

Hydrogeochemistry and pollution assessment of quaternary–tertiary aquifer in the Liwa area, United Arab Emirates

E. S. Al-Katheeri · F. M. Howari · A. A. Murad

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Abstract This study presents the data on the hydrochemical characteristics and isotope chemistry of Liwa aquifer, which could be useful to clarify the hydrochemical facies and hydrogeological regime in the study area. Electric conductivity and total dissolved solid values show that the investigated water is slightly brackish, due to the effect of evaporation and the occurrences of evaporite rocks in the adjacent Sabkhas of Abu Dhabi. Major cations and anions arranged according to their decreasing concentrations are: $\text{Na}^+ > \text{Ca}^{+2} > \text{K}^+ > \text{Mg}^{+2}$ and $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{-2}$, respectively. As sodium is the dominate cation and chloride is the prevailing anion, hydrochemically the groundwater of Liwa can be classified as Na–Cl rich, predominantly chloridic. Ion concentrations increase towards the northeast and presumably coincide with the lithological sources of ions. Factors affecting the hydrochemistry of the groundwater of the investigated area include the effect of weathering of soil and rocks, evaporation and agricultural activities. Stable isotopes of oxygen and hydrogen show that the shallow aquifers contain a single water type that originated in a distinct climatic regime. This water type deviates from the

local meteoric water line, as well as from the Eastern Mediterranean Meteoric Water Line, suggesting potential evaporation of recharged water prior to infiltration. The waters are poor in tritium, and thus can be considered generally as indication for recharge prior to 1952. The degradation of groundwater quality can be attributed to evaporation and agricultural practices in most cases.

Keywords Hydrochemistry · Isotope · Liwa · UAE · Water quality

Introduction

Variations in natural and human activities reflect spatial variations in the hydrochemical parameters of groundwater. The difference of dissolved ions concentration in groundwater is generally governed by lithology, velocity and quantity of groundwater flow, nature of geochemical reactions, solubility of salts and human activities (Drever 1982; Howari and Banat 2002; Banat et al. 2005).

Environmental isotopes now routinely contribute to water investigations, complementing geochemistry and physical hydrogeology. Meteoric processes, for instance, modify the isotopic composition of water, and so the recharge waters in a particular environment will have a characteristic isotopic signature. This signature then serves as a natural tracer for the provenance of groundwater (Clark and Fritz 1997). Also, environmental isotopes provide; however, much more than indications of groundwater provenance and age. On the other hand, the geochemical characteristics of groundwater give important information regarding the geologic history of the enclosing rocks, sources of groundwater recharge, and the velocity and direction of flow (Yair et al. 1991; Drever 1982). The

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purpose of this study is to evaluate the hydrochemical facies of the groundwater in Liwa aquifer and to assess the origin of the groundwater and associate recharge.

Study area

The study area in Abu Dhabi which is situated along the Arabian Gulf, between the latitudes 22.5°, 25° north, and longitudes 51°, 55° east. It has an area of 67,340 km², equivalent to 86.7% of the country's total area. The Emirate of Abu Dhabi comprises three major regions, Abu Dhabi city and its surroundings, eastern region including Al-Ain area, and the Western and Central Region. The analyzed data in this study covers major wells in Western region of Abu Dhabi, north of the Liwa Crescent (Fig. 1). The images in this figure is Landsat ETM+. As can be noticed from this figure, a major portion of the studied area is covered with sand dunes.

Climatology

The Emirate has an arid climate with less than 100 mm/years average rainfall, a very high evaporation rate (2–3 m/years), a low groundwater recharge rate (<4% of total annual water used) and no reliable, perennial surface water resources (Environmental Agency Abu Dhabi (EAD) 2006). Most of the rainfall occurs during the winter between October and March with February being the wettest month. Spring and summer witness only occasional concentrated heavy rainfalls. The rainfall distribution is highly variable over space and time. For example, in 2003, the mean rainfall per month was about 2.9 mm (January), 0.2 mm (February), 3.9 mm (March) and 44.7 mm (April), while there was no precipitation in the remaining months (GTZ/DCO/ADNOC 2005).

Geology and hydrogeology

The surficial geology of Abu Dhabi Emirate consists of (1) the coastal region of tidal flats, Sabkhas, and terraces along the Arabian Gulf, (2) the internal sand dune region covering most of the Emirate, and (3) the piedmont plain near Al-Ain city (Symonds et al. 2005). The Oman Mountains which are composed primarily of ophiolites with other igneous rocks, shale and limestone are about 40–50 km away from the investigated area.

The studied area is in the Arabian shelf where a sequence of continental and shallow water marine sedimentary rocks were deposited, ranging in age from Cambrian to quaternary. The lithology of the Liwa aquifer

has two main stratigraphic units as follows: (1) *Tertiary unit*, mudstones, evaporites and clastics of Miocene age. This unit has a thickness of over 350 m, (2) *Quaternary unit*, Holocene and Pleistocene Aeolian fine to medium sands and interdunal deposits. The thickness of this unit varies between 100 and 150 m, depending on the topographic height of the location within the study area.

Sediment characteristics of the studied aquifer

The quaternary unit can be divided into two subunits. The upper unit is characterized by the presence of well sorted fairly loose eolian sand dunes with occasional intercalations of fine-grained, and the presence of slightly cemented interdunal deposits. In the lower subunit of the quaternary, interdunal deposits prevail. They consist of caliche horizons with traces of organic matter, siltstones and even marls that may be interpreted as playa lake sediments and give evidence of more frequent pluvial periods in the Pleistocene.

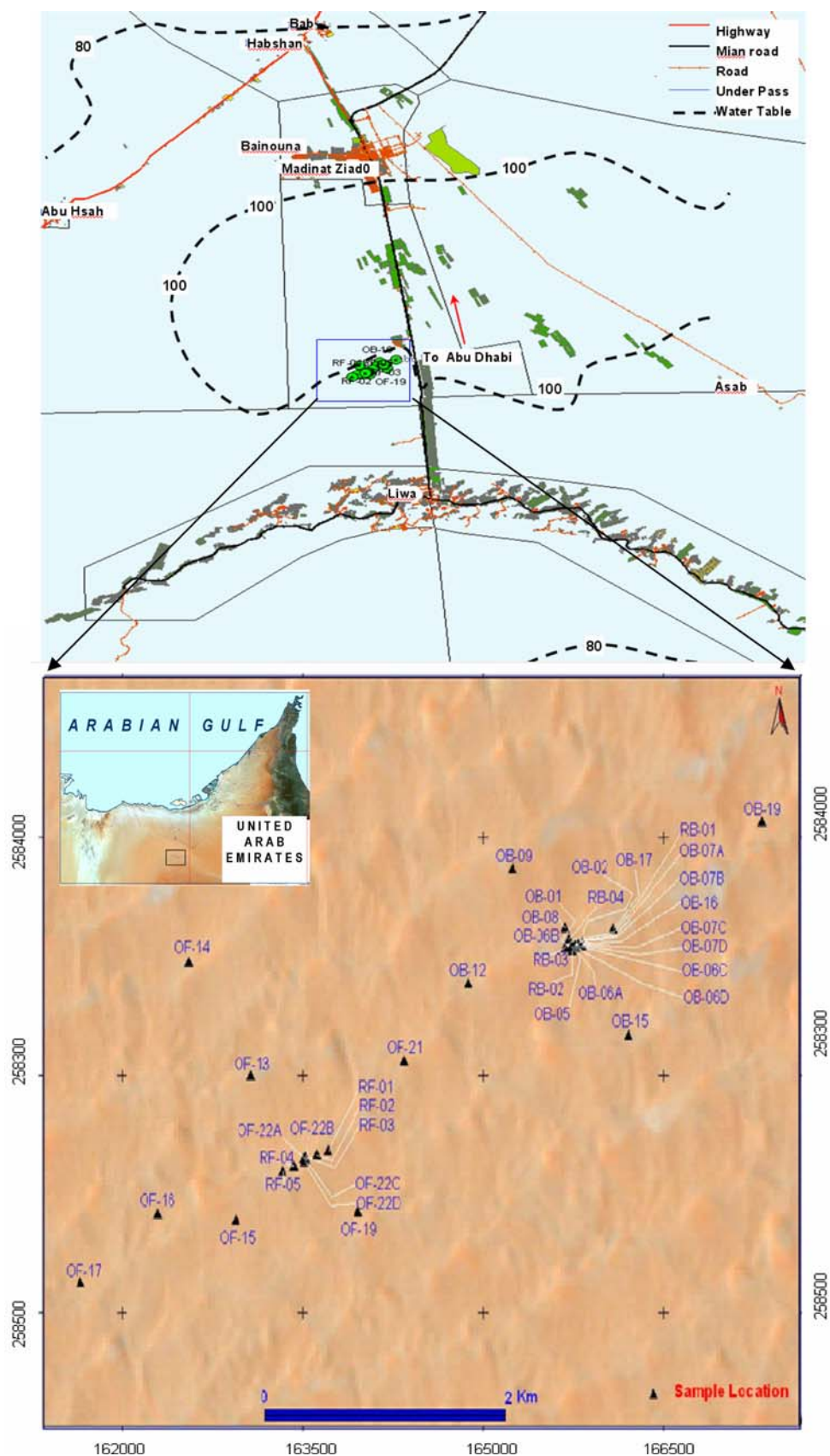
The tertiary unit can also be subdivided into an upper unit, consisting of mudstone layers and evaporites (gypsum, anhydrite, dolomite) of the lower Fars formation, and a lower subunit that is marked by the predominance of clastic sediments (sandstones, siltstones), that are intercalated with layers of mudstones and anhydrite.

Aquifer characteristics

In the Western Region (Liwa, Dhafra, Baynunah and Jabal Barakah) the shallow aquifer formation consists of sand and sandstone (thickness of 13 m to more than 60 m) underlain by siltstone, claystone and evaporites. The altitude of the groundwater level ranges from 60 to 108 m above mean seal level (a.m.s.l.) in the Liwa area. The shape of the groundwater table is convex and the convexity is oriented to the top, and elongated, striking in an E–W direction (Fig. 1). The summit is approximately 25 km north of Mizeiri'ah. The gradient of the groundwater table is mild in E–W direction (less than 0.5 m/km), moderate to the south (0.5 m/km), and steeper to the north (more than 1 m/km) (GTZ/DCO/ADNOC 2005).

The main aquifer of the Western Region consists of the upper subunit of the quaternary sediments. It is in the northern Liwa area. To the west, the aquifer extends to the Sabkha Matti area and to the east, it borders to the gravel plains in front of the Oman Mountains. A dune area covers the aquifer. Within the central model area, the static water level is between 90 and 107 m a.m.s.l. The thickness of the main aquifer is 30–50 m. Overlaying sand dunes, forming a thick unsaturated zone, cover the aquifer (GTZ/DCO/ADNOC 2005). The lower subunit of the quaternary sediments represents a fully saturated aquitard, which is above

Fig. 1 Map showing the location of the study and samples locations



the aquiclude, consisting of the tertiary lower Fars unit (GTZ/DCO/ADNOC 2005).

Methodology

Sampling and analyses

The hydrochemical and hydro-isotopical investigations of the study area started in 1999. Around 34 samples representing the study area were routinely analyzed for the environmental isotopes namely ^2H , ^{18}O and ^3H . Isotopes analyses of the samples in the study area have been carried out at Hydroisotop GmbH Woelkester, as certified lab based in Germany. Isotopes ^2H and ^{18}O were measured with stable isotope ratio mass spectrometry (IRMS) with equilibrium systems as CO_2 or H_2 gas and ^3H were analyzed in liquid scintillation analyzer with 0.5 TU as detection limits. The precision for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ was ± 1.5 and $\pm 0.15\%$, respectively, with respect to Vienna standard mean ocean water (VSMOW).

For the hydrochemical analyses, 158 samples were collected and analyzed in different time periods. These samples were analyzed for the major cations, anions and trace elements using the standard methods. Groundwater samples were collected in two polyethylene bottles. The preservation of the samples have been done according to published procedures by adding 65% of HNO_3 until the pH is < 2 for major cations and trace metals and other bottle stored cool at 4°C for major anions as suggested by Appelo and Postma 1999. The temperature, electrical conductivity (EC) and hydrogen ion concentration (pH) were measured directly with electrode at the field site to prevent changes in the chemistry of the water samples before analyses (Appelo and Postma 1999). Further analyses for major ions were preformed in Hydroisotop GmbH Woelkester, Germany as will be described. Bicarbonate (HCO_3^-) was measured by AOAC official titration method (920.194). Sodium (Na^+), potassium (K^+), magnesium (Mg^{+2}), calcium (Ca^{+2}), chloride (Cl^-), sulfate (SO_4^{-2}), nitrate (NO_3^-) and bromide (Br) were analyzed using ion chromatography. A photometer was used to measure ammonium (NH_4^+), iron (Fe), manganese (Mn^{+2}), nitrite (NO_2^-), phosphate (PO_4^{-3}) and hydrogen sulfide (HS^-). Trace elements were analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES) except for the Zn, Hg and As, which have been analyzed using atomic absorption spectroscopy (AAS). All values are reported in milligram per liter, unless otherwise indicated.

Data analysis

The water types present in the study area were compared based on both chemical and isotope characteristics. The

chemical analyses of major constituents with the aid of Surfer 8 software by RockWare, Inc. and Piper's diagrams have been prepared. These tools were used in the evaluation of groundwater chemistry and construction of hydrochemical and hydro-isotopical maps. Trilinear diagrams are used to classify the natural waters and determining the similarities and/or differences in the composition of water from specific hydrogeologic units. These diagrams are convenient for displaying a large number of analyses. In addition, the diagrams may help to show the connectivity between the hydrogeologic units and whether groundwater has been affected by dissolution or precipitation of a salt (Sara and Gibbons 1991). The trilinear diagram was prepared by Plotchem software from Scientific Software Group. The isotopic signatures were superimposed on $\delta^2\text{H}$ and $\delta^{18}\text{O}$ and compared with the local meteoric water line (LMWL). Table 1 presents the isotopic data for collected groundwater samples. The investigated water samples were evaluated based on the World Health Organization (WHO) standards for drinking water. Trace elements were also evaluated based on their enrichment.

Results and discussion

pH, EC and TDS

The groundwater samples of the study area have pH values ranging from 7.17 to 9.78 (alkaline type) with an average value of 8.03. Among the different locations, there is an increase trend of pH values toward well no. OB-01 OF-22C, OB-07C and RB-01 (Fig. 1). Large part of the aquifer is alkaline, particularly in eastern and western parts of the study area. The high value of pH concentration has resulted from the increase of CaCO_3 from caliche that is present in the study area. Drinking water with a pH between 6.5 and 8.5 is generally considered satisfactory. Acid waters tend to be corrosive to plumbing and faucets, particularly if the pH is below 6. Alkaline waters are less corrosive (North Dakota Department of Health 2005).

In the study area, the EC ranges between 388 and 2556 $\mu\text{S}/\text{cm}$, with an average of 729.26 $\mu\text{S}/\text{cm}$. Lowest values of EC are found in the central Liwa area (between 1,400 and 4,100 $\mu\text{S}/\text{cm}$). Intermediate values are found in areas surrounding the central Liwa area: 2,570–6,175 $\mu\text{S}/\text{cm}$. Figure 2 shows the distribution of the total dissolved solids (TDS) in the study area. In the Western Region, the TDS content values range between 800 and 1,300 mg/l in the central sub area of Liwa (fresh water). They are higher in the surrounding sub areas, sometimes exceeding 5,000 mg/l (medium brackish), as in the eastern sub area of Bu Hamrah (GTZ/DCO/ADNOC 2005). High

Table 1 Isotopes data for the groundwater in Liwa area

Sample identification	Sampling date	Drilling depth (from -to)		TDS	Isotopes		
		ft		mg/l	³ H	δ ¹⁸ O	δ ² H
GOW-56A	01.04.01	145	165	999	1.10	2.92	−1.30
GOW-56A	31.12.01			1,092	0.90	2.57	−1.30
GOW-71	28.12.01	77	174	427	2.80	4.42	10.00
GOW-56B	31.12.01	194	213	1,044	1	1.98	−6.40
GOW-56B	01.04.01			953	0	1.82	−11.80
GOW-56C	31.12.01	242	261	1,671	0.60	1.07	−7.20
GOW-56C	01.04.01			1,346	0.20	1.54	−2.80
GOW-63	23.09.01	194	368	826	0.10	2.17	−3.20
GOW-64	27.09.01	126	261	848	0.20	2.04	0.00
GOW-65	29.12.01	155	271	1,065	0.00	2	2.10
GOW-66	30.12.01	155	232	1,024	0.20	1.98	5.10
GOW-67	29.12.01	174	232	848	0	2.04	−0.20
GOW-68	02.01.02	174	271	897	0	1.96	1.40
GOW-69	29.12.01	174	271	823	0.30	1.75	−5.20
GOW-70	28.12.01	174	271	830	0.10	1.88	−1.10
GOW-72	11.12.01	271	368	2,417	0.10	1.67	−8.40
GWA-141	03.08.99	97	358	1,801	0	1.61	−1.50
GWA-144	04.09.99	116	325	1,029	0	1.73	−5.60
GWA-148B	29.09.99	77	203	1,008	0	1.95	0.64
GWA-151	04.11.99	116	280	863	0	2.24	6.35
GWA-153	10.11.99	116	271	845	0	1.31	6.70
GWA-156	19.11.99	136	232	1,311	0	2.09	4.00
GWA-164	23.12.99	155	290	1,047	1	2.23	2.60
GWA-172	03.03.00	116	223	985	1.70	2.06	11.15
GWA-177	20.02.00	114	250	811	1.10	2.02	6.10
GWA-178	22.02.00	136	261	1,261	0.50	2.25	14.26
GWA-215B	03.08.00	145	271	1,025	0.90	1.76	−7.70
GWA-240	11.01.01	174	261	1,117	0.60	1.96	0.10
GWA-241	22.12.00	513	1,539	1,030	0.30	3.11	2.00
GWA-295	08.09.01	116	271	12,314	0.30	1.92	−13.60
GWA-311	18.10.01	155	252	1,146	0.50	2.56	−5.40
GWA-313	02.01.02	678	1,007	669	0.00	2.43	−6.60
GWA-317	29.12.01	348	503	960	0.30	2.15	−9.60
GWA-320	27.12.01	155	542	5,485	0.10	2.07	−17.40
GWA-321	30.12.01	174	484	898	0.10	2.01	−12.20

concentrations of TDS may cause adverse taste effects. Highly mineralized water may also deteriorate domestic plumbing and appliance (North Dakota Department of Health 2005).

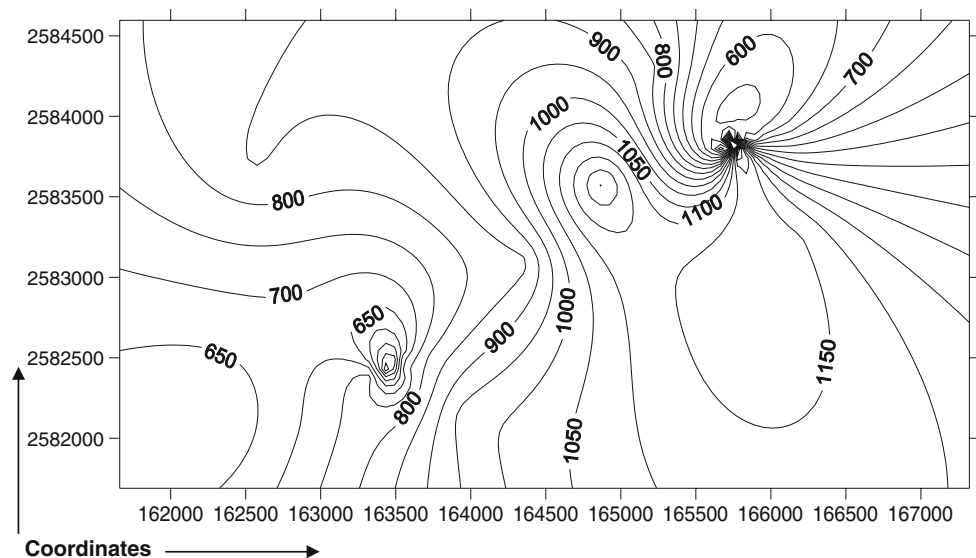
Water having EC of less than 750 $\mu\text{mhos/cm}$ is satisfactory for irrigation insofar as salt content is concerned (United States Salinity Laboratory Staff 1954) as in the case of 71% of the wells in the study area. However, the majority of the samples were acceptable for drinking water and domestic uses (70% of the samples). Total hardness is calculated to check the suitability of groundwater samples for

drinking and domestic uses. The following formula is used to calculate the total hardness for the samples (Todd 1980):

$$\text{TH} = 2.5(\text{Ca}) + 4.1(\text{Mg}), \quad \text{Ca and Mg in mg/l}$$

Generally, water with total hardness of 120 mg/l or less is considered satisfactory for most domestic uses (Taha et al. 2002). In the study area, it ranges from 5.4 to 169.73 mg/l with an average of 50.35 mg/l. The maximum hardness value in the area was approximately 170 mg/l, where all the samples are below the 120 mg/l except four wells which are OB-07A, OF-12, OF-13, OF-51 (Fig. 1).

Fig. 2 Salinity distribution in the study area



Major cations

The major sequence of cations dominance in groundwater of the quaternary–tertiary aquifer in the investigated area has the order of $\text{Na}^+ > \text{Ca}^{+2} > \text{K}^+ > \text{Mg}^{+2}$. The concentration of calcium ion (Ca^{+2}) ranges between 1.8 and 46.8 ppm with an average of 13.91 ppm. The common source for magnesium in the groundwater is dolomite in the sedimentary rocks, biotite, hornblend and augite in igneous rocks (Davis and De Weist 1966). The concentration of Mg^{+2} in water ranges from 0.1 to 15.3 ppm with an average of 3.8 ppm. The concentration of Mg^{+2} in the investigated area is mostly related to the dissolution of igneous rock particles carried by sand dunes.

Sodium ion is considered one of the most important ions in natural water. The source of sodium in water depends on the rock type through which the water moves. The main source for the presence of most sodium ions (Na^+) in the natural water is the release of soluble products during the weathering of plagioclase feldspars, which are typical constituents of many igneous rocks in Oman Mountain. It is also common in evaporites of Abu Dhabi Sabkha. The value of (Na^+) ranges between 44.1 and 520 ppm with an average of 131.11 ppm. Potassium content is generally lower than sodium. The natural sources of potassium in water are the minerals of local igneous rocks such as feldspars (orthoclase and microcline), mica and sedimentary rocks as well as silicate and clay minerals (Howari and Banat 2002). In the investigated water, the potassium content ranges between 1.70 and 17.3 ppm with an average of 6.45 ppm.

Major anions

The sequence of the major anion in the groundwater in the study area has the order of: $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-}$. The

presence of bicarbonate ions (HCO_3^-) in the groundwater is derived from carbon dioxide in the atmosphere, soils and by dissolution of carbonate rocks (Davis and De Weist 1966). Bicarbonate ion concentrations in groundwater in the study area range between 56.9 and 335 ppm with an average value of 119.03 ppm. The most extensive and important occurrences of sulfate and chloride ions in the investigated water are sedimentary rocks of Abu Dhabi Sabkhas such as gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and anhydrite (CaSO_4). The value of the sulfate in the study area ranges between 10 and 283 ppm. The value of the chloride in the study area ranges between 52.20 and 533 ppm. The dissolved nitrogen in form of nitrates (NO_3^-) is the most common contaminant identified in groundwater.

As shown in Fig. 3 the increase of Na^+ was accompanied by an increase of Cl^- (0.81, $P < 0.05$). As observed from this Figure most of the major cations are positively correlated indicating that they were derived from the same source. Analysis of the chemical data set and relations among various chemical components indicated that the relation between Ca and Mg can be used as a good indicator of the origin of salinization, since both ions exist in various evaporite sediments that act as a natural source of salinity. Evaporation increases the concentration of dissolved salts in water as a function of its initial composition, the intensity of evaporation, atmospheric humidity, etc. In arid zones this phenomenon occurs at the surface and during water infiltration to deep saturated zones (Izquierdo et al. 2005). Most of the waters had low NO_3^- and Cl^- concentrations, with 73% of the samples fallen below 6 mg/l NO_3^- and 77% below 150 mg/l of Cl^- , which were considered as indicators of human activities due to urban and agricultural settlements (Barbieri et al. 2005). The correlation of Cl^- – Na (Fig. 3) shows a linear trend, which describes the behavior of all well. This line seems to reflect

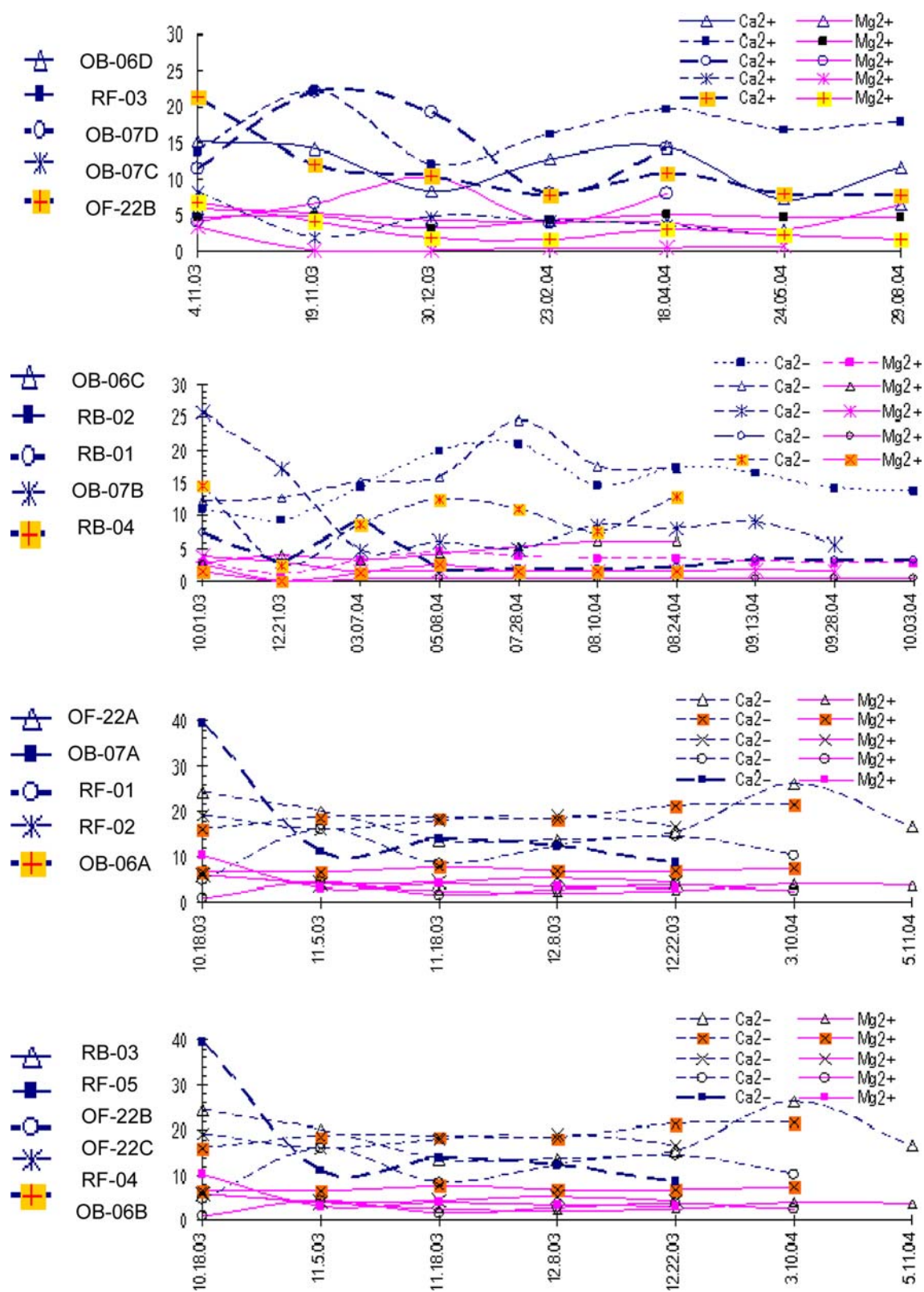


Fig. 3 Seasonal variations of ions in the study area

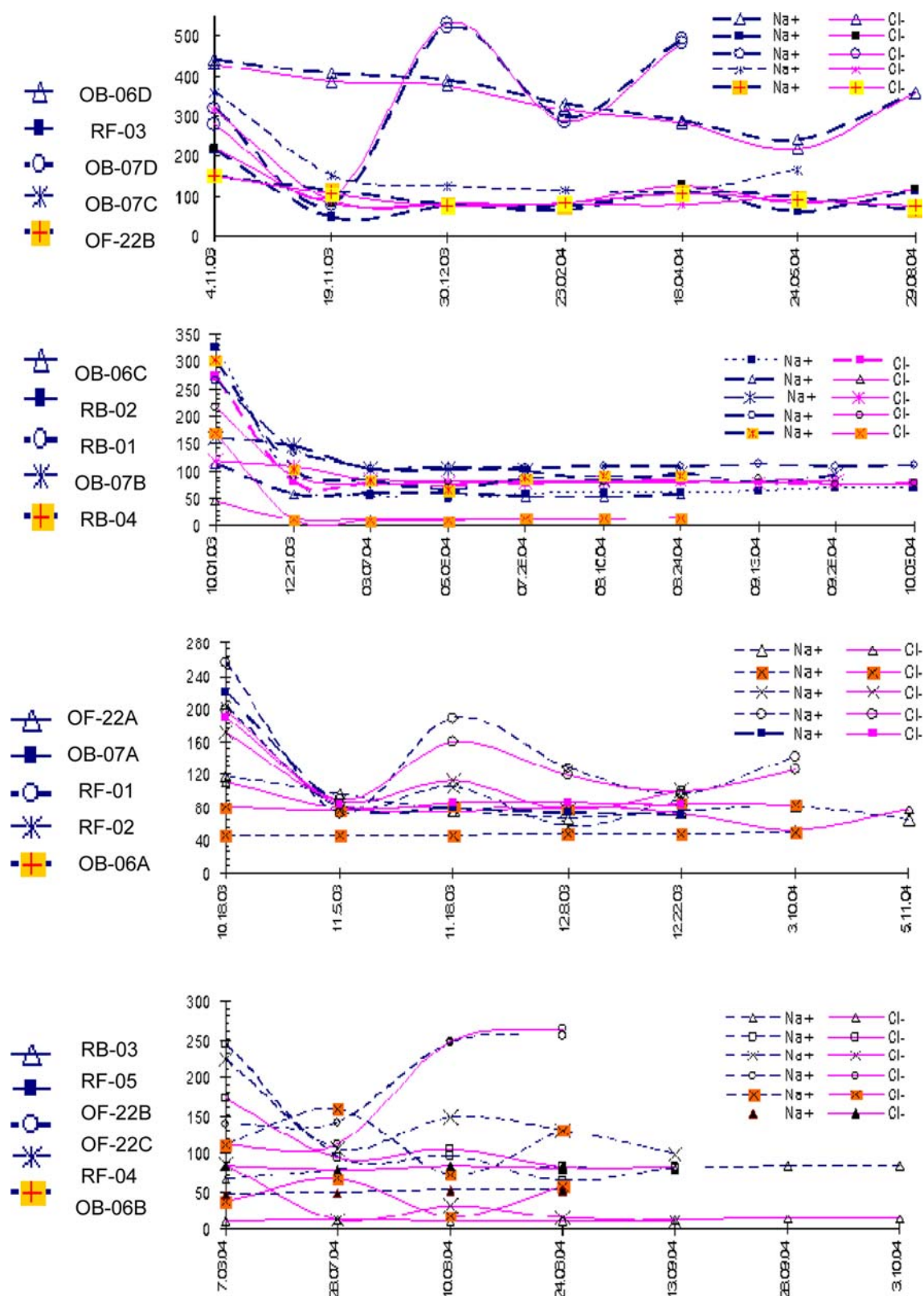


Fig. 3 continued

processes such as evaporation that might occur in the area because both ions are the major component of halite mineral which is the main geological source of natural salinity in arid regions. Similar behavior is shown for Na and SO_4^{2-} . The relation of Ca and Mg plot does not show a defined trend as observed for the other pairs of ions (Fig. 3).

Water type and genesis

In this study, the data of the chemical analysis of the groundwater samples are plotted on Piper diagram (Piper 1994). The investigated quaternary–tertiary aquifer can be discriminated in sub areas of the diamond shape illustration of Piper (Fig. 4). The appearance of most of the samples in the upper triangle of the diamond shaped illustration, points to the dominance of Ca–Mg and $\text{CO}_3\text{--HCO}_3$ water types. From the Piper diagram, it is obvious that the water of the aquifer is enriched in Na^+ . The following discussion will illustrate the significance of these results in the context of water types and pollution. The water types in the area of study were determined based on their chemical composition.

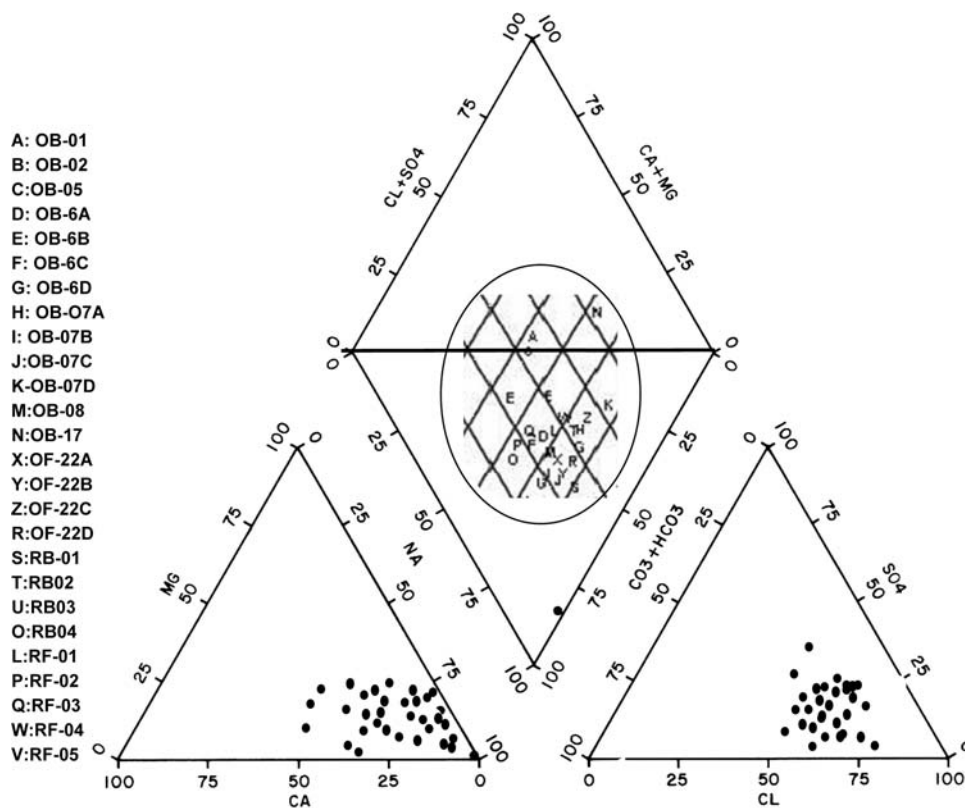
As observed from Fig. 4, the water samples are on right hand side of the diamond. As sodium is the dominant cations, and chloride is the prevailing anions, hydrochemically, the groundwater in the area can be characterized as Na–Cl rich (Furtak and Langguth, 1967).

Over the vast area of the Western region of the Emirate, the percentage of bicarbonate on the total anions is low. High concentration of bicarbonate was only found in the groundwater of the greater Liwa area north of the Liwa crescent (GTZ/DCO/ADNOC 2005). The concentration of nitrate is remarkably high for groundwater in an area remote from any domestic and agricultural activity. In general high nitrate concentrations are characteristic for the groundwater in the entire Western region and they tend to increase with depth. When compared with other groundwater resources study in the Western region, the absolute concentration of nitrate is still low. The normal acceptable values of nitrates in drinking water is 44 mg/l (Awad et al. 1996) where the recorded values in the investigated samples range from 29 to 73.40 ppm, with an average of 27.66 ppm. Excessive concentration of NO_3^- has potential to harm infant human beings and livestock if consumed on regular basis (Freez and Cherry 1979). High nitrate concentrations in the study area often indicate that agricultural seepage is responsible for water quality degradation.

Isotope characteristic of groundwater

Global meteoric water line (GMWL) is essentially a global average of many LMWLs, each controlled by local climatic factors, including the origin of the vapor mass, secondary evaporation during rainfall and the seasonality

Fig. 4 Trilinear diagram of water chemistry in the study area. (Letters from A–Z corresponds to wells number)



of precipitation. These local factors affect both the deuterium excess (*d*-excess) and the slope. The *d*-excess is a measure of the relative proportions of ^{18}O and ^2H contained in water, and can be visually depicted as an index of deviation from GMWL in $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ space (Clark and Fritz 1997).

The study of isotopes (^2H and ^{18}O) of the groundwater in UAE indicates the presence of three groundwater-flow systems: local, intermediate and regional groundwater flow (Epstein and Mayeda 1953). The flow system encountered in Liwa areas is the regional groundwater-flow system, which is characterized by old water (low ^{14}C activities and low or absence of ^3H) in agreement with previous study of Rizk and Alsharhan (1999). The stable isotopes (^2H and ^{18}O) are highly enriched in groundwater of the quaternary Liwa aquifer and their values suggest a single common source of groundwater (Rizk and Alsharhan 2003).

The average isotopic composition of present day precipitation has an average isotopic composition of $\delta^{18}\text{O} = 0.8\text{‰}$, an average $\delta^2\text{H} = 12.4\text{‰}$ and a deuterium excess (*d*) = 15, suggesting two sources of precipitation, the Mediterranean Sea in winter and Indian Ocean in summer (Rizk and Alsharhan 1999). The LMWL, which is a convenient reference line for understanding and tracing local groundwater origins and movements, used in the United Arab Emirates is given by: $\delta^2\text{H} = 8\delta^{18}\text{O} + 15$. In comparison, the groundwater samples are represented by: $\delta^2\text{H} = 4.02\delta^{18}\text{O} - 9$. As seen from Fig. 5, groundwater data fall distinctly below the relevant LMWL indicating that secondary evaporation during rainfall and seasonal variation in precipitation has occurred or that the water is ancient and were recharged in a different climatic regime that was characterized by a different local meteoric line.

Secondary evaporation might also take place in the vadose zone above the groundwater level. On the other hand, the lighter values indicate that the aquifer also contains a groundwater component, which was formed under completely different climatic conditions from the present. Decreased deuterium excess may be attributed to the secondary evaporation such as return flow and evapotranspiration in an unsaturated zone. The slope of 4.018 and the y-intercept of 9.93 also suggest that the evapotranspiration of return flow is significant in the study area. The low value of *d* is due to (1) evaporation and (2) the meteoric water was initially evaporated from the ocean under more humid conditions than present day. Evaporation may occur during rainfall through an atmosphere of lower humidity prior to infiltration or in the soil zone prior to deep infiltration or recharge to the deep groundwater system. Also more humid conditions during evaporation may also affect the deuterium excess of meteoric water. (Kendall and McDonnell 1998). This argument is also supported by a positive correlation of 0.6 between

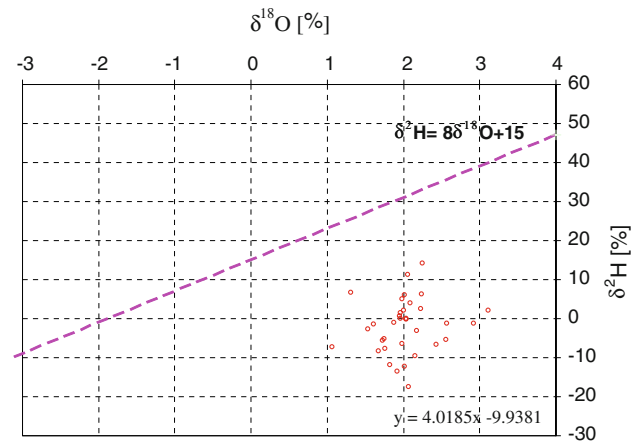


Fig. 5 δD - $\delta^{18}\text{O}$ relationship for groundwater samples from Liwa area

potassium and nitrate in the study area which suggests that the salinity of this aquifer could be from irrigation water (Murad 2004). The increase of salinity and constancy of $\delta^{18}\text{O}$ in Liwa aquifers indicate dissolution of salts from the aquifer matrix. Enrichment of stable isotopes in the Liwa aquifer indicates evaporation of recharged water prior to infiltration. However, the projection of stable isotopes in both areas on the LMWL indicates a common, high elevation recharge source (the Northern Oman Mountains).

Groundwater samples are classified based upon their depth, i.e., shallow to medium and deep aquifer (Fig. 6). These data fall along the meteoric line but reveal an internal order: values of deep groundwater are isotopically lighter (more negative) than shallow groundwater. This was taken as an indication that deep groundwater was ancient and originated from rains of a different climatic regime. This is supported by low value of ^{14}C concentration achieved from previous study in the western region. The results, in line with those reported by Rizk and

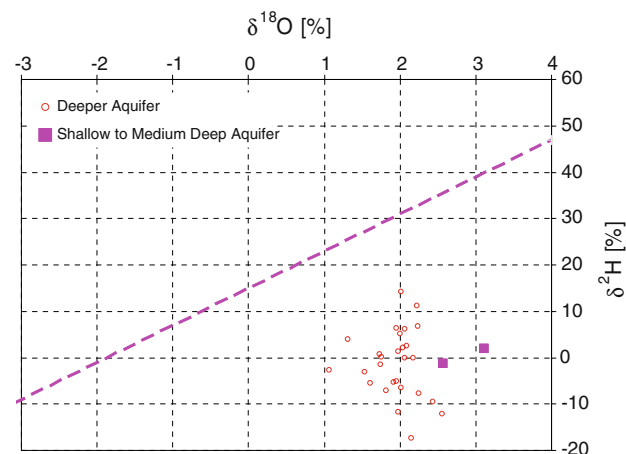


Fig. 6 Classification of samples based on their depth

Alsharhan (1999), suggest that the projection of stable isotopes on the LMWL indicates a common, high elevation recharge source (the northern Oman Mountains). Both δD and $\delta^{18}O$ show significant variations of the delta values (δ^2H : -17.40 to $+16.50\%$; $\delta^{18}O$: $+1.07$ to $+6.05\%$), indicating that the groundwater in the study area is of different origin.

From a previous study of Alsharhan et al. (2001) conducted on radiocarbon analyses of samples from the Liwa area, apparent groundwater ages are modern. On the other hand, tritium could be detected in most of the groundwater samples from the study area, with a maximum concentration of 2.8 TU for GOW-71. In general, locations with comparatively high tritium levels also show enriched stable isotopes, the highest concentrations of bicarbonate. Groundwater in the western regions has low tritium and carbon-14 activities, indicating a recharge occurred before 1952 as consistent with previous study in the region (Rizk and Alsharhan 1999).

Conclusion

The major sequence of cations dominance in groundwater of the Liwa aquifer has the order of $Na^+ > Ca^{+2} > K^+ > Mg^{+2}$ whereas, the sequence of the major anion has the order of: $Cl^- > HCO_3^- > SO_4^{2-}$. The factors affecting this sequence in the investigated area include the effect of weathering of soil and rocks, evaporation, as well as agricultural activities. The aquifer was not contaminated with Fe, Zn, Cu, and Pb. The study also found that shallow groundwater in the study area is enriched in heavy isotopes, caused by secondary evaporation of the precipitation, due to the extreme arid climate. Although precipitation is minimal in arid regions such as the study area, and may be the only supply of water to these areas, the amount of potential evaporation will greatly exceed the average annual rainfall. However, An integrated study that relates water abstraction estimation for irrigation, with evapotranspiration and salinity is recommended to manage the optimal amount of water to be extracted from this aquifer.

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