Hydrochemical and multivariate analysis of groundwater quality in the northwest of Sinai, Egypt

M. F. El-Shahat, M. A. Sadek, W. M. Salem, A. A. Embaby and F. A. Mohamed

ABSTRACT

The northwestern coast of Sinai is home to many economic activities and development programs, thus evaluation of the potentiality and vulnerability of water resources is important. The present work has been conducted on the groundwater resources of this area for describing the major features of groundwater quality and the principal factors that control salinity evolution. The major ionic content of 39 groundwater samples collected from the Quaternary aquifer shows high coefficients of variation reflecting asymmetry of aquifer recharge. The groundwater samples have been classified into four clusters (using hierarchical cluster analysis), these match the variety of total dissolvable solids, water types and ionic orders. The principal component analysis combined the ionic parameters of the studied groundwater samples into two principal components. The first represents about 56% of the whole sample variance reflecting a salinization due to evaporation, leaching, dissolution of marine salts and/or seawater intrusion. The second represents about 15.8% reflecting dilution with rain water and the El-Salam Canal. Most groundwater samples were not suitable for human consumption and about 41% are suitable for irrigation. However, all groundwater samples are suitable for cattle, about 69% and 15% are suitable for horses and poultry, respectively.

Key words | Egypt, groundwater quality, multivariate analysis, northwestern Sinai

M. F. El-Shahat
Department of Chemistry, Faculty of Science, Ain Shams University, Khalifa El-Maamon St., El-Qobba Bridge, Cairo 11566, Egypt

M. A. Sadek
W. M. Salem
F. A. Mohamed (corresponding author)
Nuclear and Radiological Regulatory Authority (ENRRA), Cairo, Egypt
E-mail: *chemfaten@gmail.com*

A. A. Embaby
Faulty of Science, Damietta University, Damietta El-Gadeeda City, Kafr Saad, Damietta 34511, Egypt

INTRODUCTION

Coastal areas are highly sensitive to natural or anthropogenic effects. The northwestern coast of Sinai (site of the study area; Figure 1) is home to many economic activities: industry, agriculture, tourism, fisheries, trading and other development programs.

Securing water resources of appropriate quantity and quality is of prime importance for development programs in this important sector. This emphasises the importance of evaluation of the sustainability, potentiality and vulnerability of water resources from a development perspective.

The annual rainfall in the study area is limited; it varies between 26 and 54.8 mm and the total quantity of rainfall generally increases northward (El-Sheikh 2008). The national project of the El-Salam Canal has been started and River Nile water is being carried to Sinai. According to the Ministry of Water Resources and Irrigation (1991, 2009) and Hafez (2005), it is expected that the Nile water supply to this area will not fulfill the requirements of all the planned projects. Therefore, the demand for freshwater supplies has accordingly increased and attention is focused on groundwater utilization as an alternative or additive to rainfall.

The quality of groundwater resources in coastal zones is affected by many constraints (natural and/or anthropogenic). These include seawater intrusion, rock/water interaction, evaporation, irrigation return and drainage water effects, etc. Identifying the principal factors that control the salinity evolution and water quality aspects helps to achieve sustainable use of coastal resources.

This paper describes the prevailing groundwater conditions in the northwestern coastal zone of Sinai and

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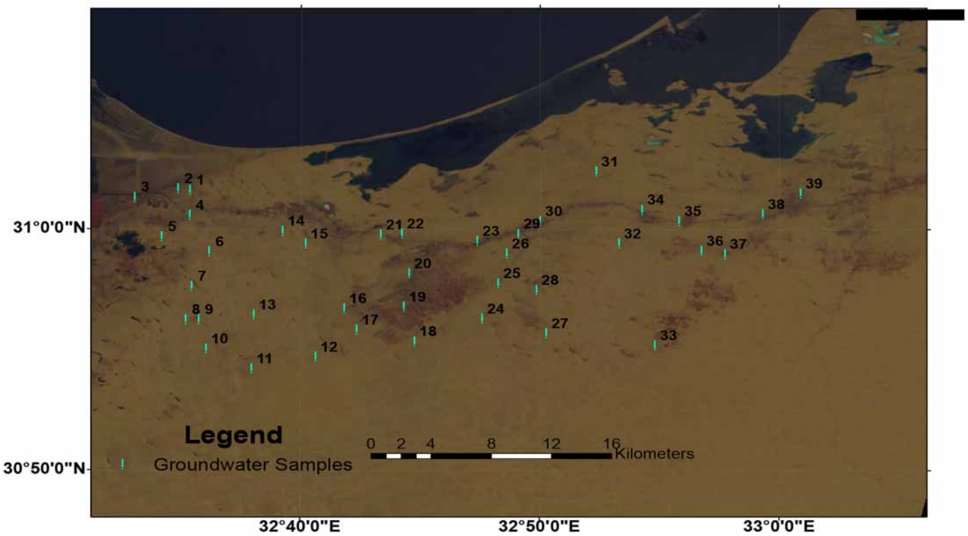

Figure 1 | Location map of the collected groundwater samples, northwest Sinai.

explores the attributes of water quality and the controlling processes. The chemometric multivariate analysis has been performed to define the principal water quality components that account for much of the variability in the system under study.

Study area

Geomorphologically, northwestern Sinai is characterized by the presence of a coastal plain, lakes such as Malaya and Al-Bardawil, salt marshes and Sabkha (salt flats) such as those located around Al-Bardawil Lake and Sahel Al-Tina, and sand dunes (compiled after Elwan et al. 1983; Geological Survey of Egypt 1992; Yousef & El-Shenawy 2000). Figure 2 shows the distribution of the geomorphological features in the northwest of Sinai.

Geologically, northwestern Sinai is covered by Quaternary rocks around Pleistocene and Holocene (after Geological Survey of Egypt 1992), as shown in Figure 3.

Hydrogeologically, the Quaternary deposits constitute the major water-bearing formations in northwestern Sinai (Geological Survey of Egypt 1992). These deposits consist mainly of loose sands with a few clay intercalations. The groundwater exists under a free water table condition with the depth to water varying from 0.5 m in the northwest to 9.1 m in the southeast. The water table ranges from −3.7 to 10 mas (Embaby & El-Barbary 2011).

MATERIALS AND METHODS

Thirty-nine groundwater samples tapping the Quaternary aquifer were collected from the study area, as shown in Figure 1. These water samples were subjected to both field and laboratory analyses. The field analyses include electrical conductivity (EC) (μS/cm) and pH, which has been measured using an EC meter and a pH meter (Jenway, model 3150).

The laboratory analyses include the determination of major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, CO_3^{2-}, HCO_3^-, and SO_4^{2-}). Chloride, calcium, carbonate and bicarbonate were determined using a titrimetric method. Sulfate ion concentration was determined calorimetrically using the turbidity method (USEPA 1979) by UV/visible spectrophotometer. Sodium and potassium content were measured by flame photometer, according to Rhoades (1982).

The results of the chemical analysis are expressed in milligram per liter (mg/l). The multivariate statistical analyses of the chemical parameters were conducted using SPSS (software 22 version).

The GALDIT index has been combined with geographic information system (GIS) tool to evaluate the vulnerability of groundwater aquifer to seawater intrusion.

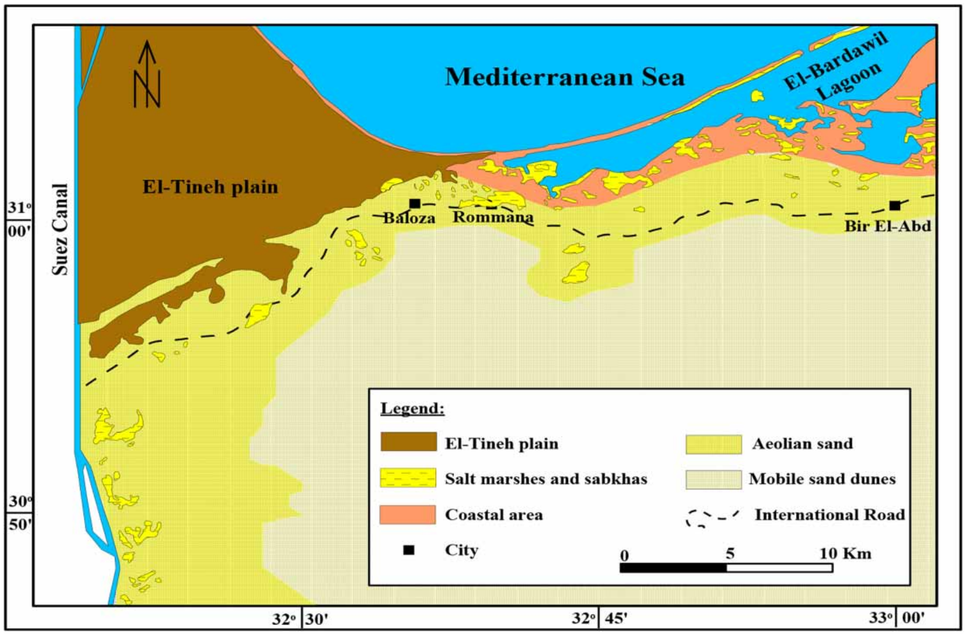

Figure 2 | Geomorphological map of northwestern Sinai (compiled after Elwan *et al.* 1983; Geological Survey of Egypt 1992; Yousef & El-Shenawy 2000).

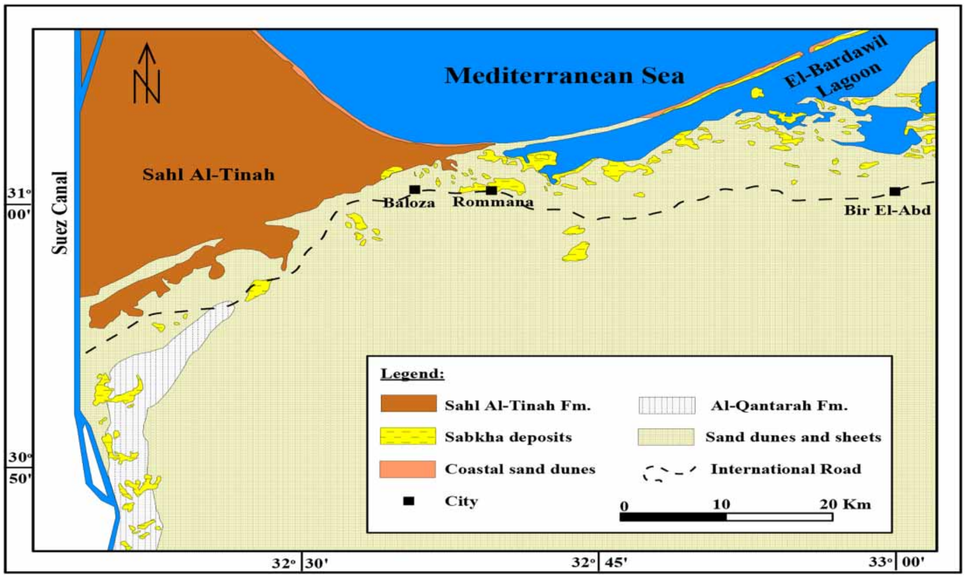

Figure 3 | Geological map of northwest Sinai, Egypt (after Geological Survey of Egypt 1992).

RESULTS AND DISCUSSION

Hydrochemical characterization

The results of hydrochemical analyses of the studied groundwater samples are shown in Table 1. These results have been statistically treated and their coefficient of variation are calculated. The coefficients of variation of the six hydrochemical parameters, Na^+, K^+, Cl^-, Ca^{2+}, Mg^{2+} and SO_4^{2-}, are equal to 0.63, 0.69, 0.53, 0.68, 0.73 and 0.49, respectively; these values are relatively high indicating heterogeneity in aquifer recharge and salinization processes.

Table 1 | Results of hydrochemical analyses of groundwater samples

ID	EC at 25 °C (mmohs/cm)	TDS (mg/l)	pH	K^+ (mg/l)	Na^+ (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^- (mg/l)
1	10.56	6,566	8.19	56.5	2,179	56	200	3,403	470	0	201
2	5.25	3,549	7.87	38.3	631	168	333	1,787	324	0	268
3	0.81	820	7.47	19.3	86	12	116	68	143	0	376
4	19.75	9,384	7.44	80.4	2,902	58	481	4,756	905	0	201
5	6.32	4,385	7.54	41.5	1,190	67	220	2,042	556	0	268
6	7.27	3,799	7.5	15.3	614	316	301	1,702	717	0	134
7	8.81	6,697	7.08	18.6	1,961	255	80	3,403	784	0	195
8	9.02	5,783	7.26	20	1,534	340	100	3,063	584	0	141
9	6.08	4,505	7.14	18.6	1,210	103	301	2,042	629	0	201
10	5.92	4,296	7.92	17.2	1,091	95	341	1,906	686	0	161
11	5.78	3,808	7.34	15.3	894	109	293	1,702	660	0	134
12	4.93	4,443	7.6	20.1	931	272	252	2,246	600	0	121
13	7.22	3,895	7.42	14.4	759	122	441	1,634	724	0	201
14	16.57	8,697	7	27.2	2,591	407	20	4,254	1,270	0	128
15	6.32	4,242	6.9	15.7	635	365	361	2,042	622	0	201
16	6.22	3,760	7.34	20	635	304	200	1,872	581	0	148
17	4.75	3,329	7.67	12.5	865	80	212	1,566	473	0	121
18	4.92	3,614	7.27	17.9	802	134	301	1,702	457	0	201
19	9.2	3,152	7.26	31.6	319	105	557	1,361	644	0	134
20	15.1	6,495	6.84	61.3	1,613	95	541	3,063	987	0	134
21	2.05	2,072	7.4	15.4	432	80	160	817	159	52.8	356
22	7.17	5,280	7.45	12.3	1,451	85	381	2,723	454	0	175
23	0.67	692	7.59	13.1	95	29	100	78	108	66	268
24	5	5,692	7.5	15.3	1,795	90	224	3,063	343	0	161
25	10.06	7,707	7.18	23.6	1,923	523	40	4,084	771	0	342
26	11.63	7,752	7.05	19.3	1,279	365	1,002	4,186	733	0	168
27	11.04	7,165	7.12	13.4	1,915	97	581	3,744	613	0	201
28	11.45	4,777	7.14	26.8	513	231	761	2,174	883	0	188
29	11.24	5,315	7.07	13.8	749	352	661	2,772	619	0	148
30	6.03	4,200	7.36	22.9	535	219	641	2,178	416	0	188
31	16.9	8,600	6.91	40.8	1,620	462	782	4,171	1,337	0	188
32	6.18	4,609	7.2	15	695	182	701	2,314	533	0	168
33	5.51	2,337	7.39	8.5	297	149	313	956	479	0	134
34	1.86	1,800	7.78	8.6	281	135	140	608	298	0	329
35	2.03	2,837	7.76	3.1	869	46	76	1,361	213	6	268
36	9.12	6,408	7.29	19.3	1,745	122	501	3,335	559	0	128
37	9.79	7,703	6.89	16.2	2,064	277	473	4,084	654	106	134
38	1.2	954	7.82	7.9	264	4	20	102	140	0	416
39	15.93	8,257	7.28	17.7	1,821	397	573	3,948	1,340	0	161

The results of chemical analysis have been used to identify the hydrochemical characteristics and salinization processes of the groundwater under study and to evaluate its quality aspects. The water types of the studied samples are classified into six major groups as follows.

Samples of Cl-Na, Cl-Ca, and Cl-Mg water types dominate 72%, 15.4% and 2.5%, respectively, of all samples and represent the highest mineralized water which may develop through leaching and dissolution of marine sediments, cation exchange and/or seawater intrusion.

Samples of HCO_3-Ca, HCO_3-Na, and SO_4-Na water types dominate a total of 10.1% of all samples; these are located in the renewable recharge area close to the irrigation canals.

The distribution of the points of the groundwater samples on a Piper diagram (Figure 4) shows that more than 90% of them occupy the zone of extremely high $SO_4 + Cl$ concentration with ratios of (Na/Ca + Mg) in the range of (20% to 80%). The remainder of the samples occupy a zone of more freshwater with HCO_3^- and Ca + Mg dominance.

Multivariate statistical analysis

Real hydrochemical data often contain some less important parameters besides the ones which encode important information about the quality (Malinowski & Howery 1980; Malinowski 1991; Lavine 2000; Jolliffe 2002; Praus 2005). Multivariate statistical analysis of the chemical analysis data has been conducted using SPSS program Version 22.0. This helps to infer the principal parameters that control the salinity and the quality of the groundwater under study.

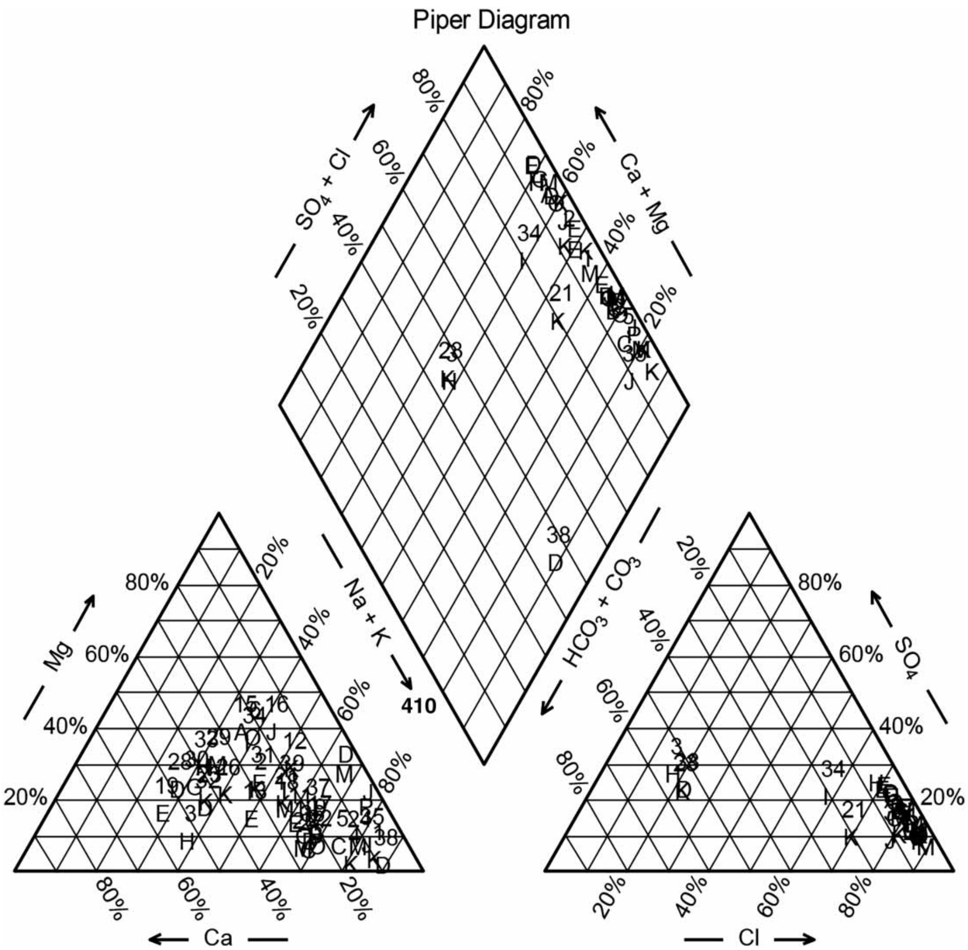

Figure 4 | The distribution of groundwater samples on a Piper diagram.

Hierarchical cluster analysis

The studied groundwater samples have been classified according to the proximity of the water quality parameters into four major clusters, A, B, C and D (Figure 5). These comprise the samples numbers A = (3, 23, 38, 21, 34, and 33), B = (5, 9, 10, 12, 15, 30, 28, 32, 6, 16, 11, 13, 2, 18, 17, 19, 35), C = (1, 7, 20, 36, 8, 24, 22, and 29) and D = (4, 14, 31, 39, 25, 37, 27, and 26). The clustering of these samples is based on total dissolved solids (TDS) and ionic composition which are controlled by hydrogeochemical and physicochemical conditions. The TDS (ppm) of A, B, C and D clusters vary in the ranges (692–2,337), (2,837–4,777), (5,280–6,697) and (7,165–9,384), respectively. This is correlated with an increase of (Cl, Na) on account of (SO_4, Ca) and (HCO_3, Ca) from A to B to C to D.

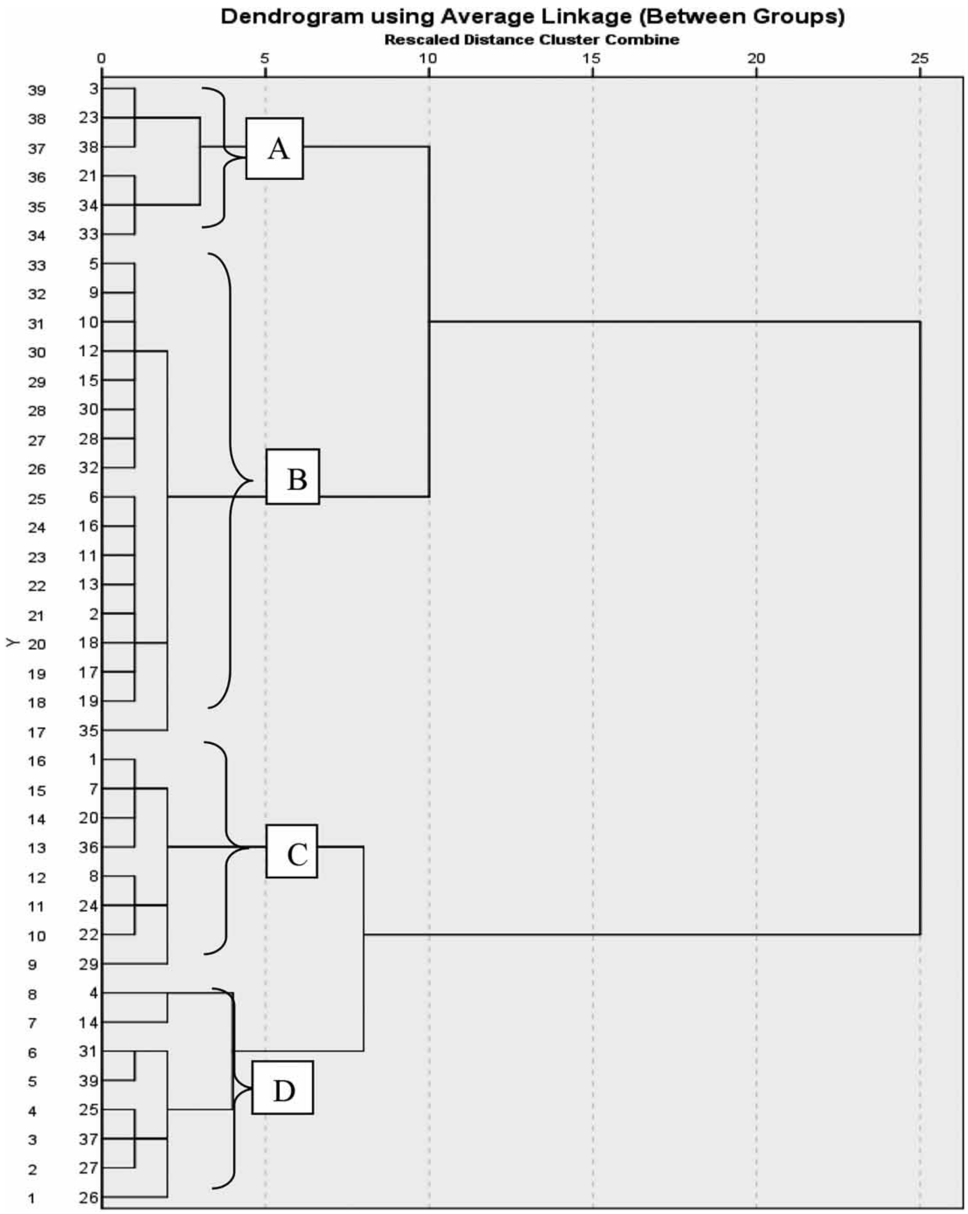

Figure 5 | Hierarchical clustering analysis of groundwater samples in the study area.

Principal component analysis

Two principal components have been defined as best descriptors of the variability of chemical composition of the groundwater samples under study. These express about 72% of the variance as indicated in Table 2.

The first component represents about 56% of the variance and combines the chemical variables TDS, Cl, SO_4, Na and Ca; the second component represents about 15.8% of the variance and combines K, Na and HCO_3. The weighting values of the specific parameters on the corresponding principal component are indicated in Table 3. These values represent their effective role on the ionic composition and water quality. The salinization processes that could contribute to the distribution of the first component parameters are evaporation, leaching/dissolution of marine salts and seawater intrusion, while dilution with rain water and the El-Salam Canal could be responsible for the second component.

Salinization processes

The general geochemical features of the studied groundwater samples and the chemometric multivariate analysis highlighted the possible salinization processes that might contribute to salt composition and water quality. To put more emphasis on this subject, three mechanisms of salinization have been checked as outlined below.

Dissolution/precipitation processes

To determine the possibility of dissolution/precipitation on salinization processes in the study area, the saturation index of the groundwater samples with respect to the relevant salts in the system (calcite, dolomite, anhydrite, halite and gypsum) has been calculated using the SOLMINEQ program (SOLMINEQ.GW 1999).

Table 4 reveals that about 90% of the groundwater samples are oversaturated with respect to dolomite and calcite, reflecting a tendency for precipitation. On the other hand, the groundwater samples are undersaturated with respect to gypsum, anhydrite and halite, reflecting a tendency for continuing dissolution of these salts from the aquifer matrix.

For further insights into dissolution of gypsum, anhydrite and halite, the relationships of Na^+ vs Cl^-, and Ca^{2+} vs SO_4^{2-}, have been constructed as shown in Figures 6 and 7. These show quite a direct distribution with high correlation indicating that the dissolution of both halite and gypsum could contribute to the groundwater salinization. The sample points show some deviation below the 1:1 line in the Na^+ vs Cl^- relationship in Figure 6 and above the 1:1 line in the Ca + Mg relationship in Figure 7. This might be attributed to the cation exchange process which will be discussed in the next section.

Ion exchange reaction

Ion exchange reactions involve the replacement of one ion for another at the surface of a particle in the hydraulic

Table 2 | Total variance explained

	Initial eigenvalues			Extraction sums of squared loadings		
Component	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	4.485	56.067	56.067	4.485	56.067	56.067
2	1.266	15.825	71.892	1.266	15.825	71.892
3	0.952	11.903	83.795			
4	0.646	8.080	91.876			
5	0.445	5.560	97.436			
6	0.203	2.537	99.973			
7	0.002	0.026	100.000			
8	8.275×10^{-6}	0.000	100.000			

Extraction method = Principal component analysis.

Table 3 | Component matrix[a] of the chemical data

	Component	
	1	2
TDS	**0.975**	0.126
K	**0.509**	**0.589**
Na	**0.827**	**0.457**
Mg	**0.599**	−0.464
Ca	**0.480**	−0.492
Cl	**0.960**	0.119
SO_4	**0.867**	−0.172
HCO_3	−0.573	**0.439**

[a]Two components extracted from matrix; Extraction method = Principal component analysis; Loadings greater than 0.3 are in bold.

system. Clay minerals have negatively charged surfaces, so they attract cations to balance the electrical charge and maintain electrical neutrality. The ion exchange process was checked by plotting a relation between ($Ca^{2+} + Mg^{2+} - SO_4^{2-} - HCO_3^-$) against ($Na^+$-$Cl^-$) (Jankowski *et al.* 1998; Figure 8). The water samples were plotted on a line of a slope equal −1 in the upper left square of the figure. This indicates that the Quaternary groundwater samples are affected by reverse ion exchange reactions where saline water invades fresh water in the aquifer leading to sodium adsorption and Ca and Mg release.

Seawater intrusion

To check the potential of seawater intrusion as a salinization process acting on the groundwater under study, the GALDIT index (Chachadi & Lobo-Ferreira 2001), one of the weighting/rating driven indicators, has been used. It is determined based on six hydrogeochemical, hydrogeological and physical parameters inherent in the groundwater system. These parameters are as follows: (i) groundwater occurrence (aquifer type; unconfined, confined and semi-confined); (ii) aquifer hydraulic conductivity; (iii) the level of groundwater relative to sea level; (iv) distance from the shore (distance inland perpendicular from the shoreline); (v) impact on existing status of seawater intrusion in the area; and (vi) the thickness of the aquifer being mapped.

Table 4 | Saturation indices of collected groundwater samples using (SPSS 22 software)

Sample ID	Anhydrite	Calcite	Dolomite	Gypsum	Halite
1	−1.453	0.929	2.653	−1.166	−3.884
2	−1.276	1.03	3.103	−0.988	−4.662
3	−1.629	0.548	1.431	−1.339	−6.847
4	−0.937	0.511	1.453	−0.651	−3.649
5	−1.222	0.517	1.852	−0.934	−4.339
6	−1.053	0.287	1.928	−0.765	−4.709
7	−1.679	−0.585	0.676	−1.392	−3.937
8	−1.694	−0.433	1.01	−1.406	−4.081
9	−1.075	0.117	1.104	−0.787	−4.338
10	−0.977	0.834	2.446	−0.688	−4.411
11	−1.009	0.22	1.341	−0.721	−4.539
12	−1.176	0.301	1.972	−0.888	−4.416
13	−0.911	0.351	1.477	−0.623	−4.628
14	−2.413	−1.288	0.084	−2.127	−3.738
16	−1.267	0.141	1.798	−0.978	−4.65
17	−1.165	0.394	1.694	−0.877	−4.579
18	−1.147	0.059	1.102	−0.858	−4.58
19	−0.75	0.347	1.298	−0.461	−5.075
20	−0.751	−0.172	0.24	−0.464	−4.069
21	−1.703	0.593	2.219	−1.414	−5.123
22	−1.153	0.454	1.599	−0.865	−4.144
23	−1.826	0.634	2.055	−1.537	−6.744
24	−1.504	0.244	1.439	−1.216	−4.003
25	−2.082	−0.583	1.299	−1.796	−3.882
26	−0.753	0.345	1.606	−0.466	−4.056
27	−0.953	0.314	1.199	−0.666	−3.912
28	−0.633	0.434	1.687	−0.345	−4.699
29	−0.893	0.192	1.458	−0.605	−4.438
30	−0.988	0.615	2.108	−0.7	−4.668
31	−0.63	0.125	1.368	−0.344	−3.964
32	−0.859	0.434	1.626	−0.571	−4.534
33	−1.05	0.275	1.556	−0.761	−5.238
34	−1.502	0.751	2.815	−1.212	−5.435
35	−1.929	0.385	1.886	−1.641	−4.614
36	−1.027	0.24	1.213	−0.74	−3.994
37	−1.077	0.21	1.54	−0.79	−3.852
38	−2.368	0.175	0.973	−2.078	−6.184
39	−0.73	0.305	1.795	−0.443	−3.932

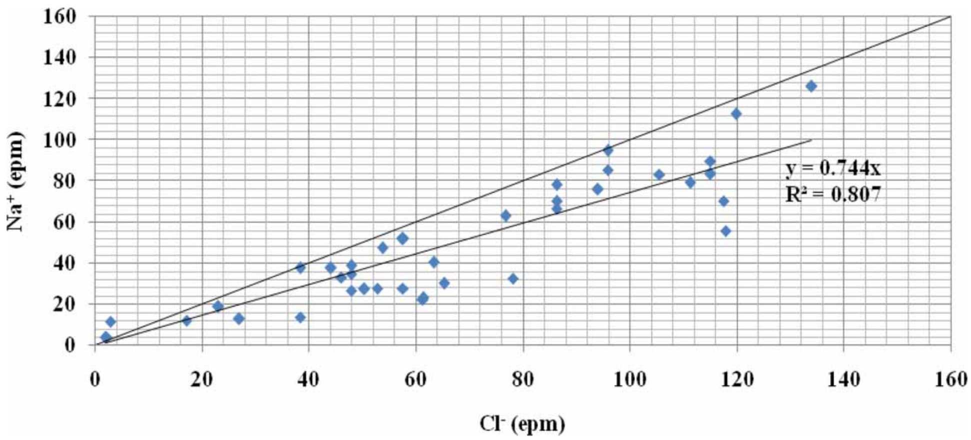

Figure 6 | Na^+ vs Cl^- relationship.

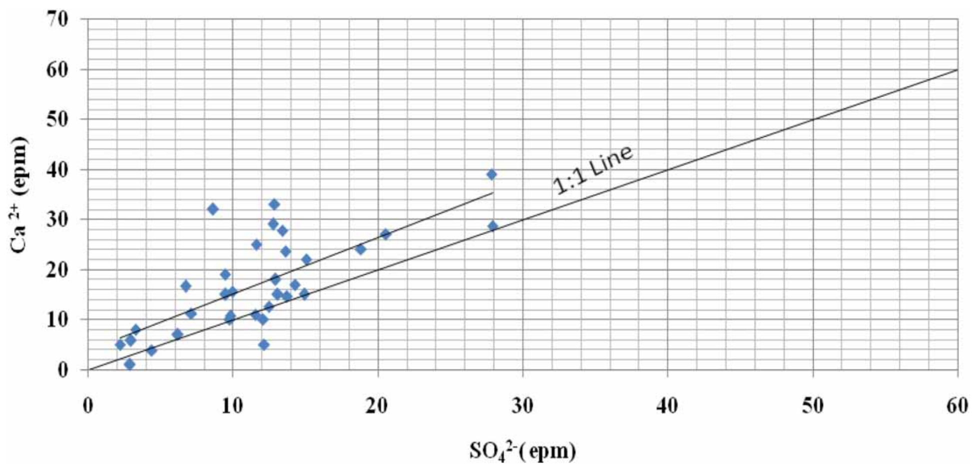

Figure 7 | Ca^{2+} vs SO_4^{2-} relationship.

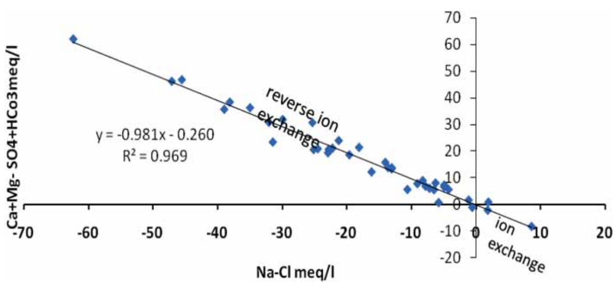

Figure 8 | Relationship between Ca + Mg-HCO_3-SO_4 versus Na-Cl for the Quaternary aquifer samples.

Each of the indicated factors has been assigned a weighting and rating scores as indicated in Table 5. Based on the values of these scores an overall GALDIT index is calculated as follows:

$$\text{GALDET} = \frac{(W1*GR) + (W2*AR) + (W3*LR) + (W4*DR) + (W5*IR) + (W6*TR)}{\sum_{i=1}^{6} Wi} \quad (1)$$

where W1–W6, and GR, AR, LR, DR, IR and TR are the weighting and rating values of the six parameters, respectively. The classification of groundwater vulnerability according to the ranges of GALDIT index is indicated in Table 5.

The data required for calculating the GALDIT index has been explored from 24 wells distributed across the study area. The (GIS) tool has been used for constructing thematic maps for different parameters of the index and

Table 5 | Rating and weighting values of different hydrogeological parameters according to their relative importance (Chachadi & Lobo-Ferreira 2001)

Indicator	Weight	Indicator variables: Class	Range	Rating
Groundwater occurrence/aquifer type	1	Confined		10
		Unconfined		7.5
		Leaky confined		5
		Bounded confined (Recharge and or impervious boundary aligned		2.5
Aquifer hydraulic conductivity (m/day)	3	High	>40	10
		Medium	10–40	7.5
		Low	5–10	5
		V. low	<5	2.5
Height of groundwater level (amsl)(m)	4	High	<1	10
		Medium	1–1.5	7.5
		Low	1.5–5	5
		V. low	>5	2.5
Distance from shore/high tide (m)	4	V. small	<500	10
		Small	500–750	7.5
		Medium	750–1,000	5
		Fair	>1,000	2.5
Impact status of existing sea water intrusion	1	High	>2	10
		Medium	1.5–2	7.5
		Low	1–1.5	5
		V. low	<1	2.5
Saturated aquifer thickness (m)	2	High	>10	10
		Medium	7.5–10	7.5
		Low	5–7.5	5
		V. low	<5	2.5

superimposing them as layers to derive the final map. The following reviews the explored data and the corresponding rating of the GALDIT index in the study area. (i) *Groundwater Occurrence* in the studied aquifer is mainly under unconfined conditions which give more opportunities for seawater intrusion than confined and semi-confined. According to Table 5, the rating score assigned to the groundwater occurrence in the study area is 7.5. (ii) *Aquifer Hydraulic Conductivity* has a high influence on the magnitude of seawater front movement; the higher the conductivity is, the higher is the inland movements of the seawater front. The hydraulic conductivity that corresponds to the lithologic composition of the water-bearing formation in the study area has values from 3 m/day at the west (at El-Tina Plain) to about 10 m/day at Bir El-Abd, (Omar 2011). The rating of this parameter is illustrated in Figure 9. (iii) *The level of groundwater above sea level* is a very important factor in evaluating seawater intrusion because it determines the availability of hydraulic pressure to push the seawater front back. The ground water level from Embaby & El-Barbary (2011) assigns the rating values shown in Figure 9. (iv) *Distance from the shore* of the sampled groundwater wells assigns an average rating value of about 2.5. (v) *Impact on the existing status of seawater intrusion*: Chachadi & Lobo-Ferreira (2001) recommended using the ratio of $Cl^-/[HCO_3^- + CO_3^{2-}]$ as the criterion to evaluate the impact of the existing status of seawater intrusion into the coastal aquifers. The results of the hydrochemical analysis of the collected groundwater samples have been used to calculate the ratio of $Cl^-/[HCO_3^- + CO_3^{2-}]$. The corresponding cartographic rating assigned the spatial distribution of the calculated ratio is indicated in Figure 9. (vi) *The thickness of the aquifer being mapped*: the thickness of the shallow unconfined aquifer in the study area ranges from 5 to 50 m. The rating of this parameter is illustrated in Figure 9.

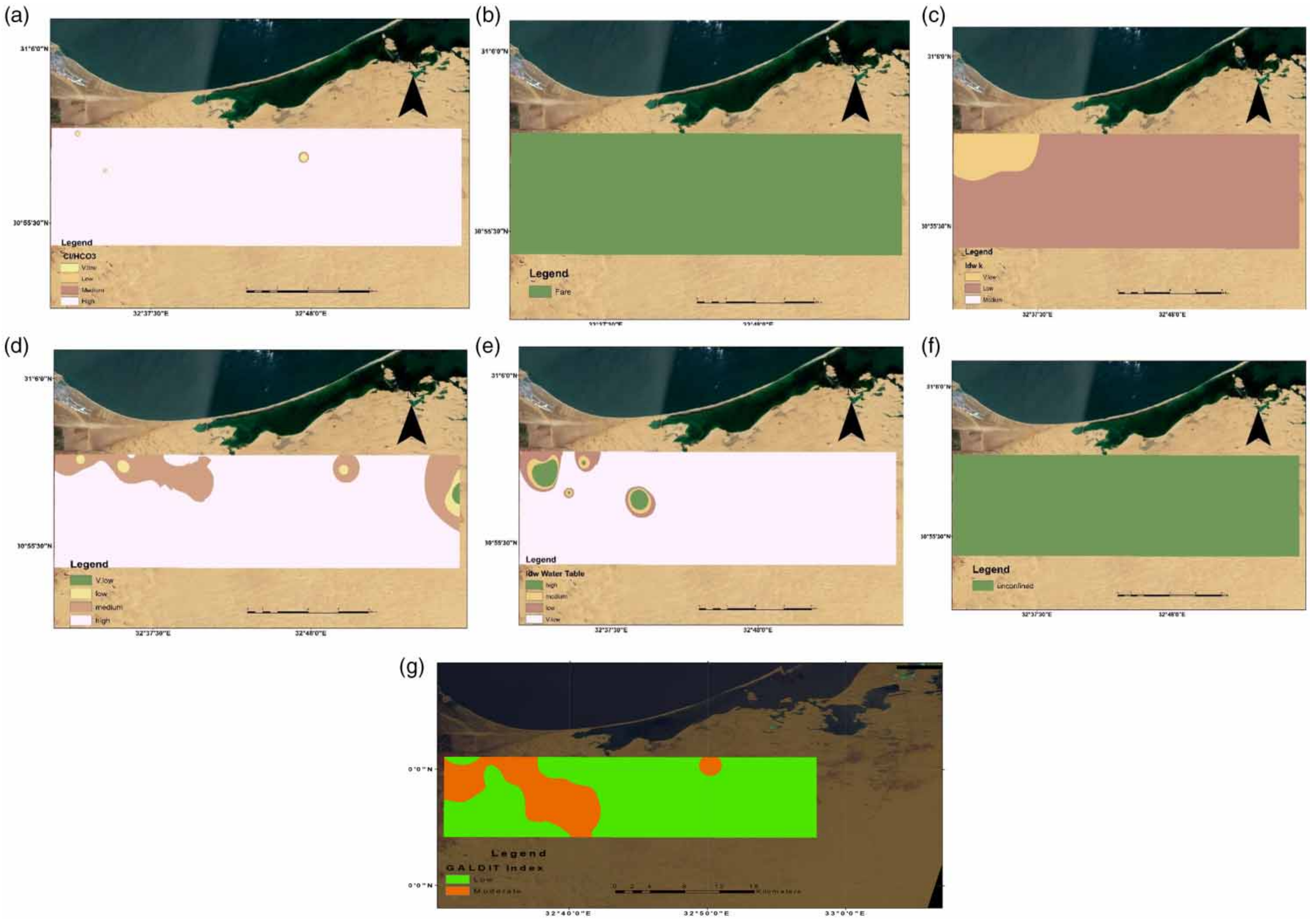

Figure 9 | GALDIT result: (a) impact status of existing seawater intrusion; (b) distance from shore; (c) aquifer hydraulic conductivity (m/day); (d) height of groundwater level (amsl)(m); (e) saturated aquifer thickness (m); (f) groundwater occurrence/aquifer type; (g) GALDIT index.

The overall GALDIT index has been calculated using Equation (1). It has been used to classify the study area according to its vulnerability to seawater intrusion. The computed GALDIT index of the studied groundwater samples has values in the range 2.5–7.5 (Figure 9). Based on Table 6, about 71% of the study area is of low seawater intrusion vulnerability and about 29% is of medium seawater vulnerability as a result of marine water associating Sabkha.

Table 6 | Rating and weighting values of different hydrogeological parameters according to their relative importance

GALDIT index range	Vulnerability classes
>7.5	High vulnerability
5–7.5	Moderate vulnerability
<5	Low vulnerability

Water quality evaluation

The evaluation of groundwater quality for various uses (drinking by both humans and livestock, as well as irrigation) is mainly based on TDS and major ions concentration in comparison with the recommended limits given in the standards for the different uses.

Evaluation of groundwater for drinking by humans

According to the Egyptian standards for drinking and domestic uses adapted from Higher Committee for Water (1995) (Table 7), about only 10% of the collected groundwater samples can be used for human drinking and the rest can not be used because their TDS and major ion concentrations exceed the permissible limits.

Table 7 | Egyptian standards for drinking and domestic uses

Chemical constituent	Max. permissible limit in mg/l
Calcium	200
Chloride	500
Hardness as $CaCO_3$	500
Magnesium	150
Nitrate	10
TDS	1,200
Sodium	200
Sulphate	250–400
pH	6.5–9.2

Evaluation of groundwater for drinking by livestock and poultry

Water to be used for livestock and poultry is subject to quality limitations like those for human consumption. According to the upper limits of concentration for stock and poultry water, shown in Table 8, it appears that nearly all the groundwater samples in the studied area are suitable for the drinking by cattle (dairy) and about 69% and 15% are suitable for horses and poultry, respectively.

Water quality for irrigation

Water quality index (WQI) is a valuable and unique rating to depict the overall water quality status in a single term that is helpful for the selection of an appropriate treatment technique to meet the issues concerned (Chowdhury *et al.* 2012). An attempt has been made to use the calculated WQI values for irrigation suitability. In this study, WQI input on overall water quality deteriorations was used to achieve the pre-planned goals of this study (Rao *et al.* 2010; Balan *et al.* 2012).

Table 8 | TDS limits for water that can be used for drinking by livestock and poultry (McKee & Wolf 1963)

Type of animal	TDS (mg/l)
Poultry	2,860
Horses	6,335
Cattle (dairy)	7,150
Cattle (beef)	10,100
Sheep (adult)	12,900

WQI was based on seven important physicochemical parameters (Table 9). WQI was calculated by using the recommended standards of irrigation using the following equation:

$$Q_i = \left[\frac{V_n - V_i}{V_S - V_i}\right] \times 100 \tag{2}$$

where Q_i is the quality rating of the *i*th parameter for a total of (n) water quality parameters, V_n represents values of the water quality parameter obtained from the laboratory analysis, V_i represents the ideal value of the parameter [$V_i = 0$, except for pH ($V_i = 7$) and DO ($V_i = 14.6$ mg/l)], and V_s represents values of the water quality parameter obtained from the recommended standard.

Then, the relative (unit) weight (W_i) was calculated to be a value inversely proportional to the recommended standard (S_i) for the corresponding parameter using the following relation,

$$W_i = \frac{K}{S_i} \tag{3}$$

where W_i is the relative (unit) weight for the *n*th parameter, S_i is the recommended standard values for the *n*th parameter (as described in the Quality rating calculation equation), and

K is a constant of proportionality calculated using the equation,

$$K = \frac{K}{\Sigma 1/Vs}. \tag{4}$$

Table 9 | Selected variables used in the WQI calculation and their recommended values (Rown *et al.* 1972)

Variables	Maximum recommended values	W_i
TDS (mgl/L)	2,000	0.00041
EC (μS/cm)	2,250	0.00037
SAR	26	0.03185
Hardness	100	0.00828
pH	6.5–8.5 (7.5)	0.11040
Ki	1	0.82799
Na%	40	0.02070
	sum of W_i	1.00000

Table 10 | WQI categories and their classifications (Rown et al. 1972)

WQI	Classification
<50	Excellent
50–100	Good
100–200	Poor
200–300	Bad
>300	Unfit

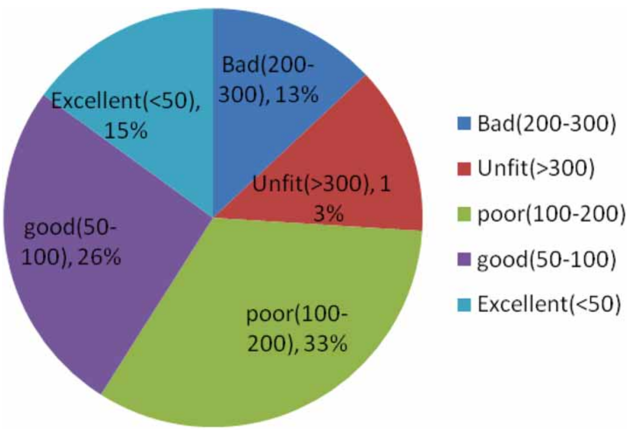

Figure 10 | WQI classification for irrigation.

Thus, the relative (unit) weights (W_i) to various water quality parameters are inversely proportional to the recommended standards for the corresponding parameters.

Finally, the overall WQI was calculated by aggregating the quality rating with the unit weight linearly by using the following equation:

$$WQI = \frac{\sum Q_i W_i}{\sum W_i} \quad (5)$$

where Q_i is the quality rating and W_i is the relative weight.

Based on Table 10, the calculated values of WQI in this study were compared with the prescribed standards to show the water quality condition for agriculture purpose as represented in Figure 10.

CONCLUSION

The quality of groundwater resources in the study area is stressed by both natural and anthropogenic constraints. The hydrogeochemical characteristics of the system, and multivariate statistical analysis have been used to explore the water quality and salinization processes of groundwater resources in the northwest of Sinai. It has been concluded that the the water with the highest mineralization is primarily developed through leaching and dissolution of marine sediments, cation exchange with a small contribution from marine water associating Sabkha. The water quality of the study area is generally not suitable for human drinking, although this water can be used for livestock and poultry drinking and for irrigation purposes with some limitations.

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