (Fig. 6a).

On other side, the plot of the groundwater samples below the 1:2 line in the relationship between bicarbonate and calcium indicates the effect of possible CO₂ dissolution (Fig. 6b). Additionally, the increase in the TDS of the studied samples is associated with an increase in the saturation index of calcite (Fig. 7a) indicating possible calcite dissolution. The relationship between sulphate and calcium in all samples indicate the presence of calcium content more than expected from gypsum dissolution (plot above the 1:1 line) precluding gypsum dissolution (Fig. 6c) as confirmed by gypsum undersaturated in all the studied samples (Fig. 7c).

The role of silicate weathering could also be confirmed using the relation of Na + K versus the total cations index 'TZ+' (Stallard and Edmond, 1983; Sarin *et al.*, 1989; Datta and Tyagi, 1996). According to Datta and Tyagi (1996), the presence

TABLE 4. Pearson correlation between the different variables in the deep zone samples.

	T	pH	EC	TDS	K ⁺	Na ⁺	Mg ²⁺	Ca ²⁺	NO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Al	Ba	Co	Cu	Fe	Mn	Ni	Zn	
T	1.00																				
pH	-0.44	1.00																			
EC	-0.43	0.13	1.00																		
TDS	-0.31	0.08	0.97	1.00																	
K ⁺	-0.38	0.32	0.89	0.88	1.00																
Na ⁺	-0.37	0.12	0.97	0.96	0.85	1.00															
Mg ²⁺	-0.40	0.09	0.88	0.87	0.82	0.83	1.00														
Ca ²⁺	-0.38	0.04	0.97	0.95	0.83	0.92	0.83	1.00													
NO ₃ ⁻	0.18	-0.16	-0.14	-0.20	-0.30	-0.04	-0.15	-0.18	1.00												
Cl ⁻	-0.40	0.11	0.99	0.97	0.87	0.99	0.87	0.95	-0.08	1.00											
SO ₄ ²⁻	-0.35	0.08	0.98	0.97	0.89	0.97	0.90	0.94	-0.06	0.98	1.00										
HCO ₃ ⁻	-0.41	0.17	0.95	0.93	0.89	0.90	0.89	0.92	-0.27	0.91	0.89	1.00									
Al	0.12	-0.26	-0.19	-0.22	-0.08	-0.29	-0.10	-0.15	-0.36	-0.26	-0.22	-0.08	1.00								
Ba	-0.18	0.14	-0.03	-0.06	0.08	-0.02	-0.05	-0.06	-0.29	-0.09	-0.13	0.19	0.26	1.00							
Co	-0.05	0.05	0.18	0.15	0.33	0.14	0.10	0.19	-0.24	0.15	0.21	0.15	0.34	0.12	1.00						
Cu	-0.13	-0.13	0.01	-0.02	0.13	-0.09	0.10	0.00	-0.27	-0.06	-0.05	0.12	0.55	0.38	0.04	1.00					
Fe	0.17	-0.34	-0.20	-0.18	-0.22	-0.20	-0.21	-0.12	-0.09	-0.19	-0.14	-0.23	0.44	-0.09	0.34	-0.34	1.00				
Mn	-0.46	-0.14	0.02	-0.04	-0.03	-0.03	0.03	0.05	0.02	0.01	0.00	-0.01	0.38	0.02	0.08	0.39	0.13	1.00			
Ni	-0.26	0.39	-0.22	-0.27	-0.16	-0.30	-0.15	-0.21	-0.32	-0.27	-0.31	-0.11	0.38	0.01	-0.08	-0.02	0.24	0.28	1.00		
Zn	0.06	-0.18	-0.13	-0.15	-0.02	-0.23	0.01	-0.10	-0.32	-0.18	-0.20	0.01	0.70	0.16	-0.1	0.60	0.01	0.36	0.54	1.00	

TABLE 5. The Kaiser-Meyer-Olkin (KMO), Bartlett's sphericity tests and the Principal component analysis (PCA) for the analyzed groundwater samples from the deep zone.

KMO and Bartlett's Test						
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.						0.512
Approx. Chi-Square Test of Sphericity						496.622
Bartlett's	Df					153
Sig.						0.000
Rotation Sums of Squared Loadings	Total	8.52	1.88	1.79	1.77	1.59
	% of Variance	47.31	10.45	9.97	9.83	8.82
	Cumulative %	47.31	57.76	67.73	77.57	86.39
		1	2	3	4	5
EC		0.994	-0.005	-0.014	-0.011	0.000
Cl ⁻		0.986	-0.081	-0.032	-0.043	-0.039
SO ₄ ²⁻		0.985	-0.087	0.028	-0.043	-0.083
TDS		0.980	-0.006	0.009	-0.063	-0.037
Na ⁺		0.97	-0.06	-0.05	-0.11	-0.06
Ca ²⁺		0.96	-0.03	0.06	0.03	-0.03
HCO ₃ ⁻		0.95	0.20	-0.01	0.01	0.09
K ⁺		0.91	0.22	0.06	-0.08	0.14
Mg ²⁺		0.91	0.02	-0.06	0.09	0.02
Ba		-0.05	0.80	0.04	-0.06	0.05
Cu		0.02	0.72	-0.20	0.57	-0.16
NO ₃ ⁻		-0.16	-0.52	-0.37	-0.05	-0.43
Fe		-0.19	-0.32	0.85	0.15	-0.02
Co		0.19	0.25	0.72	-0.10	-0.04
Mn		0.03	-0.04	0.01	0.86	0.04
Al		-0.18	0.40	0.54	0.62	0.04
Ni		-0.23	-0.09	0.15	0.39	0.83
pH		0.13	0.13	-0.25	-0.31	0.80

of data points along the $(Na + K) = 0.5$ (TZ+) refers to possible role of silicate weathering in cation compositions. In the study area, the samples plot along and above $(Na+K) = 0.5$ (TZ+) line, referring to effect of silicate weathering (Fig. 6d). Also, the trend of the studied samples in a relationship between Na/Cl and EC indicates the possible effect of silicate weathering (Jankowski and Acworth, 1997). Additionally, the relationship between sodium and chloride shows that samples plot slightly below 1:1 line, referring to that halite dissolution might not be responsible for the sodium and chloride content of the samples, where halite is undersaturated in all samples (Fig. 6f). The slight increase in chloride might be attributed to geogenic factors (Fig. 6f).

Major hypothetical salts assemblages

The hypothetical salt assemblages of the groundwater from the shallow and deep zones are the same. The hypothetical salts are: $KCl - NaCl - Na_2SO_4 - MgSO_4 - Mg(HCO_3)_2 - Ca(HCO_3)_2$. Bicarbonate salts are dominant, especially calcium bicarbonate $[Ca(HCO_3)_2]$ which might be formed due to the dissolution of carbonate rocks or leakage from neighbouring aquifers.

Classification of groundwater

The origin of groundwater and the hydrogeochemical processes controlling the hydrogeochemical conditions in the aquifer system were studied. Piper diagram, Durov diagram and Stiff diagram were used and applied on the samples of the study area.

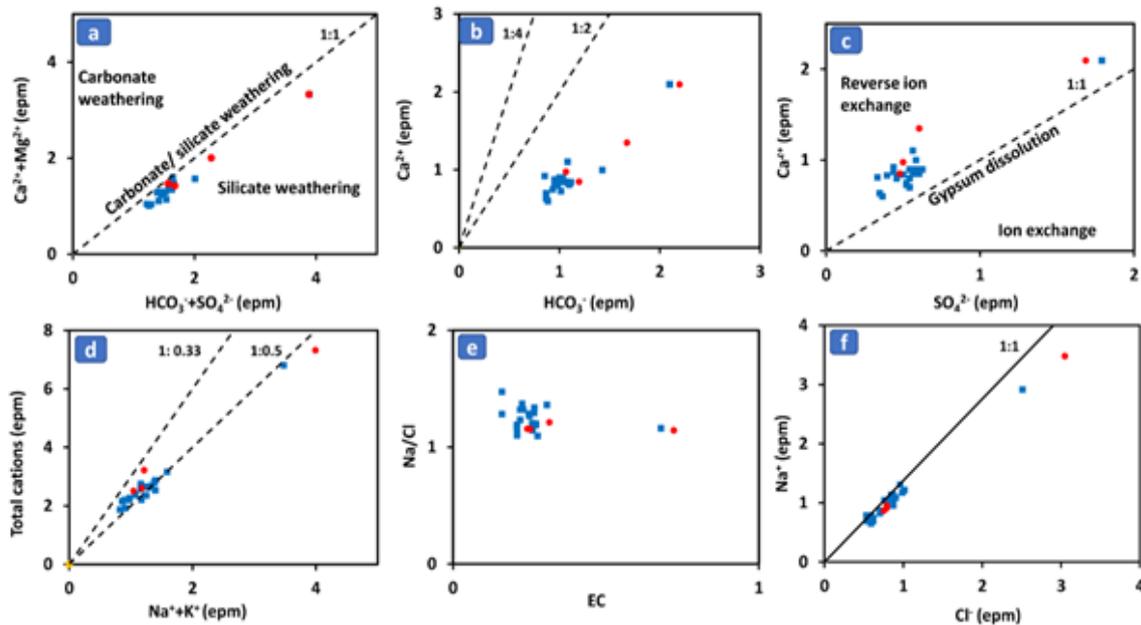


Fig. 6. Scatter diagrams of major ions' relations and ratios from the shallow and deep groundwater samples. Blue squares represent the deep zone samples, and the red circles indicate the shallow zone samples.

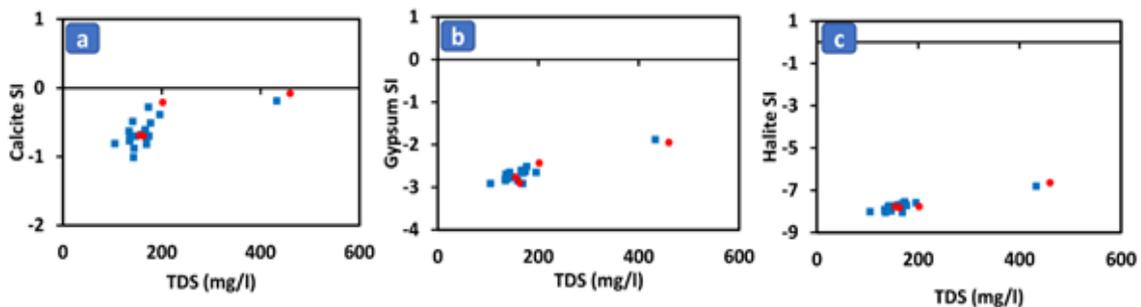


Fig. 7. Saturation indices of selected minerals versus TDS for the shallow and deep groundwater samples. Blue squares represent the deep zone samples, and the red circles indicate the shallow zone samples.

Piper trilinear diagram

This diagram depends on the equivalent ratios of alkaline earths and alkali metals against strong and weak acidic anions to identify the chemical affinity of water and the effective processes in the hydrogeological system (Piper, 1944). The divisions of Piper diagram are indicated in table 6 and Figure 8.

In the shallow zone of the NSAS, 50% of the samples plot in sub-area 9 referring to mixed type water (Fig. 9a). One sample (25% of the samples) plots in sub-area 5 referring to calcium bicarbonate type, while the remaining sample plots in sub-area 7 of sodium chloride type which might be attributed to the thick clay intercalations in well 20 that is located in Sahl Baraka.

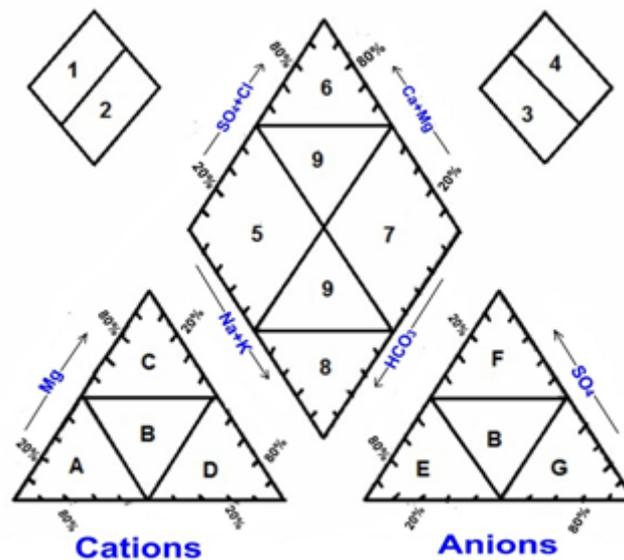
In the deep zone, 66.7% of the samples plot in sub-area 9, referring to mixed water type, while 23.8% of the samples plot in sub-area 7 referring to dominance of sodium chloride type which can be attributed to presence of thick clay beds and/or over pumping (Fig. 10b). Also, about 9.5 % of the samples belong to magnesium and calcium bicarbonate type.

Durov diagram

Durov (1948) applied a diagram consisting of one square and two basic triangles. The triangle representing the cations is located at the top of diagram, while that representing the anions is located to the left side (Fig. 10). Durov diagram is considered a tool for identifying the major hydrogeochemical processes operating in the aquifer (Singh & Kumar 2015).

TABLE 6. Zones and sub-areas of Piper diagram (after Back and Hanshaw, 1965).

Symbol	Characteristics
A	Calcium type
B	No Dominant type
C	Magnesium type
D	Sodium and potassium type
E	Bicarbonate type
F	Sulphate type
G	Chloride type
Sub-area 1	Alkaline earths (Ca+Mg) exceed alkalis (Na+K)
Sub-area 2	Alkalis exceeds alkaline earths
Sub-area 3	Weak acids (CO_3+HCO_3) exceed Strong acids (SO_4+Cl)
Sub-area 4	Strong acids exceed weak acids
Sub-area 5	Calcium or magnesium bicarbonate type 'secondary alkalinity'
Sub-area 6	Calcium chloride type 'secondary salinity'
Sub-area 7	Sodium chloride or sulfate type 'primary salinity'
Sub-area 8	Sodium bicarbonate type 'primary alkalinity'
Sub-area 9	Mixed type (No cation-anion exceeds 50%)

**Fig. 8. General subdivisions of Piper diagram (after Back and Hanshaw, 1965).**

The cation triangle showed that most samples belong to the intermediate type which indicates a mixed water type. Few samples plot in the sodium plus potassium field (Figs. 10 a & b). Also, the triangle of anions showed that most samples belong to intermediate type although presence of some samples belonging to bicarbonate type

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which refers to carbonate weathering processes (Singh and Kumar, 2015). Based on the previously mentioned results, it could be concluded that the groundwater samples in the study area are affected mainly by mixing processes or simple dissolution (Fig. 10).

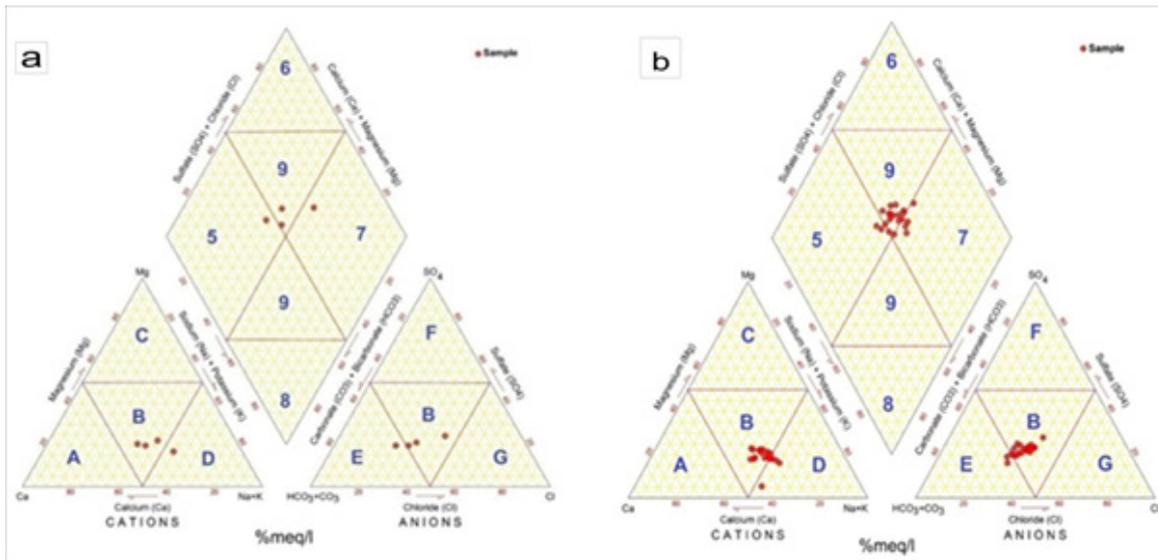


Fig. 9. Piper diagram for groundwater samples from the a) shallow zone, b) deep zone.

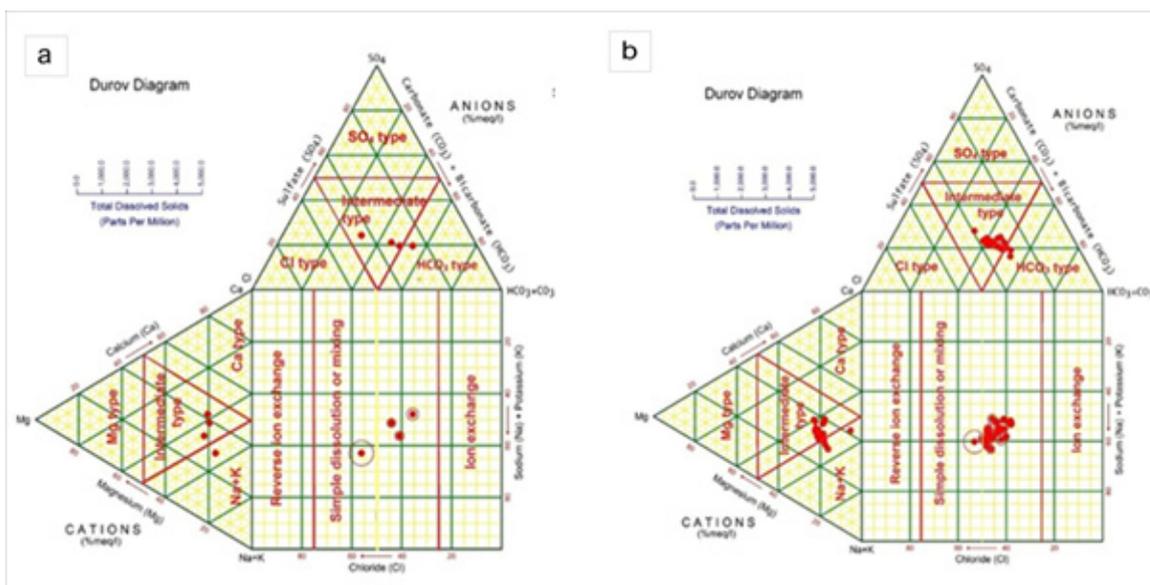


Fig. 10. Durov diagram for samples of the a) shallow zone, b) the deep zone.

Stiff diagram

Stiff (1951) diagram is used to present the ionic proportions of water samples to present their abundance. In the samples of the shallow zone, sodium and potassium showed the highest abundance in 75 % of the samples, while calcium showed the highest abundance in one sample only (25 % of samples) (Figs. 11 and 12). For anions, the bicarbonate is dominant in 75% of the samples of the shallow zone, while chloride showed

abundance in one sample (25% of the samples of this zone) (Figs. 11 and 12).

In the deep zone, potassium and sodium showed the highest abundance of cations in all samples. For anions, bicarbonate showed the highest abundance in twenty samples (95.2 % of the total samples), while chloride showed the highest abundance of anions in one sample only (4.8 % of the samples).

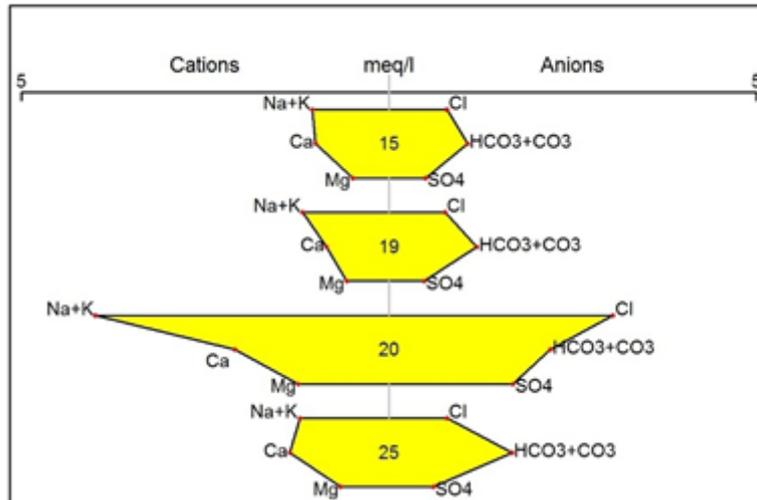


Fig. 11. Stiff diagram for samples of the shallow zone.

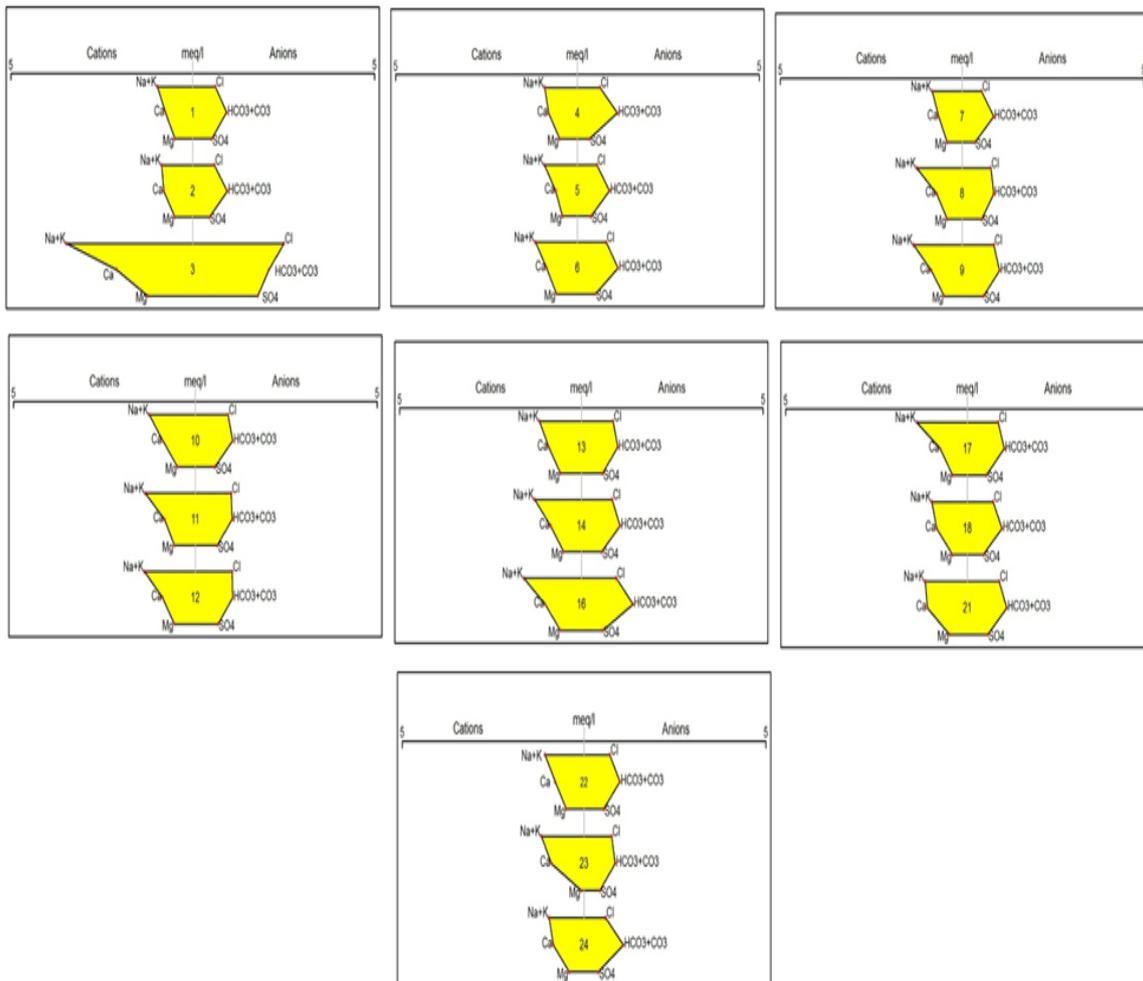


Fig. 12. Stiff diagram for samples of the deep zone.

Water Quality

The groundwater in the study area would be evaluated in terms of quality and suitability for different purposes. According to Shawky et al. (2012), the hydrochemical properties of groundwater are tied to several factors, including the type of bearing rocks or sediments, recharge sources and the effective surface geochemical processes which could affect the water chemistry.

The suitability of groundwater for drinking

The standard limits (Table 7) used for assessment of water for drinking are the World Health Organization (WHO, 2011). In terms of salinity (TDS), all samples are suitable for drinking according to WHO (2011). Also, the values of pH range between 6.49 and 7.42, indicating safe pH conditions.

On other side, copper, nickel, and zinc have concentrations less than the maximum permissible limits of WHO (2011). For aluminum, its concentrations in about 24% of deep zone samples exceed slightly the maximum permissible limit of WHO (2011), while barium has safe values in all samples except sample 16

in Sahl Baraka. The actual problem represents in the high concentration of iron, exceeding the upper permissible limit of WHO (2011) in all groundwater samples from both the shallow and the deep zones.

The suitability of groundwater for irrigation purposes

It depends on several factors, including EC, TDS, Sodium Adsorption Ratio (SAR) and Kelly's Ratio (KR). Also, Wilcox diagram had been used.

Evaluation of water based on TDS

Singh and Chawla (1964) used TDS value of 1000 mg/l as a maximum accepted limit for the use of water for irrigation purposes for most crop types. In the study area, all samples have TDS values below 1000 mg/l, showing the suitability for irrigation for most crops, especially in soils with a suitable and good drainage systems.

Evaluation of water based on EC

Tank and Chandel (2010) established three hazard categories for water suitability for irrigation purposes according to EC values (Table 8). The values of EC in the shallow zone range between

TABLE 7. Drinking water standards of WHO (2011) for some chemical parameters. TDS and elements' concentrations are in mg/l

Parameter	WHO (2011)
	pH 6.5 – 8.5
TDS	1000
	⁺ Na *200
	⁻ Cl *250
	SO ₄ ²⁻ **500
NO ₃ ⁻	50
Al	0.2
Ba	0.7
Cu	2
Fe	0.3
Mn	0.4
Ni	0.07
Zn	3

*No health-based guideline is proposed, but a taste threshold exist.

**No health-based guideline is proposed for SO₄, the threshold is for taste, corrosion, and gastrointestinal effects resulted from higher SO₄ levels.

243 to 722 $\mu\text{mhos/cm}$, including one sample below 251 $\mu\text{mhos/cm}$ in well (15), showing low salinity hazard, while the remaining three samples show values from 250- 751 $\mu\text{mhos/cm}$ in wells 19, 20 and 25, showing medium salinity hazard with good drainage conditions (Fig. 13). Well (20) has a relatively higher salinity due to possible local over discharge or thicker clay content in this location, that could cause increase in TDS in the parts around the clay units (Weert *et al.*, 2009).

On the other side, EC in wells (1, 2, 4, 5, 6, 7, 8, 17, 18, 22, 23 and 24) penetrating the deep zone are found below 251 $\mu\text{mhos/cm}$ indicating low salinity hazard and high-quality irrigation water, while samples from wells (3, 9, 10, 11, 12, 13, 14, 16 and 21) showed values ranging between 259 and 307 $\mu\text{mhos/cm}$ except well (3) which has EC reached 680 $\mu\text{mhos/cm}$ (Fig. 13). Accordingly, the groundwater of the aquifer system on the basis of EC could be considered suitable for irrigation with adequate and good drainage system.

Sodium Adsorption Ratio) SAR(

SAR is used to evaluate the suitability of water for irrigation. It is calculated based on the following formula (Karanth, 1987):

$$\text{SAR} = (\text{Na}^+) / \text{SQRT} [(\text{Ca}^{2+} + \text{Mg}^{2+})/2]$$

According to SAR classification of Tank and Chandel (2010) (Table 9) and the calculated SAR values for wells of this study (Appendix 1), the groundwater is generally suitable for irrigation in all soil types.

Kelly Ratio (KR)

KR is calculated as follows:

$$\text{KR} = (\text{Na}^+) / (\text{Ca}^{2+} + \text{Mg}^{2+})$$

If KR is less than 1, this means that water is suitable for irrigation, while KR values exceeding 1, indicate unsuitability for irrigation (Sundaray *et al.*, 2009). The calculated KR values showed the suitability for irrigation purposes in all samples except sample (20) from the shallow aquifer and sample (23) also from the deep aquifer (Appendix 1).

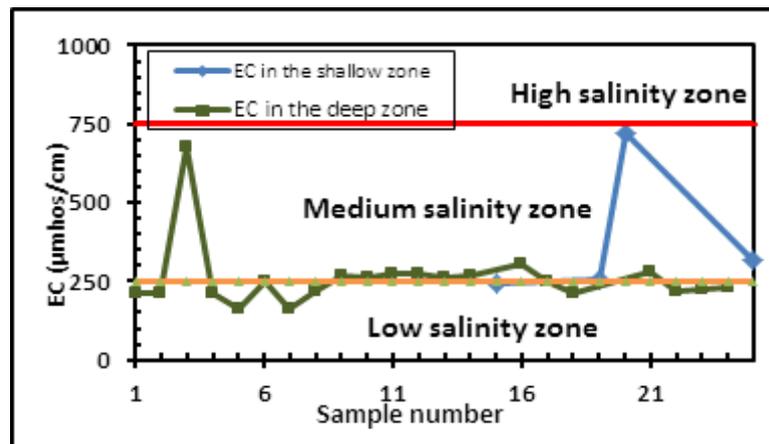


Fig. 13. Suitability of the studied water samples for irrigation based on EC.

TABLE 8. EC classification of water for suitability for irrigation (Tank & Chandel, 2010)

EC ($\mu\text{mhos/cm}$)	Characteristics
0 – 250	Low salinity water that could be used for irrigation in most soil with limited probability of increasing the soil salinity
251 – 750	Medium salinity that could be used under good drainage conditions
751 – 2250	High salinity water which can be considered unsuitable in areas of limited drainage. Also, in case of adequate drainage, good and suitable management is required for salinity control
> 2250	Very high salinity which is not suitable for irrigation in normal cases

Wilcox diagram

Wilcox (1955) diagram uses the relation between the EC and sodium percent Na% to evaluate the suitability of water for irrigation. Na% is calculated as follows (ions' concentrations are expressed in meq/l):

$$Na (\%) = (Na^{+} + K^{+}) / (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})$$

All samples in the study area plot in the excellent to good class (Fig. 14), indicating great suitability of water for irrigation in all soil types (especially with medium to high permeability).

Residual Sodium Carbonate (RSC)

Alkalinity hazard which is associated with CaCO₃ and MgCO₃ is evaluated by RSC (Eaton,

1950) as an important tool for assessment of water suitability for irrigation. If CO₃²⁻ plus HCO₃⁻ concentrations exceed (Ca²⁺ plus Mg²⁺) concentrations, the water becomes unsuitable for irrigation purposes (Eaton, 1950 and Raghunath, 1987).

RSC can be calculated as shown in the equation below, where ions' concentrations are used in meq/l):

$$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$$

Based on the calculated RSC values, the studied samples from the shallow and the deep zone are suitable and safe for irrigation (Table 10 and appendix 1).

TABLE 9. Suitability of water for irrigation according to SAR values (Tank & Chandel, 2010)

SAR	Suitability of water for irrigation
From 0 to 10	Suitable for all types of soils (except for crops with high sensitivity to sodium)
From 10 to 18	Suitable for soils with coarse grains of high permeability. It is relatively unsuitable for soils with fine grains
From 18 to 26	Unsuitable for most cases. Good drainage, high leaching and gypsum addition are required
> 26	Unsuitable for irrigation

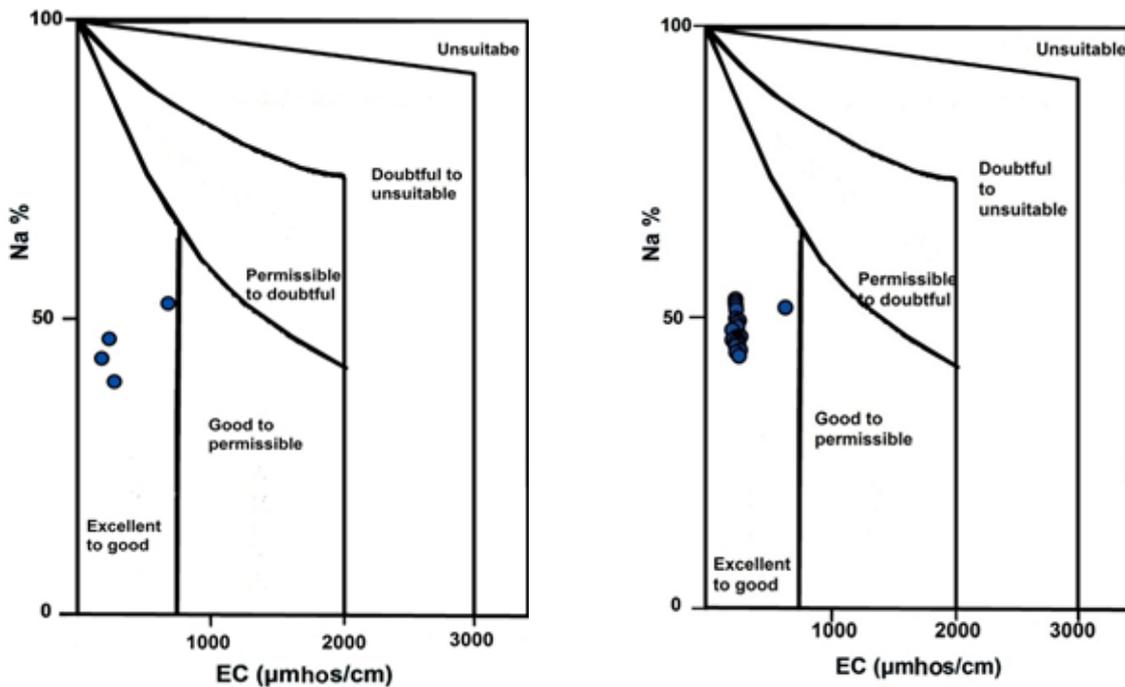


Fig. 14. Wilcox diagram (1955) for samples of the a) shallow zone and b) deep zone.

Magnesium Ratio (MR)

If Mg concentration exceeds 50% in water, the crop yield will be affected negatively because of increasing soil alkalinity (Kumar *et al.*, 2007). According to Paliwal (1972), MR is calculated as follows:

$$MR = (Mg^{2+}) / (Mg^{2+} + Ca^{2+}) * 100$$

All MR values from all samples are safe for irrigation purpose (Fig. 15).

The suitability for livestock and poultry

The National Academy of Sciences and the National Academy of Engineering NAS & NAE, (1972) used EC as an evaluation tool for water suitability for livestock and poultry Table (11).

All samples have EC values varying from 0.16 to 0.722 mmhos/cm which indicate the suitability for drinking of poultry and livestock. Also, the Australian Water Resources Council (AWRC, 1969) put accepted levels for magnesium in water for animals' drinking (Table 12). Concentration of magnesium is less than 100 mg/l in all samples, showing high suitability for drinking for the various classes of animals (<100 mg/l in all samples).

Additionally, the safe drinking levels of some heavy metals for livestock were suggested by NAS and NAE (1972) (Table 13).

The maximum concentration of aluminum was 0.338 mg/l, while the concentration of copper does not exceed 0.5 mg/l except sample 2 only

TABLE 10. Categories of water based on the values of RSC.

Range	Category
1.25 >	Safe
1.25-2.5	Doubtful
2.5 <	Unsuitable

TABLE 11. Water Quality guidelines for livestock and poultry (NAS & NAE, 1972; NAS, 1974).

EC (mmhos/cm)	Rating	Description
Less than 1.5	Excellent	Usable for all classes of livestock and poultry
1.5 – 5	Very Satisfactory	Usable for all classes of livestock and poultry. May cause temporary diarrhoea in livestock not accustomed to such water and watery droppings in poultry
>5 – 8	Satisfactory for Livestock	May cause temporary diarrhoea or be refused at first by animals not accustomed to such water
	Unfit for Poultry	Often causes watery faeces, increased mortality, and decreased growth, especially in turkeys
>8 – 11	Limited Use for Livestock	Usable with reasonable safety for dairy and beef cattle, sheep, swine, and horses. Avoid use for pregnant or lactating animals
	Unfit for Poultry	Not acceptable for poultry
>11 – 16	Very Limited Use	Unfit for poultry and probably unfit for swine. Considerable risk when used for pregnant or lactating cows, horses, or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry, and swine may subsist on waters such as these under certain conditions
More than 16	Not Recommended	Risks with such highly saline water are so great that it cannot be recommended for use under any conditions

in Lova Sobieh area which reaches 0.508 mg/l. The concentrations of lead, nitrate and zinc in all samples are below the maximum permissible limit of NAS and NAE (1972).

Generally, all samples are suitable for drinking for livestock and poultry according to EC values and concentrations of magnesium, but according to heavy metals' concentration, there is only one sample (sample 2) from the deep zone which has concentration of copper exceeding the maximum permissible limit put by NAS and NAE (1972) (Table 13).

The suitability of groundwater for industrial purposes

Corrosivity Ratio (CR)

The corrosivity ratio is used to evaluate the corrosive tendency of groundwater in metallic pipes (Ryner, 1944; Raman, 1985; Balasubramanian, 1986; Sankar, 1995; and Aravindan et al., 2004). It is calculated as follows:

$$CR = [(Cl^-/35.5) + 2 * (SO_4^{2-}/96)] / [2 * (HCO_3^- + CO_3^{2-}) / 100]$$

The ions' concentrations are expressed in mg/l. Corrosivity ratio must not exceed 1 to be safe.

The values of the shallow zone are below 1 showing safe water, except only one sample in Sahl Baraka which has CR value above 1 (Fig. 16 and Appendix 1). The deep zone's samples have 12 samples (57% of samples) which exceed 1 showing that these waters are corrosive (Fig. 16). The remaining samples of the deep zone could be considered safe. Generally, the higher values of CR require use of Polyvinyl Chloride (PVC) pipes (Das et al., 2011).

Conclusions

The hydrogeochemistry of the groundwater in the north-eastern part of El Farafra Oasis was evaluated using twenty-five samples. The hydrogeochemical evaluation in this study is based on statistical analysis, bivariate plots, Piper and Durov, and Stiff diagram. Additionally, evaluation of water quality for different purposes was also made. The statistical analyses showed several factors controlling the variance among the studied samples of the deep zone where about 47% of the total cumulative variance related to the natural salinity effect, about 10% related to geogenic with minor anthropogenic effects, about 10% related to iron factor, 9% related to geogenic factor and

TABLE 12. Magnesium limits for livestock and poultry's drinking water (AWRC 1969).

Livestock	Magnesium concentration (mg/l)
Poultry	< 250
Swine	< 250
Horses	250
(Cows (lactating	250
Ewes with lambs	250
Beef cattle	400
Adult sheep on dry feed	500

TABLE 13. Guideline levels of some heavy metals in livestock drinking water (NAS & NAE, 1972).

Constituent	Upper limit (mg/l)
Aluminium	5
Copper	0.5
Iron	Not needed
Lead ¹	0.1
Nitrate	100
Zinc	24

¹Lead is accumulative, and problems may begin at a threshold value of 0.05 mg/l.

about 10% related to nickel factor. On other side, bivariate diagrams were used to study the major ionic controls and processes in the groundwater, showing effect of silicate weathering, possible CO₂ dissolution, and calcite dissolution. Also, the chemical character of the studied samples based on Piper diagram is a mixed water type in most of the samples of the shallow and deep zones. Durov diagram showed that mixing processes are the major processes within the aquifer system. In terms of quality, the groundwater needs treatment because of the high concentrations of iron to

achieve suitability for drinking. It is also could be considered safe for irrigation and for livestock and poultry. Finally, the corrosive tendency of groundwater on metallic pipes was evaluated, showing that 75% of the samples taken from the shallow zone are safe, while 42.8% of the representative samples taken from the deep zone could be considered safe.

Acknowledgements

The authors would like to thank the Geology Department, Faculty of Science, Cairo University

Appendix 1. SAR, KR, RSC, Mg ratio, and CR of groundwater samples of the shallow and deep zones.

Aquifer	Sample No.	SAR	KR	RSC	Mg ratio (%)	CR	
Deep	1	0.94	0.60	-0.31	39.74	1	
	2	0.81	0.50	-0.34	38.21	0.91	
	3	2.26	0.88	-1.23	37.06	1.68	
	4	0.86	0.53	-0.20	37.91	0.71	
	5	1.10	0.78	-0.13	40.72	0.83	
	6	1.19	0.71	-0.30	40.66	0.95	
	7	0.96	0.67	-0.18	39.36	0.84	
	8	1.40	0.94	-0.24	37.06	1.26	
	9	1.38	0.84	-0.31	36.78	1.16	
	10	1.30	0.78	-0.36	35.47	1.15	
	11	1.39	0.82	-0.41	40.44	1.28	
	12	1.42	0.83	-0.44	39.07	1.3	
	13	1.17	0.68	-0.47	39.07	1.19	
	14	1.38	0.84	-0.28	36.78	1.08	
	16	1.47	0.83	-0.15	36.59	0.89	
	17	1.44	0.95	-0.12	36.10	1.1	
	18	1.03	0.64	-0.33	32.05	0.98	
	21	1.07	0.60	-0.52	30.89	1.09	
	22	1.08	0.67	-0.31	38.21	1.04	
	23	1.45	1.004	-0.19	11.55	1.15	
	24	0.99	0.63	-0.16	33.08	0.75	
		Min.	0.81	0.50	-1.23	11.55	0.71
		Max	2.26	1.00	-0.12	40.72	1.68
		Average	1.24	0.75	-0.33	36.04	1.06
Shallow	15	1.07	0.62	-0.40	33.59	0.99	
	19	1.03	0.61	-0.23	40.44	0.84	
	20	2.70	1.045	-1.13	37.06	1.76	
	25	0.96	0.48	-0.33	32.82	0.68	
	Min.	0.96	0.48	-1.13	32.82	0.68	
	Max	2.70	1.05	-0.23	40.44	1.76	
	Average	1.44	0.69	-0.53	35.98	1.07	

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العمليات الهيدروجيوكيميائية وتقييم جودة المياه الجوفية لنظام خزان الحجر الرملي النوبي في واحة الفرافرة، مصر

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**معهد بحوث المياه الجوفية، المركز القومي لبحوث المياه، القناطر الخيرية، مصر.

على الرغم من مناخها الجاف، تعد الصحراء الغربية المصرية منطقة واعدة للتنمية حيث تعتمد على المياه الجوفية، وخاصة مياه نظام طبقات الحجر الرملي النوبي. ركز هذا المقال على الوضع الهيدروجيوكيميائي في الجزء الشمالي الشرقي من واحة الفرافرة. تم جمع عينات المياه الجوفية وتحليلها من النطاقات الضحلة والعميقة للخزان الجوفي النوبي. وتم إجراء تقييم هيدروجيوكيميائي اعتمادًا على التحليلات الإحصائية والمخططات المرسومة ذات المتغيرين. بالإضافة إلى ذلك، تم استخدام مخططات بايبر، و داروف، و ستيف.

كشفت نتائج تحليل العوامل للمياه الجوفية في النطاق العميق عن خمسة عوامل مؤثرة مسؤولة عن معظم التباين بين العينات بنسبة تقارب ٦٨ ٪ من الاختلاف. تتحكم العوامل الجيولوجية في التركيب الأيوني للمياه الجوفية، مع تداخل طفيف للتأثيرات البشرية. من ناحية أخرى، تشير المخططات الهيدروجيوكيميائية للمياه الجوفية الخاصة بالنطاقين الضحل والعميق إلى أن العمليات السائدة التي تتحكم في كيميائية المياه هي تجوية السيليكات بجانب الذوبان المحتمل داخل تكوينات الحجر الجيري التي تملأ النظام النوبي. أما من حيث جودة المياه، فتحتاج المياه الجوفية في منطقة الدراسة إلى معالجة حتى تصبح صالحة للشرب وذلك نتيجة للتركيز العالي لعنصر الحديد، لكنها أظهرت ملاءمة عالية للري والثروة الحيوانية والدواجن.