

An overview of phosphate rocks and their mining impact on groundwater, Eastern Desert, Egypt

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Abstract The Eastern Desert of Egypt represents a remote arid area which is scarce in water resources. The area is characterized by many mining sites to exploit the phosphate deposits; thus, these activities can generate groundwater contaminants. The main objective of the present study is discussing the effect of the mining activities and phosphate bearing rocks on groundwater. The obtained results pointed out that the water bearing formations can be distinguished as Quaternary alluvial, Oligocene sandstone, Campanian phosphate limestone (Duwi Formation), and Precambrian basement rocks. Some of the investigated groundwater shows relatively high concentrations of trace elements compared to other samples, such as Pb, Zn, Cu, Cr, Ni, and Sr. This is consistent with the analyses of phosphate rocks which are also enriched in the same trace elements. The high groundwater salinity is due to evaporation, limited re-charge, and leaching of salts in rocks. The results of speciation modeling reveal that majority of groundwater samples are supersaturated with calcite, aragonite, and dolomite, and some samples are also at equilibrium or supersaturated with hydroxyapatite. The groundwater quality in the study area evaluated for human drinking, livestock and poultry domestic, and industrial purposes is not suitable in most wells. It is obvious that the groundwater contamination occurs when drilling wells penetrate the phosphate bearing

beds and not only at mining activity sites. Therefore, it is recommended to avoid any groundwater exploration from the Duwi Formation and also select the drilling sites outside the mining areas.

Keywords Egypt · Eastern Desert · Groundwater · Phosphates · Mining · Contamination

Introduction

Phosphate rocks are mineral assemblages used mainly for manufacturing of fertilizers. They occur mostly not only in sedimentary marine deposits (about 75 %) but also in crystalline and biogenic rocks (Jiang et al. 2007). Principal minerals in phosphate deposits belong to the apatite group including fluorapatite [$\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$], hydroxyapatite [$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$], and carbonate hydroxyapatite [$\text{Ca}_{10}(\text{PO}_4, \text{CO}_3)_6(\text{OH})_2$]. They frequently have significant contents of trace elements such as Cd, Zn, and also U (Mar and Okazaki 2012). This means that the exploitation of phosphate deposits may cause contamination of surface and ground waters (da Silva et al. 2010).

Egypt can be described as a water-scarce country, due to its arid climate and the increasing population. The Red Sea coast received a great attention from the Egyptian Government, which wants to develop this area especially for tourist purposes; however, the water supplies are insufficient to meet the water demand requirements. The rapid growth of tourist activities along the Red Sea coastal area leads to an urgent need of suitable and safe water resource. One of the most important problems for any development in the Red Sea Coast is the groundwater contamination resulting from many mining sites to exploit the phosphate deposits and generate this contamination (Vandenhove 2002). The Campanian

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phosphatic deposits in Egypt, called the Duwi Formation, comprise a part of the extensive Middle East to North African phosphogenic province of Late Cretaceous Paleocene age (Baoumy and Tada 2005). These beds (Duwi Formation) rest with seeming conformity on the Nubia sandstones and are overlain by the deeper water marls and clay of the Dakhla Formation. The province holds some of the greatest accumulation of phosphorites in the world, possibly in excess of 70 billion metric tons (Cook and McElhinny 1979). The phosphate resources in Egypt exceed 3 billion metric tons (Notholt 1985), and their discovery dates back to the end of the nineteenth century (Hermina 1972). Stamatis et al. (2001) have reported high concentrations of heavy metals (lead, cadmium, zinc, nickel) in groundwater samples in the Lavrio area, Greece due to mining activities. Also, Beavers (2013) stated a contamination of phosphate mining in Florida including its potential effects on hydrology and water quality. The mining of phosphate ore in Angaur Island (one of Pacific Islands) created large water-table lakes, which became filled with brackish or saline water (Arnou 1961), where the hydrologic investigation pointed out that these activities caused a damage to agricultural lands and the water supply. Jirie et al. (2004) evaluated the effluent water produced by the washing process at the Al-Hisa and Al-Abyad phosphate mines in central Jordan. They reported that there was a significant difference in water chemistry between the background groundwater and the effluent water where little mixing was occurred.

Perhaps the most significant impact of a mining project is its effects on water quality and availability of water resources. Therefore, the main objective of the present study is to discuss the effect of the mining activities on the groundwater in the Eastern Desert of Egypt close to El Quseir City and to determine whether the quality of this water in the vicinities of the mining areas remains adequate to support native aquatic life and terrestrial wildlife.

The study area and data procedures

The study area is located in the central part of the Eastern Desert of Egypt, approximately 65 km southeast from Hurgada city and includes one of the important touristic cities along the Red Sea coast, El Quseir City (Fig. 1). It extends from 33° 45' to 34° 23' 18" E and from 25° 56' 45" to 26° 37' 30" N, covers about 3252 km², and belongs to the arid belt that dominates the Red Sea coastal zone of Egypt. The groundwater wells and the phosphates mines are located inside the following basins from north to south: Wadi Queh, Wadi El Nakhil, Wadi El Ambagi, Wadi Al Bayda, Wadi Kareem, and Wadi Zareib (Fig. 1). The area is characterized by hyper-arid climate, and it has a very dry summer and a relatively humid cold winter especially at night. It has yearly total

precipitation less than 20 mm, with erratic precipitation and high evaporation. The annual rainfall comes occasionally and for short periods as storms. The hydrogeology of the Eastern Desert is described by Gomaa (1992), El Ghazawi and Abdelbaki (1991), and El-Fakharany (1989). The mountainous area in the Eastern Desert is dissected by two sets of drainage lines, which conduct their water either to the Red Sea or to the Nile Valley. The Red Sea drainage set was included in the present study area. This drains the study area, which includes the major basins of Queh, Ambagi, and Zareib from north to south.

Field sampling

Fieldwork aimed to identify the geomorphological and geological setting of the study area. Forty sites of the study area were investigated in detail with regard to geology and one composite section at surface outcrops were measured and sampled. A total of 65 rock samples from different geological units were collected and described. The field data were used for an area-wide interpretation based on Landsat satellite images and geologic map (Conoco 1986). A survey of the existing water points was carried out, and groundwater samples were collected. Here, location (GPS), pH value, and electrical conductivity (EC) were measured in situ. In addition, hydrogeological data such as depth to water table, total well depth, and water-bearing formations, as well as corresponding geomorphological units, were also determined and measured. The locations of the current and old phosphate mining sites were extracted from the metallogenic maps of Qena and Aswan Quadrangle prepared by the Egyptian Geologic Survey and Mining Authority (EGSMA 1983, 1984). These locations were checked during the field investigations.

Remote sensing and GIS

Data from the Shuttle Radar Topography Mission (SRTM, 90 m; <http://seamless.usgs.gov>) was used along with GeoCover Landsat image mosaics (2000), obtained from NASA as compressed color imagery in MrSID TM file (<https://zulu.ssc.nasa.gov/mrsid/mrsid.pl>), and field investigations to demarcate the main landforms in the study area. All the data (DEM and satellite images) were projected to the Universal Transverse Mercator (UTM) system with WGS84 datum in a Geographic Information System (GIS) for further correlation of features. The satellite images were employed for visual interpretation of surface features and geology of the study area.

Landsat GeoCover ETM+ 2000, provided by the Global Land Cover Facility with spatial resolution 15 m, was used with the 1:500,000 scale geological map (Conoco 1986) to create an updated geologic map of the study area. Global land survey (GLS) Landsat (ETM+ 2010) created by the US

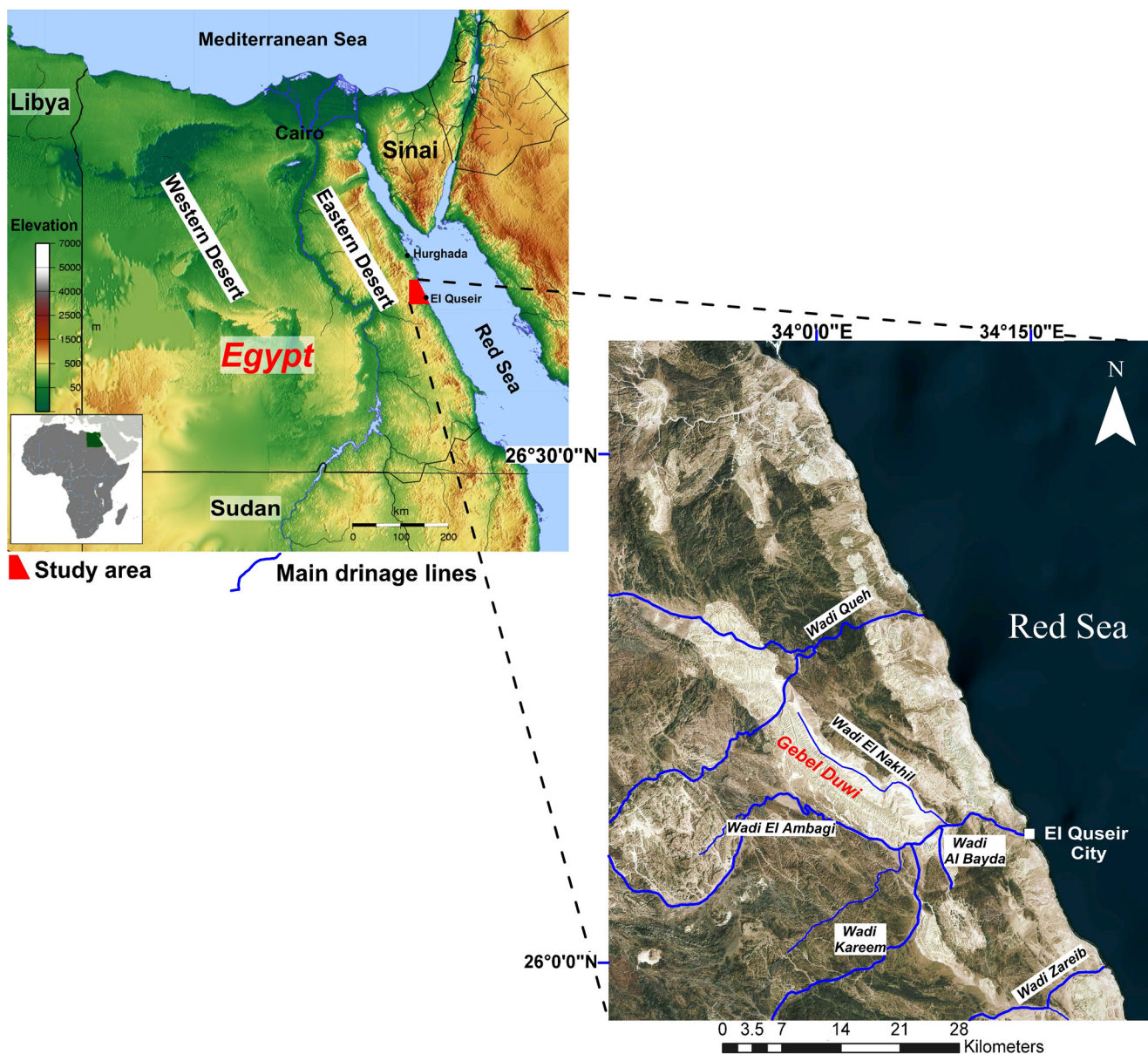


Fig. 1 Map of the study area

Geological Survey was used as a base map for the wells locations and geomorphology map. The interpretation of Landsat image was done by using ERDAS IMAGINE (ver. 9.3), where the images were first re-projected and subset to the study area, and then imported into the ESRI ArcMap GIS 10, where the spatial analysis of various data was carried out.

Chemical analysis

All groundwater samples were analyzed for major ions at the laboratory of the Desert Research Center (DRC, Cairo, Egypt), by ion chromatography (ICS-1100, Dionex, Sunnyvale, CA, USA). The analyzed major ions include sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺), magnesium

(Mg²⁺), carbonate (CO₃²⁻), bicarbonate (HCO₃⁻), chloride (Cl⁻), and sulfate (SO₄²⁻). Also, trace element concentrations (Al, B, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, V, and Zn) of the water samples were determined using atomic absorption spectrometry. The data obtained from the chemical analyses of major and trace elements were used as input data for geochemical modeling using the PHREEQC code (Parkhurst and Appelo 1999; USGS). The PHREEQC code was used to calculate saturation indices (SI) for minerals of interest. Saturation index determines whether a solution has thermodynamic potential for further dissolution or precipitation of a mineral. The saturation indices (SI) of relevant mineral are determined by the following equation: $SI = \log(IAP/K_T)$, where IAP is the ion activity products, and K_T is the solubility

product of a mineral for given temperature. The data of wells numbers (7 and 10; Tables 1, 2, and 3) were provided from the works of Abdalla and Khalifa (2013) which include chemical analyses and wells data. In addition, the data of trace elements (ppm) of Duwi Formation, Wadi Queh were obtained through their study (Tables 5 and 6).

Geology and mineralogy of the study area

The phosphorite ore deposits of Egypt are a part of the Mediterranean Phosphate Province, which extends from Morocco to Turkey and consists of strata deposited on the shallow Tethyan sea floor during Late Cretaceous and Early Tertiary time (Dabous 2003). The mineralogy of the Egyptian phosphorite deposits has been studied by many investigators (El Baz 1970; Abu-Zeid 1974; El Kammar 1974; Kamel et al. 1977; Dabous 1981; Sharafeldin 1999). The major phosphorite mineral is carbonate-fluorapatite (francolite). The non-phosphatic minerals are represented by dolomite, calcite, quartz, pyrite, goethite, gypsum, smectite, and kaolinite. The clay minerals associated with the Egyptian phosphorites occur mainly as a matrix or as a filling of the intergranular pores. Some clay minerals are also present as parts of the phosphatic pellets or as fillings of the cavity-like microstructures in the bone and teeth fragments. Smectite is the dominant clay mineral, followed by kaolinite, whereas illite and palygorskite are present in trace amounts (Sharafeldin 1999).

Changing climatic conditions over the last few million years in North Africa altered hydrological cycle episodically; for example, the Sahara Desert was fertile, with abundant lakes, streams, and shallow groundwater table only 8 ky ago (Said 1990; Dabous and Osmond 2001). Osmond et al. (1999)

and Dabous (2002) have identified a pattern of leaching and re-deposition associated with pluvial conditions in the uranium and iron deposits of the Egyptian Sahara. Dabous (2003) hypothesized that the same climatic events have caused the changes in water table and the remobilization of uranium in the phosphorites.

Geomorphologically, the study area can be divided into three units, namely the Red Sea terrains, the tableland, and the coastal plain and drainage basins (Badawy 2008) (Fig. 2). The Red Sea terrains represent the catchment area, where water flows toward the Red Sea. They range in elevation from 650 m to more than 1100 m above the mean sea level. Tablelands are located whether on the western border of the coastal plain or inland occupying the intermountain basins. Its elevation reaches about 400 m above sea level (a.s.l.) and has a general slopes varying between 5° and 25° and constituting cuestas, tabular mesas, and inselbergs. The coastal plain represents the eastern narrow strip of the study area and parallel to the Red Sea coast where it has NW-SE trend. Its elevation ranges between 0 m near the coastline and 95 m a.s.l at the footslopes of the Red Sea Mountains. Finally, the drainage basins in the study area are connected to the Red Sea where an exterior discharge occurs. Generally, drainage networks are much intense and convergent owing to geologic structure and consequent and obsequent wadis with dendritic and trellised patterns are common (Badawy 2008). Hamdan (1980) assumed that the Red Sea drainage system has been established during Pleistocene and Pliocene times, if not in Miocene, at the time when the old Nile valley was developed (Said 1993).

Geologically, the study area is dominated by a wide variety of rocks, i.e., the Precambrian basement rocks which are covered by Cretaceous, Tertiary, and Quaternary sediments.

Table 1 Hydrogeological data of the wells tapping the studied aquifers

Well no.	Well name	Long. (E)	Lat. (N)	Basin	Aquifer		Total depth (m)	Depth to water (m)	TDS mg/l
					Formation	Type			
1	Bir Al Bayda	34.15	26.07	Wadi Al Bayda	Alluvial	Hand dug	7.5	5.3	17,677
2	Nakheil 1	34.11	26.15	Wadi El Nakhil		Hand dug	5	3.75	3680
3	Nakheil 2	34.12	26.15			Hand dug	3	1.5	3924
4	Zareib 1	34.31	26.02	Wadi Zareib		Hand dug	14	11.8	14,129
5	Zareib 2	34.30	26.01			Hand dug	15	10.4	3550
6	Zareib 3	34.30	26.02			Hand dug	11	10.55	4649
7	Queh 1	33.98	26.32	Wadi Queh		Hand dug	13	11.5	1191
8	Nakheil 3	34.16	26.10	Wadi El Nakhil	Oligocene sandstone	Drilled	166	17.5	4731
9	Nakheil 4	34.15	26.11			Drilled	157	17	4241
10	Queh 2	34.09	26.35	Wadi Queh	Campanian Duwi	Bore hole	55	9	1237
11	Ain Al-Ghazal	34.19	26.11	Wadi El Ambagi	Precambrian basement	Spring	0	0	7649

Raw data for wells 7 and 10 (after Abdalla and Khalifa 2013)

Table 2 Chemical data (major and trace elements) of the investigated groundwater samples

Well no.	Aquifer	pH	EC μS/cm	TDS mg/l	Cation (mg/l)				Anion (mg/l)				T. H mg/l	SAR
					Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CO ₃ ²⁻	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻		
1	Alluvial	7.10	25,290	17,677	1500	727	3800	85	0	286	2811	8611	6733.1	20.14
2		6.60	5710	3680	231	83	1020	36	0	31	483	1813	917.8	14.65
3		7.80	5610	3924	371	172	760	21	0	110	1160	1385	1633.2	8.18
4		7.10	23,010	14,129	1239	549	2900	140	0	49	1973	7301	5349.6	17.25
5		7.40	5480	3550	273	166	780	31	0	73	753	1511	1364.0	9.19
6		7.10	7640	4649	536	204	800	57	0	61	1385	1637	2176.5	7.64
7		7.25	3080	1191	181	42	277	5	0	71	325	325	624	4.82
8	Oligocene	7.60	6830	4730	447	210	840	25	0	140	1451	1687	1979.1	8.21
9		7.27	7670	4241	422	210	834	27	0	113	467	2225	1917	8.29
10	Duwi	7.32	2750	1237	150	50	176	5	0	94	540	269	580	3.18
11	Basement	8.00	12,048	7649	800	284	1449	30	0	210	1802	3179	3164	11.2

T. H total hardness, SAR sodium adsorption ratio, trace element concentrations (mg/l)

According to the geologic map of the study area (Conoco 1986; Figs. 3 and 4), the measured composite section of Gebel Duwi and the works of Youssef (1957) and Said (1990), the general stratigraphy of the study area can be summarized from older to younger as follows: The Precambrian rocks which are forming a complex of igneous and metamorphic rocks; the Nubian sandstone (Taref Formation, Turonian-Santonian) built of sandstone with intercalations of mudstones; Duwi (phosphate) Formation (Campanian) which is made of limestone with phosphate horizons separated by beds of marl, shale, and oyster limestone (Fig. 4); Dakhla Formation (Maastrichtian-Paleocene) which is composed of marl and shale; Esna Formation composed of laminated shale with a middle limestone member; and Thebes Formation (Eocene) which consists of limestone and dolomitic limestone with flint.

Results

Hydrogeological setting

Investigations of the spatial distribution of the existing wells are important in the development of groundwater resources. Field survey of the groundwater wells indicated that they exist mainly at the downstream portion of the basins (Fig. 3). These basins are running through extensional fracture zones. The groundwater exploration of the study area is still very limited to only 10 wells, in addition to one spring (Table 1). The aquifers in the study area can be classified according to their stratigraphic position into Quaternary alluvial, Oligocene, Campanian, and Precambrian.

The alluvial aquifer has shallow groundwater occurs under free water table conditions where the total depth of shallow

Table 3 Chemical data of the investigated groundwater samples

Well no.	Al	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	Sr	V	Zn	U
1	0.03	2.06	0.001	0.001	0.02	0.010	0.030	0.004	0.003	0.0009	0.05	23.56	0.01	3.849	N/A
2	0.48	0.42	0.001	0.001	0.02	0.010	3.497	0.456	0.100	0.0009	0.01	5.72	0.01	0.542	N/A
3	0.28	0.66	0.001	0.001	0.02	1.598	0.779	0.366	0.029	0.0011	0.02	4.97	0.01	0.570	N/A
4	0.06	0.70	0.001	0.001	0.02	0.010	0.030	0.173	0.027	0.0037	0.02	6.76	0.01	0.015	N/A
5	0.06	0.67	0.001	0.001	0.02	0.010	0.030	0.003	0.035	0.0009	0.02	11.09	0.01	0.001	N/A
6	4.94	1.12	0.001	0.001	0.03	1.495	6.044	0.249	0.007	0.0130	0.05	10.40	0.02	3.141	N/A
7	N/A	N/A	0.001	0.001	0.04	1.700	0.260	0.800	N/A	0.0009	N/A	N/A	N/A	N/A	0.0003
8	0.06	0.60	0.001	0.001	0.02	0.010	0.030	0.002	0.041	0.0009	0.01	4.24	0.03	0.001	N/A
9	0.32	3.20	0.001	0.001	0.02	0.010	14.020	0.062	0.005	0.0009	0.00	8.94	0.01	0.009	N/A
10	N/A	N/A	0.001	0.001	0.04	2.300	0.220	0.500	N/A	0.0009	N/A	N/A	N/A	N/A	0.00004
11	0.02	0.27	0.001	0.001	0.02	0.010	0.030	0.002	0.056	0.0009	0.03	12.20	0.01	0.001	0.00476

Raw data for wells 7 and 10 (after Abdalla and Khalifa 2013) were provided from the works of Abdalla and Khalifa (2013) (see “The study area and data procedures” section) The U concentrations for well nos. 7, 10, and 11 (after Dabous 2003)

wells ranges from 3 to 13 m, while the depth to water table ranges between 1.5 and 11.5 m, and these wells are characterized by high salinity of groundwater (total dissolved solids (TDS) between 1191 and 17,677 mg/l), (Tables 1, 2, and 3). The Oligocene sandstone is penetrated by two wells (nos. 8 and 9) where the total depths range between 157 and 166 m and the water table depth varies from 17 to 17.5 m. The groundwater in this aquifer has TDS ranges between 4241 and 4731 mg/l (Tables 1, 2, and 3). The Campanian deposits which represented by Duwi Formation is penetrated by one well (no. 10) in Queh mining area (Table 1). The thickness of this water-bearing formation varies between 16 and 22 m (Gomaa 1992), and this aquifer can be classified as confined due to its position between clay and shale belonging to Maastrichtian-Paleocene at the top and shales belonging to upper Cretaceous at the bottom which act as non-permeable layers. The groundwater

in this aquifer is representing the main water supply source for all activities of phosphate mining carried out over the Eastern Desert. Finally, the metavolcanic basement rocks have one spring (TDS 7649 mg/l) called locally "Ain Al-Ghazal." This spring was created as a result to the role of fractures and joints which dissect the basement rocks.

Groundwater chemistry

The results of chemical analyses of water from the groundwater wells are listed in Tables 2 and 3. Groundwater in the study area can be classified as brackish in well nos. 2, 3, 5, 6, 7, 8, 9, and 10 and saline in well nos. 1, 4, and 11. The low TDS value of 1191 mg/l in well no. 7 might be due to its location close to the recharge area.

Fig. 2 Three-dimensional (3D) map showing the main geomorphologic units in the study area

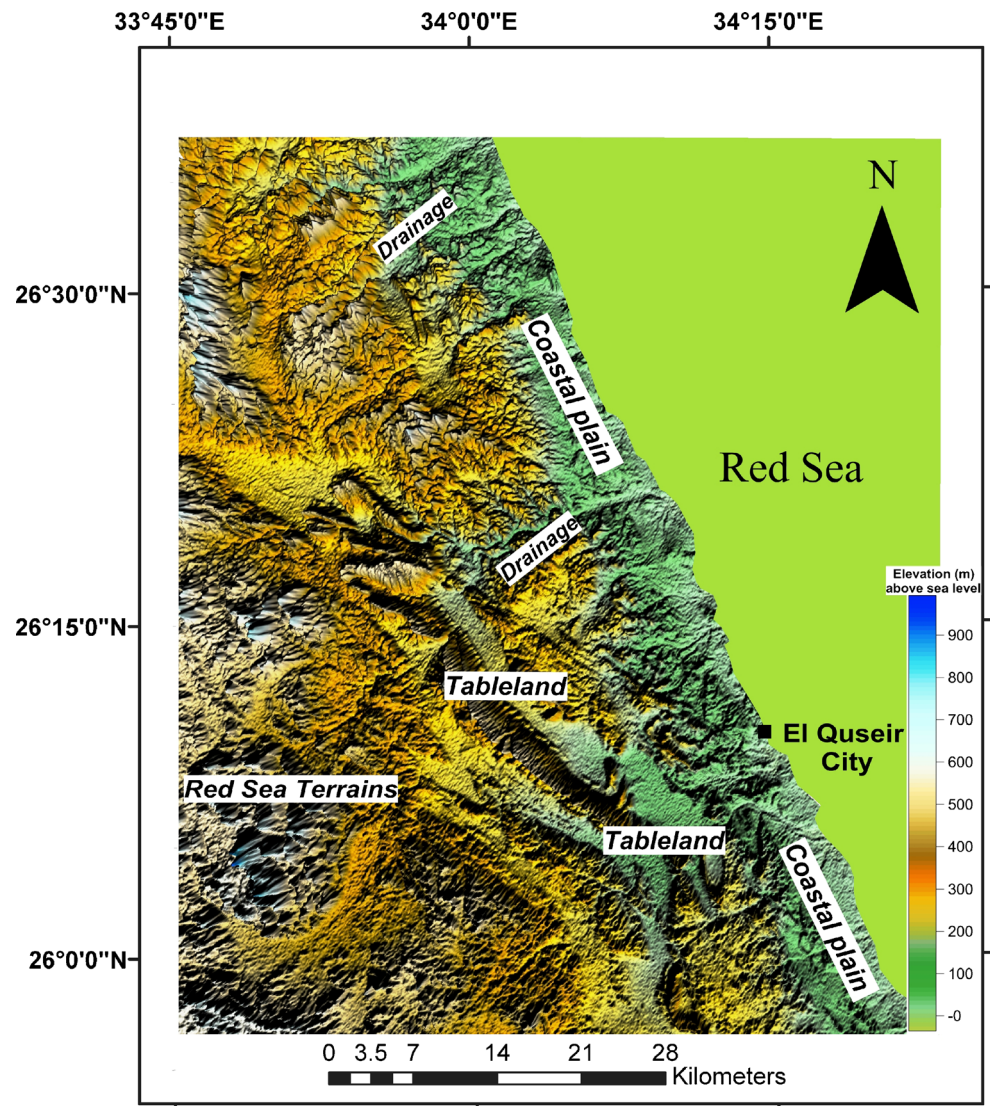
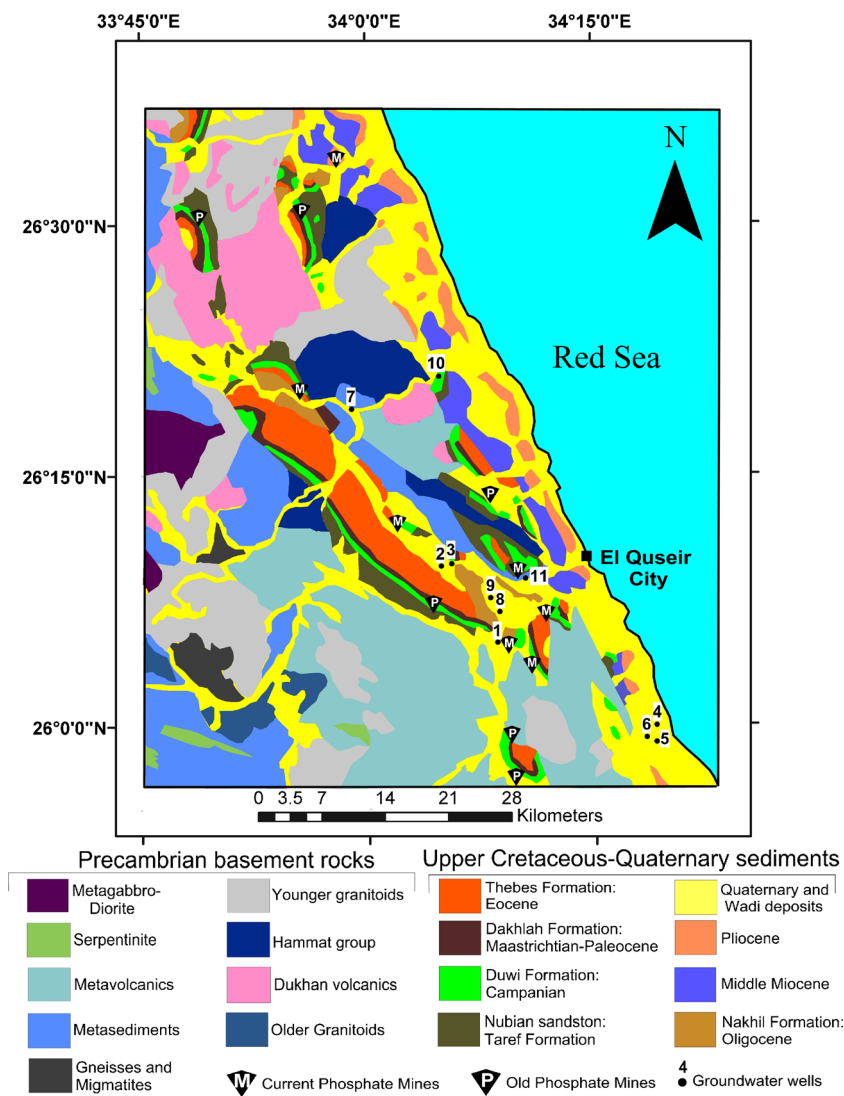


Fig. 3 Geologic setting of the study area, extracted from the geology map (Conoco 1986). The mining sites are obtained from the metallogenic maps (The Egyptian Geologic Survey and Mining Authority, EGSMA 1983, 1984). The locations of groundwater wells are illustrated where these sites were identified by GPS during the field survey



Major ions and trace elements distribution in groundwater

Based on the Piper diagram (1944), groundwaters from the Quaternary aquifer, Oligocene aquifer and Precambrian basement aquifer are of Na-Ca-Cl-SO₄ type and groundwater from the Campanian Duwi aquifer is of Ca-Na-SO₄-Cl type (Fig. 5a). The Schoeller diagram (1962) confirms it, i.e., 10 groundwater samples have the order of concentrations Na > Ca > Mg and Cl > SO₄ > HCO₃, while one sample (well no. 10) from the Campanian Duwi aquifer has the orders Na > Ca > Mg and SO₄ > Cl > HCO₃ (Fig. 5b).

The maximum concentration of Na⁺ is found in the alluvial Quaternary aquifer (3800 mg/l in well no. 1). Potassium concentrations in the groundwater show the same trend as sodium concentrations, ranging from 5 and 140 mg/l. Calcium concentrations show a large range of variation from 150 mg/l in well no. 10 to 1500 mg/l in well no. 1. The high concentration of sulfate (ranges between 325 and 2811 mg/l) might be due to

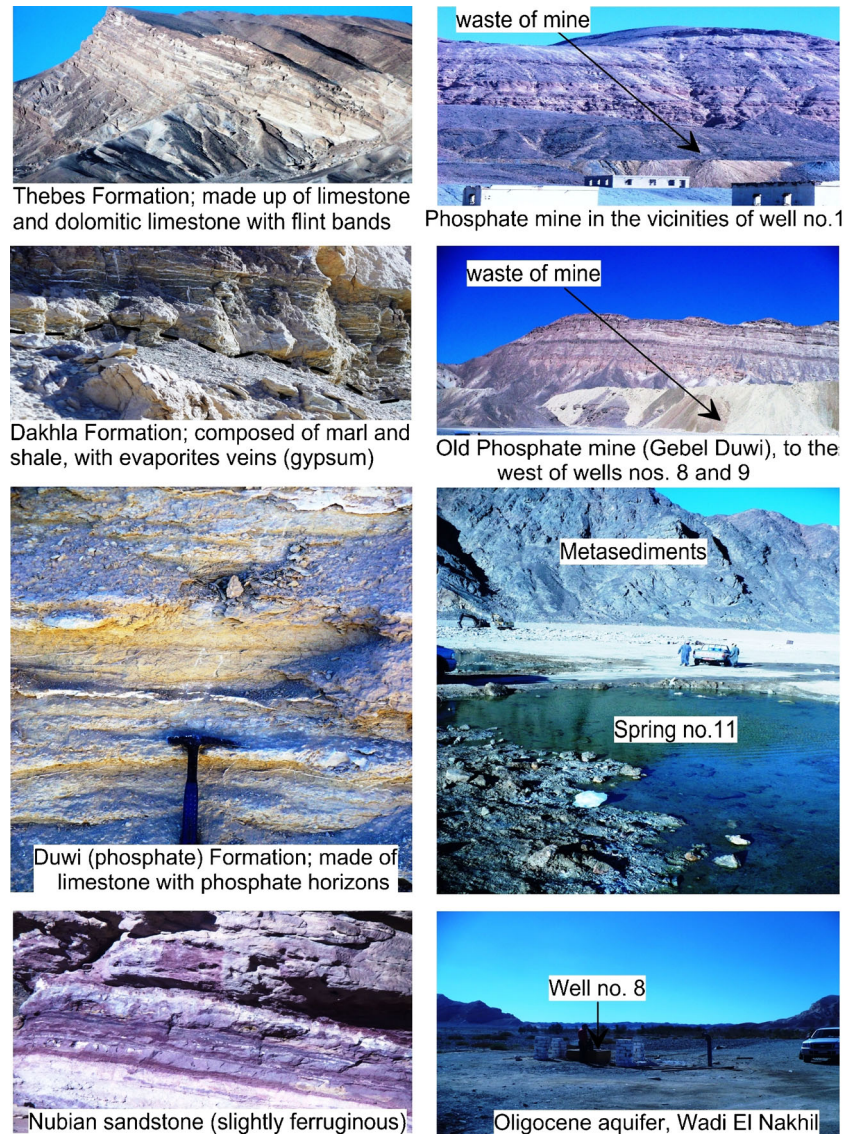
the leaching of sulfate salts. Bicarbonate concentration in the groundwater samples ranges from 31 to 286 mg/l.

Trace element concentrations of the studied groundwater samples are generally between 0.0009 and 23.56 mg/l. Concentrations of Fe, Mn, Cu, and Cr are relatively low in many wells, but they show a noticeable increase in well nos. 2, 3, 6, and 7 of alluvial Quaternary aquifer and in well no. 10 of the Campanian Duwi aquifer (Tables 2 and 3), probably due to the presence of phosphate rocks in the nearby outcrops.

Speciation modeling

Results of speciation modeling are in Table 4. Samples from basement, Oligocene Formation, and some samples from the Quaternary alluvial aquifer are supersaturated with respect to calcite, aragonite, and dolomite, but sample from the Duwi Formation (well no. 10) and most samples from the Quaternary alluvial aquifer are under saturated with respect to these minerals. Most samples are under-saturated with

Fig. 4 Field photographs showing; different rock units, groundwater wells, and some of phosphate mines



respect to gypsum, except two alluvial samples and the bed-rock sample. All samples are supersaturated with respect to gibbsite, but this may be caused by the presence of aluminum in suspended fraction. Two samples, for which dissolved phosphate data were available, are at equilibrium or supersaturated with respect to hydroxyapatite. Most samples are supersaturated with respect to goethite and hematite (not shown), but these results are not reliable due to uncertain redox status.

Discussion

The study area represents a typical area with hyper-arid conditions. However, it receives some amounts of seasonal rainfall which provide the opportunity for surface runoff and also for groundwater recharge. The highlands are the main

recharge areas, while the lowlands act as water discharge areas. This emphasizes the importance of local and small catchment areas because they receive rainfalls which drain and spread in different directions inside the basin. Therefore, the mining wastes in the vicinities of the groundwater wells can lead to aquifers contamination (Fig. 4). The studied groundwater can be classified into three groups: the first group includes the wells drilled in the vicinities of mining activity sites (well nos. 1, 2, 3, 7, 8, 9, and 11), the second group is represented by one well which penetrates the phosphate formation (well no. 10), and the third group includes background wells far away from mining activities (well nos. 4, 5, and 6).

The impacts of mining activities and phosphate rocks

The impacts of mining activity and phosphate rocks are consistent with the chemical analyses of bedrock samples from

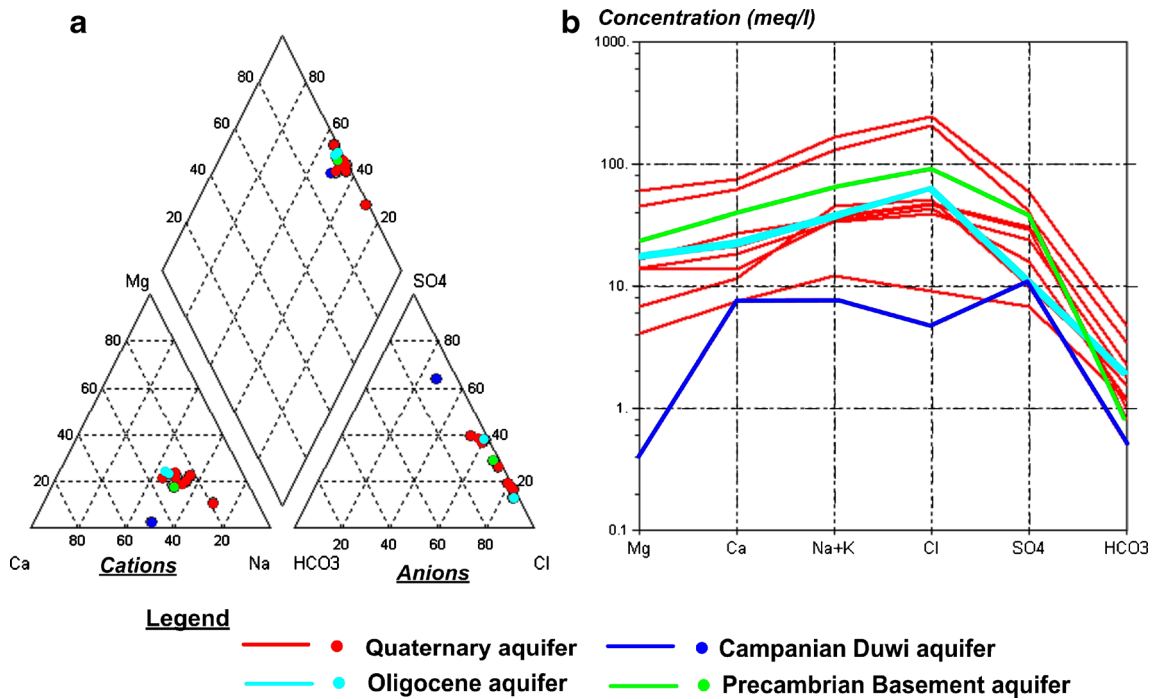


Fig. 5 Geochemical representations of chemical analyses: a Piper and b Schoeller graphs of the studied groundwater samples

the Duwi Formation (Tables 5 and 6; Dabous 2003). The analyses show that the source rocks are rich in P₂O₅, CaO, and Fe₂O₃ (Tables 5 and 6). Their leaching results in relatively high concentration of Cu, Cr, Fe, and Mn in well nos. 2, 3, 7, and 10, compared to background well nos. 4, 5, and 6. Also, high concentration of PO₄³⁻ was found in well nos. 7 and 10 (0.21 and 0.22 mg/l, respectively) drilled in the Quaternary sediments and the Duwi Formation. The phosphate rocks also have high contents of Cu, Pb, Zn, Cr, Ni, and Sr (Tables 5 and 6). The hydrogeochemical modeling reveals that groundwater in well nos. 7 and 10 is supersaturated with respect to hydroxyapatite (Table 4) as a consequence of the direct drilling

into the phosphate bearing strata in case of well no. 10 and the proximity of well no. 7 to one of exploited mines.

Also, the significant contents of leachable uranium associated with phosphate ores (Tables 5 and 6) can be a factor affecting in the groundwater quality. In both the Western Desert and the Red Sea phosphorites, marine phosphate nodules show no preferential release of uranium (Altschuler et al. 1958; Gavshin et al. 1973). Apparently, the uranium in the leachable phases has been adsorbed from groundwater at some time after initial deposition of the phosphate beds (Dabous 2003) and is relatively immobile. The concentration of U in three well nos. 7, 10, and 11 are varying from 0.00004

Table 4 Saturation indices of the studied groundwater samples using PHREEQC model

Well no.	Aquifer	Aragonite	Calcite	Dolomite	Gibbsite	Gypsum	Hydroxyapatite
1	Alluvial	0.48	0.63	1.31	1.35	0.07	–
2		–1.5	–1.38	–2.8	2.98	–0.9	–
3		0.39	0.53	1.07	1.67	–0.4	–
4		–0.32	–0.17	–0.33	1.66	0	–
5		–0.26	–0.11	0	1.4	–0.7	–
6		–1	–0.85	0	3.59	–0.2	–
7		–0.44	–0.3	–0.7	1.89	–1	0.03
8	Oligocene	0.08	0.22	0.46	1.47	–0.3	–
9		0.25	0.39	0.83	1.92	–0.7	–
10	Duwi	–0.41	–0.2	–1.6	7.73	–0.7	0
11	Basement	1.08	1.22	2.35	0.31	0	–

The positive values of the saturation indices express about the supersaturated phase (bold). The negative values of the saturation indices express about the under-saturated phase. The 0 values of the saturation indices express about the saturated phase (bold)

Table 5 Chemical data of the Egyptian phosphorites, Duwi Formation, Eastern Desert, El Quseir area and its vicinities (Dabous 2003)

Samples	P ₂ O ₅ %	CaO %	Fe ₂ O ₃ %	V ppm	U _T ppm
R1	31.02	47.78	2.01	143	119.8
R2	26.11	50.99	1.65	93	100.2
R3	21.21	45.91	1.84	87	60.2
R4	30.77	52.01	0.63	131	120.1
R5	24.89	45.01	1.11	112	93.3
R6	24.88	47.83	2.31	101	109.8
R7	22.51	46.78	1.99	107	112.2
R-median	24.89	47.78	1.84	107	109.8

U_T total uranium concentration in the whole sample, R samples along the Red Sea Coast

to 0.0047 mg/l (Tables 2 and 3). Accordingly, the sediments of the Duwi Formation and the basement rocks can be a source of U in groundwater. This corresponds to the results of Dabous (2003), confirming that the concentration of dissolved U in the Red Sea area groundwater is identical to the concentration of leachable U in the phosphate rocks.

Hydrogeochemical evolution

In general, the high values of salinity are mainly due to evaporation, limited recharge, and leaching of some soluble salts in rocks (limestone, dolomite, gypsum, shale, and marl). However, the Na and Cl presence is significant in the majority of groundwater samples (all wells except well no. 10), reflecting the contribution of leaching and dissolution of marine deposits. On the other hand, high SO₄ water type is found

Table 6 Chemical data of trace elements

Trace elements	Sample 1	Sample 2	Sample 3
Cr	38	88	111
Co	18	5	2
Ni	83	30	18
Cu	187	127	90
Zn	84	113	585
Zr	145	198	51
Rb	31	483	13
Y	–	23	121
Ba	73	756	157
Pb	13	56	2
Sr	168	185	944
Ga	7	–	–
V	27	555	126
Nb	6	5	–

The trace elements (ppm) of Duwi Formation, Wadi Queh were provided from the works of Abdalla and Khalifa (2013) (see “The study area and data procedures” section)

only in well no. 10. The investigated groundwater from all aquifers shows enrichments in Ca²⁺ and Mg²⁺. This is attributed to the dissolution of carbonate rocks encountered along the flow path of groundwater. The results of speciation modeling (Table 4) suggest that dissolution of minerals such as calcite, aragonite, and dolomite has occurred and the sources of these elements are the Thebes Formation rocks (limestone, dolomitic limestone, and dolomite). The enrichment in Mg²⁺ may indicate that some of the excess of Mg²⁺ was derived from the dissolution of dolomite. The enrichment in Ca²⁺ and Mg²⁺ contributes to the salinity and hardness of the groundwater samples. Strontium is found in significant concentrations in all groundwater samples (Tables 2 and 3). The sources of strontium in groundwater are generally its trace amounts in carbonates. Because strontium and calcium are chemically similar, strontium atoms may also be adsorbed on clay particles by cation exchange (Skougstad and Horr 1963).

The Na⁺ vs. Cl⁻ plot (Fig. 6a) shows that groundwater samples generally fall on the unity line, indicating dissolution of halite as a principal source of both ions. The Ca²⁺ vs. SO₄²⁻ plot is more complex (Fig. 6b). The plot shows that the majority of samples fall above the 1:1 line and only one sample (well no. 9 of the Oligocene aquifer) falls below the 1:1 unity line. The 1:1 line in Fig. 5b represents the gypsum dissolution line (CaSO₄·2H₂O), and lower observed Ca²⁺ concentrations suggest a sink for Ca²⁺ such as cation exchange.

Groundwater evaluation for different purposes

The suitability of the investigated groundwater for different purposes was determined by comparing its chemical composition with the Egyptian Higher Committee for Water standards (EHCW 2007), World Health Organization standards for drinking water (WHO 2011), and National Academy of Science and National Academy of Engineering (1972). The suitability of the groundwater for the drinking uses was analyzed by comparing its parameters with the World Health Organization (WHO 2011) and (EHCW 2007). It is clear that all groundwater samples are unsuitable for human drinking because TDS values range from 1191 to 17,677 mg/l, exceeding the permissible limit of 1000 mg/l. Also, with regard to the concentrations of Al, Fe, Mn, Pb, and Ni, it is obvious that the water of well nos. 1, 5, 8 and 11 complies with permissible limits for drinking water, but the remaining wells such as well 10 are unsuitable.

For livestock and poultry, the National Academy of Science and National Academy of Engineering (1972) defines the principal criteria for evaluation of the water depending on the total dissolved solids. Animals can drink water with moderately high dissolved solids (about 10,000 mg/l), but the concentrations should not exceed 5000 mg/l if possible. The groundwater in the studied area has been separated into five

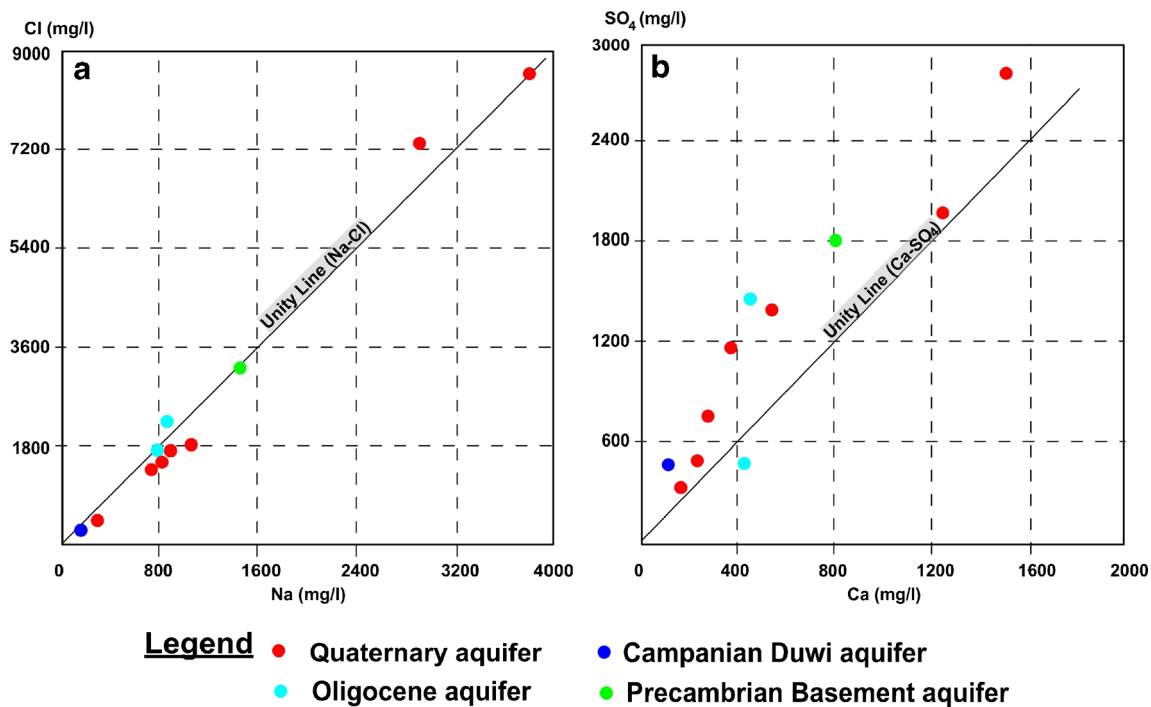


Fig. 6 Relations of a sodium versus chloride and b calcium versus sulfate

classes of quality for livestock and poultry consumption as follows:

1. Very satisfactory water (TDS 1000–3000 mg/l) is found in well nos. 7 and 10 of the Quaternary and the Campanian Duwi aquifers.
2. Satisfactory water (TDS 3000–5000 mg/l) is found in well nos. 2, 3, 5, and 6 of the Quaternary aquifer and well nos. 8 and 9 of the Oligocene aquifer.
3. Water (TDS 7000–10,000 mg/l) that is unfit for poultry and probably for swine is found in well no. 11 of the basement aquifer (spring).
4. Water with TDS more than 10,000 which is not recommended for use under any conditions; this applied only to well no. 1 of the Quaternary aquifer.

The main factor for domestic use of water is mainly restricted to water hardness. In the groundwater samples of the investigated area, the total hardness ranges between 579.9 and 6733.1 mg/l. Comparing these values with Durfor and Becker (1964) classification, all groundwater samples in the study area are unsuitable for domestic and laundry uses as values of total hardness exceed 180 mg/l.

Water for industrial use is usually classified according to its hardness. According to Twort et al. (1985) classification, all groundwater samples are unsuitable for industrial uses (very hard water), where the values of total hardness range between 579.9 and 6733.1 mg/l.

Evaluation of groundwater suitability for irrigation purposes depends on the classification of the US Salinity

Laboratory Staff’s Classification (1954). It uses the relationship between electrical conductivity (EC) and sodium adsorption ratio (SAR). The method is used only for samples which have electrical conductivity equal or less than 5000 micromhos/cm on the basis that the water which has EC value more than 5000 micromhos/cm is not valid for use in irrigation. Therefore, only two groundwater wells (well 7 from the Quaternary aquifer and well 10 from the Campanian Duwi aquifer) are falling into the good class and can be used for irrigation.

From the aforementioned results and discussion, it is obvious that the groundwater contamination can also occur in the case of drilling wells penetrating the phosphate bearing beds and not only as a consequence mining activities, i.e., groundwater concentrations of contaminants close to mining sites are similar to the background concentrations in the proximity of phosphate-bearing rocks. Therefore, it is recommended to avoid any groundwater exploration from the Duwi Formation. Also, in the case of exploration of the Nubian Sandstone which underlay Duwi Formation, the wells should be designed to prevent any hydraulic contact between both layers. On the other hand, the future exploration is preferred in the areas which are not located in the vicinities of the phosphate-bearing Duwi Formation.

Conclusion

The groundwater in the arid and hyper-arid regions is a very important resource which should be managed and protected

from any contamination because it is highly vulnerable to environmental and particularly hydrological changes. Data scarcity in most such areas, the presence of contamination sources, and the absence of pollution warning systems and the continued groundwater monitoring represent a great challenge for any hydrogeological investigations. The current research in the Eastern Desert of Egypt used the previous works, basic hydrogeological study, laboratory analyses, and field investigations to evaluate the risk of phosphate mining for water resources. The chemical analyses show significant concentrations of trace elements such as Cu, Pb, Zn, Cr, Ni, Sr, and uranium which affected groundwater in some wells. The high values of trace elements can be attributed to their high contents in the phosphate rocks which permit their leaching into the groundwater. The results of speciation modeling reveal that groundwater in some wells is supersaturated with respect to hydroxyapatite due to the direct drilling into the phosphate bearing strata and also the proximity of exploited mine. The phosphate-bearing rocks are the source of contamination even at sites where there is no mining exploitation, and groundwater exploration wells should not be installed in their proximity. The current study represents an approach to integrate geological information with hydrogeochemical study to assess the impact of phosphate mining activities and phosphate-bearing rocks on groundwater in an arid, remote, and data-scarce area. We believe that the presented approach can be used to other arid areas with similar conditions.

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