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GIS-based assessment of groundwater quality and suitability for drinking and irrigation purposes in the outlet and central parts of Wadi El-Assiuti, Assiut Governorate, Egypt

Hanaa A. Megahed*

Abstract

Background: The limited water resources in arid environments in addition to the effect of agricultural and anthropogenic activities on groundwater quantity and quality necessitate paying more attention to the quality assessment of these resources. The present studies assess the quality of groundwater resources in Wadi El-Assiuti, south Egypt, and evaluate their suitability for drinking and irrigation purposes. To achieve this goal, 159 groundwater samples were collected from the outlet and central parts of the Wadi El-Assiuti during the autumn season (October–November) of 2019 and were analyzed for major ions, trace elements and heavy metals.

Results: The results indicate that the TDS values range between 1972 and 6217 ppm, while the concentration of trace elements (Fe^{++}, Mn^{++} and Ni^{+}) ranges between 0.05 and 0.46, 0.11 and 0.221 and 0.01 and 0.6 ppm, respectively. These results show that all groundwater samples are clearly unacceptable and inappropriate for human drinking due to their high content of total dissolved solids, trace elements and heavy metals, particularly in the majority of samples according to World Health Organization (WHO) guidelines and the Egyptian standards (Eg. St. 2007) for drinking water quality. Spatial analysis of the TDS values in geographic information system environment indicates that the salinity is higher in the northeast and gradually decreases southward. Sodium adsorption ratio, US Salinity Laboratory classification (1954), residual sodium carbonate, soluble sodium percentage and permeability index show that most groundwater samples are suitable for irrigation purposes.

Conclusions: The integrated approach provided in this study highlights the spatially distributed suitability of groundwater resources in Wadi El-Assiuti and can be applied in similar basins worldwide.

Keywords: Groundwater, Irrigation, Quality, Drinking water, Suitability, Wadi El-Assiuti

Background

Water is a renewable resource, but its availability is variable and limited, especially under arid conditions (Abotalib et al. 2016). At certain times of the year, almost every country in the world experiences water shortages (Gleick 1993). In fact, water resources are of importance in increasing employment in all sectors of society. Ongley (1999) stated that experts describe the global water situation as a crisis. Freshwater quality will become the principal limiting factor for sustainable development for many countries in the twenty-first century (Elawa et al. 2013). With the upstream countries in the Nile basin proceeding with building dams on the major stream of the Nile River, the Egyptian government is paying more attention to explore new resources of groundwater and to maintain the quality of groundwater for drinking and irrigation purposes (Negm et al. 2018). The groundwater aquifers in Egypt can be classified in three major groups including

*Correspondence: hanaanarss@yahoo.com
Department of Geology, National Authority for Remote Sensing and Space Sciences (NARSS), Cairo 1564, Egypt

the Nubian Sandstone Aquifer (NAS), the fractured limestone aquifer and the Quaternary Nile aquifer (Abotalib et al. 2016; Megahed and Farrag 2019). The NAS received recharge during previous wet climatic periods and is considered as a fossil aquifer (Abotalib et al. 2019), while the Nile aquifer is currently connected with the Nile water (Megahed and Farrag 2019). In addition to these major aquifers, numerous aquifers are reported from the dense alluvium aquifers in major wadi such as Wadi El-Assiuti (Sultan et al. 2007), El-Qaa plain (Youssif et al. 2020) and El-Gallaba plain (Gaber et al. 2015).

When groundwater moves through the rocks and subsurface soil, it has the opportunity to dissolve various sources of substances and contaminants (Mahmood et al. 2017, 2018). In addition, they are distributed as an anthropogenic pollutant (Rangsivek and Jekel 2005). Trace metals in groundwater are attributed to industrial, transportation, construction activities (Hegazy et al. 2020) as well as agricultural practices (Brantley and Townsend 1999; Romic and Romic 2003), which adverse environmental effects. Fertilizers and pesticides uses for agricultural and industrial wastes have led to the ongoing accumulation of trace metals in soils (Zwolak et al. 2019; Alloway and Jackson 1991).The environmental impacts of agricultural activities and the leaching of heavy and trace metals are becoming increasingly alarming (Brindha and Kavitha 2015, Brindha et al. 2017a, b, 2020). During manufacturing processes, fertilizers are usually not sufficiently purified; they usually contain several impurities including heavy metals (Santos et al. 2002; Tanji and Valoppi 1989). Also, heavy metals are often a part of pesticide's active compounds. The heavy metal surpluses in soils are also caused by fertilizer use. With sufficient infiltration of surface water, soil pollutants such as heavy metals can leach to the groundwater (Eugenia et al. 1996). Especially vulnerable to various contaminants are unconfined aquifers overlain by permeable soils or other aquifers (Picker et al. 1992; Pogotto et al. 2001). Recently, attention has been paid to development and rehabilitation in Upper Egypt beyond the overpopulated areas to the north of the country (El Kashouty et al. 2012).

Wadi El-Assiuti represents one of the most important hydrographic basins adjacent to the Nile Valley. Knowledge about the groundwater aquifers in the area was collected partially from different studies previously (Farrag, et al. 2002; Farrag 1997, 2007). Wadi El-Assiuti may have remnants of old drainage systems, and the main channel has a NE trend with width variations from about 1.5 km (in the central part) and about 3.5 km in the western part (Yousef 2008). Most tributaries also trend toward the NW. The N–S River Nile course south of Assiut city has been shifted eastward to take the NW trend north of Assiut city. A detailed study in Wadi El-Assiuti area was made to distinguish the lateral hydrogeological distribution of this wadi (Northern, Intermediate and Outlet areas) and to provide details about all the hydrography and the correlation within (Farrag et al. 2002). For groundwater evaluation and its suitability for different uses during the past 35 years, different studies were carried out by many authors (e.g., Abbas et al. 2018, 2019; Dawoud and Ewea 2009; Elewa 2008; Yuan et al. 2005; Abu El-Ella 1999; Bakheit et al. 1992; Bakheit 1989; Mousa et al. 1993) and others on different parts in and around Wadi El-Assiuti. All these studies showed the presence of a prolific aquifer system in the wadi's Quaternary sediments. The increase in newly reclaimed areas for different agricultural activities and the vast growth of newly established settlements (e.g., new Assiut city) in Assiut governorate have led to a search for new groundwater water resources necessary for sustainable development for agricultural expansion.

Integration of remote sensing (RS) data in a GIS environment has been widely used to explore the groundwater resources in arid environments as well as understanding the groundwater dynamics and fault controls on the groundwater flow (Paul et al. 2019; Mohamed et al. 2015; Hussien et al. 2017; Abotalib and Heggy 2019). Main GIS applications in groundwater studies include mapping and suitability analysis, assessment of groundwater flow vulnerability and their quality integrated with spatial data (Megahed and Farrag 2019; Mohammad et al. 2019; Satyajit et al. 2020; Hamed et al. 2018; Engel and Navulur 1999). GIS was also used to examine groundwater contamination and the geographical relationships between groundwater characteristics, pollution sources, land uses, topography and geology (Farrag et al. 2019; Ahn and Chon 1999). GIS-based research concluded that nitrate pollution of the groundwater occurs from dense cultivation which is considered a possible source of groundwater deterioration (Levallois et al. 1998). Groundwater pollution hazard and water quality maps were produced using GIS analyst tools in Italy (Ducci 1999). GIS and multivariate statistical analysis was adopted to investigate factors controlling groundwater quality and suitability for drinking and irrigation in the Western Nile Delta of Egypt (Armanuos and Negm 2016).

The main objective of the present study is to evaluate the groundwater quality and its suitability for drinking purposes based on Egyptian and WHO standards and to finally assess groundwater for agricultural purposes based on international recommendations for irrigation in the outlet and central parts of Wadi El-Assiuti. This is achieved using the analysis of the major ions, trace elements and heavy metal concentrations in the collected groundwater samples.

Description of the study area

Location and climate

Wadi El-Assiuti constitutes a part of the Eastern Desert and is one of the most significant wadis in middle Egypt which is a natural extension of Assiut Governorate. It represents one of the most promising desert areas for sustainable development where groundwater can be extracted. It is a dry drainage basin, whose main channel is 186 km in length (Elewa 2008). The study area includes the outlet and central parts of Wadi El-Assiuti which lie to the east of the River Nile northeast of Assiut. It is located between the latitudes 27° 00′ and 27° 30′ N and the longitudes 31° 00′ and 31° 30′ E (Fig. 1) and covers an area of about 2500 km^2. According to the Egyptian Meteorological Authority (EMA 2019), Wadi El-Assiuti area is characterized by arid to semiarid climate. The annual average temperature in the area is about 29 °C (minimum temperature 18 °C and maximum temperature about 40 °C which rises throughout the year) due to the governorate's site in the hot desert zone. From the rainfall data, it can be observed that the average yearly precipitation in Wadi El-Assiuti is lower than that happened in mountainous region toward the east. In general, the amount of rainfall in the study area is not significant throughout the year. The average rainfall value is approximately 0.7 mm/month, and the relative humidity is 38%, while the average evaporation in about 14.2 mm/year and the average wind reach around 7.5 Knot/hour (Fig. 2).

Geological and hydrological setting

The study area is completely covered by sedimentary rocks from different ages ranging from lower Eocene to Holocene times (Fig. 3). In the present study, the stratigraphy of Wadi El-Assiuti and the surrounding parts is reviewed from previous studies, especially those of Said (1981, 1990; Mansour and Philobbos 1983; Klitzsch et al. 1987 and others). The wadi filling deposits are composed of gravel of different sizes with washed macrofossils and nummulites in a sandy, limey and clayey matrix; all derived from the adjacent limestone plateau during recent times and were classified from the oldest to the most recent by Said (1981) being Protonile, Penile and NeoNile sediments (Al-Ruwash and Shehata 2003), (Fig. 3). The lower Eocene sequence borders the study area at its eastern side and is composed of carbonate rocks (limestone and dolomites). It has been studied by many authors (e.g., Bishay 1961; El-Naggar 1970; Omara et al. 1970; Youssef et al. 1982; Keheila 1983; Mansour and Philobbos 1983). The main characteristic structural features of the different geological formations have been documented by the following (Said 1961, 1962; Omara and El-Tahlawi 1972; Omara et al. 1970, 1973; Osman 1980; Bakhiet 1989; Mansour and Philobbos 1983;

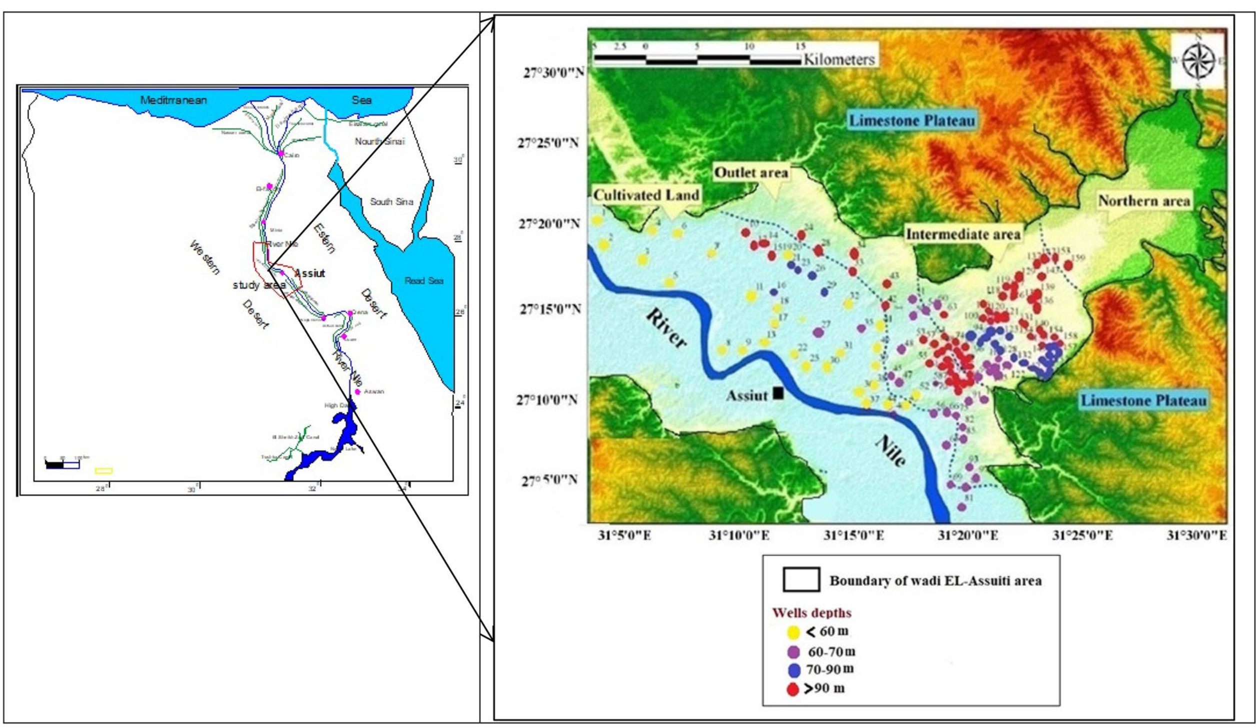

Fig. 1 Location map with monitoring wells in the study area

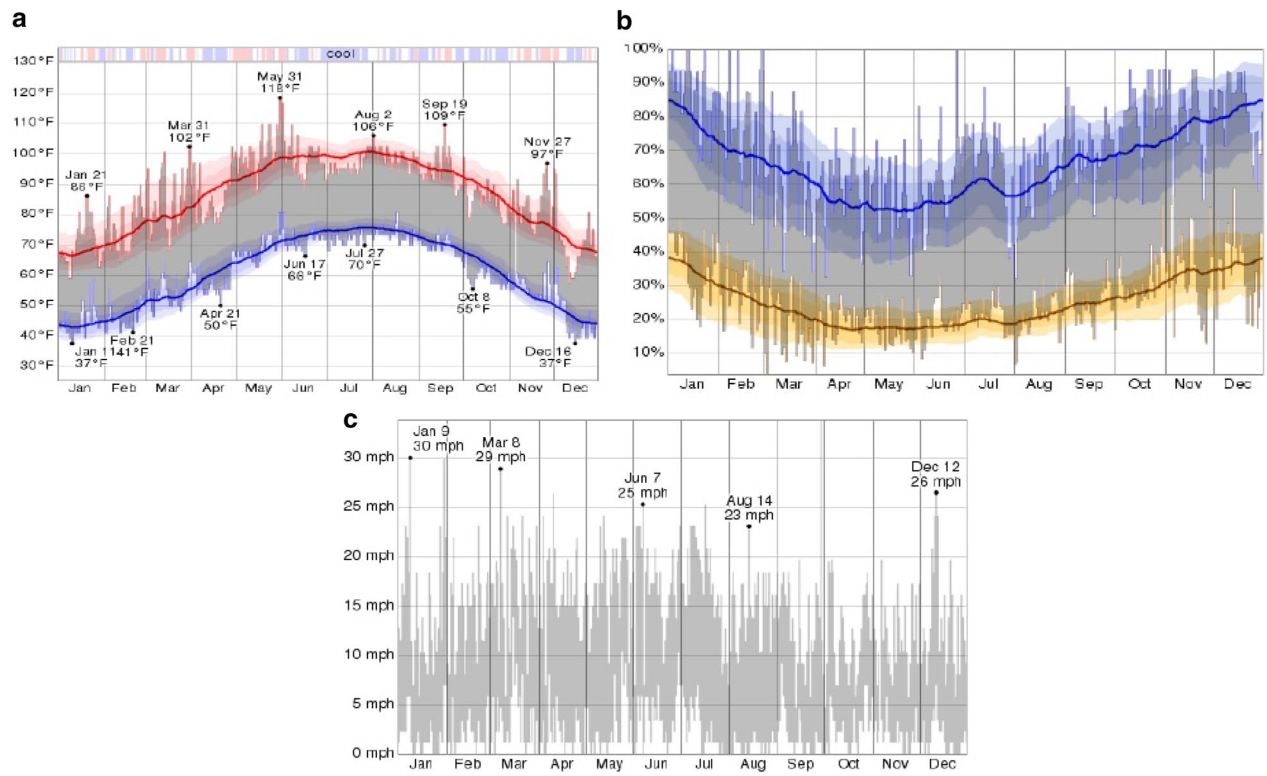

Fig. 2 Representation of the recorded **a** temperature, **b** humidity and **c** wind speed values during the year 2019 in the study area (EMA 2019)

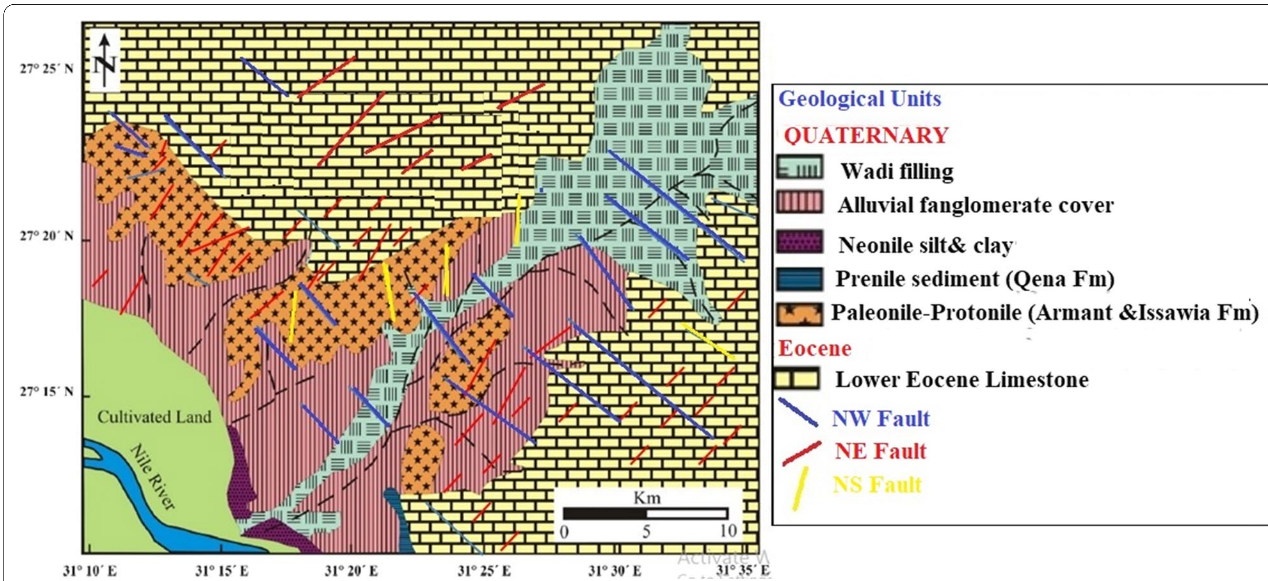

Fig. 3 Geological map of the study area, modified by Said (1981)

Shama 1972 and others). The fault trends were arranged according to their decreasing order as N–S, NW and NE trends. Anticlines and synclines are well observed. The synclines form narrow structures ranging between 100 and 200 m in amplitude and between 100 and 500 m in width. The generally symmetrical dips of the flanks reach a maximum of 60° and usually range between 30° and 45°. The anticlines form broad swells having little effect on the prevailing physiography of the Eocene plateau. The exposed limestone region around Wadi El-Assiuti is highly dissected by both major and minor joints. Some fissures and joints in different parts are sites of mineralization (Omara et al. 1973). Joints observed in the different parts of the area are mainly perpendicular to the bedding planes and show very high dip angles.

Population and economic increase causes the increase in drilling activities for groundwater extraction in the dryland environments and causes more problems concerning the groundwater potentiality. This urgently requires implementing a policy or management scheme for this critical area east of Assiut to diminish the problems (El Bastawesy et al. 2012). Hydrogeologically, the investigated water-bearing formations in Wadi El-Assiuti are classified as follows: Quaternary aquifer dominating the outlet area and the upper zone in the central part with depths ranging from 25 to 50 m. Conversely, the Plio-Pleistocene aquifer dominates the central parts of the wadi and is generally distinguished by two zones: The first has an aquifer depth ranging from 40 to 70 m; however, the second is presents greater depths reaching 180 m. The Pleistocene groundwater aquifer in the area is the most exploited one for agricultural purposes. The Eocene aquifer is lying in the southeastern border of the wadi, and its aquifer depth is more than 90 m.

Methods

To obtain the physiochemical characteristics of the groundwater in the area, some field and laboratory measurements and analysis were carried out. These included the assessment of the water's physical and chemical parameters such as total dissolved solids (TDS), concentrations of hydrogen ions (pH), electrical conductivity (EC), and concentrations of a few major and trace ions. Groundwater samples collection procedure considers the representation of all aquifers and the variability of depth in the study area. One hundred and fifty-nine groundwater samples were collected from wells located in the studied area during the autumn season (October to November) of 2019 (Fig. 1). Well locations were detected by using a Global Positioning System (GPS). The water analysis was carried out in the Geology Department, Faculty of Sciences at Assiut University, and Environmental Agency Affair according to the methods adopted by Rainwater and Thatcher (1960) and the methods described Fishman and Friedman (1985). A portable field kit was used for measurements of pH and EC in field. Cl^{-}, HCO_3^{-}, Ca^{++}, and Mg^{++} contents were measured by titration, while SO_4^{-} concentration was estimated by turbidity, and Na^{+} and K^{+} contents were estimated by flame photometer. The samples were then transported to the laboratory and stored in a refrigerator at approximately ~ 20 °C to prevent change in volume due to evaporation. The inductive couples plasma (ICP) determined trace metals (Pb, Ni, Mn, and Fe). The collection of the geological and hydrogeological data of Assiut Governorate was done from previous works and reports to prepare a base map of the studied area and to collate all the graphical representation and maps for the analytical results. A geo-spatial database was built using Arc GIS 10.1 software, (ESRI 2006) and Groundwater software for Windows (GWW) computer software to present and observe the of changes of main and trace ions distribution of groundwater samples in the study area to assess of groundwater quality and their suitability for drinking, irrigation and other uses then the visualization of results and expectation of the best locations in the studied area which contain suitable groundwater for drinking and agriculture to provide time and cost when drilling underground water wells.

Result

Laboratory analyses

The physical properties

Water temperature affects ionic strength, conductivity, dissolution, solubility and corrosion. In the study area, groundwater temperature ranged between 22 and 28 °C which may be due to structures or differences in drilling depths. With most types of groundwater in direct contact with the atmosphere, pH value ranged from 6.5 to 9.5 which reflects that the groundwater samples are neutral to strongly alkaline and EC values ranged between 1143 μmhos/cm (Well No. 11) and 9280 μmhos/cm (Well No. 42). pH and EC values of the collected groundwater samples in the studied area are shown in Table 1 and Fig. 4a, b.

Chemical properties and groundwater composition

Ions concentrations and distribution

The chemical characteristics of groundwater are mainly influenced by the surface and subsurface geochemical evolution during water movement. These processes control the water quality by increasing the dissolved ion contents by increasing water–rock interaction. The intensity of these exchanges depends on the physical and chemical properties of the surrounding rocks and water temperature. The chemical composition of the studied groundwater samples was obtained as shown in Table 2. Noticeably, the total concentration of Ca^{++}, Mg^{++}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{-} and Cl^{-} often exceeds 90% of the total dissolved solid (TDS) in water, regardless of whether the water is diluted or the salinity is higher than seawater (Freeze and Cherry 1979). TDS values of groundwater

Table 1 pH and Electrical Conductivity (EC) values for the groundwater samples in the area

Well No	pH	EC (μmhos/cm))	Well No	pH	EC (μmhos/cm)	Well No	EC (μmhos/cm)	pH	Well No	EC (μmhos/cm)	Well No	pH	EC (μmhos/cm)	Well No	pH	EC (μmhos/cm)
1	7.5	1196	25	8.55	1202	45	2600	7.68	67	1546	93	7.64	1615	116	8.1	2823
2	8.55	1190	26	8.27	1727	47	1218	8.65	69	1206	94	7.22	2471	117	8.3	2096
3	8.88	1291	27	7.95	1297	48	4816	7.58	70	1322	95	8.73	1748	118	8.05	1862
4	7.5	1985	28	8.05	7062	49	1203	7.5	71	1432	96	7.8	1967	119	7.1	4875
5	8.27	1199	29	7.5	1248	50	2297	9.5	72	1887	97	7.8	2403	120	7.03	2624
6	7.8	1854	30	7.8	1205	51	7849	8.72	73	1385	98	7.3	1901	121	8.2	1951
7	7.95	1218	31	8.88	1211	52	2405	7.87	77	1436	99	7.9	1458	122	8.5	1452
8	8.45	1240	32	8.09	1228	53	1725	7.58	78	2442	100	7.7	2808	123	8.6	2489
9	8.88	1187	33	6.45	4081	54	1545	7.58	79	1821	102	7.5	3001	127	7.9	4475
11	7.1	1143	34	9.1	8937	55	2169	7.67	80	1360	104	7.5	1266	128	8.1	1557
12	7.46	3419	35	6.22	1233	56	2243	8.9	81	1203	105	7.79	1585	129	8.6	4702
13	7.99	1313	36	6.99	1238	57	2105	8.9	82	1636	106	7.5	2064	132	9.1	1211
14	8.05	3030	37	7.5	1268	58	8879	8.99	84	1980	107	7.5	1877	135	9.32	9080
15	8.09	1634	38	7.23	1327	59	2096	8.73	86	1878	108	6.45	2716	136	9.08	3559
16	7.23	1238	39	8.12	1288	60	2461	9.05	87	1263	109	7.85	1661	139	8.5	3052
17	7.5	1197	40	8.08	1537	61	2386	9.05	88	1829	110	7.3	1960	146	8.5	2215
18	8.12	1214	41	9.4	1528	63	1931	8.49	89	2149	111	7.5	1950	147	6.5	2657
19	8.3	3212	42	6.3	9280	64	2300	7.68	90	1670	113	7.25	1324	153	6.3	2904
22	7.5	1195	43	7.15	2802	65	2063	7.3	91	1553	114	6.5	1784	159	8.05	2827
23	8.08	1469	44	6.7	1421	66	3491	7.52	92	2251	115	7.05	2309			

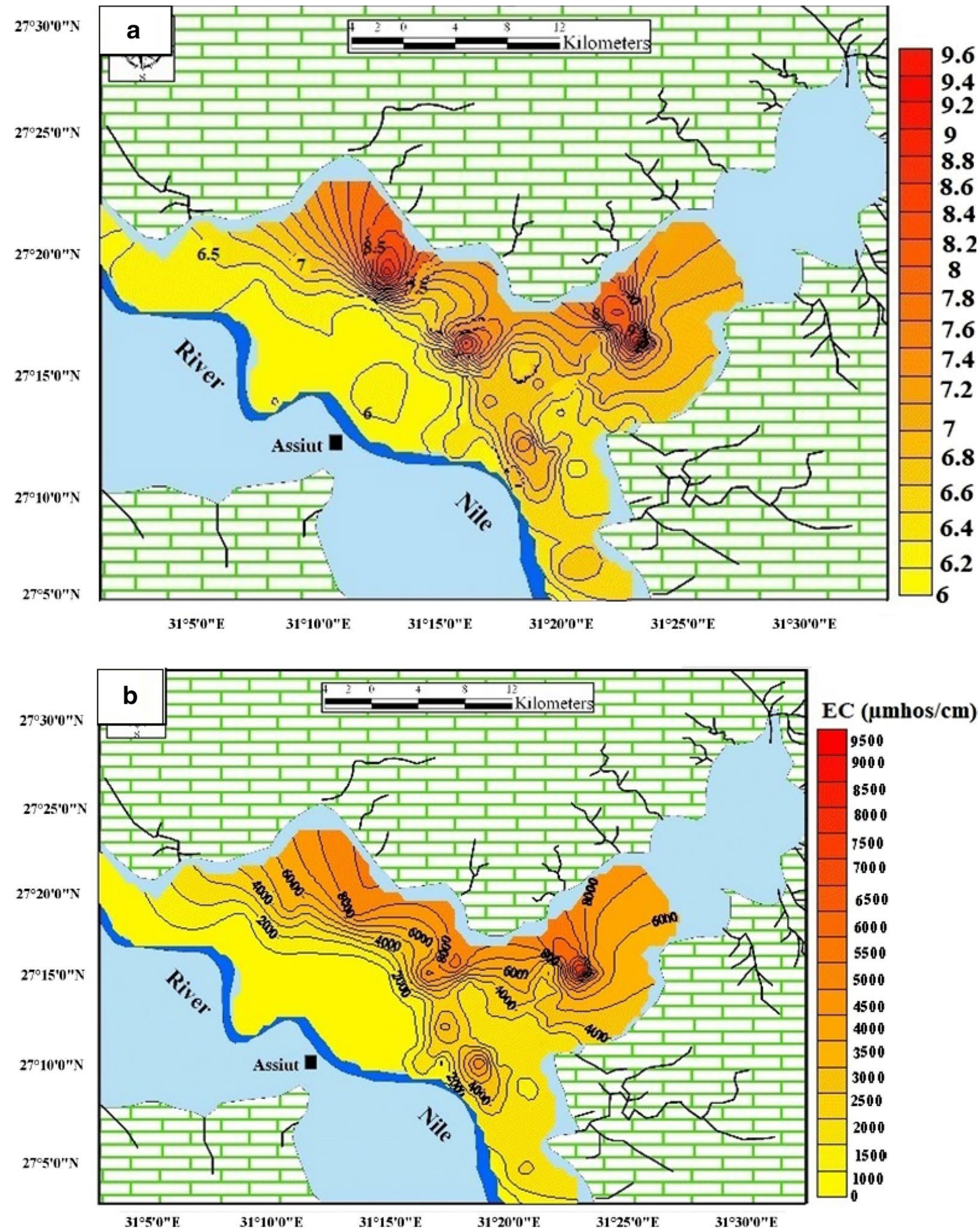

Fig. 4 **a** Concentrations of hydrogen ions (pH) and **b** electrical conductivity (EC) values of groundwater samples in the study area

in the study area varied from 1972 ppm (Well No. 11) to 6217 ppm (Well No. 42). According to classifications by Davis and Dewiest (1966) or by Hem (1970), 34.45% of the groundwater samples in the study area are freshwater and 65.54% are moderately saline (brackish water). The TDS distribution map of the studied area (Fig. 5a) shows general increases toward the north and the northeast directions close to the limestone plateau depending on the type, composition, and thickness of the water-bearing sediments and the distance to the recharging by Nile River and decreases toward the southern part. The increase in salinity toward the northeastern direction may relate to the general trend of groundwater flow in the same direction. This could be related to the change in lithology and structural pattern in water-bearing formations due to the slow groundwater movement and the

Table 2 Results of chemical analyses of groundwater samples in the study area

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
1	27.3364	31.0200	1801	Ppm	72.10	61.40	49.30	42.00	310.60	125.67	140.36	0.883
				epm	3.60	5.05	2.14	1.07	5.09	2.62	3.96	
				e%	31.40	41.11	23.78	3.71	63.73	26.60	9.67	
2	27.3147	31.0261	1797	Ppm	68.08	60.00	55.58	47.20	253.80	160.40	152.30	0.668
				epm	3.40	4.93	2.42	1.21	4.16	3.34	4.30	
				e%	22.22	53.00	24.44	0.34	48.55	20.12	31.33	
3	27.3019	31.0581	1864.78	Ppm	56.10	73.00	99.80	5.08	378.30	110.50	142	0.435
				epm	2.80	6.00	4.34	0.13	6.20	2.30	4.65	
				e%	42.61	30.78	16.90	2.13	83.65	4.75	8.29	
4	27.3272	31.0681	1329.92	Ppm	44.09	53.51	211.80	102.00	305.09	528.33	85.10	0.043
				epm	2.20	4.40	9.21	2.61	5.00	11.00	2.40	
				e%	24.01	48.04	17.69	1.25	73.63	4.01	17.02	
5	27.8017	31.0828	1803	Ppm	46.00	55.00	97.00	40.00	235.00	200.00	130	1.50
				epm	2.30	4.52	4.22	1.02	3.85	4.16	3.67	
				e%	37.71	28.16	24.31	2.22	66.82	6.31	19.15	
6	27.3247	31.0908	1242.69	Ppm	36.07	60.80	264.62	20.00	280.68	292.98	287.14	0.041
				epm	1.80	5.00	11.51	0.51	4.60	6.10	8.10	
				e%	45.26	27.32	19.56	0.09	85.15	3.39	9.88	
7	27.3067	31.1186	1816	Ppm	52.00	59.00	71.00	36.00	333.00	211.00	54	0.346
				epm	2.59	4.85	3.09	0.92	5.46	4.39	1.52	
				e%	42.61	30.78	24.13	2.48	85.74	4.75	9.51	
8	27.2225	31.1286	1830.5	Ppm	48.00	63.00	84.00	30.00	340.50	163.00	102	0.598
				epm	2.40	5.18	3.65	0.77	5.58	3.39	2.88	
				e%	24.01	48.04	26.62	1.33	74.61	4.01	21.38	
9	27.2231	31.1461	1795	Ppm	45.00	61.00	82.00	51.00	197.00	186.00	173	0.619
				epm	2.25	5.02	3.57	1.30	3.23	3.87	4.88	
				e%	37.71	28.16	31.72	2.41	68.43	6.31	25.26	
11	27.2717	31.1539	1972	Ppm	91.20	33.40	63.20	0.39	521.09	16.33	40.40	0.166
				epm	4.55	2.75	2.75	0.01	8.54	0.34	1.14	
				e%	7.41	8.15	68.44	1.43	27.46	22.42	28.83	
12	27.3133	31.1564	2290.95	Ppm	60.12	97.16	545.32	19.50	323.40	120.45	525	0.124
				epm	3.00	7.99	23.71	0.50	5.30	15.00	14.81	
				e%	31.47	36.06	26.69	1.86	48.57	26.38	15.20	
13	27.2297	31.1639	1880	Ppm	66.00	56.00	74.00	67.00	272.00	193.00	152.00	0.252
				epm	3.29	4.61	3.22	1.71	4.46	4.02	4.29	
				e%	15.95	23.94	38.01	1.55	66.53	19.95	9.08	
				Ppm	128.3	34.05	501.18	8.50	244.70	271.26	542.39	
14	27.3164	31.166	2030.34	epm	6.40	2.80	21.79	0.22	4.01	11.89	15.30	0.004
				e%	24.59	40.99	22.80	1.45	67.12	20.65	8.33	
15	27.3056	31.1717	1095.5	Ppm	24.05	16.05	307.38	12.2	276.41	174.35	284.66	0.016
				epm	1.20	1.32	13.36	0.31	4.53	3.63	8.03	
				e%	7.41	8.15	68.44	1.43	27.46	22.42	28.83	
16	27.2730	31.1730	1829.27	Ppm	65.50	59.41	69.17	55.86	222.06	169.22	188.05	0.487
				epm	3.27	4.89	3.01	1.43	3.64	3.52	5.30	
				e%	31.47	36.06	30.56	1.91	49.57	26.38	24.05	
17	27.2447	31.1742	1802.20	Ppm	63.03	55.60	66.67	59.50	208.07	168.03	181.30	0.473
				epm	3.15	4.57	2.90	1.52	3.41	3.50	5.11	
				e%	15.95	23.94	57.81	2.30	68.06	19.95	11.99	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
18	27.2592	31.1756	1813.67	Ppm	59.07	57.48	65.95	55.08	277.65	142.04	156.40	0.125
				epm	2.95	4.73	2.87	1.41	4.55	2.96	4.41	
				e%	24.59	40.99	32.64	1.78	68.32	20.65	11.03	
19	27.3064	13.1867	2152.30	Ppm	68.14	110.66	478.42	17.80	335.60	547.54	594.14	0.141
				epm	3.40	9.10	20.80	0.46	5.50	11.40	16.76	
				e%	10.07	26.96	58.01	1.19	16.13	33.87	27.07	
22	27.2193	31.1917	1800	Ppm	55.80	62.75	73.34	42.80	227.00	162.44	176.70	0.577
				epm	2.78	5.16	3.19	1.09	3.72	3.38	4.98	
				e%	30.72	33.20	35.00	1.08	56.21	19.64	24.16	
23	27.2928	31.1944	1983.27	Ppm	15.23	13.14	252.89	22.50	366.12	197.11	116.98	0.021
				epm	0.76	1.08	11.00	0.58	6.00	4.10	3.30	
				e%	5.67	8.06	58.95	2.65	42.93	30.61	15.85	
25	27.2090	31.2070	1803.03	Ppm	60.05	67.37	57.57	51.09	212.50	167.03	189.42	0.170
				epm	3.00	5.54	2.50	1.31	3.48	3.48	5.34	
				e%	23.72	38.15	35.05	3.07	59.08	21.40	19.52	
26	27.2880	312,070	1156.34	Ppm	83.40	30.40	216.39	10.95	585.60	165.00	112.00	0.477
				epm	4.16	2.50	9.41	0.28	9.60	3.44	3.16	
				e%	25.45	15.29	43.18	1.23	58.27	21.21	13.77	
27	27.2386	31.2119	1869.18	Ppm	80.16	70.53	71.04	8.20	416.14	60.04	175	1.655
				epm	4.00	5.80	3.09	0.21	6.82	1.25	4.94	
				e%	30.54	44.28	19.40	1.84	51.61	9.61	25.60	
28	27.3100	31.2020	4731.80	Ppm	380.80	343.80	862.00	11.50	122.00	511.70	2550	1.113
				epm	19.00	28.27	37.48	0.29	2.00	10.65	71.93	
				e%	22.34	33.24	55.08	0.58	2.36	12.60	42.91	
29	27.2730	31.2170	1836.21	Ppm	71.25	58.82	68.93	57.25	183.50	184.46	212.00	0.096
				epm	3.56	4.84	3.00	1.46	3.01	3.84	5.98	
				e%	20.59	24.83	51.32	3.26	62.67	11.22	26.11	
30	27.2072	31.2319	1807.50	Ppm	73.00	57.90	53.70	36.90	357.60	102.80	125.60	0.590
				epm	3.64	4.76	2.33	0.94	5.86	2.14	3.54	
				e%	45.25	27.76	26.46	0.53	83.34	1.11	15.54	
31	27.2206	31.2319	1811.23	Ppm	68.13	55.50	49.30	39.80	448.00	69.20	81.30	0.211
				epm	3.40	4.56	2.14	1.02	7.34	1.44	2.29	
				e%	36.80	38.98	23.42	0.80	88.82	4.47	6.71	
32	27.2636	31.2372	1822.76	Ppm	69.04	61.90	54.40	52.90	278.70	142.02	163.80	0.440
				epm	3.45	5.09	2.37	1.35	4.57	2.96	4.62	
				e%	14.36	45.92	36.45	3.27	66.91	7.20	25.89	
				Ppm	183.57	149.20	474.71	39.51	234.00	224.78	475	
33	27.2930	31.2410	2734.04	epm	9.16	12.27	20.64	1.01	3.84	25.50	13.40	1.968
				e%	21.26	28.48	54.67	1.98	8.77	59.67	16.34	
34	27.3080	31.2430	14,220	Ppm	454.30	500.60	717.47	9.77	152.50	319.60	833.30	0.084
				epm	22.67	41.17	31.19	0.25	2.50	69.12	23.51	
				e%	23.79	43.21	41.53	0.24	2.62	72.66	12.51	
35	27.2406	31.2497	1825.90	Ppm	63.04	56.75	66.90	56.95	269.80	150.83	161.63	0.227
				epm	3.15	4.67	2.91	1.46	4.42	3.14	4.56	
				e%	14.23	31.30	53.76	0.71	63.46	16.08	20.47	
36	27.1867	31.2497	1829.57	Ppm	69.07	63.21	58.97	49.90	254.80	153.62	180	0.128
				epm	3.45	5.20	2.56	1.28	4.18	3.20	5.08	
				e%	22.99	48.54	27.20	1.27	59.95	9.67	30.39	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
37	27.1733	312,547	1849.78	Ppm	77.08	67.56	57.86	43.39	242.41	172.12	189.36	0.495
				epm	3.85	5.56	2.52	1.11	3.97	3.58	5.34	
				e%	28.29	49.51	22.06	0.14	31.14	57.38	11.48	
38	27.1917	31.2611	1889.00	Ppm	48.00	14.00	253.00	8.00	24.00	192.00	363	0.410
				epm	2.40	1.15	11.00	0.20	0.39	4.00	10.24	
				e%	16.24	7.80	86.28	1.31	2.65	27.32	35.32	
39	27.2097	31.262	1863.00	Ppm	112.00	62.00	58.00	12.00	55.00	456.00	108	0.274
				epm	5.59	5.10	2.52	0.31	0.90	9.49	3.05	
				e%	41.35	37.72	28.56	2.32	6.56	70.63	11.69	
40	27.2250	31.2639	1030.03	Ppm	88.00	50.40	118.70	8.97	628.00	36.96	99.00	0.248
				epm	4.39	4.14	5.16	0.23	10.30	0.77	2.79	
				e%	31.53	29.76	26.03	1.39	73.08	5.55	15.97	
41	27.2431	31.2667	1034	Ppm	88.00	50.00	161.00	12.00	49.00	514.00	150.00	0.234
				epm	4.39	4.11	7.00	0.31	0.80	10.70	4.23	
				e%	27.77	26.01	57.27	1.63	5.01	68.01	13.76	
42	27.2610	31.2700	6217	Ppm	611.52	532.26	855.17	34.79	217.00	175.0	2360	0.495
				epm	30.51	43.77	37.18	0.89	3.56	41.12	66.57	
				e%	27.16	38.96	43.54	1.08	3.17	36.96	30.25	
43	27.2810	31.2720	1877.03	Ppm	126.25	27.97	517.24	26.58	175.00	382.00	725	0.785
				epm	6.30	2.30	22.49	0.68	2.87	7.95	20.45	
				e%	19.83	7.24	79.36	2.00	8.98	25.43	33.99	
44	27.1736	31.2636	1951.78	Ppm	72.00	26.40	190.00	4.68	285.50	265.00	135.00	0.492
				epm	3.59	2.17	8.26	0.12	4.68	5.52	3.81	
				e%	25.40	15.35	54.23	0.65	34.88	40.42	14.25	
45	27.2000	31.2764	11,742	Ppm	106.00	55.00	380.00	16.00	67.00	802.00	316	0.062
				epm	5.29	4.52	16.52	0.41	1.10	16.70	8.91	
				e%	19.78	16.91	73.26	1.18	4.05	62.52	17.03	
47	27.1944	31.2833	1815.90	Ppm	69.10	58.20	66.70	54.20	152.70	230.00	185	0.040
				epm	3.45	4.79	2.90	1.39	2.50	4.79	5.22	
				e%	31.85	29.42	35.53	3.20	8.73	64.90	26.38	
48	27.2220	31.2850	3226.85	Ppm	314.00	123.23	570.10	11.72	192.80	1300	715.00	0.487
				epm	15.67	10.13	24.79	0.30	3.16	27.07	20.17	
				e%	30.79	19.91	64.58	0.54	6.23	53.71	20.55	
49	27.1744	312,989	1806	Ppm	75.00	59.00	66.00	39.00	128.00	276.00	163	0.075
				epm	3.74	4.85	2.87	1.00	2.10	5.75	4.60	
				e%	37.36	32.55	27.90	2.19	5.07	70.62	24.31	
50				Ppm	148.30	51.07	326.50	8.00	12.20	303.00	690	
	27.2521	31.2948	1539	epm	7.40	4.20	14.20	0.20	0.20	6.31	19.46	0.053
				e%	28.46	16.15	75.51	0.98	0.76	24.29	37.60	
				Ppm	565.21	198.20	985.75	29.30	170.00	2220	1350	
51	27.2680	31.2950	5258.64	epm	28.20	16.30	42.86	0.75	2.79	46.22	38.08	0.583
				e%	32.01	18.50	68.68	0.83	3.07	54.93	20.36	
				Ppm	102.20	35.30	398.00	22.00	24.00	580.00	450	
52	27.1846	31.2983	1611	epm	5.10	2.90	17.30	0.56	0.39	12.08	12.69	1.385
				e%	19.71	11.22	81.77	1.85	1.53	47.99	25.07	
				Ppm	52.10	60.80	269.70	3.90	210.00	81.00	500	
53	27.2317	31.3047	1155.8	epm	2.60	5.00	11.73	0.10	3.44	1.69	14.10	0.497
				e%	13.38	25.74	57.94	0.60	18.13	8.02	39.74	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
54	27.2581	31.3053	1035	Ppm	46.40	14.58	295.00	5.10	160.00	90.00	424	0.041
				epm	2.32	1.20	12.83	0.13	2.62	1.87	11.96	
				e%	14.06	7.28	76.44	0.75	15.81	11.39	39.47	
55	27.2111	31.3097	1452.9	Ppm	140.00	70.50	271.00	5.40	88.00	228.00	650	0.364
				epm	6.99	5.80	11.78	0.14	1.44	4.75	18.34	
				e%	28.28	23.47	61.49	0.76	5.85	19.36	38.37	
56	27.1681	31.31.25	1503	Ppm	120.00	53.00	322.00	8.00	24.00	466.00	510	0.141
				epm	5.99	4.36	14.00	0.20	0.39	9.70	14.39	
				e%	24.39	17.75	73.85	0.84	1.59	39.63	29.58	
57	27.2294	31.3139	1410.5	Ppm	136.00	68.09	260.00	5.40	88.00	228.00	625	0.017
				epm	6.79	5.60	11.30	0.14	1.44	4.75	17.63	
				e%	28.48	23.50	61.16	0.78	6.02	19.93	38.16	
58	27.1940	31.3150	5949.25	Ppm	516.00	379.49	876.60	9.77	140.33	228.53	1198.53	0.168
				epm	25.75	31.21	38.11	0.25	2.30	58.89	33.81	
				e%	27.01	32.74	53.03	0.25	2.42	61.99	17.98	
59	27.2200	31.31.60	1404	Ppm	136.00	68.09	260.00	5.40	80.00	220.00	635	0.050
				epm	6.79	5.60	11.30	0.14	1.31	4.58	17.91	
				e%	28.48	23.50	61.59	0.80	5.48	19.24	38.67	
60	27.2617	31.3167	1648.65	Ppm	35.20	16.25	529.00	3.20	165.00	270.00	630	0.147
				epm	1.76	1.34	23.00	0.08	2.70	5.62	17.77	
				e%	6.71	5.11	84.80	0.26	10.33	21.54	35.85	
61	27.2097	31.3204	1598.44	Ppm	42.77	13.60	225.25	320.80	538.44	72.58	385.00	0.124
				epm	2.13	1.12	9.79	8.20	8.83	1.51	10.86	
				e%	10.04	5.26	35.05	28.95	30.02	7.13	32.30	
63	27.2839	31.3231	1294	Ppm	52.20	30.40	336.00	9.80	268.50	192.10	405	0.348
				epm	2.60	2.50	14.61	0.25	4.40	4.00	11.42	
				e%	13.05	12.52	67.13	1.08	21.92	20.17	32.28	
64	27.2339	31.3239	1541.26	Ppm	140.00	65.66	330.00	5.60	100.00	185.00	749	0.481
				epm	6.99	5.40	14.35	0.14	1.64	3.85	21.13	
				e%	25.99	20.09	66.64	0.72	6.13	14.47	40.74	
65	27.1392	31.3247	1382.44	Ppm	44.09	92.42	279.79	5.08	219.66	331.40	410	0.065
				epm	2.20	7.60	12.16	0.13	3.60	6.90	11.57	
				e%	9.96	34.40	51.77	0.57	16.22	31.27	28.51	
66	27.1675	31.3250	2339	Ppm	236.00	89.00	446.00	8.00	24.00	691.00	845.00	0.097
				epm	11.78	7.32	19.39	0.20	0.39	14.39	23.84	
				e%	30.44	18.92	71.01	0.60	1.01	37.26	30.99	
67	27.2136	31.3553	1035.78	Ppm	52.11	39.40	239.80	3.90	239.20	110.47	350.90	0.759
				epm	2.60	3.24	10.43	0.10	3.92	2.30	9.90	
				e%	15.89	19.80	58.95	0.60	24.18	14.27	34.65	
69	27.103	31.3275	807.83	Ppm	67.40	55.50	82.00	32.90	230.00	140.03	200	0.027
				epm	3.36	4.56	3.57	0.84	3.77	2.92	5.64	
				e%	20.16	37.76	38.52	3.56	32.78	10.81	56.41	
70	27.1944	31.3272	1886	Ppm	36.00	18.00	255.00	4.00	31.00	192.00	350	0.302
				epm	1.80	1.48	11.09	0.10	0.51	4.00	9.87	
				e%	12.42	10.23	84.13	0.65	3.51	27.80	34.84	
71	27.2027	31.3281	959.32	Ppm	28.95	4.20	308.80	3.80	308.27	65.00	307	0.811
				epm	1.44	0.35	13.43	0.10	5.05	1.35	8.66	
				e%	9.43	2.26	70.95	0.49	33.33	8.98	34.19	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
72	27.2084	31.3282	1263.98	Ppm	37.29	6.32	227.37	193.60	415.91	56.90	326.60	0.003
				epm	1.86	0.52	9.89	4.95	6.82	1.18	9.21	
				e%	10.81	3.02	44.58	21.68	30.76	6.88	33.36	
73	27.1926	31.3327	1927.74	Ppm	23.53	4.54	246.40	49.60	274.10	44.56	285	0.255
				epm	1.17	0.37	10.71	1.27	4.49	0.93	8.04	
				e%	8.68	2.76	63.58	7.29	30.51	6.89	35.74	
77	27.2222	31.3344	1961.84	Ppm	60.80	19.44	240.00	4.60	172.00	110.00	355	0.201
				epm	3.03	1.60	10.43	0.12	2.82	2.29	10.01	
				e%	19.98	10.53	69.70	0.75	18.50	15.14	36.43	
78	27.1867	31.333	11,636	Ppm	104.21	94.85	369.68	5.08	30.58	273.30	758.30	0.484
				epm	5.20	7.80	16.07	0.13	0.50	5.69	21.39	
				e%	17.81	26.71	65.59	0.57	1.73	21.02	38.77	
79	27.2178	31.3358	1219.96	Ppm	36.16	11.70	216.79	151.27	519.89	69.15	215	0.105
				epm	1.80	0.96	9.43	3.87	8.52	1.44	6.06	
				e%	11.24	5.99	41.38	16.63	42.84	8.98	25.74	
80	27.1958	31.33.58	1911	Ppm	40.00	19.00	258.00	8.00	37.00	187.00	367	0.429
				epm	2.00	1.56	11.22	0.20	0.61	3.89	10.35	
				e%	13.32	10.43	82.54	1.29	4.03	26.21	35.42	
81	27.0872	31.3375	1806	Ppm	69.10	67.70	53.90	25.00	317.30	143.23	130	0.185
				epm	3.45	5.57	2.34	0.64	5.20	2.98	3.67	
				e%	37.37	46.34	11.06	0.71	77.44	13.50	6.92	
82	27.1558	31.3378	1095	Ppm	52.10	51.07	239.79	5.08	260.50	100.90	386.50	0.235
				epm	2.60	4.20	10.43	0.13	4.27	2.10	10.90	
				e%	14.98	24.20	54.80	0.77	24.54	12.16	35.91	
84	27.2122	31.3388	1326.37	Ppm	38.76	8.77	263.14	156.94	478.40	70.37	310	0.159
				epm	1.93	0.72	11.44	4.01	7.84	1.47	8.74	
				e%	10.68	3.98	47.63	16.21	35.54	8.12	30.88	
86	27.2081	31.3395	1258.15	Ppm	37.00	8.48	175.55	246.99	458.87	61.27	270	0.238
				epm	1.85	0.70	7.63	6.32	7.52	1.28	7.62	
				e%	11.19	4.23	34.43	27.77	33.09	7.77	30	
87	27.2150	31.3412	1846.50	Ppm	22.00	9.70	232.30	15.60	97.60	333.00	136.30	0.066
				epm	1.10	0.80	10.10	0.40	1.60	6.93	3.84	
				e%	8.86	6.44	78.31	2.10	12.52	56.01	16.59	
88	27.2250	31.3414	1225.50	Ppm	52.00	47.40	294.90	4.60	180.60	245.00	401	0.152
				epm	2.59	3.90	12.82	0.12	2.96	5.10	11.31	
				e%	13.35	20.06	64.76	0.56	15.19	26.33	31.56	
89	27.1031	31.3428	1439.86	Ppm	80.16	95.00	275.00	7.50	207.00	196.90	578.30	0.324
				epm	4.00	7.81	11.96	0.19	3.39	4.10	16.31	
				e%	16.69	32.61	51.20	0.98	14.14	17.22	36.76	
90	27.2008	31.3444	1118.80	Ppm	50.00	26.80	300.00	8.00	24.00	341.00	369	0.125
				epm	2.50	2.20	13.04	0.20	0.39	7.10	10.41	
				e%	13.90	12.28	82.32	0.99	2.17	39.66	29.36	
91	27.1778	31.3444	1040.40	Ppm	116.20	29.20	170.00	8.00	49.00	533.00	135	0.276
				epm	5.80	2.40	7.39	0.20	0.80	11.10	3.81	
				e%	36.71	15.20	68.43	1.05	5.05	70.64	12.40	
92	27.2088	31.3451	1508.12	Ppm	35.17	12.21	242.17	266.84	523.06	83.66	345	0.160
				epm	1.76	1.00	10.53	6.82	8.57	1.74	9.73	
				e%	8.73	4.99	39.09	24.66	31.91	8.69	30.81	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-	
93	27.1211	31.3453	1082.02	Ppm	48.10	53.50	232.10	5.10	262.30	123.92	357	0.209
				epm	2.40	4.40	10.09	0.13	4.30	2.58	10.07	
				e%	14.10	25.85	53.33	0.76	25.17	15.22	33.94	
94	27.2359	31.3456	1655.60	Ppm	134.30	40.10	386.20	8.00	31.00	466.00	590	0.263
				epm	6.70	3.30	16.79	0.20	0.51	9.70	16.64	
				e%	24.83	12.22	80.72	0.75	1.88	36.13	31.20	
95	27.1950	31.3458	1171	Ppm	54.00	28.00	317.00	8.00	18.00	341.00	405	0.437
				epm	2.69	2.30	13.78	0.20	0.30	7.10	11.42	
				e%	14.19	12.13	83.10	0.96	1.55	37.73	30.46	
96	27.2171	31.3464	1317.83	Ppm	38.95	9.22	222.08	202.16	489.38	82.03	274	0.196
				epm	1.94	0.76	9.66	5.17	8.02	1.71	7.73	
				e%	11.09	4.33	40.90	21.05	35.45	9.78	28.66	
97	27.1122	31.3503	1609.91	Ppm	60.12	114.30	331.75	5.90	222.31	198.53	677	0.184
				epm	3.00	9.40	14.42	0.15	3.64	4.13	19.10	
				e%	11.12	34.85	52.22	0.68	13.48	15.38	38.04	
98	27.1995	31.3513	1273.87	Ppm	28.28	11.63	211.51	209.71	458.38	82.37	272.00	0.072
				epm	1.41	0.96	9.20	5.36	7.51	1.71	7.67	
				e%	8.34	5.65	39.93	22.55	33.75	10.15	29.16	
99	27.2317	31.3539	976.55	Ppm	32.13	32.13	260.00	4.69	243.50	160.00	291	0.442
				epm	1.60	2.64	11.30	0.12	3.99	3.33	8.21	
				e%	10.23	16.86	62.60	0.64	25.50	21.45	30.17	
100	27.2506	31.3547	1881.30	Ppm	98.00	41.60	528.00	3.70	95.00	235.00	880	0.141
				epm	4.89	3.42	22.96	0.09	1.56	4.89	24.82	
				e%	15.59	10.91	81.90	0.32	4.96	15.64	40.64	
102	27.2625	31.3569	2010.80	Ppm	88.00	43.80	600.00	3.00	76.00	257.00	965	0.498
				epm	4.39	3.60	26.09	0.08	1.25	5.35	27.22	
				e%	12.86	10.55	84.12	0.24	3.73	15.00	40.89	
104	27.2097	31.3597	1848	Ppm	46.00	25.00	225.00	8.00	24.00	110.00	410	0.312
				epm	2.30	2.06	9.78	0.20	0.39	2.29	11.57	
				e%	16.01	14.34	78.66	1.61	2.72	16.07	41.02	
105	27.2038	31.3628	1062.13	Ppm	32.57	4.25	215.74	133.43	336.83	69.31	272	0.441
				epm	1.63	0.35	9.38	3.41	5.52	1.44	7.67	
				e%	11.01	2.37	50.26	17.27	30.69	9.90	31.97	
106	27.2558	31.3629	1382.60	Ppm	100.00	34.00	345.00	8.00	36.60	255.00	604	0.095
				epm	4.99	2.80	15.00	0.20	0.60	5.31	17.04	
				e%	21.70	12.16	80.64	0.97	2.59	23.14	37.58	
107	27.2475	31.3633	1258	Ppm	94.19	47.79	269.70	2.00	189.15	231.00	436	0.488
				epm	4.70	3.93	11.73	0.05	3.10	4.81	12.30	
				e%	23.03	19.26	62.35	0.26	15.54	23.72	32.47	
108	27.2383	31.3639	1819.90	Ppm	96.00	43.30	500.00	3.60	112.00	235.00	830	0.067
				epm	4.79	3.56	21.74	0.09	1.84	4.89	23.41	
				e%	15.87	11.80	79.84	0.32	6.07	16.23	40.03	
109	27.2286	31.3653	1113.10	Ppm	58.10	15.80	322.00	8.00	12.20	202.00	495	0.093
				epm	2.90	1.30	14.00	0.20	0.20	4.21	13.96	
				e%	15.75	7.06	89.15	1.10	1.08	22.90	38.18	
110	27.2088	31.3661	1313	Ppm	33.38	9.63	190.36	258.50	455.45	70.70	295	0.245
				epm	1.67	0.79	8.28	6.61	7.47	1.47	8.32	
				e%	9.60	4.57	35.76	27.75	31.28	8.53	30.66	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
111	27.2503	31.3683	1306.26	Ppm	44.08	31.62	378.90	10.60	169.02	72.04	600	0.817
				epm	2.20	2.60	16.47	0.27	2.77	1.50	16.93	
				e%	10.21	12.07	76.46	1.26	13.07	7.08	79.85	
113	27.2147	31.3694	1887	Ppm	50.00	26.00	230.00	8.00	24.00	154.00	395	0.323
				epm	2.50	2.14	10.00	0.20	0.39	3.21	11.14	
				e%	16.82	14.41	78.52	1.48	2.63	21.75	38.18	
114	27.2014	31.3700	1195	Ppm	70.00	42.00	275.00	8.00	20.00	440.00	340	0.074
				epm	3.49	3.45	11.96	0.20	0.33	9.16	9.59	
				e%	18.28	18.08	75.00	0.95	1.70	48.01	25.33	
115	27.2225	31.3712	1547.20	Ppm	96.60	28.00	425.30	8.00	6.10	288.20	695	0.220
				epm	4.82	2.30	18.49	0.20	0.10	6.00	19.61	
				e%	18.67	8.92	87.64	0.83	0.39	23.34	38.12	
116	27.2390	31.3712	1891.30	Ppm	142.30	50.00	466.00	4.00	31.00	509.00	689	0.504
				epm	7.10	4.11	20.26	0.10	0.51	10.60	19.44	
				e%	22.49	13.02	64.17	0.32	1.66	34.70	63.64	
117	27.2500	31.3733	1404	Ppm	41.88	44.50	379.80	0.95	245.30	170.50	521.10	0.036
				epm	2.09	3.66	16.51	0.02	4.02	3.55	14.70	
				e%	9.38	16.42	74.09	0.11	18.06	15.94	66	
118	27.2696	31.3739	1247.63	Ppm	66.13	32.80	335.70	8.00	35.00	210.00	560	0.131
				epm	3.30	2.70	14.60	0.20	0.57	4.37	15.80	
				e%	15.87	12.97	70.18	0.98	2.77	21.08	76.16	
119	27.2278	31.3764	3266	Ppm	116.00	47.00	1053.00	16.00	31.00	163.00	1840	0.035
				epm	5.79	3.87	45.78	0.41	0.51	3.39	51.90	
				e%	10.37	6.92	81.98	0.73	0.91	6.08	93.01	
120	27.2542	31.3764	1758	Ppm	89.60	31.00	520.00	4.40	148.00	165.00	800	2.30
				epm	4.47	2.55	22.61	0.11	2.43	3.44	22.57	
				e%	15.03	8.57	76.02	0.38	8.53	12.08	79.38	
121	27.2500	31.3769	1307.33	Ppm	52.00	29.20	379.80	2.00	188.00	49.00	612	0.745
				epm	2.59	2.40	16.51	0.05	3.08	1.02	17.26	
				e%	12.04	11.14	76.59	0.24	14.51	4.71	80.78	
122	27.2092	31.3792	1973	Ppm	74.00	38.00	219.00	8.00	31.00	154.00	449.00	0.497
				epm	3.69	3.13	9.52	0.20	0.51	3.21	12.67	
				e%	22.32	18.89	57.55	1.24	3.27	20.64	76.09	
123	27.2346	31.3794	1667.80	Ppm	32.00	26.80	519.00	29.00	167.00	149.00	745.00	0.467
				epm	1.60	2.20	22.57	0.74	2.74	3.10	21.02	
				e%	5.89	8.13	83.24	2.74	10.25	11.37	78.38	
127	27.2746	31.3831	2998.50	Ppm	110.20	43.10	991.20	21.70	76.60	155.70	1600.00	2.90
				epm	5.50	3.54	43.10	0.55	1.26	3.24	45.13	
				e%	11.33	6.70	81.41	0.57	1.25	4.59	94.16	
128	27.2167	31.3833	1043	Ppm	54.00	28.00	278.00	8.00	24.00	216.00	435.00	0.370
				epm	2.69	2.30	12.09	0.20	0.39	4.50	12.27	
				e%	15.59	13.32	69.91	1.18	2.29	26.21	71.50	
129	27.281	31.3872	3150.50	Ppm	176.00	28.00	1007.00	12.00	29.00	27.00	1901.00	1.072
				epm	8.78	2.30	43.78	0.31	0.48	0.56	53.62	
				e%	15.92	4.17	79.35	0.56	0.73	0.44	98.83	
132	27.2119	31.3934	811.35	Ppm	29.52	12.53	224.48	15.00	135.46	104.06	290.30	0.282
				epm	1.47	1.03	9.76	0.38	2.22	2.17	8.19	
				e%	3.61	1.58	93.84	0.97	17.75	7.92	74.33	

Table 2 (continued)

Well No.	Latitude	Longitude	TDS (ppm)	Units	Major cations				Major anions			Error
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	SO_4^{2-}	Cl^{-}	
135	27.2660	31.4010	6083.78	Ppm	144.00	150.78	1950.00	7.00	112.00	520.00	3220.00	0.779
				epm	7.19	12.40	84.78	0.18	1.84	10.83	90.83	
				e%	6.87	11.86	81.10	0.17	1.78	10.52	87.70	
136	27.2590	31.4030	2384.80	Ppm	72.00	14.60	800.00	3.20	140.00	130.00	1225.00	0.127
				epm	3.59	1.20	34.78	0.08	2.30	2.71	34.56	
				e%	9.06	3.03	87.71	0.21	5.80	6.84	87.36	
139	27.2710	31.4040	12,044	Ppm	22.00	12.16	720.00	2.80	130.00	222.00	936.00	0.476
				epm	1.10	1.00	31.30	0.07	2.13	4.62	26.40	
				e%	3.28	2.99	93.52	0.21	6.52	13.89	79.60	
146	27.2117	31.4111	1483.97	Ppm	23.44	5.53	390.00	140.00	290.00	70.00	565.00	0.027
				epm	1.17	0.46	16.96	3.58	4.75	1.46	15.94	
				e%	5.28	2.05	76.51	16.16	21.46	6.58	71.96	
147	27.3019	31.4125	1779.69	Ppm	22.00	12.16	600.00	10.80	160.00	235.00	740.00	0.124
				epm	1.10	1.00	26.09	0.28	2.62	4.89	20.87	
				e%	3.46	3.15	93.16	0.23	8.21	14.66	77.13	
153	27.3028	31.4194	1945.84	Ppm	48.00	19.64	640.00	3.20	185.00	105.00	945.00	0.066
				epm	2.40	1.62	27.83	0.08	3.03	2.19	26.66	
				e%	7.50	5.06	87.18	0.26	9.51	6.86	83.63	
159	27.2964	31.4306	1894.10	Ppm	24.00	36.50	620.00	3.60	192.00	123.00	895.00	0.470
				epm	1.20	3.00	26.96	0.09	3.15	2.56	25.25	
				e%	3.83	9.61	86.27	0.29	10.88	7.20	81.92	

long distance from the southern to the northern parts and may also be due to the prolonged duration underground. It is observed that wells No. 11 and 135 are of high TDS content which is mainly due to the presence of contamination sources. The type of water varies between "slightly hard" and "excessively hard" as shown in the iso-hardness contour map (Fig. 5b), indicating that hardness increased toward the north and it had a local variation in the southern part of the study area. Inspection of the spatial distribution of well depth (Fig. 1) compared to the measured TDS shows that with increasing depths. The TDS values generally decrease. This could be attributed to the agriculture activates, high hydraulic characteristics of the surfaced aquifer and arid climatic conditions. In the studied area, the total hardness (TH) ranges from "slightly hard" to "excessively hard. According to the TH classification, 59.66% of the groundwater samples are considered very hard water, 20.17% are excessively hard water, 15.97% are moderately hard water, and 5.04% are slightly hard water (Tables 3 and 4).

Major and trace ions distribution

Calcium ion concentration ranges in the studied area were from 15.23 ppm (Well No. 23) to 611.2 ppm (Well No. 42) while magnesium concentrations in groundwater ranged from 4.20 ppm (Well No. 71) to 532.26 ppm (Well No. 42). Generally, calcium and magnesium concentrations increase in the north and northeast directions toward the limestone plateau (Fig. 6a, b). Sodium ion content varied from 49.30 ppm (Well No. 1) to 1950 ppm (Well No. 135), and potassium concentrations ranged between 0.39 ppm (Well No. 11) and 320.80 ppm (Well No. 61). The total concentrations of sodium and potassium in the studied area varied from one place to another ranging between 63.59 ppm (Well No. 11) and 1957 ppm (Well No. 135). The concentration of sodium and potassium ions showed a general increase in the northeastern part of the studied area, consistent with the distribution of TDS (Fig. 6c, d). The distribution of bicarbonate in the study area shows some anomalies especially in the central and northwestern parts (Fig. 7a). This is mainly due to leaching with either the remaining limestone or the limestone plateau. In general, the sulfate ions concentrations in most wells are not high ranging between 11.50 ppm (Well No. 129) and 3319 ppm (Well No. 34) (Fig. 7b). It is noticed that there is a general increasing trend northeast, in addition to positive anomalies in the central part. These high concentrations may be due to the presence of gypsum deposits at these localities. Finally, the distribution of chloride ions shows a general increase in the northeastern direction and decreases toward the

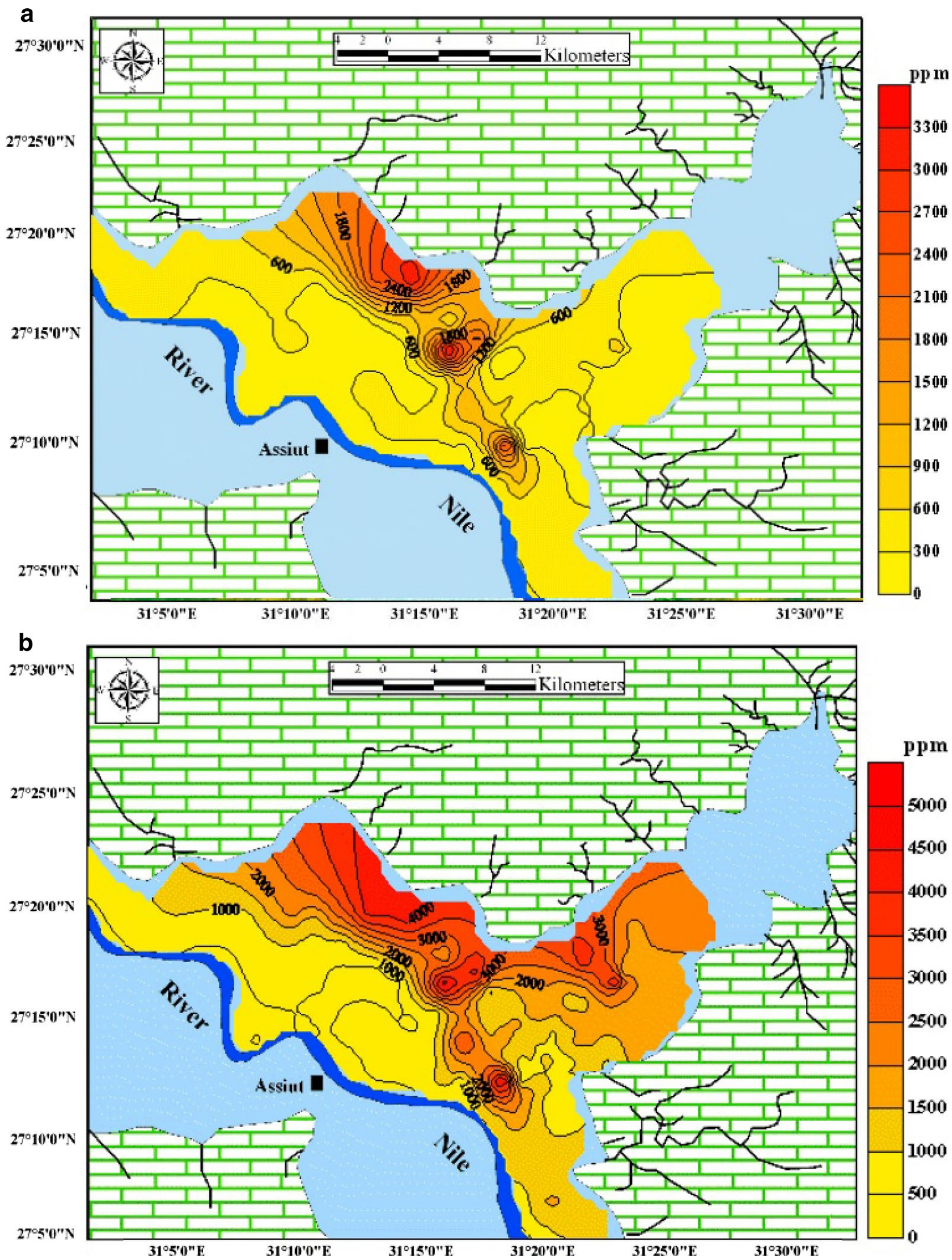

Fig. 5 **a** Total dissolved solid (TDS) and **b** water hardness distribution contour map in the area

southwestern direction and ranges between 40 ppm (Well No. 11) and 3200 ppm (Well No. 135) (Fig. 7c). The high chloride concentration is possibly related to leaching of the soluble chloride minerals in deep sedimentary basins, especially shale sequences with the upwelling of deep groundwater from the Nubian Aquifer along vertical sub vertical faults (Sultan et al. 2007; Abotalib et al. 2016). This direction is compatible with the regional groundwater flow pattern in the studied area. Many elements are present in groundwater in low concentrations (less than 0.1 ppm) and sometimes much higher. Some trace elements such as Fe^{++}, Mn^{++}, Ni^{+} and Pb^{+} were measured at some water points in the study area (Table 5). The iron concentration measured

Table 3 Total hardness (TH) values of the groundwater samples in the area

Well No.	TH (ppm)	Well No.	TH (ppm)	Well No.	TH (ppm)	Well No.	TH (ppm)	Well No.	TH (ppm)	Well No.	TH (ppm)
1	433	28	2366	55	640	82	340	110	123	137	522
2	417	29	420	56	518	84	133	111	240	138	354
3	441	30	421	57	620	85	140	112	250	139	105
4	330	31	399	58	2850	86	127	113	232	140	622
5	341	32	427	59	620	87	95	114	348	141	125
6	340	33	1072	60	155	88	325	115	356	142	154
7	373	34	3195	61	163	89	591	116	561	143	124
8	379	35	391	62	121	90	235	117	288	144	300
9	363	36	433	63	255	91	410	118	300	145	210
10	180	37	471	64	620	92	138	119	483	146	81
11	365	38	177	65	490	93	340	120	351	147	105
12	550	39	535	66	956	94	500	121	250	148	145
13	395	40	427	67	292	95	250	122	341	149	241
14	460	41	426	68	320	96	135	123	190	150	450
15	126	42	3718	69	397	97	621	124	200	151	122
16	408	43	430	70	164	98	118	125	310	152	310
17	386	44	288	71	90	99	212	126	450	153	201
18	384	45	491	72	119	100	416	127	453	154	100
19	626	46	300	73	77	101	400	128	250	155	155
20	300	47	412	74	300	102	400	129	555	156	144
21	210	48	1291	75	315	103	210	130	455	157	250
22	398	49	430	76	90	104	218	131	125	158	222
23	92	50	581	77	232	105	99	132	125	159	210
24	545	51	2227	78	651	106	390	133	130		
25	427	52	400	79	138	107	432	134	110		
26	333	53	380	80	178	108	418	135	980		
27	490	54	176	81	451	109	210	136	240		

Table 4 Classification of the water according to degrees of hardness in the studied area

Water type	Hardness	No. of well samples
Soft water	0–55	–
Slightly hard water	56–100	6
Moderately hard water	101–200	19
Very hard water	201–500	71
Excessively hard water	More than 500	23

in some groundwater samples ranged between 0.05 and 0.46 ppm while manganese concentrations ranged between 0.11 and 0.221 ppm. Lead concentration was not detected in many samples; however, it appeared at 0.05 ppm in some samples which is within the permissible limits (0.01 mg/L). Nickel ions in the study samples were rare although in some samples it was detected with very low concentration ranges between 0.01 and 0.6 ppm.

Hypothetical salt combinations

The hypothetical salts assemblages are the most widely used and easiest method for displaying the chemical analysis of water samples using PHREEQCA computer program (Parkhurst and Appelo 1999). Hypothetically, strong acid ions (Cl^- and SO_4^-) are generally combined with alkalis (Na^+ and K^+) and alkaline earth (Ca^{++} and Mg^{++}) are combined with the remainder of the radicals. If the latter is in surplus in the water, then they will combine with weak acids (CO_3^-, HCO_3^-). The calculated hypothetical salt combinations for the studied area are tabulated in Table 6 and revealed the presence of different groups of salt assemblages. The hypothetical salt combinations in the studied area indicated the presence of a variety of salts as follows: NaCl, $Ca(HCO_3)_2$, $Mg(HCO_3)_2$, Na_2SO_4, $MgSO_4$, $CaSO_4$, $NaHCO_3$, KCL and $MgCl_2$. Figure 8 shows the relationships between cations and anions in bar graph form. Their average equivalent

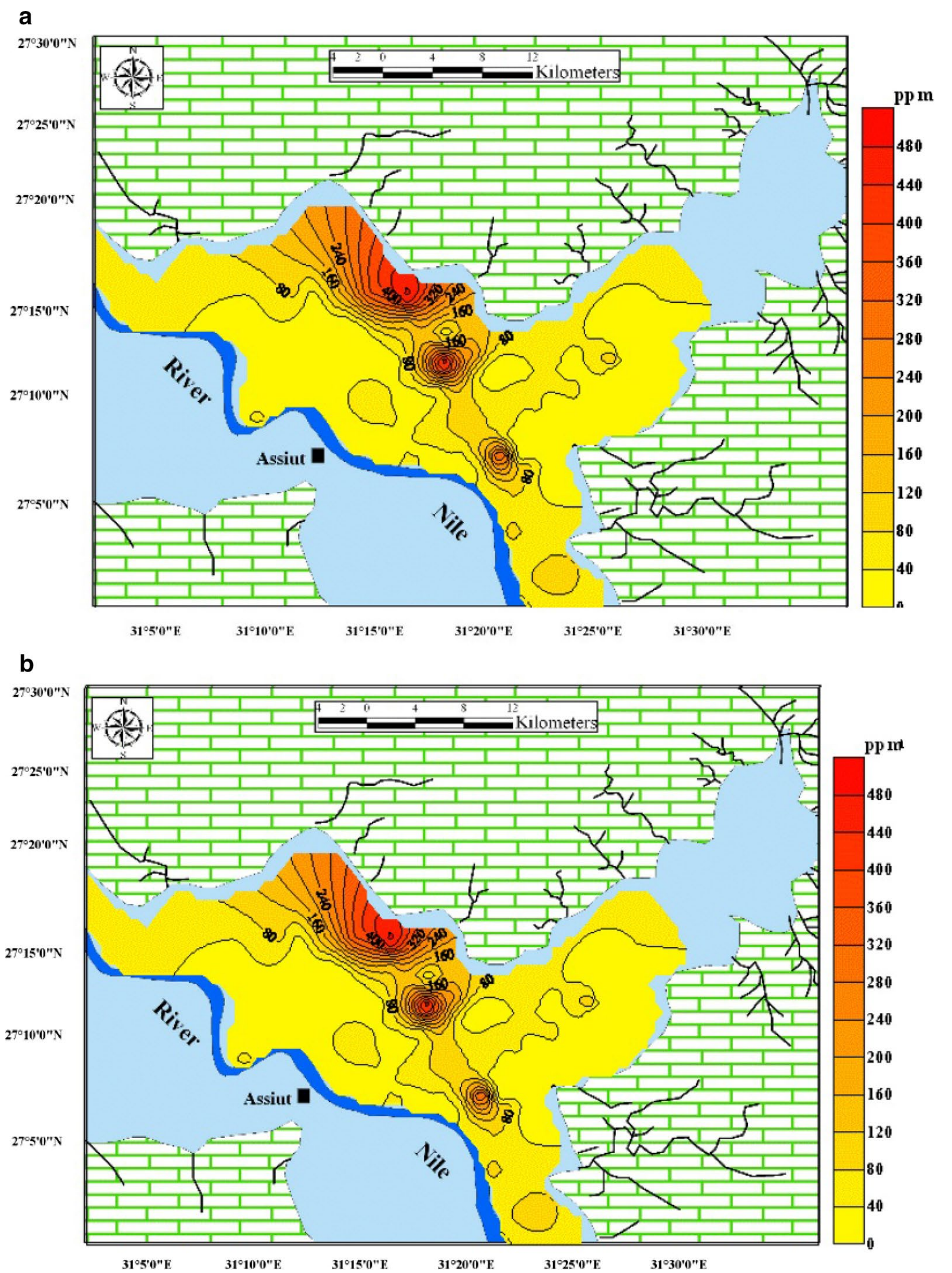

Fig. 6 Spatial distribution of major ions in studied groundwater samples: **a** calcium, **b** magnesium, **c** sodium and **d** potassium ions

percentages are 44.108%, 11.526%, 8.43%, 8.108%, 8.044%, 6.873%, 5.118%, 3.978% and 3.270%, respectively.

Hydrochemical facies and groundwater genesis

The hydrogeochemical facies and groundwater genesis can be understood by plotting the geochemical data on Piper (1944) trilinear diagrams. The Piper trilinear diagram includes three distinct plotting fields, two lower left, lower right triangular fields and a diamond-shaped field intersecting the two triangles at the upper part. Generally, the groundwater samples appear in the upper diamond field and have secondary salinity properties, where

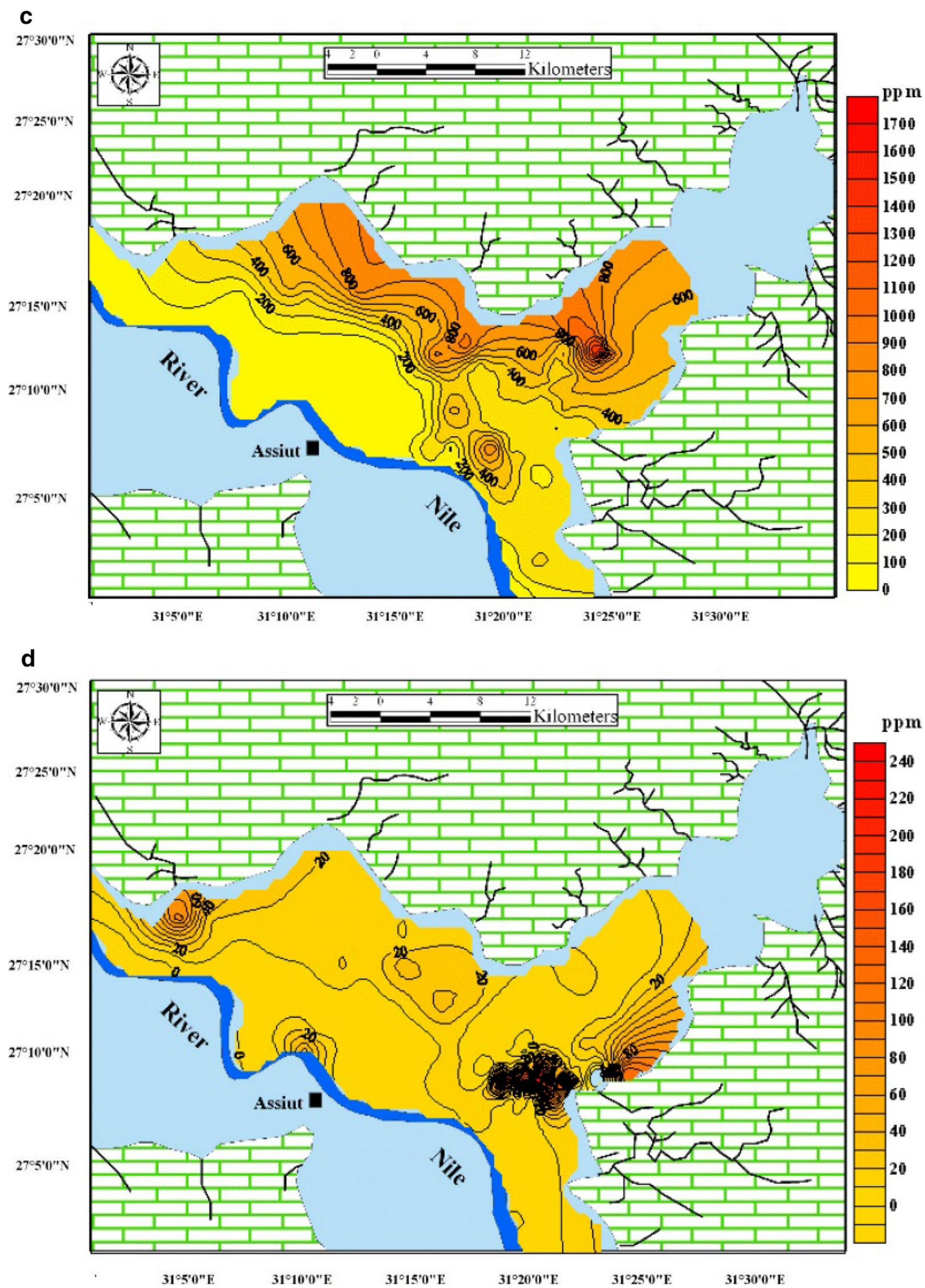

Fig. 6 continued

sulfate and chloride exceed sodium and potassium. On the other side, those that appear in the lower triangle are considered as having alkaline properties, where carbonates and bicarbonates exceed calcium and magnesium. The results of the analyzed samples were plotted on Piper diagrams (Fig. 9). This diagram illustrates that most of the groundwater samples are located close to each other which indicates that they are of similar origins. In the

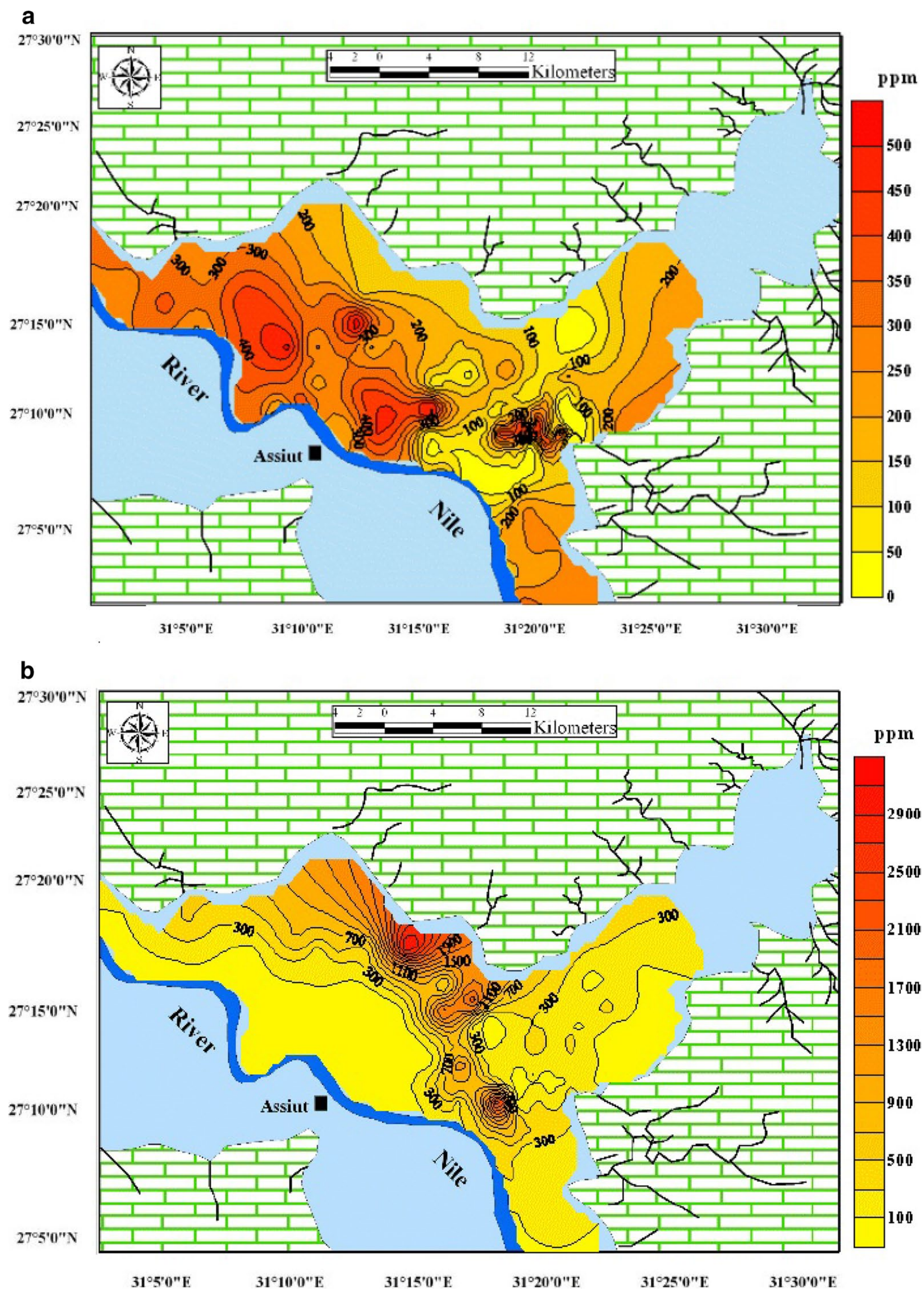

Fig. 7 Spatial distribution of minor ions in studied groundwater samples: **a** bicarbonate, **b** sulfate, and **c** chloride ions

outlet and intermediate areas, it is clear that sodium and potassium ions represent the main dominating cations, while chloride ions are the main dominating anions. This reflects that most of the samples have sodium chloride facies. In the majority of the groundwater samples collected from the old cultivated land areas, sodium ions represent the most dominant cations. Alternatively, bicarbonate ions are the dominating anions in most

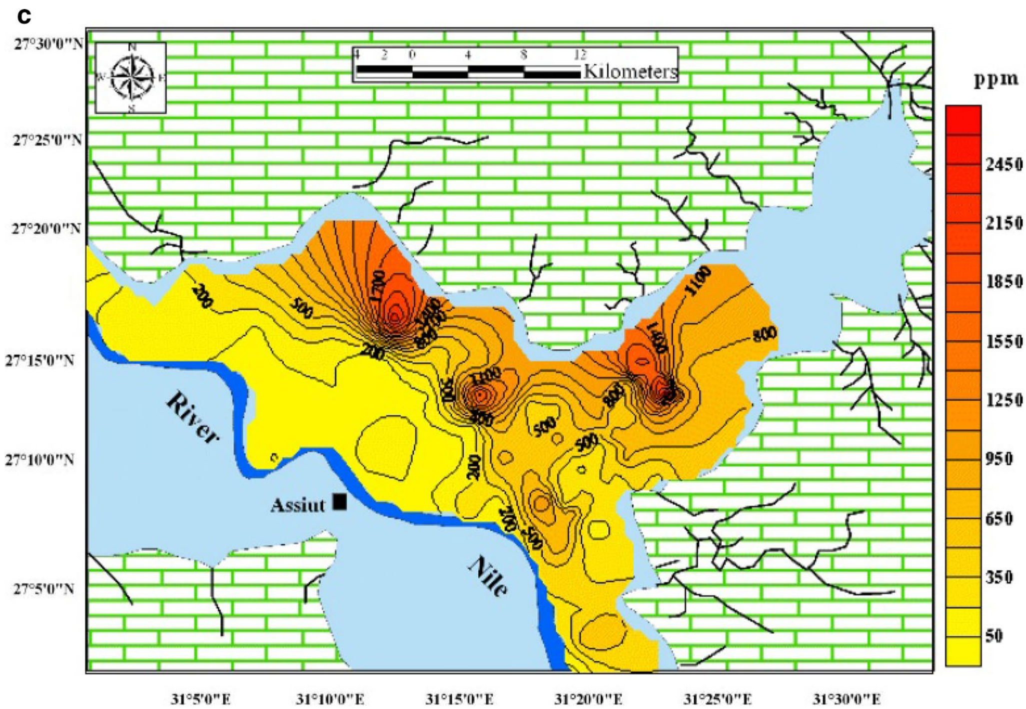

Fig. 7 continued

Table 5 Results of the chemical analysis of the trace elements in some groundwater samples

Well No.	Trace elements				Well No.	Trace elements			
	Fe^{++}	Mn^{++}	Ni^{+}	Pb^{+}		Fe^{++}	Mn^{++}	Ni^{+}	Pb^{+}
4	0.21	0.151	0.01	0.05	71	0.12	0.155	0.75	0.04
6	0.14	0.145	0.01	Nil	79	Nil	Nil	–	–
10	0.14	0.163	0.62	Nil	84	Nil	Nil	–	–
12	0.16	0.221	0.09	0.01	86	Nil	Nil	–	–
14	0.13	0.141	0.28	0.04	96	0.05	Nil	–	–
15	0.13	0.133	0.13	0.05	98	Nil	Nil	–	–
19	0.14	0.164	0.17	Nil	105	0.16	Nil	–	–
23	0.19	0.165	0.14	0.03	110	0.27	Nil	–	–
63	0.13	0.11	0.05	0.1	132	0.01	Nil	–	
99	0.11	0.15	0.11	Nil	146	0.46	Nil	–	–

samples with magnesium and calcium bicarbonate representing the main facies.

According to the calculated percentages of the hydrochemical composition, Sulin's (1948) diagram was used to reveal the groundwater genesis and the type of water. This genetic diagram consists of two equal quadrants. The water samples which are plotted in the upper right square indicate the marine origin of $MgCl_2$ and $CaCl_2$ water type, while the water samples projected in the lower left square indicate the meteoric origin of Na_2SO_4 and $NaHCO_3$ water types. Plotting groundwater samples on the Sulin diagram (Fig. 10) indicates that most of the samples are of meteoric origin (Na_2SO_4 and $NaHCO_3$), while other samples could be of a mixed origin with deeper groundwater sources such as the Nubian water (Himida 1970).

Discussion

Groundwater suitability for drinking

Groundwater quality parameters (pH, TDS, EC, TH, Ca^{++}, Mg^{++}, SO_4^{-}, Cl^{-}, Na^{+} and K^{+}) were used to

Table 6 Hypothetical salt combination groups of the obtained groundwater samples

Group	Salt assemblages	Sample No.
1	NaCl > $CaHCO_3$ > $MgHCO_3$	12, 14, 9, 28, 33, 34, 38, 41, 42, 43, 44, 45, 47, 48, 49, 50, 5, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 63, 64, 65, 66, 67, 69, 70, 71, 72, 73, 77, 78, 79, 80, 82, 84, 87, 88, 89, 90, 91, 92, 100, 102, 104 105, 106, 107, 108, 109, 110, 111, 113, 123, 127, 128, 129, 132 135, 136, 139, 146, 147, 153
2	NaCl > $CaHCO_3$ > Na_2SO_4	2, 3, 32, 36, 39, 42, 43, 50, 53, 54, 55, 56, 57, 58, 61, 64, 65, 66, 67, 69, 71, 72, 73, 77, 78, 79, 88, 89, 92, 94, 96, 97, 102, 104, 105, 106, 107, 108, 110, 111, 13, 115, 116, 117, 118, 119, 120, 121, 122, 127, 128, 129, 135
3	NaCl > Na_2SO_4 > $MgHCO_3$	6, 12, 14, 19, 28, 33, 34, 37, 38, 41, 43, 45, 47, 48, 49, 51, 52, 54, 58, 60, 61, 63, 70, 71, 72, 73, 77, 80, 84, 86, 88, 90, 95, 96, 98, 99, 05, 109, 110, 114, 123, 132, 136, 139, 146, 147, 153
4	NaCl > $MgHCO_3$ > KCl	3, 6, 12, 15, 16, 19, 23, 27, 37, 44, 53, 54, 60, 61, 63, 65, 67, 71, 72, 73, 79, 82, 84, 86, 87, 88, 92, 93, 96, 97, 98, 99, 105, 110, 111, 121, 123, 132, 139, 146, 147, 153, 159
5	NaCl > Na_2SO_4 > $NaHCO_3$	3, 6, 8, 9, 2, 4, 15, 16, 19, 22, 32, 33, 34, 37, 38, 7, 43, 48, 49, 51, 54, 58, 60, 63, 65, 67, 70, 77, 79, 80, 88, 90, 85, 99, 109, 114, 116, 123, 136, 139, 147, 153, 159
6	NaCl > $MgSO_4$ > $CaSO_4$	2, 3, 6, 12, 14, 16, 9, 22, 25, 27, 36, 44, 45, 53, 54, 58, 60, 63, 65, 67, 69, 70, 77, 80, 81, 82, 87, 88, 89, 90, 91, 93, 97, 107, 111, 114, 117, 123
7	NaCl > MgCl > KCl	2, 27, 28, 36, 39, 42, 50, 53, 55, 56, 57, 59, 64, 66, 69, 78, 82, 97, 100, 102, 104, 106, 107, 108, 111, 115, 118, 119, 120, 121, 22, 27, 129, 135
8	NaCl > $MgSO_4$ > $CaHCO_3$	3, 6, 12, 19, 38, 42, 45, 48, 51, 52, 56, 58, 65, 66, 70, 80, 89, 90, 91, 93, 94, 95, 97, 100, 104, 106, 107, 108, 113, 114, 115, 116, 128, 135
9	NaCl > $CaSO_4$ > $MgSO_4$	28, 38, 42, 48, 51, 52, 55, 56, 57, 59, 64, 66, 78, 94, 95, 100, 102, 104, 106, 108, 115, 116, 118, 119, 120, 122, 127, 28, 29, 136
10	NaCl > $MgHCO_3$ > $NaHCO_3$	3, 6, 12, 16, 29, 37, 44, 53, 54, 60, 63, 65, 67, 69, 82, 87, 88, 93, 97, 99, 111, 117, 121, 123, 139, 147, 153, 159–
11	NaCl > $CaHCO_3$ > $MgSO_4$	2, 3, 14, 22, 43, 53, 54, 60, 63, 67, 69, 77, 8, 82, 87, 111, 117, 120, 121, 122, 123, 136, 159
12	NaCl > MgCl > $MgSO_4$	27, 28, 42, 50, 53, 55, 57, 59, 64, 66, 69, 78, 89, 97, 100, 104, 106, 119, 122, 129, 135
13	$MgHCO_3$ > NaCl > KCl	1, 2, 5, 7, 8, 9, 11, 17, 18, 22, 25, 26, 30, 31, 32, 35, 36, 40, 81
14	$CaHCO_3$ > NaCl > $MgSO_4$	5, 7, 8, 9, 11, 16, 17, 18, 22, 25, 26, 27, 30, 31, 40, 81
15	$MgHCO_3$ > NaCl > Na_2SO_4	2, 5, 7, 8, 9, 11, 22, 29, 31, 32, 35, 36, 40
16	$MgHCO_3$ > NaCl > $NaHCO_3$	1, 2, 5, 8, 18, 29, 30, 32, 35, 36, 40, 81
17	$CaHCO_3$ > NaCl > Na_2SO_4	5, 7, 8, 9, 11, 16, 22, 30, 31, 37, 40
18	$MgHCO_3$ > Na_2SO_4 > NaCl	3, 8, 9, 16, 18, 22, 32, 65, 67, 81, 93
19	NaCl > $NaHCO_3$ > Na_2SO_4	5, 29, 30, 35, 40, 71, 73, 105, 132, 146
20	$NaHCO_3$ > NaCl > $MgHCO_3$	23, 61, 72, 79, 84, 92, 96, 98, 110
21	$MgHCO_3$ > $CaHCO_3$ > NaCl	1, 8, 13, 17, 17, 25, 31, 81
22	$CaHCO_3$ > $MgHCO_3$ > NaCl	7, 9, 11, 22, 26, 30, 40
23	$MgSO_4$ > NaCl > Na_2SO_4	33, 34, 37, 39, 41, 47, 49
24	NaCl > $MgHCO_3$ > $CaHCO_3$	3, 5, 6, 5, 23, 99
25	NaCl > $NaHCO_3$ > $MgHCO_3$	15, 71, 73, 105, 32, 146
26	$MgSO_4$ > NaCl > $CaHCO_3$	33, 34, 39, 41, 47
27	$MgHCO_3$ > NaCl > $CaHCO_3$	2, 29, 32, 35
28	Na_2SO_4 > NaCl > $MgHCO_3$	23, 44, 87, 91
29	$CaHCO_3$ > Na_2SO_4 > NaCl	18, 25, 26, 81
30	$CaHCO_3$ > NaCl > $MgHCO_3$	16, 27, 37
31	Na_2SO_4 > $MgHCO_3$ > $CaHCO_3$	4, 6, 99
32	$MgHCO_3$ > $NaHCO_3$ > NaCl	7, 31
33	Na_2SO_4 > $MgHCO_3$ > NaCl	26

assess the suitability for drinking purposes according to WHO (2004) and Eg. St. (2007) limits, (Table 7). Water quality in the study area varied greatly regarding the appropriateness for drinking and domestic purposes. According to salinity TDS, all groundwater samples are unsuitable due to their high content of total dissolved solids (Fig. 11). Also, according to minor and trace constituents, 90% of groundwater samples are unsuitable for human drinking because of the higher content of measured trace elements in the majority of samples. About 80% of the groundwater proved to be unsuitable for domestic and laundry usage because the ranges were from hard to very hard and 6% to the extent of moderate.

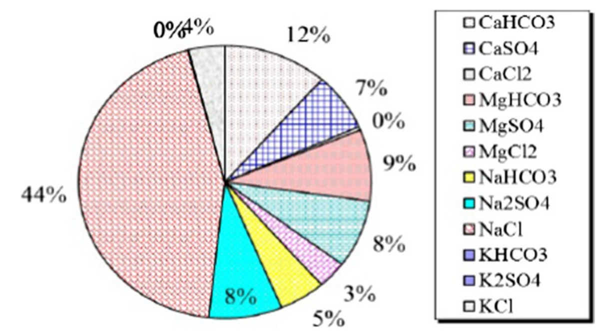

Fig. 8 Hypothetical salt combinations of the obtained samples in the area

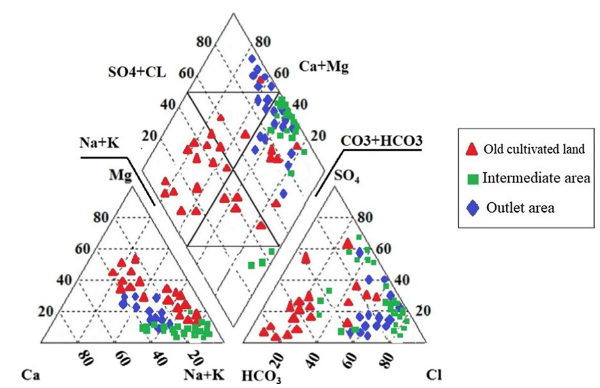

Fig. 9 Piper trilinear diagram representation of groundwater samples in the (red triangle) old cultivated land area, (blue diamond) outlet area and (green square) intermediate area of wadi El-Assiuti

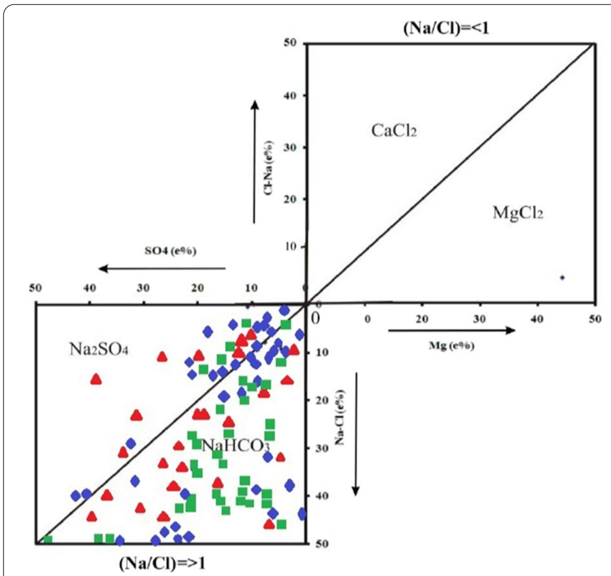

Fig. 10 Sulin's diagram for some groundwater samples in the (red triangle) old cultivated land area, (blue diamond) outlet area and (green square) intermediate area of wadi El-Assiuti

Groundwater suitability for irrigation

Groundwater suitability for agriculture depends on various factors such as effective salinity hazard, sodium adsorption ratio (SAR), soluble sodium percentage (SSP), residual sodium carbonate (RSC) and permeability index (PI). Mineral constituents of groundwater affect soil structure and permeability, which in turn indirectly affects crop growth.

Sodium adsorption ratio (SAR)

The main problem of high concentration of sodium is its impact on the permeability of the soil, water infiltration and total salinity increase in its therefore harmful to sensitive crops. Sodium concentration is estimated by the sodium absorption ratio which is calculated by the following formula (Richards 1954), (Eq. 1):

$$\mathrm{SAR} = \frac{\mathrm{Na}^{1+}}{\sqrt{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2}} \quad \text{Values in meq/L} \tag{1}$$

The irrigation water is classified according to SAR into four main classes as indicated in Table 8. Continued use of water with high SAR results in a deterioration of the soil's structure. Sodium replaces calcium and magnesium that is absorbed by clay minerals and allows the soil particles to disperse. This dispersion leads to a deterioration of soil aggregates and induces soil cementation under drying conditions, as well as preventing rainwater infiltration. For the studied area, the calculated SAR values of the collected groundwater samples and their corresponding classes are given in Table 9. SAR values range between 1.03 and 30.57 in the studied groundwater samples. Thus, 78.15% of the groundwater samples are considered excellent and can be used for all soil types with no harmful effects from sodium, 12.6% of the groundwater samples are good, 7.56 of the groundwater samples are fair, and 1.68% of the groundwater samples are of poor quality for irrigation purposes.

Salinity hazard

In general, salinity problems are more severe during the early stages of growth and vegetable crops are more sensitive to salinity than field crops. Good drainage systems coupled with good irrigation management strategies are the most effective tools to control salinity in most soils. The irrigation water can be classified into four main categories based on the EC and the sodium adsorption ratio (SAR) (Tables 10, 11).

The values of the salinity hazard (EC) and the sodium adsorption ratio (SAR) of the available groundwater samples are plotted on the Wilcox diagram with the aid of the United Nations and GWW software program 1994

Table 7 Maximum acceptable concentration for drinking water according to the WHO (2004) and Egyptian Standard (Eg. St. 2007), and the related measurements in the studied area

Constituent	Unit	Maximum acceptable concentration (WHO 2004)	Egyptian maximum permissible limits (EHCW 2007)	Concentration range for the studied samples
pH		6.5–8.5	6.5–8.5	6.45–9.45
Electric conductivity (EC)	μmhos/cm	1500	–	340–8000
Total dissolved solids (TDS)	ppm	1000	1000	1972–6217
Total hardness (TH)	mg/l ($CaCO_3$)	500	500	34–960
Sodium (Na)	ppm	200	200	49.30–1950
Calcium (Ca)	ppm	200	200	15.23–611.52
Magnesium (Mg^{++})	ppm	150	150	4.20–532.26
Potassium (K^+)	ppm	10	–	0.39–320.80
Chloride (Cl)	ppm	250	250	40.40–3200
Sulfate (SO_4^-)	ppm	400	–	72–580
Bicarbonate (HCO_3^-)	ppm	200	250	6.10–628
Nickel (Ni)	ppm	0.02	0.02	0.01–0.6
Lead (Pb)	ppm	0.01	0.01	0.05
Iron (Fe)	ppm	0.3	0.3	0.05–0.46
Manganese (Mn)	ppm	0.4	0.4	0.11–0.221

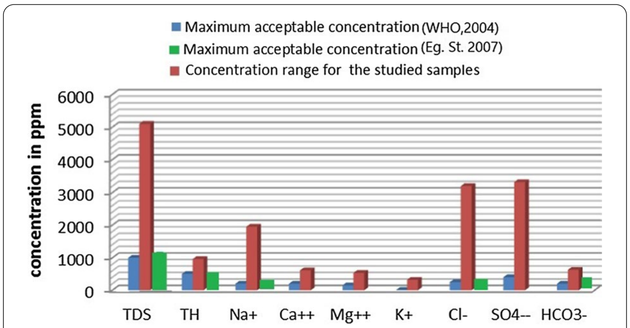

Fig. 11 Ion concentrations in the available groundwater samples and their relations with the WHO standards

(Fig. 12). The representation of groundwater samples parameters on the Wilcox diagram indicates that almost all of the samples are located in C3-S1 and C3-S2 classes (low sodium hazard and high salinity hazard), except for a few samples which are in C4S4 class (very high sodium hazard and very high salinity hazard) and some fewer samples in C4S3 class (very high sodium hazard and high salinity hazard). This indicates that the water can be used in all types of soil except the last samples which can be used for soils with restricted drainage. From the above discussion, the suitability of the studied groundwater samples for irrigation purposes indicates that most of the groundwater samples can be used for all soils and most crop types.

Table 8 Classification of irrigation water based on SAR values (College of Agricultural Sciences 2002; U.S. Salinity Laboratory Staff 1954)

Level	SAR	Quality	Class	Hazard	Use of water for irrigation
S1	0–10	Low sodium	Excellent	No harmful effects from sodium	In all types of soil
S2	10–18	Medium sodium	Good	Problems on fine texture soils sodium sensitive plants, especially under low leaching conditions, but could be used on sandy soils with good permeability	In coarse textural soils with high permeability and rich in organic matter
S3	18–26	High sodium	Fair	Harmful effects could be anticipated in most soils and amendments such as gypsum would be necessary to exchange sodium ions	Requires good drainage and chemical amendments
S4	> 26	Very high sodium	Poor	Generally unsatisfactory for irrigation	Very poor for irrigation, require low salinity water, good drainage and addition of gypsum

Table 9 Water quality according to sodium adsorption ratio (SAR) for the groundwater samples in the studied area

Well No.	SAR	Class	Well No.	SAR	Class	Well No.	SAR	Class	Well No.	SAR	Class
1	1.03	Excellent	35	1.47	Excellent	67	6.10	Excellent	105	9.44	Excellent
2	1.18	Excellent	36	1.23	Excellent	69	1.79	Excellent	106	7.60	Excellent
3	2.07	Excellent	37	1.16	Excellent	70	8.66	Excellent	107	5.64	Excellent
4	5.07	Excellent	38	8.26	Excellent	71	14.19	Good	108	10.64	Good
5	2.28	Excellent	39	1.09	Excellent	72	9.06	Excellent	109	9.66	Excellent
6	6.24	Excellent	40	2.50	Excellent	73	12.18	Good	110	7.47	Excellent
7	1.60	Excellent	41	3.39	Excellent	77	6.86	Excellent	111	10.63	Good
8	1.88	Excellent	42	6.10	Excellent	78	6.30	Excellent	113	6.57	Excellent
9	1.87	Excellent	43	10.84	Good	79	8.01	Excellent	114	6.42	Excellent
11	1.44	Excellent	44	4.87	Excellent	80	8.41	Excellent	115	9.80	Excellent
12	10.11	Good	45	7.48	Excellent	81	1.10	Excellent	116	8.56	Excellent
13	1.62	Excellent	47	1.43	Excellent	82	5.65	Excellent	117	9.74	Excellent
14	10.16	Good	48	6.90	Excellent	84	9.93	Excellent	118	8.43	Excellent
15	11.91	Good	49	1.38	Excellent	86	6.77	Excellent	119	20.84	Fair
16	1.49	Excellent	50	5.89	Excellent	87	10.37	Good	120	12.07	Good
17	1.48	Excellent	51	9.09	Excellent	88	7.12	Excellent	121	10.45	Good
18	1.46	Excellent	52	8.65	Excellent	89	4.92	Excellent	122	5.16	Excellent
19	8.32	Excellent	53	6.02	Excellent	90	8.51	Excellent	123	16.37	Good
22	1.60	Excellent	54	9.68	Excellent	91	3.65	Excellent	127	20.27	Fair
23	11.46	Good	55	4.66	Excellent	92	8.96	Excellent	128	7.65	Excellent
25	1.21	Excellent	56	6.16	Excellent	93	5.47	Excellent	129	18.60	Fair
26	5.16	Excellent	57	4.54	Excellent	94	7.51	Excellent	132	8.72	Excellent
27	1.40	Excellent	58	7.14	Excellent	95	8.72	Excellent	135	27.09	Poor
28	7.71	Excellent	59	4.54	Excellent	96	8.31	Excellent	136	22.47	Fair
29	1.46	Excellent	60	18.50	Fair	97	5.79	Excellent	139	30.57	Poor
30	1.14	Excellent	61	7.68	Excellent	98	8.45	Excellent	146	18.81	Fair
31	1.07	Excellent	63	9.14	Excellent	99	7.76	Excellent	147	25.47	Fair
32	1.14	Excellent	64	5.77	Excellent	100	11.26	Good	153	19.65	Fair
33	6.31	Excellent	65	5.50	Excellent	102	13.05	Good	159	18.60	Fair
34	5.52	Excellent	66	6.28	Excellent	104	6.63	Excellent			

Table 10 Classification of irrigation water based on salinity (EC) and (SAR) values; College of Agricultural Sciences (2002) and U.S. Salinity Laboratory Staff (1954)

Class	EC	TDS (ppm)	SAR	Order	Suitability
Excellent	0–250	< 200	< 10	Low	Suitable
Good	250–750	200–500	10–18	Medium	Moderately suitable
Fair	750–2250	500–1500	18–26	High	Fairly suitable
Poor	2250–5000	1500–3000	> 26	Very high	Unsuitable

Bicarbonate and carbonate's negative effects can be indicated by the high concentrations of Ca^{++} and Mg^{++}. The RSC equation (Eq. 2) (Eaton 1950) is used to indicate the potential for Ca^{++} and Mg^{++} precipitation at the soil surface and the removal of Ca^{++} and Mg^{++} from the soil solution. As RSC increases, calcium and some magnesium are precipitated from the solution, raising sodium percentages and the sodium adsorption rate on soil particles, which in turn raises the potential for sodium hazard. The RSC is calculated by the following formula:

$$\mathrm{RSC} = \left(\mathrm{CO}_3^{2-} + \mathrm{HCO}_3^{-}\right) - \left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right)\ \mathrm{meq/L} \tag{2}$$

Residual sodium carbonate (RSC) values for the available groundwater samples are tabulated in Table 12 and Fig. 13. It is clear that most of the groundwater samples are considered safe for irrigation according to their RSC contents (86%) and are not hazardous, whilst some other samples have high (12%), medium (1%) and low (1%) values of RSC. Therefore, most of the available groundwater samples in the area are suitable for irrigation according to their calculated RSC values.

Table 11 Water quality for irrigation according to College of Agricultural Sciences (2002) and U.S. Salinity Laboratory Staff (1954)

EC class	Water quality	EC range (pS/cm)	Usage	SAR class	Water quality	SAR range	Usage
C1	Low salinity	0–250	Can be used for irrigation of most crops on most soils	S1	Low sodium	0–10	Can be used for all soils
C2	Medium salinity	250–750	Can be used if a moderate amount of leaching is occurs	S2	Medium sodium	10–18	Preferably used with good permeability
C3	High salinity	750–2250	Cannot be used with restricted drainage	S3	High sodium	18–26	Can produce harmful effects
C4	Very high salinity	> 2250	Can be used for irrigation of cannot be used with drainage. restricted	S4	Very high sodium	26–100	Unsuitable for irrigation except at low and medium salinity

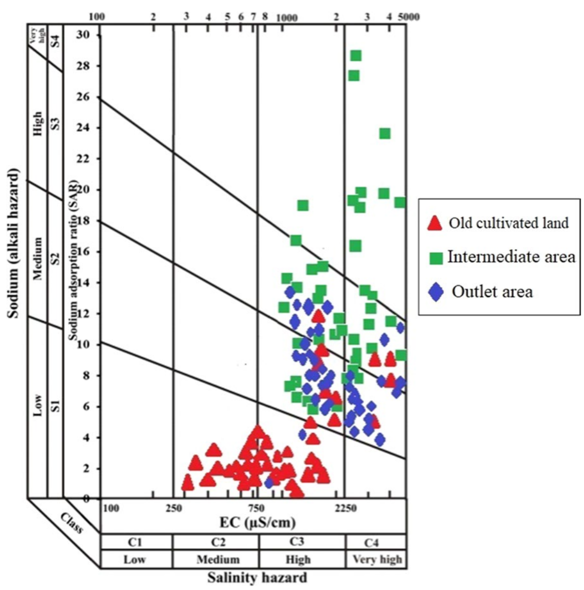

Fig. 12 Groundwater suitability for irrigation for the available groundwater samples in the (red triangle) old cultivated land area, (blue diamond) outlet area and (green square) intermediate area according to US Lab. Classification (1954)

Soluble sodium percentage (SSP)

Soluble Sodium Percentage (SSP) is an estimation of the sodium hazard of irrigation water such as SAR, but represents the percentage of sodium out of the total cations as with SAR. The correlations of sodium only with Ca^{2+} and Mg^{2+} and is determined by the following equation (Eq. 3):

$$SSP = \left(\frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+}\right) \times 100 \quad \text{(Value in meq/L)} \tag{3}$$

According to the results in Table 13 and Fig. 14, it deduced that 1% of the samples are excellent, 23% are good, 20% are permissible, 25.2% are doubtful, and 31% are unsuitable for irrigation.

Wilcox (1955) designed a graph to represent the relation between sodium percent (Na %) and specific conductance (EC) to defined the propriety of groundwater samples for irrigation. He divided the graph into five zones which represent the changes in irrigation water classes.

According to sodium percent classification in Table 14 and Wilcox diagram in Fig. 15a, we showed that most samples were good and forty samples are doubtful due to the high sodium concentration. Also, few samples were permissible and twenty-one samples were excellent for irrigation.

Permeability index (PI)

Sodium is significant chemical components in irrigation water that can cause reduce of soil permeability. To calculate the PI were used calcium, magnesium, sodium and bicarbonate ions which are given by Eq. 4 (Doneen 1964). According to PI classification, all samples were plotted in group I&II and suitable for irrigation (Fig. 15b).

$$PI = \frac{(Na^+ + \sqrt{HCO_3^-}}{(Ca^{2+} + Mg^{2+} + Na^+)} \times 100 \quad \text{(Value in meq/L)} \tag{4}$$

Table 12 Evaluation of groundwater samples for irrigation uses according to their RSC content

Well No.	RSC (epm)	Hazard	Well No.	RSC (epm)	Hazard	Well No.	RSC (epm)	Hazard	Well No.	RSC (epm)	Hazard
1	−3.56	None	35	−3.39	None	67	−1.92	None	105	3.55	High
2	−4.17	None	36	−4.47	None	69	−4.16	None	106	−7.19	None
3	−2.60	None	37	−5.43	None	70	−2.77	None	107	−5.53	None
4	−1.60	None	38	−3.15	None	71	3.26	High	108	−6.52	None
5	−2.97	None	39	−9.79	None	72	4.44	High	109	−4.00	None
6	−2.20	None	40	1.76	Medium	73	2.95	High	110	5.01	High
7	−1.99	None	41	−7.70	None	77	−1.81	None	111	−2.03	None
8	−1.99	None	42	−71.29	None	78	−12.50	None	113	−4.24	None
9	−4.03	None	43	−5.90	None	79	5.76	High	114	−6.62	None
11	1.24	Low	44	−1.08	None	80	−2.95	None	115	−7.02	None
12	−5.69	None	45	−8.71	None	81	−3.81	None	116	−10.70	None
13	−3.44	None	47	−5.73	None	82	−2.53	None	117	−1.73	None
14	−5.19	None	48	−22.64	None	84	5.19	High	118	−5.42	None
15	2.01	Medium	49	−6.50	None	86	4.98	High	119	−9.15	None
16	−4.51	None	50	−11.40	None	87	−0.30	None	120	−4.59	None
17	−4.31	None	51	−42.00	None	88	−3.53	None	121	−1.91	None
18	−3.12	None	52	−7.61	None	89	−8.42	None	122	−6.31	None
19	−7.00	None	53	−4.19	None	90	−4.31	None	123	−1.06	None
22	−4.22	None	54	−0.89	None	91	−7.40	None	127	−7.79	None
23	4.16	High	55	−11.34	None	92	5.82	High	128	−4.60	None
25	−5.05	None	56	−9.95	None	93	−2.50	None	129	−10.69	None
26	2.94	High	57	−10.94	None	94	−9.49	None	132	−0.28	None
27	−2.98	None	58	−54.66	None	95	−4.70	None	135	−17.75	None
28	−45.28	None	59	−11.07	None	96	5.32	High	136	−2.50	None
29	−5.38	None	60	−0.39	None	97	−8.76	None	139	0.03	None
30	−2.54	None	61	5.57	High	98	5.15	High	146	3.13	High
31	−0.62	None	63	−0.70	None	99	−0.25	None	147	0.53	Low
32	−3.97	None	64	−10.75	None	100	−6.75	None	153	−0.98	None
33	−17.59	None	65	−6.20	None	102	−6.75	None	159	−1.05	None
34	−61.34	None	66	−18.70	None	104	−3.96	None			

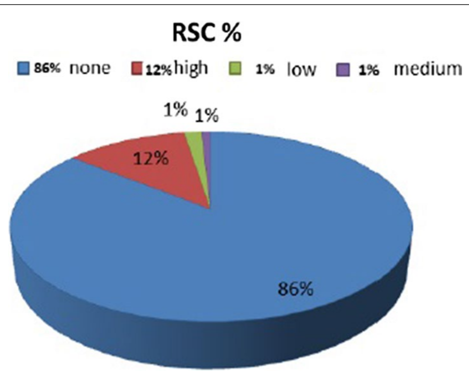

Fig. 13 Groundwater classes according to the percentage of RSC in the available groundwater samples

Conclusions

It is necessary to assess and map the available groundwater resources for different purposes in some remote areas to support urbanization and land reclamation projects. Groundwater quality and suitability for drinking and agricultural purposes were assessed using the spatial and hydrochemical analysis of the available wells. GIS of groundwater quality and suitability for various purposes provides essential input for the management and planning of the research area and similar regions. The results showed that large values of TDS observed in the middle part of the study area are possibly related to the increase in the agricultural activities and pumping rates in these areas so an urgent need

Table 13 Evaluation of groundwater samples for irrigation uses according to SSP

Well No.	SSP	Water class	Well No.	SSP	Water class	Well No.	SSP	Water class	Well No.	SSP	Water class
1	20.26	Good	35	24.84	Good	67	52.30	Permissible	105	57.32	Permissible
2	21.91	Good	36	23.18	Permissible	69	25.29	Good	106	73.21	Doubtful
3	27.78	Good	37	22.72	Good	70	53.21	Permissible	107	58.92	Permissible
4	58.14	Permissible	38	52.82	Permissible	71	62.39	Doubtful	108	104.69	Unsuitable
5	28.99	Permissible	39	19.01	Excellent	72	65.98	Doubtful	109	66.79	Doubtful
6	61.06	Doubtful	40	29.69	Good	73	54.91	Permissible	110	65.66	Doubtful
7	23.77	Good	41	38.41	Good	77	50.41	Permissible	111	80.03	Unsuitable
8	26.16	Good	42	227.74	Unsuitable	78	83.93	Unsuitable	113	49.42	Permissible
9	27.71	Good	43	108.92	Doubtful	79	60.07	Doubtful	114	60.01	Doubtful
11	16.02	Excellent	44	41.11	Permissible	80	54.32	Permissible	115	88.67	Unsuitable
12	120.76	Unsuitable	45	83.12	Unsuitable	81	20.09	Excellent	116	98.60	Unsuitable
13	27.20	Good	47	24.66	Permissible	82	53.58	Permissible	117	80.51	Unsuitable
14	104.50	Unsuitable	48	127.52	Unsuitable	84	69.60	Doubtful	118	71.23	Doubtful
15	64.35	Unsuitable	49	23.05	Good	86	61.32	Doubtful	119	216.91	Unsuitable
16	25.45	Good	50	71.21	Doubtful	87	49.06	Permissible	120	107.54	Unsuitable
17	24.94	Good	51	219.91	Doubtful	88	64.19	Doubtful	121	79.08	Doubtful
18	24.54	Good	52	85.35	Unsuitable	89	65.26	Doubtful	122	48.41	Permissible
19	108.56	Unsuitable	53	60.42	Doubtful	90	63.50	Doubtful	123	109.47	Unsuitable
22	25.30	Good	54	60.98	Doubtful	91	37.73	Good	127	204.74	Unsuitable
23	54.29	Unsuitable	55	61.79	Permissible	92	77.10	Doubtful	128	59.21	Permissible
25	23.45	Good	56	70.51	Permissible	93	52.29	Permissible	129	205.41	Doubtful
26	47.43	Permissible	57	59.35	Permissible	94	82.06	Unsuitable	132	47.70	Permissible
27	22.09	Good	58	214.25	Unsuitable	95	67.01	Doubtful	135	405.78	Unsuitable
28	207.93	Unsuitable	59	59.35	Permissible	96	66.07	Doubtful	136	161.78	Unsuitable
29	25.47	Good	60	107.75	Unsuitable	97	78.38	Doubtful	139	145.51	Unsuitable
30	20.27	Good	61	79.24	Unsuitable	98	65.18	Doubtful	146	93.15	Unsuitable
31	19.45	Excellent	63	71.24	Doubtful	99	55.70	Permissible	147	122.35	Unsuitable
32	22.44	Good	64	73.13	Permissible	100	110.13	Unsuitable	153	130.29	Unsuitable
33	113.83	Unsuitable	65	65.72	Permissible	102	124.68	Unsuitable	159	128.03	Unsuitable
34	194.53	Unsuitable	66	98.90	Unsuitable	104	48.32	Good			

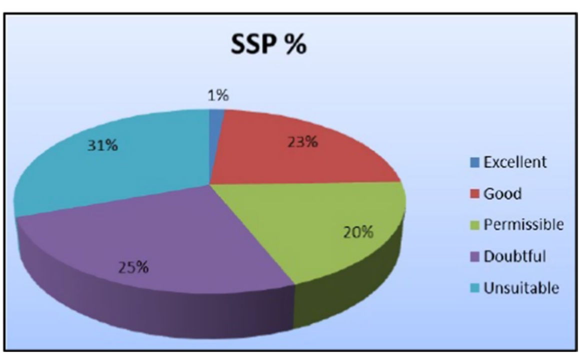

Fig. 14 Groundwater classes according to the percentage of SSP in the available groundwater samples

Table 14 Classification of irrigation water according to sodium percent (Wilcox 1955)

Water class	Sodium percent	Specific conductance (EC) (μs/cm)	Number of groundwater samples
Excellent	< 20	< 250	21
Good	20–40	250–750	93
Permissible	40–60	750–2000	5
Doubtful	60–80	2000–3000	40
Unsuitable	> 80	> 3000	–

to implement strategies to reduce these problems in this area is required. In accordance with international irrigation guidelines, most characteristics of the wells are appropriate and acceptable for irrigation purposes.

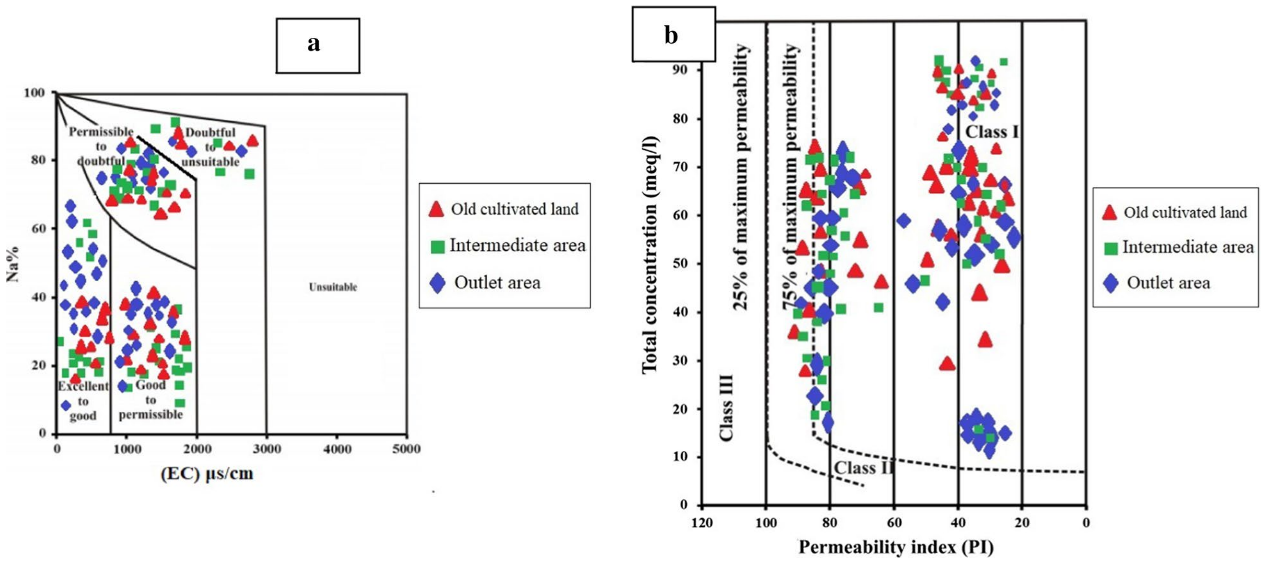

Fig. 15 Suitability of water for irrigation based on **a** salinity and SAR, **b** PI in the (red triangle) old cultivated land area, (blue diamond) outlet area and (green square) Intermediate area

The present conditions indicate that groundwater in the study area will worsen unless urgent measures are taken to protect the Quaternary groundwater aquifers and mitigation of contamination risk. Therefore, the study recommends that well depth in the area should not be less than 120 m to avoid the percolation of polluted water, controlling the application of agrochemicals on agricultural lands and managing the use of hazardous fertilizers and pesticides. In addition, the removal of iron is recommended using the physical treatment method as levels in the majority of the studied wells exceeds 0.3 ppm.

Abbreviations

GIS: Geographic Information System; RS: Remote Sensing; WHO: World Health Organization; Eg. St: Egyptian Standard; SAR: Adsorption Ratio; RSC: Residual Sodium Carbonate; SSP: Soluble Sodium Percentage; GWW: Groundwater software for Windows; TDS: Total Dissolved Solids; pH: Concentrations of Hydrogen Ions; EC: Electrical Conductivity; GPS: Global Positioning System; PI: Permeability Index.

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Authors' contributions

HAM contributed her idea, studied the geology and climate of the study area, collected the groundwater samples, performed the chemical analyses of these samples and representation of the hydrochemical data were used by the Geographic Information System (Arc GIS Ver 10.1) software to determine the suitability of groundwater for drinking and irrigation uses. Finally, reviewed and writing the final manuscript. The author read and approved the final manuscript.

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