Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2019.24423

162 (2019) 14–29
September

Assessment of groundwater quality using GIS, hydrogeochemistry, and factor statistical analysis in Qena governorate, Egypt

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Received 18 December 2018; Accepted 14 May 2019

ABSTRACT

Groundwater is an important freshwater source for agricultural, drinking and industrial use in arid areas. The present study integrates geographic information system (GIS), hydrochemistry, and factor analysis to assess groundwater quality under expanding agricultural activities in Qena Governorate, Egypt. A total of 73 groundwater samples were collected and analyzed for pH, electrical conductivity (EC), total dissolved solids, major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), major anions (HCO_3^-,Cl^-, SO_4^{2-}, F^-), and total hardness. The spatial distribution of these analyzed physico-chemical parameters was mapped with GIS. According to the World Health Organization and Egyptian water standards, the computed water quality index shows that about 62% of the groundwater wells are suitable for drinking. Groundwater suitability for irrigation was assessed on the basis of sodium adsorption ratio (SAR), residual sodium carbonate (RSC), Kelley ratio (KR), magnesium hazard (MH). It is found that 99% of the wells are suitable for irrigation when considering the values of EC, and SAR only. However, only 50% of the wells are suitable for irrigation if Na^+%, RSC, and KR are considered. Hydrochemical classification and factor analysis indicate that the groundwater is Na^+–Cl^- (58%) and MgCl (23%) dominant which signifies the role of evaporation under intensive irrigation and hot climate. Dissolution of evaporites loads the system with Na^+ and Cl^- whereas return flow from irrigation transports solutes to groundwater. Increasing Mg^{2+} is due to dolomitic dissolution and the use of fertilizers. Moreover, ionic exchange activities increase Na^+ concentration in the groundwater at the expense of Ca^{2+}, but does not affect Mg^{2+}. The integration of traditional hydrochemical analysis and GIS with factor analysis is useful to understand the factors controlling groundwater chemistry and may aid decision makers toward effective groundwater quality management.

Keywords: Groundwater quality; Hydrochemistry; GIS; Factor analysis; Drinking and irrigation; Egypt

1. Introduction

Groundwater is the most important source of water supply in arid and semi-arid regions such as Egypt where freshwater resources are mainly supplied from the groundwater and the River Nile. Groundwater quality deterioration observed in Egypt represents a serious concern for domestic, industrial, and agricultural uses. During the last five decades, Egypt's population has tripled while the available renewable water resources remained unchanged. Agricultural consumption is the largest exceeding (85%) and contributes

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significantly to the socioeconomics especially in the rural areas. Due to the ever-growing demand for drinking and irrigation and a shortage of available surface water from the Nile River, the importance of groundwater is exponentially increasing. The study area (Qena) is one of the Upper Egypt governorates, which depends on groundwater for different purposes. In the last two decades, people in Qena installed many pumping wells for drinking and irrigation purposes. Although Qena governorate is located along the Nile River and the surface water is presumably available, shortage in the infrastructure for direct surface water intake has led to intensive uses of groundwater in the areas near and far from the Nile River. This is associated with a larger expansion in agriculture driven by increasing demand for food, the fertility of soil and availability of land for cultivation. It is, therefore, a necessity to assess groundwater suitability in the area for drinking and irrigation purposes to avoid potential health and environmental disasters. Hydrochemical assessment of the groundwater in the study area will lead to its proper management and protection, which in turn contributes to the sustainability of agriculture in the region.

Reclamation of desert areas in Egypt is vital to cover the growing demand for food associated with population growth and changes in diet. Such reclamation, which has been active for the past 30 years, requires expansion into lands with scarce surface water and thus depends entirely on groundwater. Therefore, gradual changes in groundwater quality and storage are anticipated. On the other hand, studying groundwater chemistry is also important to assess its suitability for agricultural, domestic and industrial purposes. Groundwater contamination has been considered dangerous [1–3] and its remediation is expensive and time consuming. Groundwater quality depends on its natural and physical state and on the changes induced by human activities [4]. The concentration of ions dissolved in groundwater is often many factors affecting groundwater quality (natural and anthropogenic). Understanding these factors is important for designing exploitation plans, future development, and required infrastructure.

Statistical factor analysis has been widely used to investigate groundwater geochemistry [5–14]. Factor analysis is a multivariate statistical technique that correlates measured chemical variables by showing multivariate patterns that may be helpful to classify the original data [6]. It allows developing unobservable information from water quality data [15]. Liu et al. [6] used Factor analysis to identify pollution indicators for prospecting and delineating the boundaries of seawater salinization and arsenic pollution in a blackfoot disease area of Taiwan. It was also used to describe the main hydrochemical processes and identify the possible causes of groundwater salinization and arsenic pollution in the coastal aquifer of Yun-Lin. Love et al. [7] found that factor analysis is useful to separate signatures due to uncontaminated groundwater, agricultural activities and mining activities as well as sewage effect. Yu et al. [9] concluded that factor analysis is a useful method that could assist decision makers in determining the extent of pollution via practical pollution indicators. Kudoda and Abdalla [13] integrated conventional hydrogeological and hydrochemical analysis with a statistical method to characterize groundwater resources in Khartoum State, Sudan. It has been demonstrated that the integration of conventional hydrochemical analysis with factor analysis represents a powerful mean to understand the factors controlling groundwater chemistry.

Geographic information system (GIS) is an effective tool for mapping. In particular GIS can be used to map and monitor groundwater quality. It may serve as a database system to create distributed maps of ions concentration and groundwater quality assessment [16–21].

This paper assesses groundwater quality in Qena governorate using conventional and the multivariate statistical analysis (factor analysis), and display spatial distribution of groundwater quality using GIS. It will also determine the factors controlling groundwater quality based on multivariate analysis (factor analysis) and GIS. Quality assessment will be on the basis of the WHO [22] and Egyptian standards for drinking water [23].

2. Study area

2.1. Location

The study area, located in Upper Egypt, covers about 3,415.36 km^2 as part of Qena Governorate that is distant about 600 km south of Cairo (Fig. 1). The governorate's total area covers 10,798 km^2 located within the narrow Nile valley and between the western and the eastern deserts.

The study area is located in zone 36 North in UTM coordination system in 393,760 N and 2,915,210 E and 503,099 N and 2,841,700 E. The two main sources of freshwater are the River Nile, which bisects the study area, and the Quaternary groundwater aquifer. The surface topography varies between flat around the Nile (around 50 m a.m.s.l) and relatively elevated (530 m a.m.s.l) in the eastern parts of the study area (Fig. 2). It is characterized by a desert climate that is very hot and dry in summer and cold in winter. The average annual temperature is 25°C, the average annual rainfall is 2.5 mm, and the mean monthly evapotranspiration is relatively high 6.2 mm/d [24].

2.2. General geology, hydrogeology and land use

The study area is located on the alluvial plains of the Nile Valley and covered by sedimentary rocks ranging in age from Holocene to Paleozoic. The geology of the Qena area was previously investigated by many researchers (e.g., Said [25–27], Ahmed [28], El-Balasy [29], Mansour and Kamal El-Dein [30]). The geological succession (Fig. 3) of the area is composed of from top to bottom:

- Holocene sediments represent the top upper layer and are formed from silty clay of the Nile floodplain and Wadi deposits.
- Late Pleistocene sediments represent the main aquifer in the study area (Quaternary aquifer) and are composed of sand and gravel with clay intercalations.
- Plio-Pleistocene sediments, this unit is composed of clay, sand and gravels and represent the Proto and Pre-Nile deposits of the study area.
- Pliocene deposits composed of clay with sand interbeds and act as the base of a Quaternary aquifer in the area under study.

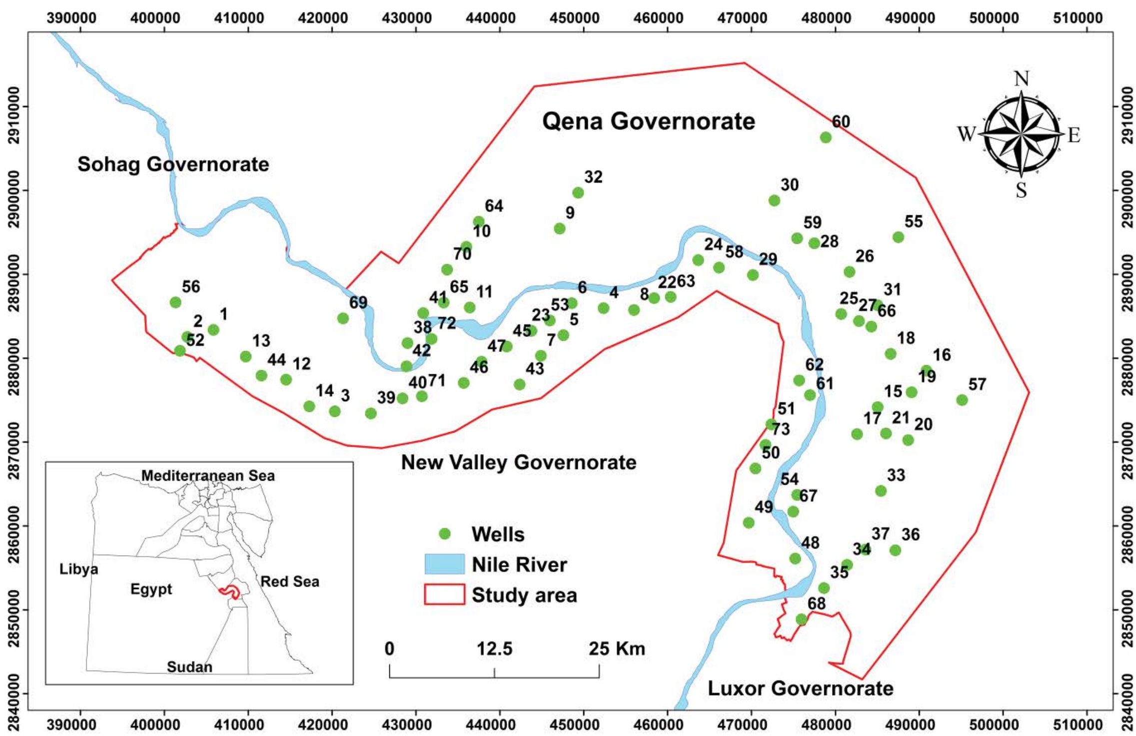

Fig. 1. Map of the study area showing sample locations.

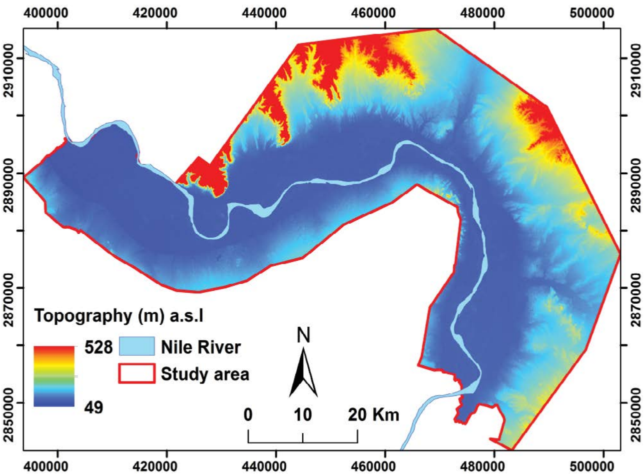

Fig. 2. Topographic map of the study area.

- Eocene Limestone rocks formed from chalky and dolomitic limestone and marl. The limestone rocks present in the western part of the Nile Valley in Egypt have some pockets of halite and gypsum [31,32].
- Paleocene-Late Cretaceous shale with thin interbeds of chalk and phosphate.
- Late Cretaceous-(Paleozoic) sediment is represented by sandstone with shale intercalations.

Structurally, the River Nile is drained in the central part and bounded by two limestone plateaus on the east and west (Fig. 3). The near-surface Pliocene-Holocene sediments in the central part of the Nile Valley rest unconformably on a succession of Late Cretaceous to Early Eocene age [34].

The Quaternary aquifer represents the main aquifer in the study area which is composed of fluvial sands and gravels with minor clay intercalations (Prenile, Qena Formation) [31]. This aquifer is semi-confined in the floodplain, but becomes unconfined in the desert fringes due to the absence of the Pliocene clay. The main source of recharge to the Quaternary aquifer is the return flow from irrigation. Active agriculture in the area heavily depends on the Nile Valley, irrigation canals and pumping groundwater wells depending on proximity to the Nile. The extensive pumping from the drilled wells, which are used for irrigation, represents the main groundwater discharge mechanism, as well as the baseflow to the Nile River. Dawoud and Ismail [35] modeled the interaction between the Nile River and the Quaternary aquifer along the Nile Valley and concluded that the Nile River is a gaining stream along most of its course in Egypt.

Notable agricultural activities take place in the study area along the Nile valley. These activities extend into the desert when soil fertility as well as land and water availability permit such extensions (Fig. 4). Farms are irrigated from the surface water drained from the Nile and canals' network and/or from groundwater abstracted from several scattered pumping wells. Intensive use of fertilizers such as magnesium phosphate characterizes these farms in addition to the use of lime for pre-cultivation land preparation.

3. Materials and methods

In order to achieve the objectives of the study, 73 groundwater samples were collected from different locations of

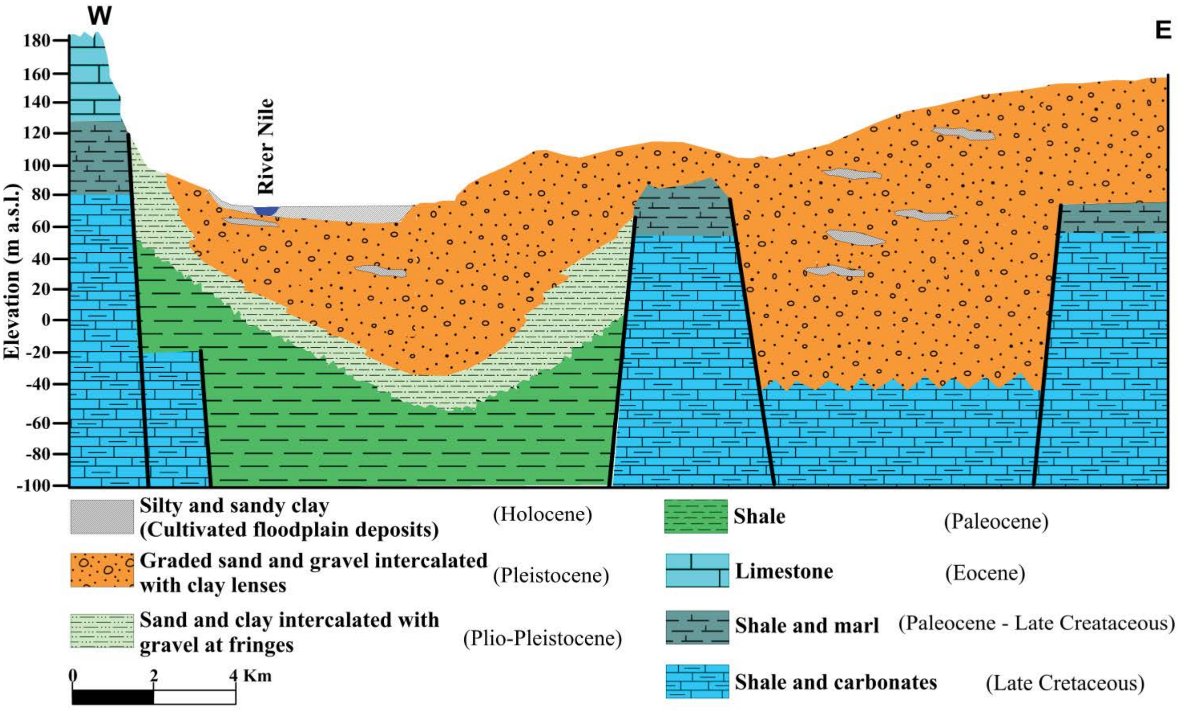

Fig. 3. Geologic cross-section of the study area, modified after RIGW [33].

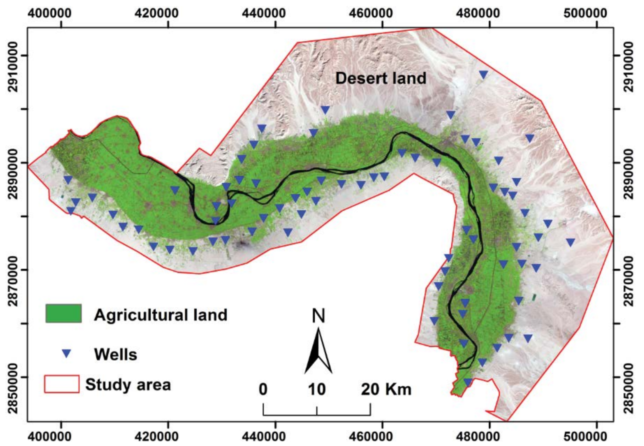

Fig. 4. A map that shows extension of agriculture with reference to the Nile in the study area.

the study area (Fig. 1) in the period between July 2013 and January 2014. The water samples were collected in new pre-cleaned polyethylene bottles (1 L capacity) and transported to the laboratory in an ice-box for further analysis. The coordinates and ground elevation for each water point are recorded by using a global positioning system (GPS). Before collecting groundwater samples, the wells were pumped for about 1 h to remove stagnant groundwater. Temperature, pH, total dissolved solids (TDS), and electrical conductivity (EC) were measured by Ultrameter SM101 instrument in the field immediately after sampling. The groundwater depth was measured for each sampled point and information about total drilled depth was collected from the well owners, which are used to construct water level map by subtracting the depth to groundwater from DEM (Fig. 2) to interpret the water flow. The complete chemical analysis of the collected groundwater were carried out in the Laboratory of Engineering Faculty, Minia Univeristy, El Minia, Egypt, in accordance to the standard methods adopted by the American Public Health Association (APHA) [36]. Calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), and chloride (Cl^-) were analyzed by volumetric titration methods, whereas sodium (Na^+) and potassium (K^+) were measured using the flame photometer. Sulphate (SO_4^{2-}) was determined by UV spectrophotometer.

The results are evaluated in accordance with the drinking water quality standards given by the World Health Organization (WHO) [22] and the Egyptian standards for drinking water [23]. Irrigation quality parameters (i.e., EC, SAR, sodium percentage Na%, residual sodium carbonate (RSC), Kelley's ratio (KR), magnesium hazard (MH), permeability index (PI), and Gibbs diagram were calculated based on the physico-chemical analyses of groundwater samples. The correlation of the analytical data has been attempted by plotting different graphical representation such as those of Piper [37]; Richards [38]; and Wilcox [39] to classify groundwater and its suitability for different purposes by ascertaining various factors dependence on the chemical characteristics of water. The spatial distribution maps of groundwater quality parameters have been prepared using ArcGIS 10.2.2 (Arc Map). The inverse distance weighted (IDW) technique is used to generate spatial interpolation maps for different parameters in the spatial analyst tool. Factor analysis and statistical summaries were computed using XLSTAT software. GWW software is used for chemical classification of water.

4. Results and discussion

The results obtained during this study will be presented and discussed in the following sections:

4.1. Groundwater level

Groundwater flows from the elevated areas into the Nile as indicated by the map (Fig. 5a) and the hydraulic heads range between 36.34 and 504.34 m above (m.s.l.). This confirms the finding of Dawoud and Ismail [35] as they concluded that the Nile is a gaining stream at Qena. The depth to groundwater ranges between 3 and 40 m below ground surface and increases toward the east and west directions (desert fringes), which impacts the cost of groundwater abstraction for irrigation (Fig. 5b).

4.2. Hydrogeochemical characteristics of groundwater

The analytical results of the major cations and anions data for the analysed 73 groundwater samples and the calculated values of total hardness (TH), SAR, sodium percentage (% Na), RSC, KR, MH, and PI of the study area are shown in Table 1.

The descriptive statistics (minimum, maximum, average, and standard deviation) were calculated for the physicochemical variables in groundwater samples of the study area, and the values of maximum allowable limits of different parameters, according to the WHO [22] and Egyptian water standards (EHCW) [23] are represented in Table 2.

The groundwater pH ranges between 6.1 and 8.84 with an average of 7.74 that indicates more or less neutral groundwater mostly suitable for drinking [22,23]. The EC is an important parameter to assess salinity hazards and suitability for irrigation. The EC is variable (334–6,045 μS/cm) with an average of 1,544 μS/cm. Higher EC values are recorded in the groundwater wells in the newly reclaimed area due to dissolution of limestone as well as there is no direct recharge from the surface water.

TDS is a measure of the combined content of all inorganic and organic substances contained in a liquid as a molecular, ionized, or micro-granular (colloidal sol.) suspended form [40]. According to Hem [41], 62% of the groundwater samples are freshwater with TDS less than 1,000 mg/L (Table 3) whereas 37% are slightly saline (TDS 1,000–3,000 mg/L). The increasing salinity may be due to mineral dissolution such as evaporites present in the sediments or salts-leaching from the soil as return flow joins groundwater. Salts accumulate in the soil profile due to high evaporation that is characteristic of dry and hot climates. TDS contour map (Fig. 6) shows that the northeastern part is characterized by low TDS due to its connection to the irrigation system, while the southwestern part is characterized by the higher TDS due to mineral dissolution and lack of recharge as it is located farther from the irrigated areas.

The TH of water primarily depends upon the amount of Ca^{2+} and Mg^{2+} which are among the abundant ions in groundwater. Hard water causes scales in the boilers, pipes and other domestic appliances, while soft water is more corrosive and contains more metal contaminants from the water pipes [42]. TH classification [43] indicates that about 64% of the groundwater samples are hard to very hard reflecting dissolution of limestone and dolomitic limestone present in the western part of the study area (Table 4). The use of fertilizers will also contribute to the increased hardness as they mostly contain Mg.

The aerial distribution of the major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and major anions (HCO_3^-, Cl^-, SO_4^{2-}) is shown in Figs. 7 and 8, respectively. The concentration of all ions increases in the west due to the dissolution of limestone and absence of direct recharge from surface water. On the contrary, ions concentration decreases in the east because of direct connection with the surface water from the Nile and irrigation canals, which is in accordance with the TDS trend.

The hydrochemical data of the study area is presented in the Piper diagram [37] to classify its groundwater (Fig. 9a). The major ions, in the order of their concentration (first more abundant), presented in the Piper diagram are Na^+, Cl^-, HCO_3^-, Mg^{2-}, Ca^{2-}. The triangular cationic field (Fig. 9a) reveals that most of the groundwater samples are sodium dominant class, while only 7% and 3% of the samples

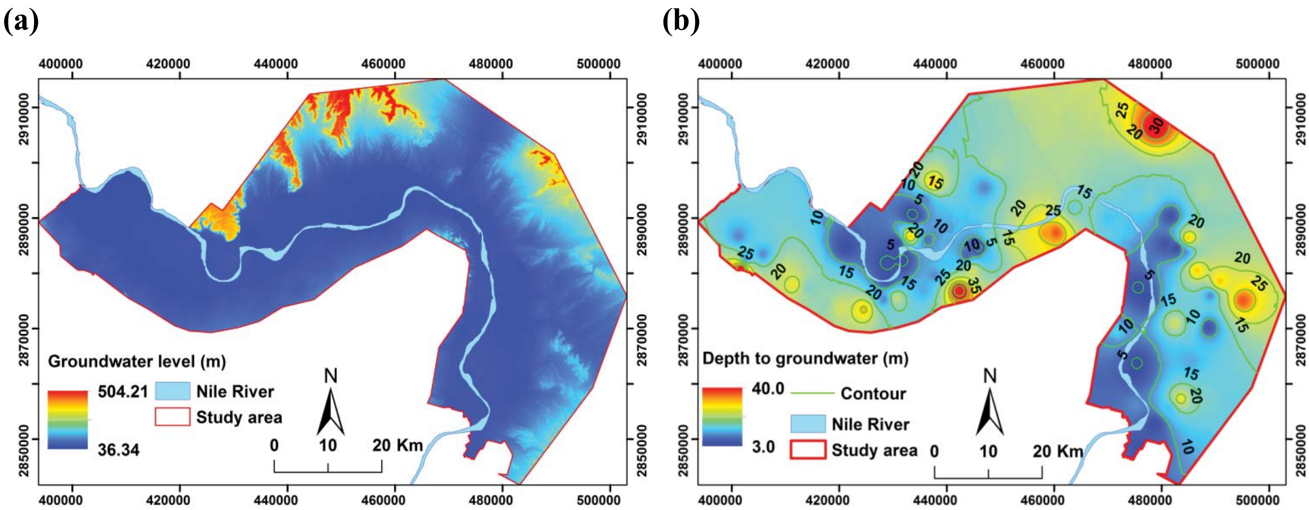

Fig. 5. Maps show the groundwater level (a) and the depth to the groundwater (b) in the study area.

Table 1
Hydrogeochemical characteristics for all samples in the study area in mg/L with the calculated of TH (mg/L), SAR (meq/L), RSC (meq/L), KR (%), MH (%), and PI (meq/L)

S. no.	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	TH	SAR	RSC	KR	MH	PI
		µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	meq/L	meq/L	%	%	meq/L
1	9	1,015	680	8	14	198	1.1	234	200	20	78	9.8	2.3	6	74	104
2	8	1,285	861	69	68	90	1.1	125	278	152	452	1.8	–7	0	62	41
3	9	1,433	960	16	24	226	0.8	302	191	110	139	8.3	2.2	4	71	95
4	8	2,394	1,604	56	63	380	4.8	117	710	128	399	8.3	–6.1	2	65	73
5	8	1,463	980	20.8	18	288	4.6	151	355	124	126	11.2	0	5	59	93
6	8	764	512	1.6	31.5	112	2.5	185	85	104	134	4.2	0.4	2	97	87
7	7	597	400	8	14	86	0.8	102	106	41	78	4.2	0.1	2	74	95
8	8	2,388	1,600	154	122	150	2.8	309	420	348	887	2.2	–12.7	0	57	36
9	8	2,269	1,520	24	58	423	1.6	156	731	62	299	10.6	–3.4	3	80	82
10	8	1,288	863	72	97	46	0.2	122	320	128	579	0.8	–9.6	0	69	25
11	8	1,555	1,042	106	97	66	1.3	326	280	166	664	1.1	–7.9	0	60	32
12	7	1,463	980	11.2	34	246	1.1	239	264	132	168	8.3	0.6	3	83	90
13	9	960	643	12.8	24	92	0.4	68	144	72	131	3.5	–1.5	2	76	76
14	8	1,003	672	11.2	19	196	0.9	292	148	74	106	8.3	2.7	4	74	100
15	9	927	621	1.6	18	161	2.1	195	142	68	78	7.9	1.6	5	95	102
16	7	707	474	6.4	22.5	60	1.3	97	85	40	109	2.5	–0.6	1	85	80
17	8	716	480	1.6	22.5	224	2.6	312	99	182	97	9.9	3.2	5	96	102
18	7	6,045	4,050	304	189	865	3.2	219	2,130	240	1,537	9.6	–27.1	1	51	58
19	6	3,582	2,400	296	191	202	1.3	122	970	490	1,525	2.3	–28.5	0	52	26
20	8	707	474	9.6	9	120	0.5	244	64	32	61	6.7	2.8	4	61	112
21	7	1,373	920	56	43	164	0.7	190	236	180	317	4	–3.2	1	56	66
22	8	1,672	1,120	32	36	269	3.2	165	426	78	228	7.7	–1.9	3	65	82
23	8	3,373	2,260	280	97	323	1.2	170	710	640	1,098	4.2	–19.2	1	36	44
24	8	1,134	760	16	38	151	0.6	146	248	56	196	4.7	–1.5	2	80	77
25	8	697	467	24	29	78	0.7	120	106	102	179	2.5	–1.6	1	67	68
26	7	640	429	4.8	19	109	1	185	49	101	90	5	1.2	3	87	99
27	7	1,284	860	88	24	159	0.6	219	220	170	318	3.9	–2.8	1	31	66
28	8	1,022	685	48	29	113	0.5	331	115	51	239	3.2	0.6	1	50	75
29	7	2,269	1,520	148	125	124	1.6	370	444	222	884	1.8	–11.6	0	58	34
30	8	1,239	830	80	94	29	0.1	126	288	140	587	0.5	–9.7	0	66	21
31	8	1,761	1,180	72	145	69	1.1	201	412	196	776	1.1	–12.2	0	77	26
32	8	1,916	1,284	96	111	120	2.1	200	300	365	696	2	–10.6	0	66	37
33	8	745	499	16	14	119	0.5	134	128	64	98	5.2	0.2	3	59	93
34	8	1,213	813	24	24	195	0.9	366	148	74	159	6.7	2.8	3	62	94

(continued)

35	8	2,925	1,960	196	140	181	2.6	352	560	370	1,066	2.4	–15.5	0	54	35
36	8	363	243	9.6	14	44	1	60	68	42	82	2.1	–0.6	1	71	81
37	7	1,836	1,230	24	38	286	1.2	375	280	134	216	8.5	1.8	3	72	89
38	7	3,278	2,196	80	81	518	3.5	131	880	304	533	9.8	–8.5	2	63	72
39	7	2,566	1,719	128	97	287	1.1	204	816	30	719	4.7	–11	1	56	53
40	8	1,090	730	16	43	129	0.9	105	220	100	217	3.8	–2.6	1	82	69
41	8	334	224	3.2	9.7	55	0.4	122	21	41	48	3.5	1	3	83	113
42	8	1,075	720	16	19	170	0.6	170	142	144	118	6.8	0.4	3	66	93
43	8	2,328	1,560	104	63	291	1.1	268	639	34	519	5.6	–6	1	50	64
44	8	1,175	787	128	19	93	0.4	204	211	132	398	2	–4.6	1	20	49
45	8	1,146	768	8	9	250	2.3	170	268	94	57	14.4	1.6	10	65	104
46	7	3,128	2,096	432	29	105	1.5	392	504	384	1,198	1.3	–17.5	0	10	25
47	8	1,057	708	8	29	154	1	200	126	126	139	5.7	0.5	2	86	89
48	6	1,809	1,212	32	145	133	0.6	97	464	232	677	2.2	–11.9	0	88	36
49	8	1,924	1,289	96	92	166	0.7	146	448	224	618	2.9	–10	1	61	45
50	8	1,763	1,181	48	29	301	1.3	292	340	170	239	8.5	0	3	50	85
51	7	2,627	1,760	239	145	98	1.1	336	547	372	1,193	1.2	–18.4	0	50	23
52	8	888	595	10	19	91	0.3	224	59	34	103	3.9	1.6	2	76	97
53	8	343	230	16	14	33	0.1	170	1,253	182	98	1.5	0.8	1	59	92
54	8	773	518	6.4	19.4	130	0.6	175	130	66	96	5.8	1	3	83	97
55	9	888	595	1	19	153	0.5	366	66	22	81	7.4	4.4	4	97	110
56	8	1,433	960	112	43	126	2	200	260	192	457	2.6	–5.8	1	39	50
57	8	960	643	24	53	88	0.4	160	210	50	278	2.3	–2.9	1	78	58
58	8	573	384	8	38	50	0.6	100	120	40	176	1.6	–1.9	1	89	60
59	8	764	512	14	24	104	0.5	165	120	64	134	3.9	0	2	74	85
60	8	1,433	960	72	34	144	2.2	142	254	165	320	3.5	–4.1	1	44	61
61	8	1,851	1,240	56	24	290	0.8	180	299	285	239	8.2	–1.8	3	41	82
62	7	1,284	860	65	21	170	0.6	180	236	135	249	4.7	–2	2	35	74
63	9	1,373	920	12	29	248	2.1	97	357	104	149	8.8	–1.4	4	80	87
64	8	660	442	9.6	9	120	2.3	102	159	33	61	6.7	0.5	4	61	100
65	8	2,522	1,690	128	97	287	2.4	146	854	26	719	4.7	–12	1	56	52
66	8	1,910	1,280	80	116	128	0.6	219	398	224	677	2.1	–9.9	0	71	39
67	8	1,284	860	32	72	120	0.4	175	208	198	376	2.7	–4.7	1	79	54
68	8	2,716	1,820	56	77	411	1.2	219	705	176	457	8.4	–5.5	2	69	73
69	9	1,403	940	4.8	53	201	1.1	195	256	146	230	5.8	–1.4	2	95	79
70	8	955	640	24	48	71	0.6	317	89	28	257	1.9	0	1	77	65
71	7	382	256	20	8	51	0.5	46	89	33	83	2.4	–0.9	1	40	79
72	8	2,776	1,860	160	116	302	0.9	219	795	232	877	4.4	–13.9	1	54	49
73	8	1,346	902	6	34	242	0.7	248	298	58	155	8.5	1	3	90	92

Table 2
Minimum, maximum, average, and standard deviation values of different elements of water samples of the study area

Elements	Minimum	Maximum	Mean	Standard deviation	WHO desirable limit	WHO allowable limit	Egypt limit
pH	6	9	7.8	0.57	6.5–8.5	8.5	7–8.5
Electrical conductivity (EC) (μS/cm)	350	6,045	1,544	945.8	1,500	1,500	–
Total dissolved solids (TDS) (mg/L)	224	4,050	1,034	633.7	500	1,000	500
Calcium (Ca^{2+}) (mg/L)	1.0	432	63.8	83	75	75	75
Magnesium (Mg^{2+}) (mg/L)	8.0	191	53.9	45.5	30	30	50
Sodium (Na^{+}) (mg/L)	29	865	179.1	129.1	200	200	200
Potassium (K^{+}) (mg/L)	0.1	4.8	1.3	1.0	10	10	–
Bicarbonate (HCO_3^-) (mg/L)	46	392	198.8	84.6	100	100	–
Chloride (Cl^-) (mg/L)	21	2,130	346.6	330.6	200	200	200
Sulfate (SO_4^{2-}) (mg/L)	20	640	144.9	118.1	200	200	400
Total hardness (TH) (mg/L)	47.9	1,536.8	381.1	357.9	300	600	500
Sodium adsorption ratio (SAR) (meq/L)	0.5	14.4	4.9	3.1	–	–	–
Residual sodium carbonate (RSC) (meq/L)	–28.5	4.4	–4.4	7.0	–	–	–
Kelley ratio (KR) (%)	0.1	9.5	1.9	1.8	–	–	–
Magnesium hazard (MH) (%)	10	97	65.9	18.1	–	–	–
Permeability index (PI) (meq/L)	20.8	113.2	70.6	25.52	–	–	–

Table 3
Classification of water types according to Hem [41]

Water type	TDS (mg/L)	Number of samples	Percentage of samples
Freshwater	<1,000	45	62%
Slightly saline	1,000–3,000	27	37%
Moderately saline	3,000–10,000	1	1%
Very saline	10,000–35,000	–	–
Brine	>35,000	–	–

are Mg^{+2} and Ca^{2+}, dominant, respectively. In the anionic triangle, most of the samples are chloride dominant and only 10% is bicarbonate dominant. The diamond-shaped central field shows the dominance of Na^+ and Cl^- over the other ions. The alkali metal Na^+ exceeds the alkaline earth metals ($Ca^{2+} + Mg^{2+}$). The total concentration of strong acids (SO_4^{2-} + Cl^-) exceeds that of the weak acids (HCO_3^-). The Na^{2+} and Cl^- ions are driven from the gypsum dissolution of evaporitic minerals as well as from intensive evaporation due to high temperature and aridity while the area is under intensive irrigation. The return flow from irrigation facilitates the leaching of salts along the soil profile to reach the shallower groundwater. This leads to the dominance of Na^+ and Cl^-. On the other hand, the use of fertilizers in the area introduced increased the concentration of particular ions such as Mg^{2+} and SO_4^{2-} [32]. HCO_3^- is driven from the dissolution of carbonate rocks in the new reclaimed area [44] and it also increases in locations close to the surface water bodies due to the direct recharge from the Nile River and irrigation canals [45].

The hydrochemical classification of the groundwater (Fig. 9b) shows five water types (NaCl 58%, $MgCl_2$ 23%, $NaHCO_3$ 14%, $CaCl_2$ 4%, and Mg $(HCO_3)_2$ 1%). The sodium chloride and magnesium chloride dominant water types indicate the dissolution of evaporites and the extensive use of fertilizers while the presence of sodium bicarbonate water type indicates recharge from the surface water. Such recharge occurs as a return flow from irrigation which also leaches

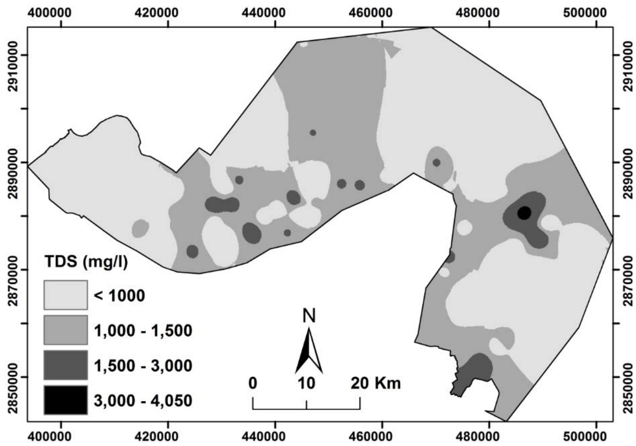

Fig. 6. Total dissolved solids zonation map for the study area.

Table 4
Classification of groundwater quality based on hardness

Total Hardness (mg/L)	Classification	Number of samples	Percentage of samples
<75	Soft	4	6%
75–150	Moderate hard	22	30%
150–300	Hard	17	23%
>300	Very hard	30	41%

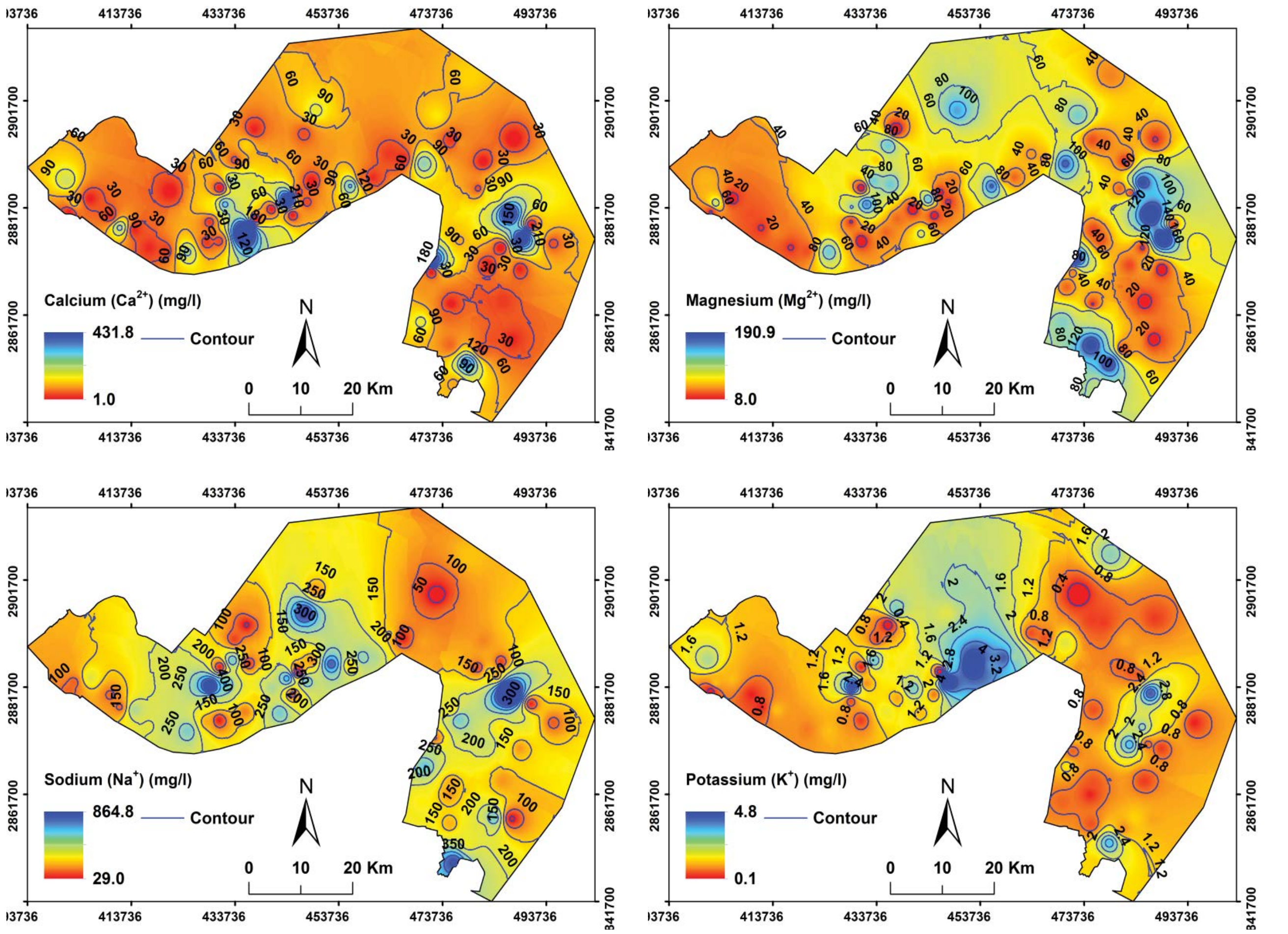

Fig. 7. Aerial distribution of the major cations Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} in the study area.

the soil and loads groundwater with the ions present in the soil profile.

4.3. Assessment of groundwater quality for drinking and domestic purposes

Natural and/or anthropogenic processes and activities affect groundwater quality. In the evaluation of groundwater quality for drinking and domestic purposes reference will be made to the specific standards set by various agencies including the drinking water standards of WHO [22] and the Egyptian standards for drinking water [23] (Table 2). By correlating the analyzed data with the domestic and drinking standards, it is observed that, 62% of the collected groundwater samples are suitable for drinking due to the low salinity (TDS < 1,000 ppm) while 38% are unsuitable due to high salinity (TDS > 1,000 ppm). Most of the collected groundwater samples (64%) are hard to very hard water, which labels these waters as unsuitable for domestic purposes.

4.4. Assessment of groundwater quality for irrigation purposes

The important hydrochemical parameters of groundwater used to determine its suitability for irrigation are EC, percentage sodium (Na%), SAR, RSC, KR, MH, PI, and Gibbs diagram. Salinity may harm plant's growth physically by limiting the uptake of water through modification in the osmotic processes or chemically by metabolic reactions such as those caused by toxic constituents [46]. The EC values indicate that 78% of the groundwater in Qena is suitable for irrigation with 18% being good and 60% permissible (Table 5). Only 1% is unsuitable and 21% is doubtful.

4.4.1. Sodium percentage (Na%)

The sodium percentage (Na%) defined by Raghunath [47] is calculated using the formula given in the following:

$$\text{Na\%} = \frac{\left(\text{Na}^{2+} + \text{K}^{+}\right)}{\left(\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^{2+} + \text{K}^{+}\right)} \times 100 \qquad (1)$$

where all the concentrations are expressed in milliequivalents per liter. The Na% indicates that about 52% of the collected groundwater samples are excellent to permissible for irrigation while the 48% is doubtful to unsuitable water (Table 6).

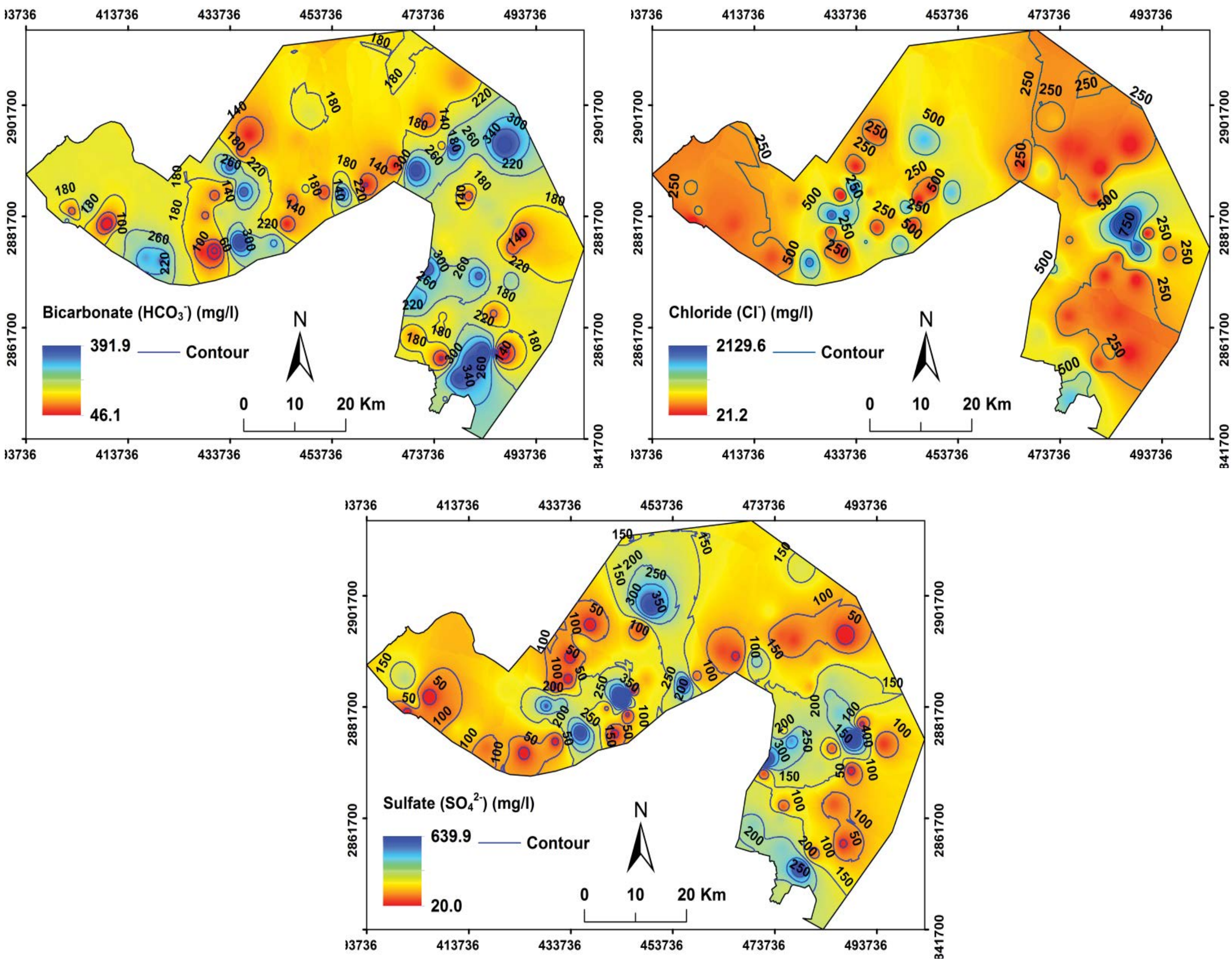

Fig. 8. Aerial distribution of the major anions HCO_3^-, Cl^-, and SO_4^{2-} in the study area.

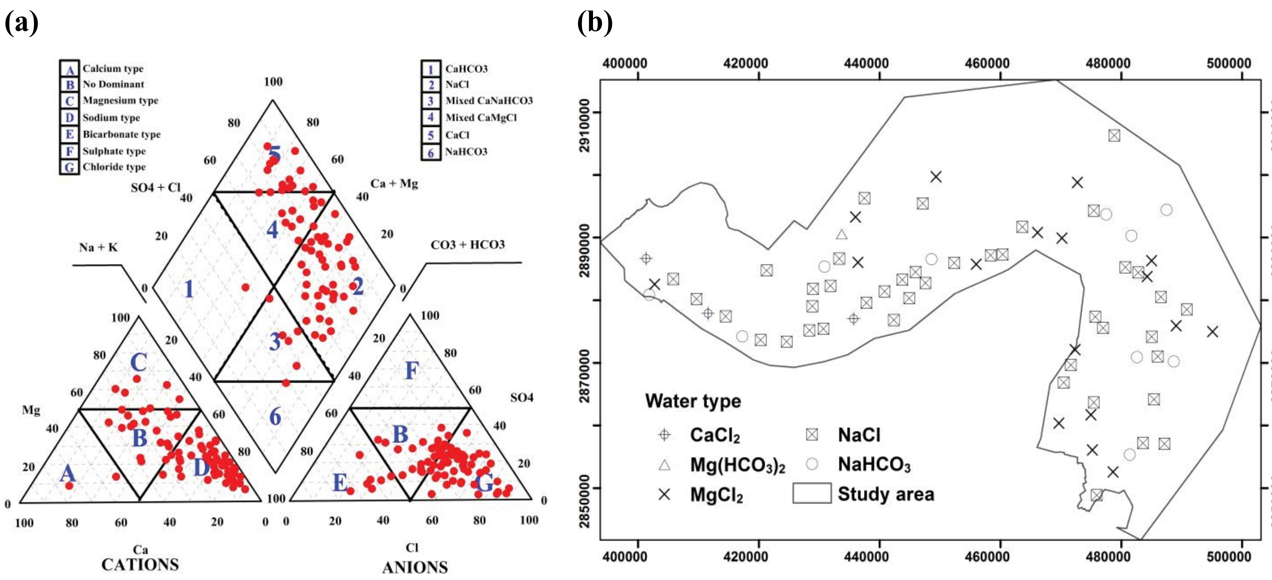

Fig. 9. (a) Piper trilinear diagram; (b) chemical water types of the groundwater wells in the study area.

Table 5
Quality of irrigation water based on electrical conductivity [46]

EC (μS/cm)	Classification	Number of locations	Percentage of locations
<250	Excellent	–	–
250–750	Good	13	18%
750–2,250	Permissible	44	60%
2,250–5,000	Doubtful	15	21%
>5,000	Unsuitable	1	1%

Table 6
Quality of irrigation water based on Na%

Na%	Classification	Number of locations	Percentage of locations
<20	Excellent	6	8%
20–40	Good	14	19%
40–60	Permissible	18	25%
60–80	Doubtful	26	36%
>80	Unsuitable	9	12%

4.4.2. Sodium Adsorption Ratio (SAR)

SAR, defined by Karanth [48], is an important parameter for determining the suitability of groundwater for irrigation. It is a measure of alkali/sodium hazard to crops and estimated as:

$$SAR = \frac{Na^{2+}}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}} \quad (2)$$

where the concentrations are reported in milliequivalents per liter. About 90% of the groundwater in the study area falls in the low-sodium class (S1) and 10% in good class (S2) (Table 7) which means that all the analyzed samples are suitable for irrigation purposes.

4.4.3. Residual sodium carbonate

The quantity of bicarbonate and carbonate in excess of alkaline sediments (Ca^{2+} and Mg^{+2}) also influences the suitability of water for irrigation purposes. When the sum of carbonates and bicarbonates is in excess of calcium and magnesium, there may be the possibility of complete precipitation of Ca^{2+} and Mg^{2+} [47]. RSC has been computed by the following equation:

$$RSC = \left(HCO_3^- + CO_3^{2-}\right) - \left(Ca^{2+} + Mg^{2+}\right) \quad (3)$$

All ionic concentration is in milliequivalents per liter. Waters with RSC values above 2.5 meq/L are not suitable for irrigation and these with values less than 2.5 meq/L are suitable. In the studied water samples 52% have RSC values above 2.5 meq/L and unsuitable for irrigation, while 48% have values less 2.5 meq/L and suitable for irrigation.

Table 7
Quality of irrigation water based on SAR

SAR	Alkalinity hazard	Classification	Number of locations	Percentage of locations
<10	S1	Excellent	66	90%
10–18	S2	Good	7	10%
18–26	S3	Doubtful	–	–
>26	S4	Unsuitable	–	–

4.4.4. Kelley's ratio

KR is a method of evaluating the effect of sodium on water quality for irrigation water. Sodium measured against calcium and magnesium was considered by Kelly [49] for calculating KR. Kelly's ratio is calculated by the following equation:

$$KR = \frac{Na^{2+}}{\left(Ca^{2+} + Mg^{2+}\right)} \quad (4)$$

where all the concentrations are expressed in milliequivalents per liter. Groundwater having KR more than one is generally considered as unfit for irrigation. In the study area, 53% of the groundwater samples have KR value < 1, indicating the good quality of the water for irrigation, and 47% is unsuitable for irrigation as the KR values are more than one.

4.4.5. Magnesium hazard

The MH of irrigation water is proposed by Szabolcs and Darab [50] with the following equation:

$$MH = \frac{Mg^{2+}}{\left(Ca^{2+} + Mg^{2+}\right)} \times 100 \quad (5)$$

where all the ionic concentrations are expressed in milliequivalents per liter. The MH values exceeding [51] are considered unsuitable for irrigation. The analyzed water samples reflect that about 82% of the groundwater wells are exceeding the magnesium ratio of 50 and hence is unsuitable for irrigation.

The SAR vs. EC values for groundwater samples of the study area were plotted in the USSL graphical diagram of irrigation water (Fig. 10). Based on the USSL diagram [52]; the salinity hazard ranges between medium to very high whereas the sodium hazard is mostly low to medium. The samples are distributed in the C2S1, C3S1, C3S2, C4S1, C4S2 (medium to very high salinity with low to medium sodium) category and only one sample falls out of the diagram. This shows that the majority (99%) of groundwater samples are satisfactory for irrigation in almost all soil types under ordinary conditions.

4.4.6. Permeability index

The PI values indicate suitability of groundwater for irrigation, as the soil permeability is affected by a long-term use of irrigation water, influenced by the Na^+, Ca^{2+}, Mg^{2+}

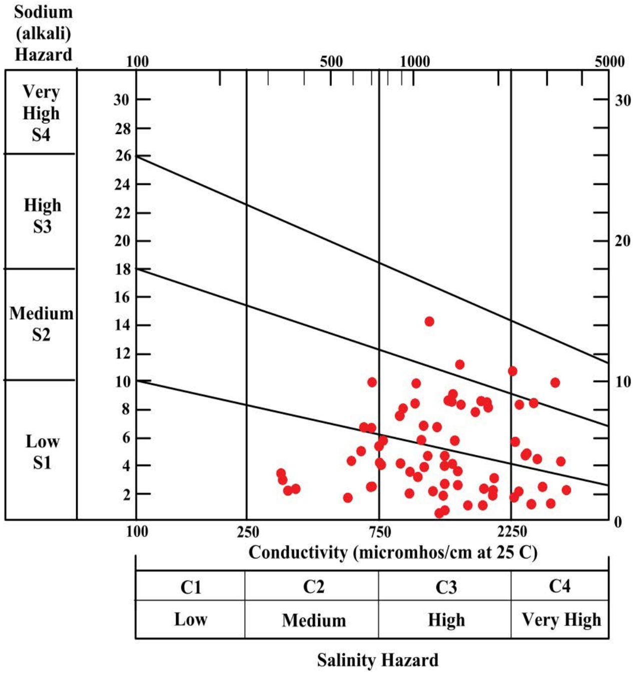

Fig. 10. Groundwater suitability for irrigation according to US Lab. classification [52].

HCO_3^- and K^+ contents of the soil. Doneen [53] developed PI parameter for assessing a water suitability classification for irrigation water. The PI was calculated by the following equation:

$$PI = \frac{Na^+ \pm \sqrt{HCO_3^-} \times 100}{Ca^{+2} + Mg^{+2} + Na^+ + K^+} \quad (6)$$

According to the permeability index values of Doneen's chart [54] (Fig. 11), 56% of the samples falls under class 1 and reflects good suitability for irrigation purposes, 47% falls in class II which indicates moderate suitability for irrigation and 15% falls in class III with poor or unsuitability for irrigation (Table 8).

4.4.7. Gibbs groundwater chemistry

Gibbs diagram [55] represents the ratio 1 for cations [(Na + K)/(Na + K + Ca)] and ratio 2 for anions [Cl/(Cl + HCO_3)] as a function of TDS to assess the groundwater chemistry. This diagram helps to understand the groundwater chemistry and the relationship of its chemical components to aquifers, such as the chemistry of rock types, the chemistry of precipitated water, and evaporation rate. The chemical data of the collected groundwater samples are plotted in the Gibbs diagram as shown in Fig. 12. From this figure, the majority (79%) of the groundwater samples suggests that the chemical weathering of rock-forming minerals is influencing the groundwater quality through the dissolution of the host rock; only 15% of the collected groundwater samples is affected by evaporation and the rest by precipitation.

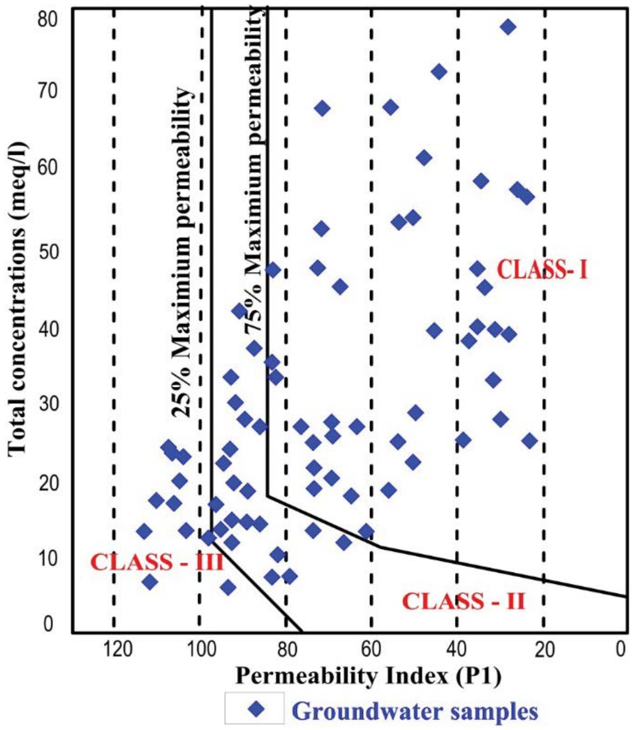

Fig. 11. Doneen's [53] classification for irrigation water based on the permeability index.

Table 8
Quality of irrigation water based on PI

PI%	Water quality	Classification	Number of locations	Percentage of locations
>75	Class I	Good	41	56
75–25	Class II	Moderate	21	29
<25	Class III	Poor	11	15

4.5. Statistics analysis

4.5.1. Correlation analysis

The correlation coefficient is commonly used to measure the relationship between two variables. It is simply a measure to exhibit how well one variable predicts the other. The correlation matrices for EC, TDS, TH, and major ions (Table 9) show that EC and TDS have a high positive correlation with Ca^{2+} and Mg^{+2}. A high positive correlation between TH and Ca^{2+} (r = 0.92) and Mg^{2+} (r = 0.90) confirms that groundwater hardness is related to these constituents. The pH shows a weak negative correlation with other parameters. Correlation analysis can give information about the source of major ions. The close relationship between Ca^{2+} and Mg^{2+} and SO_4^{2-} may indicate sulfate minerals dissolution (gypsum). The positive correlation between Na and Cl indicates dissolution of chloride minerals that present in the study area (as pockets in limestone and filling the cracks of Pliocene clay). The bicarbonate negatively correlates with Cl, which indicates that the Cl is from a different source as compared with the bicarbonate.

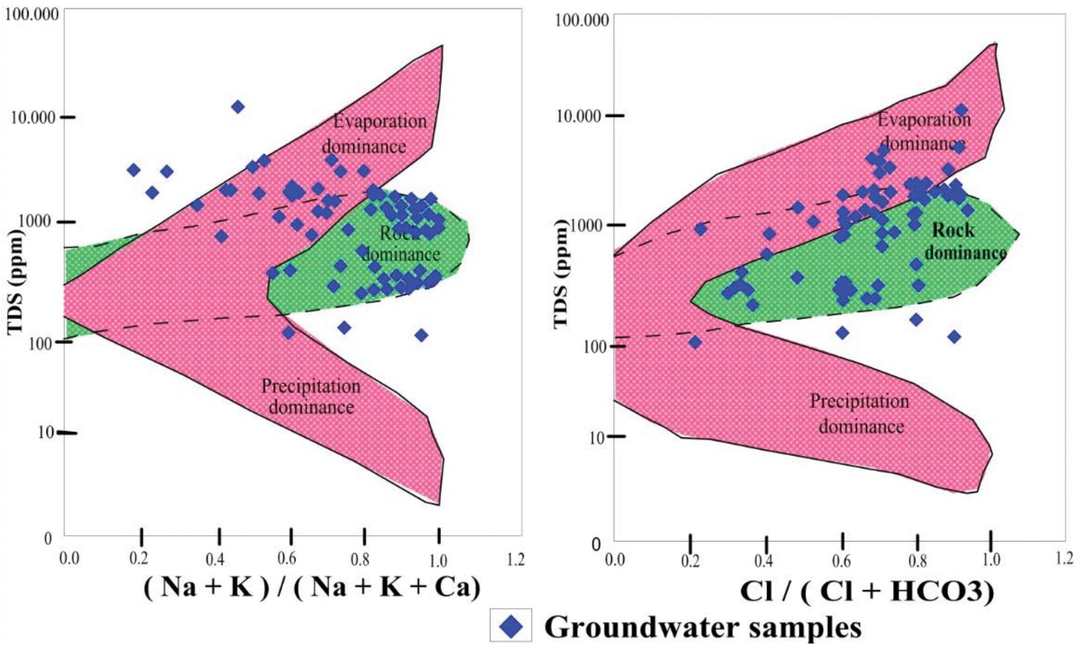

Fig. 12. Gibbs diagram of groundwater samples.

Table 9
Correlations coefficient of Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, EC, pH, TDS for the samples of the study area

Variables	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	Cl^-	EC	pH	TH	TDS
Na^+	**1**										
K^+	0.539	**1**									
Ca^{2+}	0.285	0.194	**1**								
Mg^{2+}	0.301	0.186	**0.647**	**1**							
HCO_3^-	0.104	0.012	0.297	0.119	**1**						
SO_4^{2-}	0.210	0.209	**0.745**	**0.623**	0.189	**1**					
Cl^-	**0.714**	0.362	**0.606**	**0.644**	0.023	0.436	**1**				
EC	**0.747**	0.434	**0.796**	**0.760**	0.236	**0.647**	**0.834**	**1**			
pH	–0.167	–0.089	–0.459	–0.389	0.043	–0.376	–0.386	–0.416	**1**		
TH	0.323	0.210	**0.917**	**0.897**	0.234	**0.757**	**0.688**	**0.858**	–0.469	**1**	
TDS	**0.747**	0.434	**0.796**	**0.760**	0.236	**0.647**	**0.834**	**1.000**	–0.416	**0.858**	**1**

Bold values indicate high correlation between variables.

4.5.2. Factor analysis

In order to identify the main factors affecting the groundwater quality and water types in the study area, factor analysis was used as a statistical method. Factor analysis is a multivariate statistical method that has the ability to reduce the number of variables to be studied and to detect how they are inter-linked. Factor analysis yields to explain the correlation coefficient between the variables and the factors [9]. The factor analysis distinguishes between dependent and independent variables. Table 10 represents factor analysis, calculated eigenvalues, percentage total variance, and cumulative variance results for all samples analyzed in the study area. The factor analysis generated three important factors which explained 77.28% of the total variance. The following factors have been identified as the main drivers of the groundwater chemistry:

- Factor 1 explains about 57.57% of the total variance and includes TH, TDS, EC, Ca^{2+}, Cl^-, Mg^{2+}, SO_4^{2-}, and pH, with, respectively, loading values of 0.924, 0.991, 0.991, 0.840, 0.917, 0.794, 0.702, and –0.441. Even Na shows a reasonable correlation with this factor but stronger with factor 2. The increasing TDS, TH, and EC are mainly driven by increasing concentration of the ions SO_4^{2-}, Cl^-, Na^+, Ca^{2+}, and Mg^{2+}, which is facilitated by agricultural practices such as the extensive use of fertilizers and application of lime. These practices introduce excess ions to the system that is subject, when under irrigation, to intensive evaporation that enriches ion concentration in the solution and

Table 10
Factor analysis of Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, EC, pH, TDS for the study area

Variable	F1	F2	F3
Na^+	0.651	**0.743**	0.157
Ca^{2+}	**0.840**	–0.350	0.019
Mg^{2+}	**0.794**	–0.225	–0.156
HCO_3^-	0.240	–0.243	**0.858**
SO_4^{2-}	**0.702**	–0.319	–0.031
Cl^-	**0.917**	0.314	–0.120
EC	**0.991**	0.128	0.049
pH	**–0.441**	0.141	0.207
TH	**0.924**	–0.369	–0.095
TDS	**0.991**	0.128	0.049
Eigenvalue	6.33	1.31	0.86
Total variance (%)	57.57	11.90	7.81
Cumulative variance (%)	57.57	69.47	77.28

Bold values indicate high correlation between variables.

the soil profile. Then the return flow under the action of gravity will transfer these solutes into the groundwater system.

- Factor 2 accounts for about 11.9% of the total variance and includes Na^+ with loading value of 0.743. This factor suggests the dominance of ionic exchange. The high loading of Na^+ is not associated with high loading of Cl. The Na/Cl ratio is a good indicator for the efficiency of the base exchange reactions. Low Na/Cl ratios (i.e., below the original value of the irrigation water) reflect continuation of exchange reaction, whereas an increase of Na/Cl ratio toward the original Na/Cl value of the irrigation water suggests exhaustion of the exchangeable sites and reduction in the clay capacity for exchange reactions [56]. Gavrieli et al. [57] showed that irrigation with calcium-rich water causes an opposite reaction, in which Na is released and the residual groundwater has an Na/Cl ratio higher than that of irrigation water related to ionic exchange; mainly with Ca.
- Factor 3 accounts for only 7.81% of the total variance and includes HCO_3^- which has loading value of 0.858 and negatively correlates with Cl and TH. Such factor can be explained by recharge from irrigation canals. The chemistry of the Nile water, which is the sole source of canals water, is known to be bicarbonate dominant. This leads to the increase of HCO_3 ion and is evident from the bicarbonate contour map (Fig. 8) that shows the increase of the bicarbonate concentration with the proximity to the Nile where irrigation from the Nile water is widely used.

5. Conclusions

The main objective of this study was to evaluate the groundwater quality in Qena Governorate using traditional hydrochemical analysis, GIS, and Factor analysis method. Quaternary aquifer represents the main aquifer in the study area and this aquifer is composed of fluvial sands and gravels with minor clay intercalations. The main source of recharge to the Quaternary aquifer is taking place from the irrigation system, which is represented by the River Nile and irrigation canals in the study area. Water level (range between 3.0 and 40 m a.m.s.l.) decreases in the floodplain area and increases at the desert fringes. Groundwater flow is mainly from the south to north and from the west and east parts to the River Nile. GIS and the inverse distance weighted (IDW) technique have been successfully used to map groundwater quality and visualize and identify mapping the spatial distribution of groundwater quality parameters in Qena Governorate has been successfully carried out using GIS and the IDW technique.

According to the WHO and EHCW, the computed water quality index (WQI) shows that 62% of groundwater is suitable for drinking due to the low salinity. Most of the collected groundwater samples are not suitable for domestic uses due to high level of hardness. The Piper plot showed that 58% of groundwater is NaCl dominant suggesting dissolution from evaporites. The concentration of alkali metals exceeds that of alkaline earth metals. The suitability of groundwater for irrigation was evaluated based on the irrigation quality parameters. Among these parameters, EC reveals 99% of the samples are suitable for irrigation. SAR indicates that the groundwater is excellent for irrigation, Na%, RSC, and KR shows that half of samples are suitable and the other half is unsuitable for irrigation. MH reveals that 82% is unsuitable and 18% of samples are suitable for irrigation purposes. The factor analysis generated three important factors which explained 72.53% of the total variance: Factor 1 explains that about 55.89% of the total variance and includes TH, TDS, EC, Ca^{2+}, Cl^-, Mg^{2+}, SO_4^{2-}, pH in respective order; Factor 2 accounts about 11.59% of the total variance and includes Na^+, and K^+ in respective order; and Factor 3 accounts for only 5.05% of the total variance and includes HCO_3^-.

PI reveals that 56% of the samples reflect good suitability for irrigation purposes, 47% indicates moderate suitability for irrigation and 15% reflects poor or unsuitability for irrigation. According to Gibbs diagram, 79% of the samples suggest that the chemical weathering of rock-forming minerals is influencing the groundwater quality through the dissolution of the host rock; only 15% of the samples is affected by evaporation and the rest by precipitation.

In general, most of the groundwater elements in the study area are below the maximum acceptable limits of the WHO, and EHCW, indicating its suitability for drinking and irrigation. Finally, the current study has confirmed that the integration of traditional hydrochemical analysis and GIS with statistical factor analysis can provide a powerful tool to identify factors controlling the chemistry of the groundwater in the study area.

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