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Monitoring Microbial Diversity of a Full-Scale Municipal Wastewater Treatment Plant in Dubai

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Natural radioactivity and groundwater quality assessment in the northern area of the Western Desert of Egypt

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A R T I C L E I N F O

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A B S T R A C T

The chemical composition and natural radioactivity of the northern area of the western desert groundwater were determined to evaluate hydrogeochemical facies and assess groundwater quality for different uses. Many the groundwater samples belong to the Na^{+}- Cl^{-}, $Na_2SO_4^{-}$ type, followed by Ca^{2+}- Mg^{2+}- Cl^{-} type. Only a few samples are of the Na^{+}- HCO_3^{-} type. The spatial distributions of the major ions describe similar anomalies, with the highest concentrations found at the extreme northeastern margin of the oasis, as well as in its northern and northwestern parts. Fe is the most abundant toxic metal, followed by Cu and Mn. Anomalies of Cr, Ni and Zn are also detected. Rock/water interactions strongly affect the chemical composition of the groundwater. Dissolution and cation exchange are the main processes controlling the hydrogeochemistry. Most of the irrigation groundwater problems in the study area may be resolved using an effective drainage system. The estimated total annual dose due to ingestion of ^{238}U, ^{232}Th and ^{40}K in groundwater samples reveals that the groundwater is safe for human consumption. However, the toxic metal content of the Bahariya groundwater exceeds the permissible levels for both irrigation and consumption, and the water must be filtered through suitable membranes to exclude these toxic metals. Regular monitoring of the quality of this water for drinking is strictly required.

1. Introduction

The Western Desert covers about two-thirds of Egypt's land area. It spans from the Mediterranean Sea south to the Sudanese border and from the Nile River Valley west to the Libyan border. It is one of the driest areas of the Sahara. The irrigated oases and agricultural schemes are good breeding areas for grasshoppers. They are less suitable for the Desert Locust which generally prefers natural vegetation in the desert. Groundwater is the sole source of water supplying arid and semiarid regions such as the study area which known locally as Bahariya Oasis. Geochemical characteristics of groundwater, particularly the levels of potentially harmful metals and radionuclides, are significant factors in controlling groundwater usage and for health considerations (Baba and Tayfur 2011; Murad et al., 2014; Arslan and Turan 2015). The groundwater geochemistry and contamination levels are naturally influenced by the geological setting of the area (Edmunds and Shad 2008; Al-Katheeri et al., 2009; Banat and Howari 2003; Banat and Howari 2005; Banat et al., 2005) and the lithological composition of the aquifer (Yuce et al., 2009; Howari 2016; Howari et al., 2005; Howari and Banat 2001), in addition to anthropogenic factors, such as agricultural practices (Wongsasuluk et al., 2014), waste disposal (Dong et al., 2015), and industrial and mining activities (Dokou et al., 2015; Hao et al., 2016).

Assessment of the potentially harmful metals and the natural radioactivity levels in groundwater sources is important in

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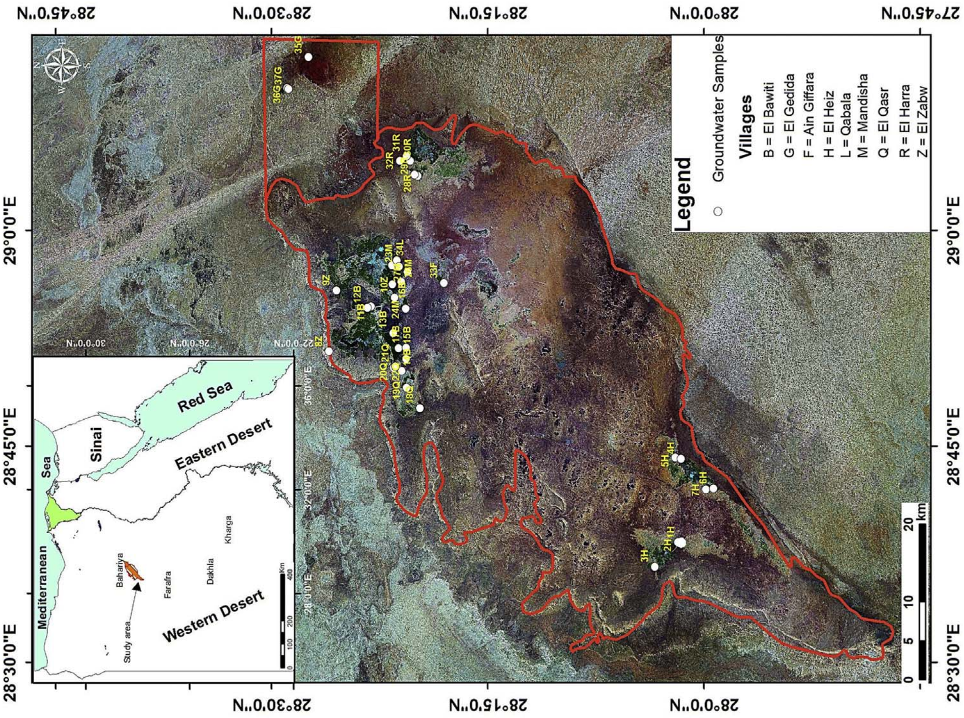

Fig. 1. Satellite image of the study area showing the groundwater sampling sites.

protecting the population against toxicity and high radiation dose due to ingestion (Yuce et al., 2009). The main sources of gamma radiation in natural waters are 238U, 232Th series and 40 K (ICRP, 2012). In the study area, groundwater represents the sole water source for irrigation and other human uses. Groundwater depletion and decline in water quality are the main concerns in this area. Consequently, many hydrogeochemical studies of the groundwater in the Bahariya Oasis have been published since the late 1980s (e.g. Eweida and Abdallah 1980; Shehata 1992; Kornay et al., 2002; Hamdan and Sawires 2013). However, few of these studies dealt with water contamination by toxic metals and radionuclides (Shahin et al., 1996; Khater 2003). The aim of the present work is three-fold: (1) contributing to the database on quality of groundwater in the northern part of the western desert; (2) assessing water pollution levels due to toxic metals and natural radioactivity; and (3) evaluating the suitability of this groundwater for irrigation, domestic and drinking needs.

2. Materials and methods

2.1. The study area

The study area in the northern part of the Western Desert of Egypt between longitudes 28° 35′ and 29° 10′ E and latitudes 27° 48′ and 28° 30′ N (Fig. 1). The approximate area of the depression is about 2000 km^2 (94 × 42 km). It has an elevation of 128 m above sea level and suffers from hyper-arid climate. Inhabitants of the area (population of 34,000) depend mainly on agriculture, with areas of cultivation at a few separate localities. The main Egyptian iron mines are also located in this oasis. Thus, the Bahariya Oasis is a prospective area for reclamation extension, geotourism and industrial activities.

2.2. Geology and hydrogeology

Several hills and high scarps (~175 m height) surround the Bahariya depression. They include mainly exposures of the Lower Cretaceous-Oligocene formations. This succession is overlain by Miocene volcanic rocks (typically basalt) and Quaternary surficial deposits (Said 1962; El Akkad and Issawi 1963; Catuneanu et al., 2006 and others). The Nubian Sandstone (1800 m thick) of pre-Cenomanian to Early Cenomanian age is the groundwater aquifer of the Bahariya Oasis (Korany 1984; Shehata 1992). This aquifer has been described as a multilayered artesian aquifer system that behaves as one hydrogeologic system (Youssef 1999; Hamdan and Sawires 2013). It consists of three successive water-bearing ferruginous and calcareous sandstone units separated by semi-permeable, regionally discontinuous clay and/or shale layers (Korany et al., 2002). The groundwater flow in the Bahariya Oasis has a (SW-NE) general pattern that is similar to that reported for the groundwater of the Nubian Sandstone Aquifer in the Western Desert of Egypt (Korany 1984; Shata 1982; Abdel Ati 2002; Hamdan and Sawires, 2013). The major part of the oasis floor is a flat or gently undulating ground of sandstone and layers of clay, strewn with fragments of rocks derived from the hills (Howari et al., 2016; Said,

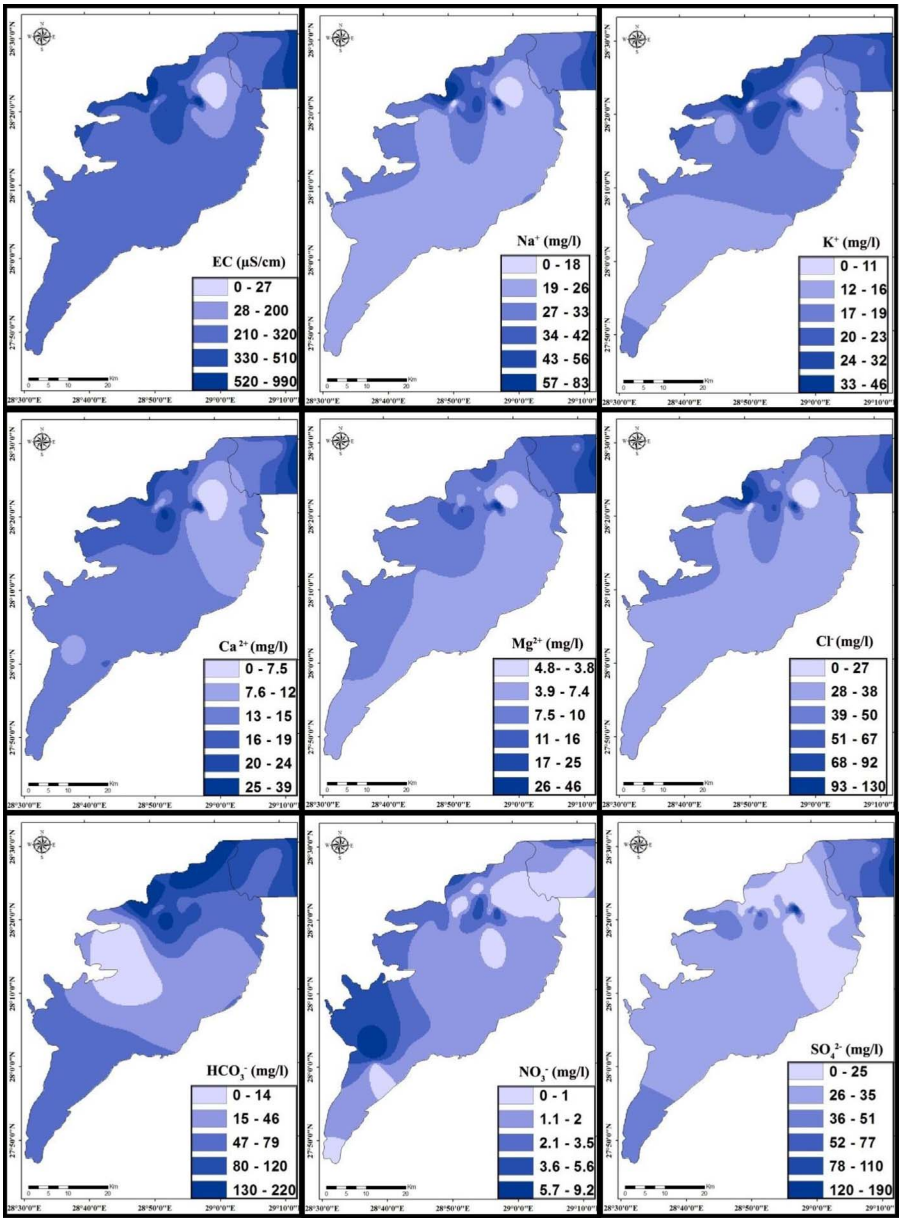

Fig. 2. Spatial distributions of EC and ions in the studied groundwater.

1962). The most important geomorphic features include: 1) the alternating weak and strong beds and their influence on topography 2) the marked parallelism of NE-SW ridges, and 3) Geologic structure and its control of the small wadis and 4) The position and outlines of the folds, exemplified in the ridges formed by the alternating weak and strong beds.

The geological section in Bahariya Oasis and its surroundings comprises the following units from the oldest to the youngest. These features are summarized from Howari et al., 2016 as below:

Bahariya Formation, is mostly formed of friable, false-bedded, variegated sandstones with harder dark brown ferruginous quartzitic sandstone beds. Fluviatile sandstone and siltstone in the lower part grading upward into alternating beds of estuarine sandstone and shale in the essential composition.

Heiz formation, it marks the first carbonate deposits in Bahariya Oasis, made of 30 m thick clastics with carbonate interbeds and dolostone member at top. Basal and upper members of reddish brown dolomatic sandstone and siliceous dolostone, enclosing a middle member of sandy clay and calcareous grit, varicolored, with ironstone concretions and flint. They represent shallow marine deposits.

Hefhuf Formation*,* this formation is exposed on both the eastern and western scarps of the Bahariya Oasis, and also in almost all the northerly isolated hillocks especially these well developed at Gebel Hefhuf. Dolostone with sandstone and sandy clay interbeds, occasional thin gritty phosphatic beds in the upper part is the general composition.

Table 1
Physico-chemical parameters, concentrations of ions and toxic metals and radionuclides activity concentrations of the studied groundwater.

No.	Locality	Well Name	Physico-chemical Parameters					Major Cations (mg/l)				Major Anions (mg/l)			
			Depth (m)	T (C°)	pH	EC (μS/cm)	TDS (mg/l)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	HCO_3^-	NO_3^-	SO_4^{2-}
1 H	El Hiez	Ain El Eza 1	1152	49.5	6.8	273.4	175	22	13	11.0	9.0	32	68	4.0	26
2 H		Ain El Eza 2	1152	49.5	6.8	373.4	239	30	14	21.6	11.0	70	24	9.0	56
3 H		Ain Om Kholiph	300	29	6.8	265.6	170	22	17	14.2	7.1	30	46	0.3	51
4 H		Tablamoun 1	320	32.1	6.9	270.3	173	22	14	15.2	6.2	32	58	1.4	33
5 H		Tablamoun 2	320	32	7.0	384.4	246	30	14	22.1	11.2	70	25	1.2	61
6 H		El Ris 1	370	30.4	6.8	256.3	164	20	15	15.2	5.5	30	59	1.3	32
7 H		El Ris 2	370	31.8	7.0	237.5	152	19	17	12.8	5.3	28	65	2.6	20
8 Z	El Zabw	Qasaa 3	954	23.8	7.6	356.3	228	31	18	20.3	10.0	47	82	6.0	40
9 Z		Qasaa 1	780	40.1	7.6	470.3	301	38	31	18.9	15.5	50	165	2.0	24
10 Z		El Zabu Station	950	24.1	7.3	375.0	240	35	22	16.8	10.1	51	68	3.6	32
11 B	El Bawiti	El Matar	997	47.6	7.2	359.4	230	36	20	18.4	7.7	55	88	2.9	27
12 B		Khalawy	324	31.6	7.6	318.8	204	28	23	16.5	6.9	38	102	0.9	21
13 B		Nebiga	1000	45.3	7.1	365.6	234	36	22	14.9	9.0	54	97	1.0	22
14 B		Ain Embash	205	35.8	7.0	270.3	173	18	14	15.0	12.1	25	78.8	1.6	40
15 B		El Beshmou	1082	50	7.2	296.9	190	31	18	13.6	6.0	46	78	0.2	21
16 B		Karem	840	41	6.9	318.8	204	30	20	15.7	7.7	47	83	1.6	26
17 B		El Bawiti Station	1100	23.9	6.9	448.4	287	29	25	25.3	16.5	42	125	1.6	60
18 Q	El Qasr	Mady	345	30	7.0	270.3	173	20	16	16.5	7.6	29	53	2.0	48
19 Q		El Tibnia	809	37.3	7.5	437.5	280	39	32	17.0	13.0	51	156	3.0	20
20 Q		Dedela Hot	891	45	6.9	460.9	295	52	27	17.6	9.6	80	123	0.9	19.2
21 Q		Dedila Station	800	24	7.2	265.6	170	18	13	14.0	12.0	23	76	0.8	41
22 Q		Bir Wald	1167	50	6.7	300.0	192	31	17	14.1	7.4	45	85	0.2	22
23 M	Mandisha	Mandisha Station	1050	23.9	6.9	1020.3	653	78	41	40.0	48.3	110	87	4.0	200
24 M		El Aguz	1045	45	7.6	440.6	282	50	25	16.0	9.3	70	78	4.7	21
25 M		El Maissra	1080	46	7.2	296.9	190	28	15	14.4	6.0	40	73	0.2	23
26 M		El Gazair	1005	41	7.1	412.5	264	27	25	19.1	16.6	41	110	1.0	58
27 M		Segam	781	41.5	7.1	382.8	245	38	23	16.4	11.0	56	93	4.6	35
28 R	El Harra	Ain Wady	830	41.4	7.6	243.8	156	24	15	12.3	5.2	36	58	1.2	22
29 R		Ain Hadad	995	45	7.1	260.9	167	25	16	13.0	5.1	38.2	61	0.3	23
30 R		Ain Yousef 1	820	40.2	7.3	251.6	161	23	15	13.0	5.2	34	60	0.2	23
31 R		Ain Yousef 2	684	31.1	7.4	246.9	158	24	16	13.3	5.5	35	64	0.6	24
32 R		Ain El Bahariya	750	41.2	7.3	246.9	158	25	15	12.5	5.9	33	68	0.2	26
33 F	Ain Giffara	Ain Giffara	869	38.4	6.8	235.9	151	23	16	10.1	6.1	34	60	0.2	23
34 L	Qabala	Qabala	1138	40	7.0	296.9	190	30	19	12.0	8.0	46	71	0.9	27
35 G	El Gedida	Well 9	1063	36.5	7.0	867.2	555	66	28	35.0	40.0	90	150	1.0	175
36 G		Well 7	1117	50	6.8	292.2	187	29	19	12.6	7.1	43	75	0.3	26
37 G		Well 8	1003	30	6.7	445.3	285	33	27	18.0	17.0	46	112	5.0	62
Min.			205.0	23.8	6.7	235.9	151.0	18.0	13.0	10.1	5.1	23.0	24.0	0.2	19.2
Max.			1167.0	50.0	7.6	1020.3	653.0	78.0	41.0	40.0	48.3	110.0	165.0	9.0	200.0
Average			774.5	37.7	7.1	359.1	229.8	31.4	19.9	16.9	10.9	46.7	81.8	1.9	40.8

No.	Locality	Well Name	Toxic Metals (ppm)								Radionuclides (Bq/l)		
			Cr	Cu	Fe	Mn	Ni	Pb	V	Zn	^{238}U	^{232}Th	^{40}K
1 H	El Hiez	Ain El Eza 1	0.029	1.923	2.269	0.453	0.005	0.021	0.013	0.067	56.06	2.89	10.8
2 H		Ain El Eza 2	0.001	0.088	7.7	0.641	0.002	0.003	0.001	0.373	29.58	3.59	7.91
3 H		Ain Om Kholiph	0.08	0.207	3.901	0.257	0.001	0.004	0.017	0.026	0.00	2.6	7.11
4 H		Tablamoun 1	0.005	0.195	3.475	0.275	0.001	0.006	0.024	0.054	0.00	4.68	22.05
5 H		Tablamoun 2	0.002	0.129	1.16	0.859	0.004	0.009	0.001	0.063	0.00	4.68	22.05
6 H		El Ris 1	0.003	0.171	5.419	0.496	0.004	0.001	0.022	0.04	61.33	2.21	9.15
7 H		El Ris 2	0.001	0.196	1.035	0.412	0.002	0.003	0.023	0.058	61.33	2.21	9.15
8 Z	El Zabw	Qasaa 3	0.002	0.185	0.622	0.566	0.008	0.004	0.027	0.079	39.94	1.68	6.2
9 Z		Qasaa 1	0.002	0.144	0.726	0.089	0.041	0.002	0.05	0.058	40.67	3.41	14.08
10 Z		El Zabu Station	0.007	0.34	2.521	0.526	0.004	0.008	0.067	0.114	27.71	2.79	6.71

Table 1 *(continued)*

No.	Locality	Well Name	Toxic Metals (ppm)								Radionuclides (Bq/l)		
			Cr	Cu	Fe	Mn	Ni	Pb	V	Zn	^{238}U	^{232}Th	^{40}K
11 B	El Bawiti	El Matar	0.001	0.134	2.539	0.331	0.001	0.001	0.005	0.011	43.79	1.61	7.58
12 B		Khalawy	0.005	0.061	0.924	0.096	0.004	0.008	0.058	0.042	52.65	2.6	7.23
13 B		Nebiga	0.002	0.143	3.16	0.086	0.002	0.01	0.048	0.042	38.48	2.79	6.99
14 B		Ain Embash	0.015	0.142	4.184	0.477	0.001	0.009	0.057	0.081	60.30	1.49	5.27
15 B		El Beshmou	0.003	0.226	3.831	0.717	0.007	0.009	0.063	0.158	69.31	1.89	8.3
16 B		Karem	0.008	0.171	2.766	0.444	0.002	0.002	0.068	0.034	62.78	3.2	10.95
17 B		El Bawiti Station	0.003	0.235	5.393	0.857	0.01	0.005	0.057	0.051	44.67	2.26	19.37
18 Q	El Qasr	Mady	0.001	0.154	4.827	0.559	0.003	0.002	0.043	0.035	51.42	1.11	6.06
19 Q		El Tibnia	0.001	0.101	0.484	0.041	0.001	0.001	0.052	0.025	33.84	2.17	14.48
20 Q		Dedela Hot	0.003	10.47	3.03	0.555	0.045	0.023	0.053	0.083	70.26	2.44	9.34
21 Q		Dedila Station	0.005	0.159	0.55	0.545	0.003	0.015	0.047	0.45	47.30	4.53	20.44
22 Q		Bir Wald	0.033	0.206	3.91	0.758	0.004	0.001	0.053	0.102	47.89	3.17	12.47
23 M	Mandisha	Mandisha Station	0.024	0.131	0.545	0.952	0.002	0.002	0.064	0.053	40.64	3.05	8.05
24 M		El Aguz	0.038	0.369	3.151	1.291	0.004	0.012	0.058	0.111	41.91	1.75	5.81
25 M		El Maissra	0.321	0.166	4.936	0.937	0.002	0.002	0.072	0.095	42.12	2.91	9.3
26 M		El Gazair	0.003	5.901	2.253	0.298	0.016	0.014	0.097	0.056	26.53	2.52	5.87
27 M		Segam	0.002	4.451	1.492	0.235	0.005	0.011	0.001	0.037	47.39	1.89	11.03
28 R	El Harra	Ain Wady	0.008	0.433	3.32	0.513	0.004	0.006	0.069	0.071	54.07	5.74	15.47
29 R		Ain Hadad	0.027	0.402	3.211	0.508	0.004	0.006	0.048	0.052	46.33	2.64	6.7
30 R		Ain Yousef 1	0.066	2.868	3.67	0.573	0.003	0.013	0.064	0.059	17.92	3.12	5.33
31 R		Ain Yousef 2	0.003	4.977	2.664	0.639	0.013	0.017	0.076	0.071	72.51	3.65	10.31
32 R		Ain El Bahariya	0.002	5.662	2.361	0.477	0.008	0.012	0.07	0.066	91.95	3.66	6.46
33 F	Ain Giffara	Ain Giffara	0.001	0.097	1.548	0.135	0.002	0.002	0.001	0.005	37.56	2.15	9.5
34 L	Qabala	Qabala	0.083	4.012	2.756	0.173	0.004	0.021	0.001	0.027	64.83	4.3	8.17
35 G	El Gedida	Well 9	0.047	2.208	27.29	1.052	0.008	0.006	0.001	0.24	51.52	2.62	17.75
36 G		Well 7	0.093	3.258	1.348	0.167	0.003	0.01	0.001	0.013	39.81	3.6	6.91
37 G		Well 8	0.003	0.258	0.757	0.093	0.002	0.003	0.001	0.02	73.68	4.5	10.55
Min.			0.001	0.061	0.484	0.041	0.001	0.001	0.001	0.005	0.0	1.1	5.3
Max.			0.321	10.47	27.29	1.291	0.045	0.023	0.097	0.45	45.6	2.9	10.3
Average			0.025	1.378	3.398	0.489	0.006	0.008	0.040	0.082	92.0	5.7	22.1

Khoman Chalk, this of 50 m thick chalk and limestone beds with hard dolomitic limestone band at top. Snow-white to light tan, chalky calcilutite, moderately hard, fractured and with calcite fillings.

Plateau Limestone, it is succession of limestone beds with few marly and clayey interbeds uncomfortably overlies different Cretaceous rocks at different parts of the Bahariya area.

The Ghorabi Iron Ore Member, the origin of this important economic deposits has stirred much dispute among several workers from lacustrine deposits of Oligocene age.

The Qazzun Formation, this Formation covers a large tract of the plateau surface north and northwest of the Bahariya Oasis. Lagoonal limestone exist as white to gray to yellowish, thinly-bedded, partly crystalline, partly chalky, occasionally siliceous and/or dolomitic, common calcite pockets. The limestone includes characteristic melon-shaped concretions of siliceous limestone.

The Hamra Formation, the hamra makes many of the hills and ridges of the Bahariya northern and western plateaus. Shore line, partly algal reef limestone, yellowish-brown, abundant detrital grains, numerous skeletal remains, intraformational conglomerates.

The Radwan formation, The formation is 40 m at its type section in Gebel Radwan located at the central west part of the depression. Lithologically, the Radwan is formed of dark brown non-fossiliferous ferruginous grits and sandstones. The formation was probably formed in connection with an Oligocene sinous river system which flowed over the Bahariya area before the depression was formed.

The Volcanic Rocks, These rocks occur in the Bahariya Oasis mainly as capping Gebel Maysera, Gebel Mandisha, the northern part of gebel Hefhuf, the Basalt Hill and small conical hill to the west of Qala Siwa. The volcanic cover of the Bahariya Formation and the sandstones at the contact are altered by the eruptions.

2.3. Sampling

A total of 37 groundwater samples were collected during February 2010 from the available drilled wells (Fig. 1). The accurate sampling locations were determined using GPS. Samples were collected after 10 min of pumping and were stored in polyethylene bottles. Samples for toxic metals analysis were collected in acid-leached polyethylene bottles and preserved by adding ultra pure nitric acid (5 mL/l). Sampling was handled according to the standard methods for examination of water (APHA, 1999). Field

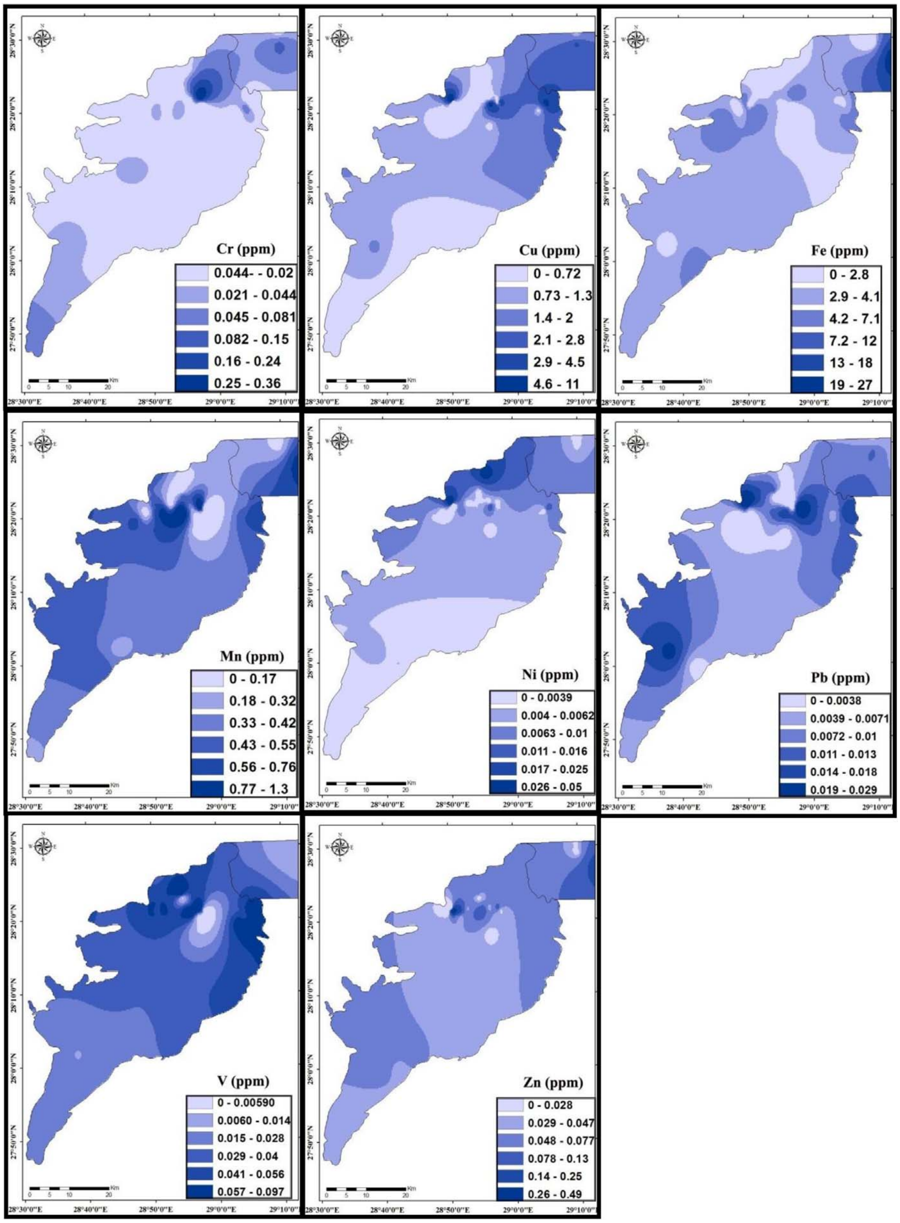

Fig. 3. Spatial distributions of the toxic metals in the studied groundwater.

parameters (temperature, EC and pH) were measured in-situ using a portable digital EC-pH-meter.

2.4. Chemical analysis

The collected groundwater samples were filtered through 0.45 μm pore-diameter filter paper. The concentrations of major cations and total toxic metals were determined using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) with ultrasonic Nebulizer (USN) (Perkin Elmer Optima 3000, USA). The major anion concentrations, on the other hand, were determined using Ion Chromatography (IC), model DX-500 chromatography system.

2.5. Radioactivity measurements

The groundwater samples were transferred to Marinelli beakers (1 L) and sealed for a period of about 4 weeks before counting by gamma spectrometry. The counting time for each sample was nearly 24 h The ^{238}U, ^{232}Th and ^{40}K activity concentrations were measured using HPGe EG & Gortec Model GEM-50210-P. This equipment was used for counting and detection of radionuclide content of all samples. The instrument has a depleted, sensitive thickness of centimeters, and therefore can be used as a total absorption detector for gamma rays up to few MeV. Cooled to liquid nitrogen temperatures (196° C), it produces spectroscopic data and pulses proportional to the captured photon energy. The HPGe detector used is a P-type and has a diameter of 78 mm, length 69.6 mm, 16 K channels with relative efficiency of 80% and a resolution of 2.3 Kev at the 60 Co line of 1.33 Mev. The spectrometer was equipped with the necessary electronics.

3. Results and discussion

3.1. Groundwater hydrochemistry

The physico-chemical parameters and concentrations of the ions and toxic metals in the studied groundwater samples are given in Table 1. The spatial distributions of these ions and metals, and EC, are illustrated in Figs. 2 and 3. From Table 1 it is evident that the groundwater in the Bahariya Oasis is characterized by a wide range of discharge temperature (23.3–50 °C), and ranges from slightly acidic (pH as low as 6.7) to slightly alkaline (pH as high as 7.6). According to Chebotarev (1955) and Detay (1997) it can be classified as slightly to moderately mineralized water and fresh water. Na^+ is the dominant cation, followed by Ca^{2+}, Mg^{2+} and K^+. On the other hand, HCO_3^- is the dominant anion, followed by Cl^-, SO_4^{2-} and NO_3^-. Generally, the major ions show more or less similar locations for anomalies, with the highest concentrations being recorded in El Gedida (well-9) at the extreme northeastern margin of the oasis, and in its northern and northwestern parts.

Fe is the most abundant toxic metal in the Bahariya Oasis groundwater, followed by Cu and Mn. The concentrations of Fe are elevated at El Heiz area, and reach a maximum value in well-9. Cu contents show significant levels in El Harraarea and in Mandisha area, reaching a maximum in El Qasr area. Mn and Cr concentrations are high in El Gedida area (well-9 and well-7), while Ni

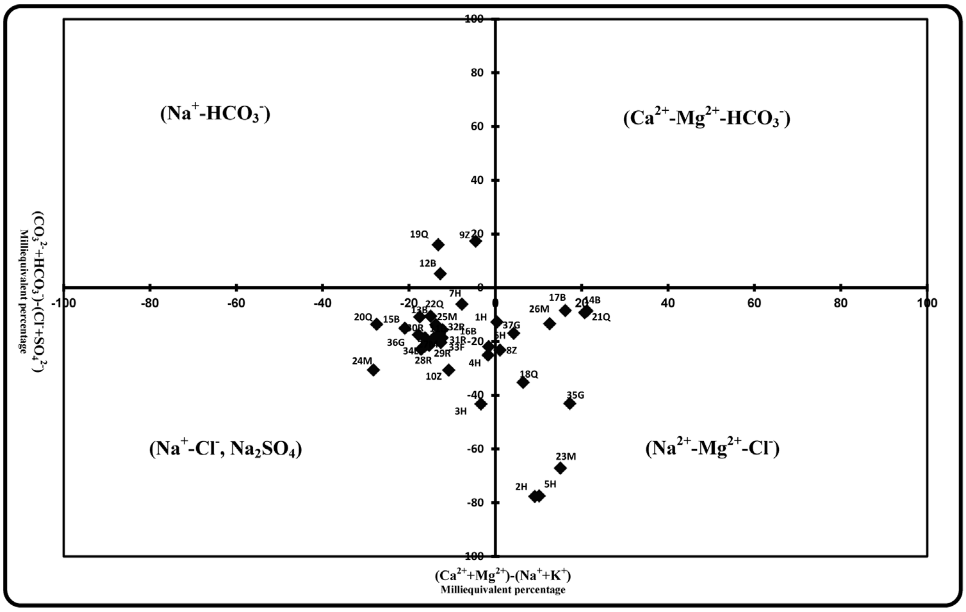

Fig. 4. Plots of the collected groundwater samples on the rectangular diagram proposed by Chadha (1999).

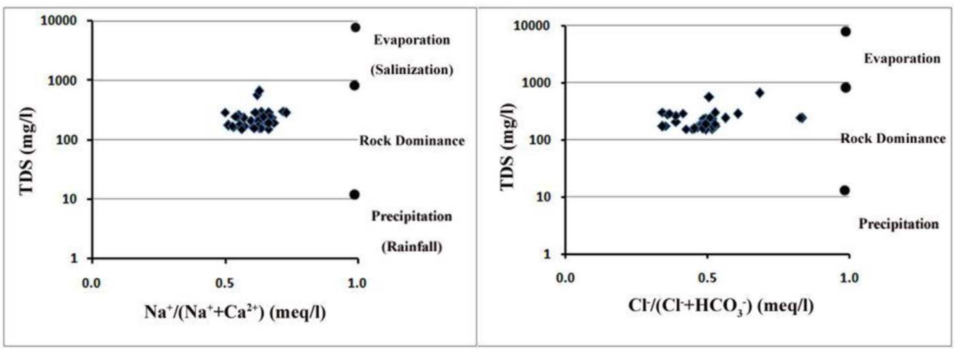

Fig. 5. Plots of the investigated groundwater samples on the diagrams proposed by Gibbs (1970).

concentrations are high in El Qasr area, Mandishaarea and El Bawiti area. Zn concentrations are significant in El Gedida (well-9) and reach maximum levels in El Harra (Ain El Eza) and El Qasr (Dedela station). Generally, the toxic metals are highly concentrated in the northern parts of the oasis. The elevated concentrations of Fe and Mn in the Bahariya Oasis reflect the lithology of the aquifer, which is composed of ferruginous sandstones, with local ironstone and manganese-rich bands (Youssef 1999).

3.2. Hydrogeochemical facies and processes

The concentrations of major ions in the groundwaters of the Bahariya Oasis were plotted on a discrimination diagram proposed by Chadha (1999). On this diagram it is clear that the majority of the groundwater samples belong to the Na^+- Cl^-, $Na_2SO_4^-$ type, followed by the Ca^{2+}- Mg^{2+}- Cl^- type. A few samples are of the Na^+- HCO_3^- type (Fig. 4).

Several scatter diagrams for major ions were used to trace the source of each element and identify the mechanisms that have contribute to Bahariya groundwater evolution. The rock–water interaction for the groundwater was identified using the scatter diagrams of Gibbs (1970). Fig. 5 shows that the aquifer rocks were the dominant factor controlling the chemical evolution of the groundwater within the Nubian Sandstone. The relationship of Na^+ to Cl^- (Fig. 6) shows that the majority of the studied samples lie slightly above the halite dissolution line. Halite has not been recorded in the Nubian Sandstone Aquifer. Hence, the high Na^+ and Cl^- contents are most likely related to the dissolution of chloride salts during infiltration of the groundwater. The additional Na^+ resulted most probably from cation exchange in the clay minerals that constitute the shale intercalations within the Nubian Sandstone Aquifer. This may have led to the adsorption of Ca^{2+} on clay minerals and contemporaneous release of Na^+ ions (cf. Magaritz et al., 1981). These predicted cation exchanges are confirmed by the results of plotting Ca^{2+} vs Na^+, Ca^{2+} vs HCO_3^- and (Ca^{2+} + Mg^{2+}) vs. (HCO_3^- + SO_4^{2-}) (Fig. 6). Most of the data lie below and close to the uniline of these relations, which indicates the depletion of the groundwater in Ca^{2+} and Mg^{2+} ions. These latter cations were derived from the weathering of carbonate minerals in the Nubian Sandstone Aquifer, and were accompanied by cation exchange with Na^+ (cf. Reddy and Kumar 2010).

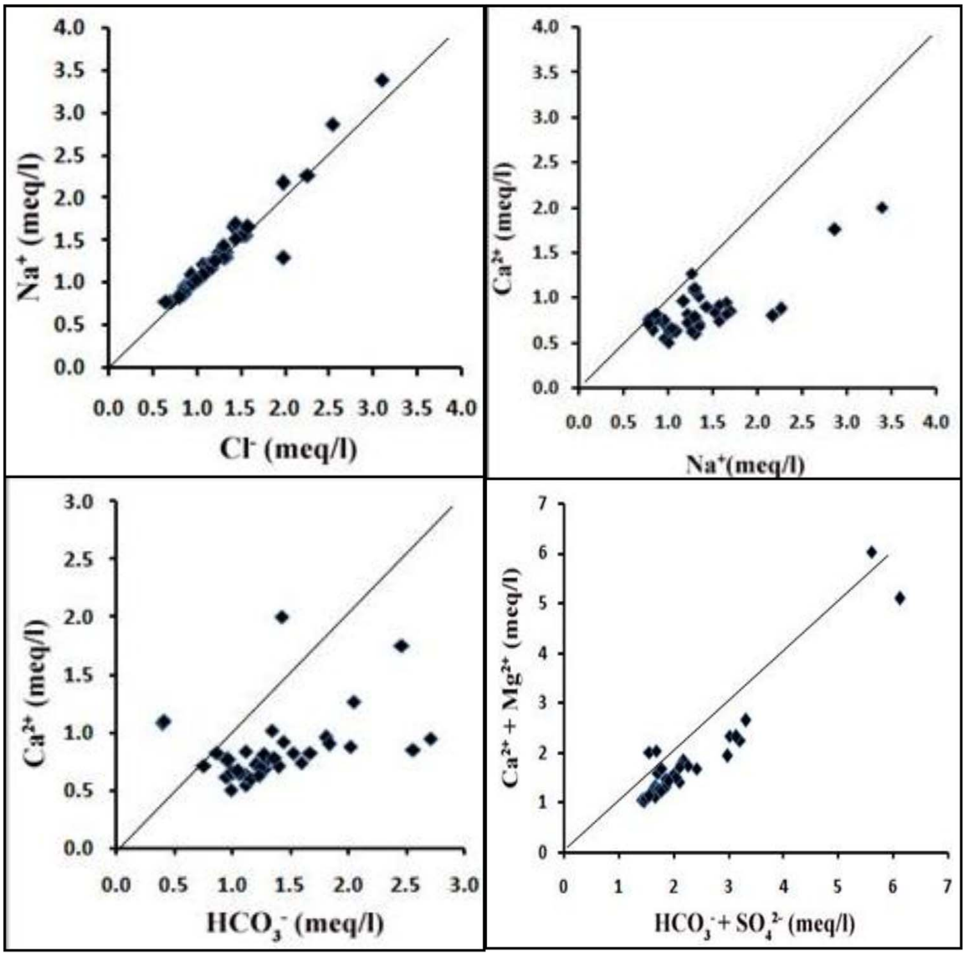

Fig. 6. Plots of the analyzed groundwater samples on different scatter diagrams.

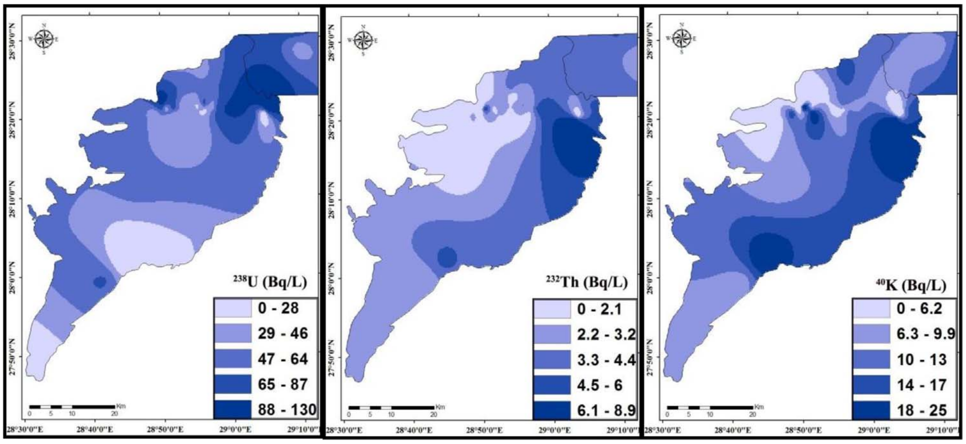

Fig. 7. Spatial distributions of the activity concentrations of 238U, 232Th and 40 K in the groundwater samples.

3.3. Radioactivity

The activity concentrations of the natural radionuclides ^{238}U, ^{232}Th and ^{40}K and their spatial distributions in the Bahariya Oasis groundwater samples are given in Table 1 and shown on Fig. 7. There are significant activity concentrations of ^{238}U in the groundwater of El Harra (Ain El Bahariya). Similarly, there is a high activity concentration of ^{232}Th in groundwater of El Harra (Ain Wady), and of 40 K in groundwater of El Heiz (Tablamoun). Several U-238 and Th-232 values exceeded the maximum allowed by WHO (2011). These variations in the activity concentrations of 238U, 232Th and 40 K indicate different origins. They were inherited

Table 2
Suitability of the studied groundwater for irrigation.

Parameter	Equation (conc. unit meq/l)	Range	Class	Sample No.	No. of Samples	%
EC (μS/cm; Handa 1969)	–	< 250	Excellent	7H, 28R, 31R, 32R, 33F	52	13.5
		251–750	Good	1H, 2H, 3H, 4H, 5H, 6H, 8Z, 9Z, 10Z, 11B, 12B, 13B, 14B, 15B, 16B, 17B, 18Q, 19Q, 20Q, 21Q, 22Q, 24M, 25M, 26M, 27M, 29R, 30R, 34L, 36G, 37G	30	81.1
		750–2500	Permissible	23M, 35G	2	5.4
		2501–6000	Doubtful	–	–	
		6001–10,000	Unsuitable	–	–	
SSP (Eaton, 1950)	$SSP = \frac{(Na^{+} + K^{+})x100}{(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})}$	< 60	Safe	Rest of samples	34	91.9
		> 60	Unsafe	15B, 20Q, 24M	3	8.1
SAR (Todd, 1980)	$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$	S1 < 10	Excellent	All studied samples	All studied samples	100
		S2 10–18	Good		–	
		S3 18–26	Doubtful		–	
		S4 > 26	Unsuitable		–	
RSC (Todd, 1980)	$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$	< 1.25	Excellent	All studied samples	All studied samples	100
		1.25–2.5	Doubtful		–	
		> 2.5	Unsuitable		–	
MAR (Todd, 1980)	$MAR = \frac{Mg^{2+}x100}{Ca^{2+} + Mg^{2+}}$	< 50	Suitable	2H, 3H, 4H, 5H, 6H, 7H, 8Z, 10Z, 11B, 12B, 15B, 16B, 18Q, 20Q, 22Q, 24M, 25M, 27M, 28R, 29R, 30R, 31R, 32R, 36G	24	64.9
		> 50	Unsuitable	1H, 9Z, 13B, 14B, 17B, 19Q, 21Q, 23M, 26M, 33F, 34L, 35G, 37G	13	35.1

from different sources, depths and experienced transportation through different pathways in the geological layers.

3.4. Groundwater quality for irrigation purposes

The evaluation of the investigated groundwater for irrigation purposes (Tables 2 & 3) is based on their Electrical Conductivity (EC), Soluble Sodium Percentage (SSP), Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), Magnesium Adsorption Ratio (MAR), and toxic metal content. The measured values of EC indicate that the groundwater at Mandisha station and Well 9, which represent 5.4% of the total samples, can be classified as permissible. The calculated values of combined SSP, SAR and RSC revealed that there is no problem in relation to sodium content for this groundwater to be used in irrigation. However, the SSP values revealed that the samples collected from Dedela Hot, El Beshmou and El Aguz, which represent 8.1% of the total samples, are unsafe. This problem in the study area may be resolved using an effective drainage system. On the other hand, the calculated values of MAR indicate that 35.1% of the studied samples are unsuitable for irrigation. The concentrations of Mn, Cu, Fe and Cr in the irrigation groundwater of the Bahariya Oasis (Table 3) exceed the maximum allowable limits (MAL) proposed by Ayers and Westcot (1985) and CCME (1999).

3.5. Groundwater quality for domestic purposes

The evaluation of the Bahariya Oasis groundwater for domestic purposes is based on their Total Dissolved Solids (TDS), Total Hardness (TH) and Corrosivity Ratio (CR). Table 4 shows that both Mandisha station and Well 9 groundwater samples (5.4% of the

Table 3
Percentages of the groundwater samples which exceed the maximum allowable limit for irrigation.

Metal	MAL (ppm)	Samples Exceed	%
Cr	0.1[a]	25M	2.7
Cu	0.2 [a]	1H, 3H, 10Z, 15B, 17B, 20Q, 22Q, 24M, 26M, 27M, 28R, 29R, 30R, 31R, 32R, 34L, 35G, 36G, 37G	51.4
Fe	5 [a,b]	2H, 6H, 17B, 35G	10.8
Mn	0.2 [a, b]	1H, 2H, 3H, 4H, 5H, 6H, 7H, 8Z, 10Z, 11B, 14B, 15B, 16B, 17B, 18Q, 20Q, 21Q, 22Q, 23M, 24M, 25M, 26M, 27M, 28R, 29R, 30R, 31R, 32R, 35G	78.4
Ni	0.2 [a, b]	–	–
Pb	0.2 [b]	–	–
V	0.1 [a,b]	–	–
Zn	2 [a]	–	–

[a] = Ayers and Westcot (1985).
[b] = CCME (1999).

Table 4
Suitability of the studied groundwater samples for domestic purposes.

Parameter	Equation	Range	Class	Sample No.	No. of Samples	%
TDS (mg/l; Bruvold and Daniels 1990)	–	< 80	Excellent		–	
		80–500	Good	Rest of samples	35	94.6
		500–800	Fair	23M, 35G	2	5.4
		800–100	Poor			
		> 1000	Unacceptable			
TH (mg/l; Sawyer and McCarthy 1967)	$TH = 2.5 \times Ca^{2+} + 4.1 \times Mg^{2+}$	< 75	Soft	1H, 3H, 4H, 6H, 7H, 12B, 13B, 15B, 16B, 18Q, 22Q, 25M, 28R, 29R, 30R, 31R, 32R, 33F, 34L, 36G	20	54.1
		75–150	Moderately Hard	2H, 5H, 8Z, 9Z, 10Z, 11B, 14B, 17B, 19Q, 20Q, 21Q, 24M, 26M, 27M, 37G	15	40.5
		150–300	Hard	23M, 35G	2	5.4
		> 300	Very Hard			
CR (Ryznre 1944)	$CR = \frac{\frac{Cl^-}{35.5} + \frac{SO_4^{2-}}{96}}{2xHCO_3^-} x100$	< 1	Safe	1H, 7H, 9Z, 12B, 13B, 14B, 15B, 16B, 17B, 19Q, 21Q, 22Q, 25M, 26M, 31R, 32R, 36G, 37G	18	48.6
		> 1	Unsafe	2H, 3H, 4H, 5H, 6H, 8Z, 10Z, 11B, 18Q, 20Q, 23M, 24M, 27M, 28R, 29R, 30R, 33F, 34L, 35G	19	51.4

total samples) can be classified as fair or hard, according to their TDS concentrations and calculated values of TH, respectively. On the other hand, the CR values reveal that 51.4% of the samples are unsafe for domestic uses.

3.6. Groundwater quality for drinking

The evaluation of the Bahariya Oasis groundwater for drinking is based on their Nitrate Pollution Index (NPI), toxic metal content, radiation hazard and Water Quality Index (WQI). The calculated NPI values for the studied groundwater samples (-0.55 to -0.99) reveals that all samples are free from nitrate pollution. However, the concentrations of the toxic metals Fe, Mn, Pb, Cu, Cr, Ni and V all exceed the MAL for drinking water (Table 6). In order to assess the radiation exposure for inhabitants of the Bahariya Oasis, the estimation of total annual dose due to ingestion of ^{238}U, ^{232}Th and ^{40}K in groundwater samples was estimated based on the activity concentrations and dose conversion factors of these radionuclides. The dose per unit intake for ^{238}U is 4.5×10^{-8} mSv/Bq, for ^{232}Th is 2.3×10^{-7} mSv/Bq and for ^{40}K is 6.2×10^{-9} (ICRP, 2012). The annual water consumption for each adult is 730 L (2 L daily) (WHO 2011). The values of total annual dose (TAD) of natural radionuclides calculated for the Bahariya oasis groundwater samples range from 0.00047 to 0.00366 mSv/year, which does not exceed the recommended annual dose values for drinking water. All chemical parameters were used to calculate the WQI for the Bahariya Oasis groundwater samples, applying the software developed by Nabizadeh et al. (2013). According to Sahu and Sikdar (2008) the obtained values (Table 5) reveal that this groundwater can be classified as excellent (13.52%), good (40.54%), poor (40.54%), very poor (2.7%) or unsuitable (2.7%).

4. Conclusions

The chemical composition of the Bahariya Oasis groundwater is strongly affected by its interaction with the lithologies of the Nubian Sandstone Aquifer. Dissolution of some aquifer rock components (carbonates and iron oxides) and chloride salts during infiltration of the groundwater, and addition of cations by ionic exchange of Na^{+} by Ca^{2+} in clay minerals, are the two main processes controlling the geochemistry of the studied groundwater. Most of the irrigation groundwater problems in the study area can be resolved by an effectively managed drainage system. There are no health hazards associated with natural radioactivity in this groundwater, however, the Bahariya Oasis communities experience other water quality problems. The Bahariya groundwater is contaminated by toxic metals with elevated levels higher than permissible for either irrigation or drinking purposes. The groundwater is not safe to use for domestic purposes, unless there is filtration of the water through suitable membranes capable of excluding the toxic metals. More research is required in some groundwater localities, such as Mandisha (Mandisha station) and El Gedida (Well 9). The Water Quality Index (WQI) reveals that about 45.9% of the studied groundwater samples are poor, very poor or unsuitable. In order to ensure safe usage of the groundwater for human consumption, regular monitoring of the water quality is vitally necessary.

Conflict of interests

Yes, I do not have conflict of interest to declare.

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Table 5
Suitability of the investigated groundwater for drinking purposes.

Parameter	Equation	Range	Class	Sample No.	No. of Samples	%
NPI(Obeidat et al., 2012)	$NPI = \frac{C_S - HAV}{HAV}$ Where, C^S is the analytical concentration of nitrate in the sample and HAV is the threshold value of anthropogenic source (human affected value) taken as 20 mg/l.	< 0	Unpolluted	All studied samples	All studied samples	100
		0–1	Light pollution		–	
		1–2	Moderate pollution		–	
		2–3	significant pollution		–	
		> 3	very significant pollution		–	
TAD(ADWG, 1996)	$TAD(mSy/year) = \text{Dose per unit intake}(mSv/Bq) \times \text{Annual water consumption}(litre/year) \times \text{Radionuclide concentration}(Bq/l)$	< 0.1	Safe	All studied samples	All studied samples	100
		> 0.1	Unsafe		–	
WQI (Sahu and Sikdar, 2008)	$q_i = \frac{C_i}{S_i} x100$ $SI_i = W_i x q_i$ $WQI = \sum SI_i$ where q_i is the quality rating, C_i is the concentration of each chemical parameter in each water sample, and S_i is the drinking water standard for each chemical parameter according to WHO (2011), SI_i is the subindex of i^{th} parameter; q_i is the rating based on concentration of i^{th} parameter.	< 50	Excellent	7H, 12B, 19Q, 33F, 37G	5	13.52
		50–100	Good	3H, 4H, 5H, 8Z, 9Z, 10Z, 11B, 13B, 16B, 21Q, 23M, 27M, 28R, 29R, 36G	15	40.54
		100–200	Poor	1H, 2H, 6H, 18Q, 14B, 15B, 17B, 20Q, 22Q, 24M, 26M, 30R, 31R, 32R, 34L	15	40.54
		200–300	Very poor	25M	1	2.70
		> 300	Unsuitable	35G	1	2.70

Table 6
Percentages of the groundwater samples which exceed the maximum allowable limit for drinking purposes.

Metal	MAL (ppm)	Samples Exceed	%
Cr	0.05[a,b]	3H, 25M, 30R, 34L, 36G	13.5
Cu	2 [a,b]	20Q, 26M, 27M, 30R, 31R, 32R, 34L, 35G, 36G	24.3
Fe	0.3 [a,c]	All samples	100
Mn	0.4 [a]	1H, 2H, 5H, 6H, 7H, 8Z, 10Z, 14B, 15B, 16B, 17B, 18Q, 20Q, 21Q, 22Q, 23M, 24M, 25M, 28R, 29R, 30R, 31R, 32R, 35G	64.9
Ni	0.02 [a] – 0.07 [b]	9Z, 20Q	5.4
Pb	0.01 [a,b]	1H, 20Q, 21Q, 24M, 26M, 27M, 30R, 31R, 32R, 34L	27
V	0.07[c]	25M, 26M	5.4
Zn	3 [a,b,c]	–	–

[a] = ESDW (2007).
[b] = WHO (2011).
[c] = US EPA (2007).

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