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ORIGINAL ARTICLE

Environmental isotope systematics of the groundwater system of southern Kuwait

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Abstract The carbonate Dammam Formation of Eocene age and the unconformably overlying clastic Kuwait Group of rocks of Mio-Pliocene age are the two aquifers that provide useable groundwater (salinity 5000 mg/l or less) in Kuwait. These aquifers extend beyond the political limits of the country to Saudi Arabia and Iraq. A detailed environmental isotopic ($^{2/1}$H, $^{18/16}$O, $^{13/12}$C, ^{3}H, ^{14}C) characterization of the groundwater system of southern Kuwait (a regional aquifer extending beyond the political limits of the country to Saudi Arabia and Iraq) has been carried out to understand its hydrodynamics so as to evolve a better conceptual flow model of the aquifer system. From the study, it was observed that the groundwater salinity of the Kuwait Group aquifer increases generally from south-west to north-east, although locally a few of them show low values. Groundwater samples from the Dammam Formation aquifer are characterized by a relatively low mineralization, compared with those of Kuwait Group aquifer. The water in the Kuwait Group aquifer in the south-western part of the country is Na–Cl type and in the Dammam Formation aquifer is Na–Cl to SO_4–Na ($Cl > SO_4$) type. A wide range of *d*-excess of the groundwater samples was seen (Kuwait Group aquifer +16.0 to −20.6 ‰; Dammam Formation aquifer: +22.8 to −19.6 ‰), indicating that the groundwater system contains more than one type of water with different origin (recharge area) and history (time, evaporation, climate). In both the aquifers, the groundwater samples from south and central parts and along the coast showed negative *d*-excess values with heavier ^{18}O and ^{2}H, indicating older recharge and greater degree of evaporation prior to recharge. The δ^{18}O and δ^{2}H of the initial recharge waters, respectively, are −8.8 and −40 ‰ for the Kuwait Group aquifer and −7.2 and −32 ‰ for the Dammam Formation aquifer. The corrected ^{14}C ages (Tamer's model) of groundwater samples of Kuwait Group aquifer ranged from ~5000 to 24,000 a, B.P, and that of Dammam Formation aquifer ranged from ~6000 to 20,000 a, B.P. The intermediate groundwater in the south-west and central parts of Kuwait Group aquifer is recharged during humid period (~5000 to 10,000 a, B.P), whereas deeper groundwater in the south is recharged during arid period (~9000–16,000 a, B.P). The recharge to the Dammam Formation aquifer mostly occurred during a cooler (humid) phase in the past. The Dammam Formation aquifer water is hydraulically well mixed below 350 m depth. Interconnection between the two aquifers established near the coast and south-west border of the country. The results of the study were used to refine the existing conceptual groundwater flow model for the aquifer system.

Keywords Kuwait Group aquifer · Dammam Formation aquifer · Hydrodynamics · Groundwater age · Palaeo-climate

Introduction

The carbonate Dammam Formation of Eocene age and the overlying clastic sediments of Kuwait Group of Mio-Pliocene age are the two main aquifers that yield useable water (salinity <5000 mg/l) in Kuwait. Except for the localized small accumulations of freshwater lenses in North Kuwait (Milewski et al. 2014), most of the usable brackish water (salinity 2500–5000 mg/l) in these aquifers

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occurs in the southern and south-western parts of the country. In the water-starved arid climate of the country, useable (both fresh and brackish) reserves of groundwater constitute a strategic resource. Although desalination provides bulk of the freshwater consumed in the country, the brackish groundwater is heavily exploited for agriculture, animal husbandry, industrial activities, and mixing with desalinated water to make it potable.

Large-scale exploitation of the brackish groundwater resources in Kuwait started in the 1970s through the development of the well fields in these areas (Al-Awadi et al. 1998). Prior to this date, the general hydraulic gradient in these aquifers was towards the north-east and east towards the discharge zone along the Arabian Gulf with an upward vertical component. The groundwater saturating these aquifers was in chemical equilibrium with the respective aquifer materials and had, therefore, some subtle difference in quality. With continued exploitation of these aquifers, the vertical component of the hydraulic gradient has changed its direction downward in the central and southern parts of the country. With the change in the flow direction, water from the Kuwait Group aquifer is flowing to the Dammam Formation aquifer in these areas, and as a result the hydrochemical equilibrium is expected to be disturbed. This could have some impacts on the quality of the water currently pumped from the aquifers. The drop in potentiometric heads of the aquifers due to continued production could also affect the cost of utilization of the aquifers.

The environmental isotopes, both stable and radioactive, of water and its dissolved constituents, to name a few $^{2/1}$H, $^{18/16}$O, $^{13/12}$C, $^{15/14}$N, $^{34/32}$S, $^{11/10}$B, $^{87/86}$Sr, ^{14}C, ^{3}H amongst others, provide valuable information on the source, age, flow paths, geochemical evolution, vulnerability to contamination, and categorization of contaminant of groundwater. Today, the isotopic characterization of an aquifer system is considered a modern and powerful hydrological tool to understand the aquifer system, leading to an optimum development and exploitation pattern of groundwater resources in any given locality.

A detailed isotopic characterization ($^{2/1}$H, $^{18/16}$O, $^{13/12}$C, ^{3}H, ^{14}C) of the Kuwait Group and Dammam Formation aquifers of Kuwait was carried out to understand the hydrodynamics of groundwater system in terms of origin, age, and flow paths of water within the aquifers, in conjunction with in situ physicochemical and hydrochemical data, so as to evolve a better conceptual flow model of the aquifer system. A better conceptual flow model of the aquifer system could help in understanding the impacts of the production on the potentiometry and the associated hydrochemical equilibrium in the aquifers and on the produced water quality to ensure the continued sustainable management of the available brackish water resources of the country.

Hydrogeology of Kuwait

The State of Kuwait is situated at the north-eastern corner of the Arabian Peninsula. It comprises an area of approximately 17,600 km^2 extending between latitudes 28°30′N and 30°05′N and between longitudes 46°33′E and 48°33′E. In addition to the mainland, Kuwait also includes a few islands such as Bubiyan, Failaka, and Al-Qubbar. There is little difference in the country's altitude with the highest point in the country being 306 m above mean sea level.

The climatic conditions in the State of Kuwait are hot and arid with scanty rainfall. Based on the 1996 to 2007 records maintained by Kuwait Institute for Scientific Research (KISR), the mean total rainfall rate was 118 mm a year with rainfall mainly during November–April, and the average annual temperature was 26 °C. The weather is warm to hot in October and mild to cold, with thunderstorms sometimes in November. The weather is coldest in January with temperature reaching about 12 °C (The recorded maximum and minimum temperature, respectively, was 50.8 °C in June 1954 and −4 g °C in 1964).

The main lithostratigraphy units forming the bedrock of Kuwait are unconsolidated to semi-consolidated clastic sediments of the Kuwait Group (post-Eocene Age), which unconformably overlies the dolomitic Dammam Formation of the Eocene Age. The generalized stratigraphy of the Tertiary sediments in Kuwait and surrounding areas is given in Fig. 1. The Dammam Formation and Kuwait Group of rocks age are the two aquifers that provide useable groundwater (salinity <5000 mg/l) in Kuwait. These aquifers extend beyond the political limits of the country to Saudi Arabia and Iraq (Al-Awadi et al. 1998). The aquifers in the Kuwait Group appear to be layered semi-confined system with a free water table in the uppermost horizon, and the Dammam Formation acts as a semi-confined to confined aquifer. In spite of the lithologic heterogeneity within the Kuwait Group aquifer and the variation in the degree of karstification within the Dammam Formation, the two aquifers are hydraulically connected. Under natural undisturbed conditions, there is an upward hydraulic gradient component from the Dammam Formation to the Kuwait Group aquifer. The generalized groundwater flow system in Kuwait is given in Fig. 2.

Sampling programme

From November 2012 to February 2013, 60 rainwater samples were collected from the installed rain gauges at ten locations spread across Kuwait for the environmental isotopic analyses (^{2}H, ^{18}O, ^{3}H). The meteorological parameters at the rain gauge stations such as air temperature,

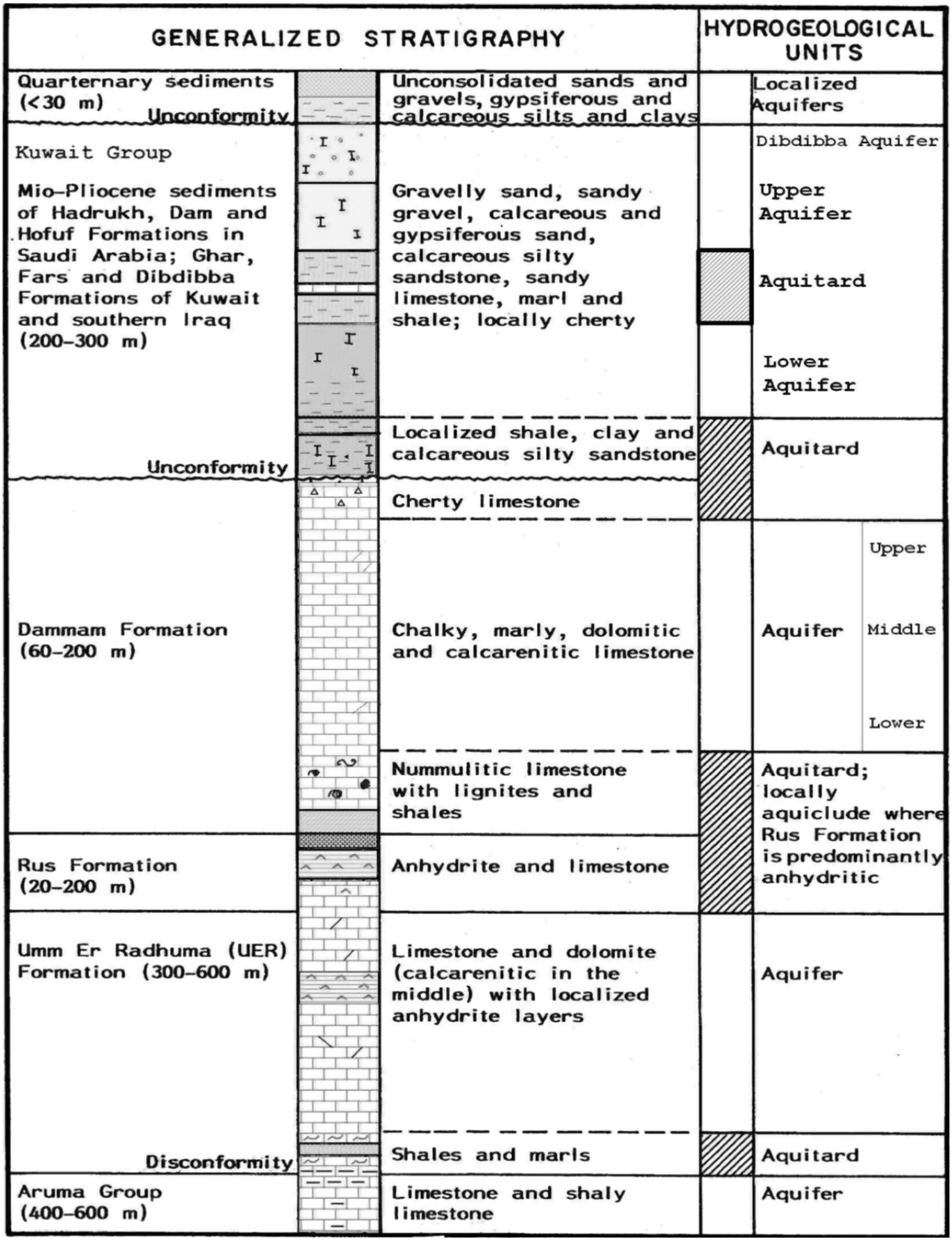


Fig. 1 Generalized stratigraphy of the tertiary sediments in Kuwait and surrounding areas (*Source*: Mukhopadhyay et al. 1996)

humidity, pressure, wind direction, and speed were also measured continuously during the study.

Thirty groundwater samples were collected from the Kuwait Group and Dammam Formation aquifers for the in situ physicochemical parameters [temperature (*T*), electrical conductivity (EC), pH, dissolved oxygen (DO)], hydrochemistry (major cations and anions), and isotopic analyses ($^{2/1}$H, $^{18/16}$O, $^{13/12}$C, ^{3}H, ^{14}C). The sampling locations are shown in Fig. 3. Prior to the selection of sampling locations, a thorough study on the available well

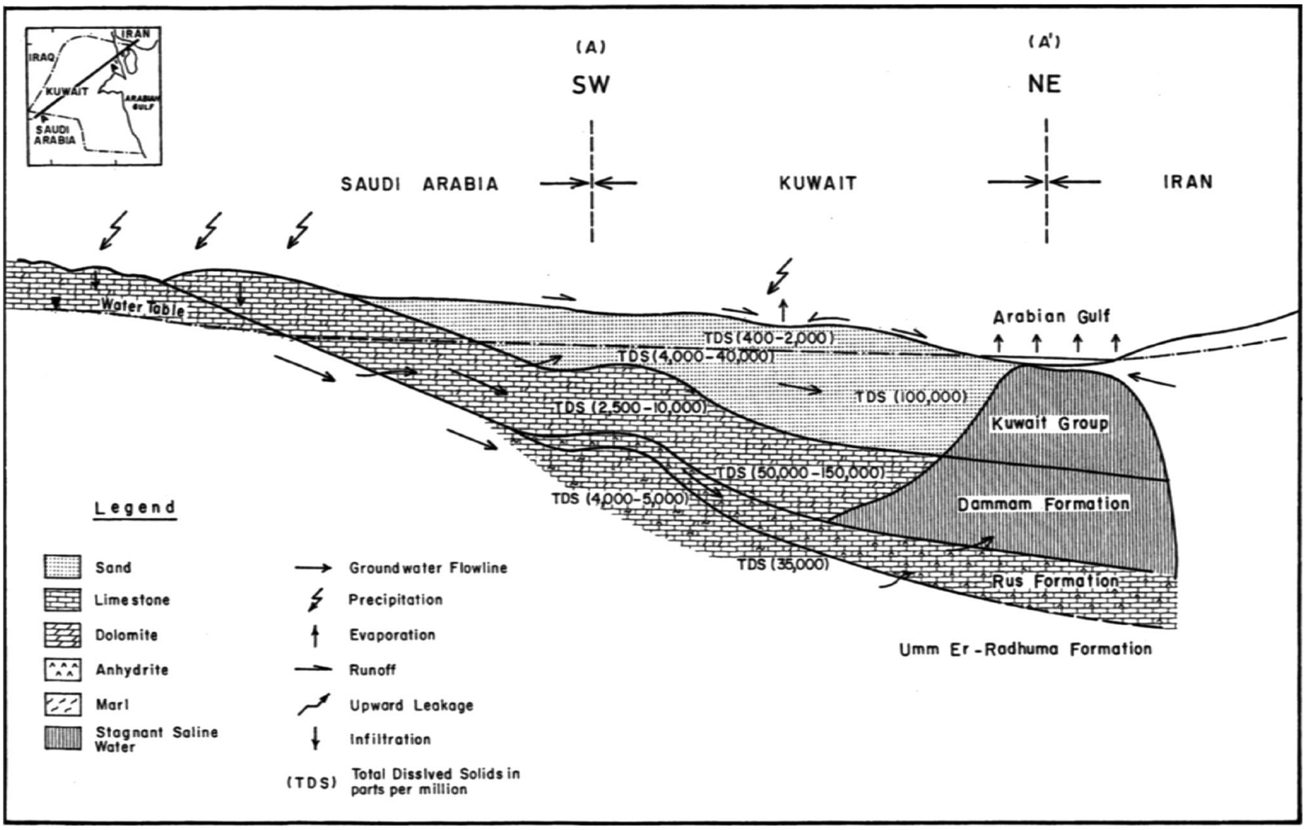


Fig. 2 Generalized groundwater flow system in Kuwait (*Source*: Senay et al. 1987)

lithologs was made, to ensure that groundwater samples cover all the zones of the Kuwait Group and Dammam Formation aquifers.

The samples were analysed for environmentally stable ^{18}O and ^{2}H isotopes using liquid water isotope analyser (LGR Make) at the Water Research Center (WRC) of Kuwait Institute for Scientific Research (KISR). The ^{2}H and ^{18}O results are expressed in the standard δ-notation with respect to Vienna Standard Mean Ocean Water (V-SMOW) (precision ±0.5 and ±0.1 ‰, respectively). The environmentally stable ^{13}C and radioactive ^{3}H and ^{14}C isotopes analyses were carried out at the Laboratory of Radio Analysis and Environment, National School of Engineers of SFAX, Tunis, Tunisia, through International Atomic Energy Agency (IAEA), Vienna, Austria. $\delta^{13}C$ was measured using isotope ratio mass spectrometer in the form of carbon dioxide gas (standard: Pee Dee Belemnite; precision ±0.5 ‰). Environmental ^{3}H content of water samples was analysed using liquid scintillation counter after electrolytic enrichment and expressed in tritium units (TU) (precision ±0.5 TU). Environmental ^{14}C analyses were carried out using accelerated mass spectrometry, and the results are expressed in percentage modern carbon (pMC) (precision ±0.5 pMC). The samples were analysed for major cations and anions using ion chromatograph (DIONEX) at WRC, KISR. The major ions are reported in mg/l units (charge balance error ±5 %). The in situ physicochemical parameters were measured in the field. The results of analyses are given in Tables 1, 2 and 3.

Results

Potentiometric head

In keeping with the regional flow pattern, all the aquifers had initial hydraulic gradients towards north and east. As Kuwait is situated in discharge zone, the vertical gradient has been upwards (i.e. from the Dammam Formation aquifer to the Kuwait Group aquifer) before the regular high volume production of these aquifers that started in the 1960s. With the large-scale exploitation of the aquifers (mainly the Dammam Formation aquifer) starting in the 1960s, the vertical hydraulic gradient had reversed downward in the central part of the Kuwait by mid-1980s, as indicated by the monitoring of the potentiometric heads in these two aquifers. The potentiometric head map prepared on the basis of the water level data for the entire country is presented in Fig. 4. The maps indicate that the general groundwater flow direction is towards the discharge zones

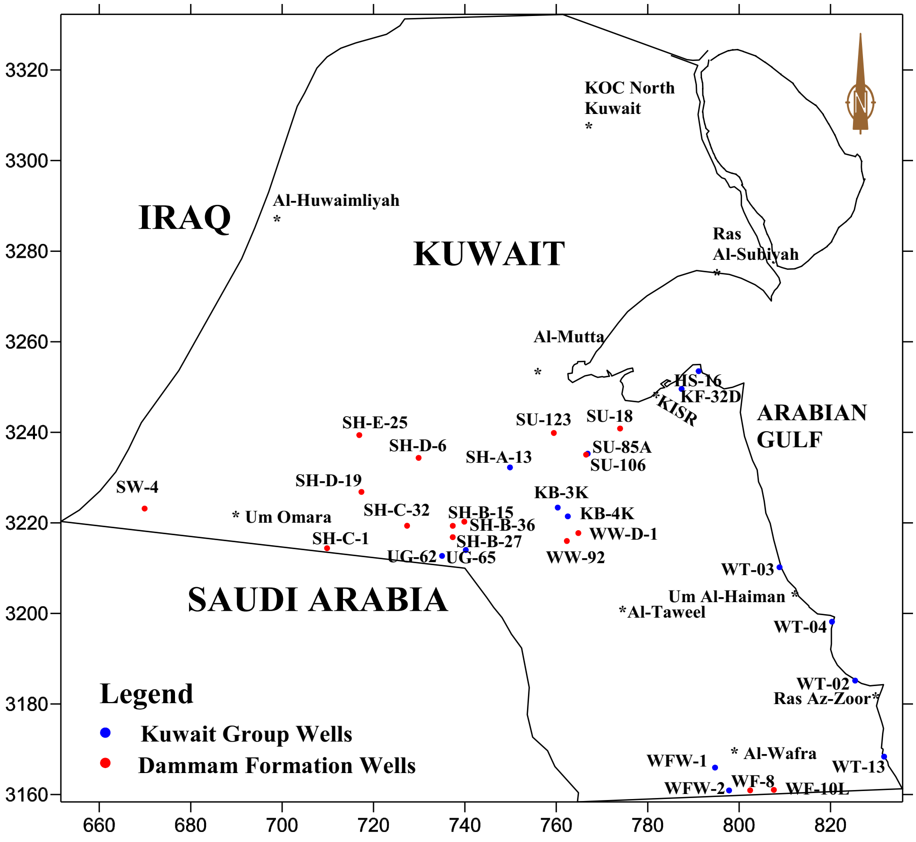


Fig. 3 Sampling locations of rainwater (*) and groundwater (•)

near the Arabian Gulf where the water becomes almost stagnant or of very slow movement.

Hydrochemistry

Most groundwater samples collected are characterized by high total mineralization. The groundwater salinity of the Kuwait Group aquifer increases generally from south-west (from about 3500 mg/l, brackish water) to north-east (reaching to more than 64,500 mg/l, salty and brine water, although locally a few of them showed low values. Groundwater samples from the Dammam Formation aquifer are characterized by a relatively low mineralization, compared with those of Kuwait Group aquifer, with total dissolved solids (TDS) ranging from 2500 mg/l in the south-west to 6900 mg/l in the north-east and the central part of the country.

Based on the relative abundance of different anions in the water, the water in the Kuwait Group aquifer in the south-western part of the country is Na–Cl type (Fig. 5) and in the Dammam Formation aquifer is Na–Cl to SO_4–Na (Cl > SO_4) type. The brackish water in the Dammam Formation aquifer in the southern, south-western, and central parts of Kuwait ranges in salinity between 2500 and 6900 mg/l with salinity increasing towards east and north-east. The water type changes from sulphate–chloride to chloride–sulphate in the same direction. The water becomes saline to brine (>10,000 mg/l and more) further to the east, north-east, and north-west with chloride predominating over sulphate (chloride–sulphate type). This change in water type can be related to the movement of the groundwater from its recharge zone in Saudi Arabia to its zone of discharge near the Arabian Gulf where water becomes almost stagnant or of very slow movement (Mukhopadhyay et al. 1996).

δ^2H–δ^{18}O relationships in rainwater

The δ^2H–δ^{18}O of the rainwater samples show a large variation (δ^2H −4 to +1 ‰ and δ^{18}O −4 to +1 ‰), with enriched values during February–May and depleted values in November and December (Table 2; Fig. 6). The regression line for the rainwater samples of Kuwait (i.e. Kuwait Meteoric Water Line, KWML) is:

$$\delta^2\mathrm{H}(‰) = 6.1(\pm 0.3) * \delta^{18}\mathrm{O} + 11.1(\pm 0.4)\left[n = 35,\ R^2 = 0.96\right] \quad (1)$$

The KMWL falls above the global meteoric water line (GMWL) [GMWL defines the relationship between ^{2}H and ^{18}O in precipitation on a global scale and has the relation: $\delta^2\mathrm{H} = 8 * \delta^{18}\mathrm{O} + 10$ (Craig 1961)].

Table 1 Results of chemical analysis of groundwater samples

Sample ID	SH-A-13	SH-B-15	SH-B-27	SH-B-36	SH-C-1	SH-C-32	SH-D-6	SH-D-19	SH-E-25	SW-4
TOC (mg/l)	0.408	0.413	0.308	0.322	0.338	0.292	0.337	0.452	0.515	0.262
$BOD_{5\ day}$ (mg/l)	<1.0	<1.0	<1.0	2	1	<1.0	<1.0	<1.0	1	<1.0
COD (mg/l)	7.0	4.0	13.0	6.0	6.0	12.0	9.0	8.0	21.0	6.0
Total hardness (mg/l)	1320	1220	1700	1200	1146	1380	1165	1370	1250	1335
Sodium Na (mg/l)	630	440	800	600	450	660	590	630	540	550
Potassium K (mg/l)	16	14	18	15	12	18	15	14	16	15
Bicarbonate HCO_3 (mg/l)	90	120	50	106	102	129	139	125	140	90
Carbonate CO_3 (mg/l)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Chloride Cl (mg/l)	1088	765	1450	740	600	800	720	860	700	720
Calcium Ca (mg/l)	360	299.2	504	312	303.2	380	306	320	298	366
Magnesium Mg (mg/l)	102.6	115.3	107.4	102.6	94.7	105	97.67	139.2	123.3	102.6
Sulphate SO_4 (mg/l)	1200	1000	1600	1100	980	1300	1100	1200	1100	1200
Nitrate NO_3 (mg/l)	40.4	5.72	74.8	18.92	23.32	4.4	4.84	7.48	4.84	34.76
TDS evp 180 °C	3607	2785	4896	3005	2570	3413	2974	3300	2961	3100
Total coliform (MPN/100 ml)	NIL	NIL	NIL	6.3	2	NIL	NIL	NIL	NIL	1
E. coli (MPN/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Faecal coliform (MPN/100 ml)	NIL	NIL	NIL	2	NIL	NIL	NIL	NIL	NIL	NIL
Salmonella (cfu/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Sulphur-reducing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Nitrate-oxidizing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Nitrate-reducing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Streptococcus faecal	NIL	NIL	NIL	10	NIL	NIL	NIL	NIL	NIL	NIL

Sample ID	UG-62	UG-65	SU-85A	SU-18	SU-106	SU-123	KB-3K	KB-4 K	WW-92	WW-D-1
TOC (mg/l)	0.386	0.184	0.407	0.349	0.345	0.511	0.286	0.564	0.469	0.371
$BOD_{5\ day}$ (mg/l)	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
COD (mg/l)	6.0	6.0	9.0	7.0	11.0	15.0	11.0	16.0	12.0	8.0
Total hardness (mg/l)	1425.0	1500.0	2495.0	2705.0	2510.0	1915.0	1950	1820	1440	1435
Sodium Na (mg/l)	670	780	1250	930	1250	680	1000	850	730	640
Potassium K (mg/l)	17	18	26	26	26	19	23	21	20	19
Bicarbonate HCO_3 (mg/l)	53	68	79	108	78	137	78	99	103	127
Carbonate CO_3 (mg/l)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Chloride Cl (mg/l)	1100	1250	2550	1740	2650	645	1565	1375	1200	980
Calcium Ca (mg/l)	422	464	642	696	654	524	580	532	400	340
Magnesium Mg (mg/l)	90.35	83	217.3	235.6	213.7	147.7	122.1	119.6	107.4	142.8
Sulphate SO_4 (mg/l)	1000	1200	1800	2300	1700	2000	1800	1600	1100	1100
Nitrate NO_3 (mg/l)	53.24	64.68	86.24	6.6	85.8	7.48	77.44	35.64	25.52	3.08
TDS evp 180 °C	3410	3959	6854	6172	6807	4165	5590	4664	3700	3360
Total coliform (MPN/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	8.5	NIL
E. coli (MPN/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Faecal coliform (MPN/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Salmonella (cfu/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Sulphur-reducing Bacteria	−ve	−ve	−ve	+ve	−ve	−ve	−ve	−ve	−ve	−ve
Nitrate-oxidizing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Nitrate-reducing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Streptococcus faecal	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL

Table 1 continued

Sample ID	WFW-1	WFW-2	WF-8	WF-10L	KF-32D	HS-16	WT-02	WT-03	WT-04	WT-13
TOC (mg/l)	0.197	1.213	0.478	0.217	0.806	1.998	0.526	0.254	0.195	0.427
$BOD_{5\ day}$ (mg/l)	<1.0	1	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
COD (mg/l)	9.0	35.0	13.0	8.0	23.0	41.0	18.0	7.0	9.0	13.0
Total hardness (mg/l)	3275	4070	1045.0	1640.0	1930.0	10,520.0	13,000	5400	9500	9800
Sodium Na (mg/l)	2600	1950	900	920	1300	16,057	17,600	4200	15,400	13,200
Potassium K (mg/l)	108	103	47	48	43	640	685	120	633	564
Bicarbonate HCO_3 (mg/l)	136	186	10	130	164	305	100	165	160	95
Carbonate CO_3 (mg/l)	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Chloride Cl (mg/l)	5520	4100	1775	1735	1600	37,086	30,500	8100	27,200	23,100
Calcium Ca (mg/l)	900	1086	328	634	468	3739	2520	1404	1240	1840
Magnesium Mg (mg/l)	250.3	330.9	54.9	13.4	185.6	1658	1636	463.9	1563	1270
Sulphate SO_4 (mg/l)	1700	2900	600	1200	2700	3000	4700	2100	4400	4100
Nitrate NO_3 (mg/l)	4.4	62.92	4.4	4.4	33.44	112.6	7.04	7.48	11	11
TDS evp 180 °C	11,843	10,760	3744	4756	7216	64,522	58,137	16,695	51,846	44,648
Total coliform (MPN/100 ml)	93.3	4.1	NIL	NIL	NIL	NIL	38.6	11	235.9	79.4
E. coli (MPN/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Faecal coliform (MPN/100 ml)	15.8	NIL	NIL	NIL	NIL	NIL	21.1	7.5	17.1	9.7
Salmonella (cfu/100 ml)	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
Sulphur-reducing Bacteria	−ve	−ve	−ve	−ve	−ve	+ve	+ve	−ve	+ve	+ve
Nitrate-oxidizing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Nitrate-reducing Bacteria	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve	−ve
Streptococcus faecal	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL

Not many studies have been reported on the isotopic composition of rainwaters in this region. Michelsen et al. (2015) carried out an isotopic study on 28 rain events that occurred in Riyadh between 2009 and 2013 and found that the rain samples showed $\delta^{18}O$ and δ^2H values scattering between −6.5 and +9.5 ‰ and between −30 and +50 ‰ V-SMOW, respectively. The isotopic variations observed in the rainwater samples at Riyadh are comparatively larger than seen at Kuwait. For comparison purpose, the North Oman Meteoric Water Line (NOMWL) ($\delta^2H = 8\ \delta^{18}O + 16$; Gat and Carmi 1970) is also shown in the figure.

Relation between the isotopic composition of rainwater and climatic factors

The Middle East region is under the influence of three types of moisture influx, namely the Mediterranean and Atlantic Ocean (winter season—from December to February) and the monsoon front (autumn season—September to November). Generally, isotopic composition of rainwater samples depends on the origin of moisture source (inland, sea), geographical (latitude, longitude, altitude), rainfall characteristics (amount, intensity) and climatic and meteorological conditions (temperature, relative humidity, atmospheric pressure, wind direction, and speed).

To understand the effect of various climatic factors on the isotopic composition of rainwater, a continuous measurement of atmospheric temperature (°C), relative humidity (%), rainfall (mm), barometric pressure (mbar), wind direction (degree), wind speed at 1, 4, 6, 8 10 m height (m/s), solar radiation (W/m^2), etc. were continuously measured at all rainwater sampling locations using standard methods.

From the daily averages of the measured climatic and meteorological parameters figure, it was observed that in late November and December, at rainwater sampling locations away from the coast such as Um Omara and Al-Wafra the rainy days are associated with high-speed winds, whereas at locations close to coast (KISR, Al-Mutla, Ras Al-Subiyah, etc.) that is not the case. This indicates that high-speed winds are responsible for bringing the moisture from a distance source (Mediterranean Sea/Atlantic Ocean) for condensation (rain-out process). Also, it was observed that rainfall is proportional to relative humidity and wind speed. In February, the relative humidity and amount of rainfall are less and wind speed is much higher compared to late November and December. This probably indicates monsoonal winds.

Table 2 Isotopic results of rainwater samples

Location	Months	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d*-Excess (‰)	Location	Months	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d*-Excess (‰)
Al-Taweel	Nov 2012	−1.0	+3.8	+11.8	KOC North Kuwait	Nov 2012	−3.3	−6.7	+19.7
	Dec 2012	−1.9	−1.6	+13.6		Dec 2012	−3.3	−6.8	+19.6
	May 2013	–	–	–		May 2013	−3.8	−18.1	+12.3
Um Al-Haiman	Nov 2012	−1.4	+1.2	+12.4	Um Omara	Nov 2012	−2.9	−6.0	+17.2
	Dec 2012	−1.2	+2.3	+11.9		Dec 2012	−2.7	−5.2	+16.4
	Feb 2013	–	–	–		Feb 2013	−0.8	+5.4	+11.8
	Mar 2013	−0.8	+9.9	+16.3		Mar 2013	−0.8	+6.0	+12.4
	Apr 2013	–	–	–		Apr 2013	–	–	–
	May 2013	–	–	–		May 2013	−2.7	−8.0	+13.6
Al-Huwaimliyah	Nov 2012	–	–	–	Ras Al-Subiyah	Nov 2012	−0.7	+4.3	+9.9
	Dec 2012	−0.9	+2.1	+9.3		Dec 2012	−4.0	−12.6	+19.4
	Feb 2013	−0.5	+8.4	+12.4		Feb 2013	+0.5	+13.2	+9.2
	Mar 2013	−0.5	+3.9	+7.9		Mar 2013	–	–	–
	Apr 2013	–	–	–		Apr 2013	–	–	–
	May 2013	–	–	–		May 2013	−3.8	−18.1	+12.3
KISR	Nov 2012	−1.7	+1.3	+14.9	Al-Wafra	Nov 2012	–	–	–
	Dec 2012	−1. 6	−0.3	+12.5		Dec 2012	−2.7	−5.7	+15.9
	Feb 2013	−0.1	+9.2	+10.0		Feb 2013	+0.9	+16.9	+9.7
	Mar 2013	+0.9	+16.5	+9.3		Mar 2013	+0.8	+17.9	+11.5
	Apr 2013	–	–	–		Apr 2013	+1.0	+18.1	+10.1
	May 2013	–	–	–		May 2013	–	–	–
Al-Mutla	Nov 2012	−3.1	−6.1	+18.7	Ras Az-Zoor	Nov 2012	–	–	–
	Dec 2012	−3.2	−7.2	+18.4		Dec 2012	−2.6	−6.1	+14.7
	Feb 2013	−0	+12.6	+12.6		Feb 2013	+0.4	+12.9	+9.7
	Mar 2013	+0.3	+12.4	+10.0		Mar 2013	+0.2	+12.3	+10.7
	Apr 2013	–	–	–		Apr 2013	–	–	–

As mentioned earlier, the rainwater samples collected in November and December are depleted in $\delta^{2}H$ compared to February samples. However, the climatic and meteorological parameters fairly remained the same during those months. Hence, the observed difference in isotopic composition of rainwater collected in November/December and February is attributed to origin of moisture source. The moisture source from the Mediterranean Sea/Atlantic Ocean will be depleted owing to far-off distance of the source from Kuwait (continental effect).

$\delta^{2}H$–$\delta^{18}O$ relationships in groundwater samples

The $\delta^{2}H$ and $\delta^{18}O$ of most of the groundwater samples of both the Kuwait Group aquifer and Dammam Formation aquifer (Fig. 7) showed that they fall below the KMWL with their regression equation (called as regression line or evaporation line), respectively, being:

$$\delta^{2}H = 1.6 * \delta^{18}O - 20.3 [n = 14, R^{2} = 0.59] \quad (2)$$

$$\delta^{2}H = 3.5 * \delta^{18}O - 11.7 [n = 16, R^{2} = 0.60] \quad (3)$$

Also, it is seen from the figure that the groundwater samples showed large variations in their isotopic composition.

$\delta^{13}C$, ^{14}C, and ^{3}H content of groundwater samples

Groundwater samples measured very low environmental ^{3}H values (Kuwait Group aquifer 0.16 to 1.01 TU; Dammam Formation aquifer 0 to 0.73 TU (Table 3). Since most of the groundwater samples measured very low tritium values (close to the analytical error; ±0.5 TU), they are mostly old groundwaters and not modern groundwaters. Hence, ^{14}C content of the dissolved inorganic carbon (DIC) of the groundwater samples was analysed and found to range from 4.6 to 38.3 pMC in the Kuwait Group aquifer and from 6 to 17.5 pMC in the Dammam Formation aquifer. The $\delta^{13}C$ values range from −8.1 to −13.6 ‰ for the groundwaters of Kuwait Group aquifer and from −7.3 to −12.3 ‰ for the groundwaters of the Dammam Formation aquifer.

Corrections to apparent ^{14}C ages are normally done based on either mass balance of ^{13}C or major chemical

Table 3 Isotopic results of groundwater samples

No.	Well no.	East	North	Screen depth (m)	Elev. (m asl)	EC (μS/cm)	pH	Temp.(°C)	DO (mg/l)	^{18}O (‰) v-SMOW	^{2}H (‰) v-SMOW	*d*-Excess (‰)	^{3}H (TU)	^{14}C (pMC)	^{13}C (‰)
Kuwait Group aquifer															
1	SH-A-13	749,865	3,232,240	187.44	130.1	4550	7.23	30.9	0.27	−3.3	−25	+1.4	0.33	15.2	−10.1
2	SU-85A	766,873	3,235,273	131.06	59.4	8780	7.18	32.9	0.38	−4.5	−20	+16.0	0.51	38.3	−13.6
3	UG-62	735,000	3,212,699	253.89	200.2	4800	7.48	31.8	0.50	−3.4	−27	−0.2	0.27	20.0	−11.7
4	UG-65	740,199	3,214,000	234.68	174.3	5120	7.39	31.4	0.48	−5.7	−26	+19.6	0.75	29.2	−12.3
5	KF-32D	787,408	3,249,568	50.78	7.9	8380	7.03	30.3	0.21	−0.2	−12	−10.4	1.01	–	–
6	HS-16	791,136	3,253,496	57.00	6.1	77,730	6.01	30.5	0.06	−2.4	−27	−7.8	–	4.6	–
7	KB-3 K	760,309	3,223,377	341.36	124.2	7030	7.18	33.0	0.43	+0.7	−15	−20.6	0.33	20.5	−10.7
8	KB-4 K	762,513	3,221,429	313.93	121.0	5870	7.14	32.5	0.15	−0.3	−21	−18.6	0.16	19.5	−9.1
9	WT-02	825,388	3,185,172	25.00	–	51,900	6.76	30.6	2.80	+0.1	−8	−8.8	–	–	–
10	WT-03	808,838	3,210,195	25.00	–	18,300	6.71	29.0	7.00	−2.8	−24	−1.6	–	17.8	−9.6
11	WT-04	820,324	3,198,168	29.00	–	74,500	6.62	28.4	1.93	+1.3	+6	−4.4	–	15.0	–
12	WT-13	831,722	3,168,381	29.00	–	41,600	6.88	34.4	2.87	+0.8	−4	−10.4	–	–	–
13	WFW-1	794,729	3,165,957	–	–	15,180	6.97	31.1	0.40	−0.4	−19	−15.8	–	8.2	−8.8
14	WFW-2	797,797	3,160,913	–	–	12,860	6.76	29.6	0.25	+0.4	−11	−14.2	0.45	16.0	−8.1
Dammam Formation aquifer															
1	SH-B-15	739,870	3,220,254	358.12	176.2	3370	6.54	41.4	0.02	−5.5	−30	+14.0	0.68	6.0	−8.1
2	SH-B-27	737,372	3,219,340	373.06	188.9	5890	7.37	30.3	0.48	−4.6	−24	+12.8	0.15	–	–
3	SH-B-36	737,338	3,219,340	380.98	179.0	3750	6.58	31.9	0.50	−5.6	−27	+17.8	0.42	10.0	−9.8
4	SH-C-1	709,836	3,214,398	368.18	250.4	3200	7.41	32.0	0.24	−5.9	−31	+16.2	0.22	17.5	−8.3
5	SH-C-32	727,340	3,219,361	377.94	214.7	3770	7.18	34.0	0.03	−6.4	−33	+18.2	0.39	8.3	−8.8
6	SH-D-6	729,871	3,234,353	426.70	181.0	3530	7.32	33.3	0.05	−6.6	−30	+22.8	0.20	10.7	−8.7
7	SH-D-19	717,358	3,226,828	426.70	225.2	3710	6.68	32.9	0.02	−6.3	−30	+20.4	0.08	10.4	−9.7
8	SH-E-25	716,882	3,239,379	426.70	207.2	3520	7.19	33.9	0.07	−6.8	−33	+21.4	0	10.0	−8.2
9	SU-18	773,950	3,240,828	182.87	24.9	7240	7.23	35.0	0.01	0	−21	−21.0	0.73	14.0	−10.6
10	SU-106	766,509	3,240,828	306.61	62.9	8730	7.11	31.0	0.28	+1.5	−16	−28.0	–	28.0	−12.5
11	SU-123	759,452	3,239,849	350.50	74.3	4530	6.96	34.4	0.03	−1.4	−31	−19.2	0.21	6.2	−8.4
12	WW-D-1	764,818	3,217,737	284.99	106.9	3670	7.12	35.4	0.11	−1.8	−29	−14.6	0.26	14.6	−8.6
13	WW-92	762,307	3,215,995	182.88	–	4450	7.12	31.8	0.18	−0.8	−26	−19.6	0.69	16.3	−10.4
14	WF-10L	807,599	3,161,039	243.84	83.0	6270	7.07	33.5	0.25	−0.8	−15	−8.6	0.17	12.2	−7.3
15	WF-8	802,412	3,160,931	–	–	5730	9.02	38.1	0.01	−0.5	−15	−11.0	0.43	–	–
16	SW-4	669,913	3,223,160	252.97	279.0	3320	7.29	32.3	0.40	−6.4	−29	+22.2	0.40	–	–

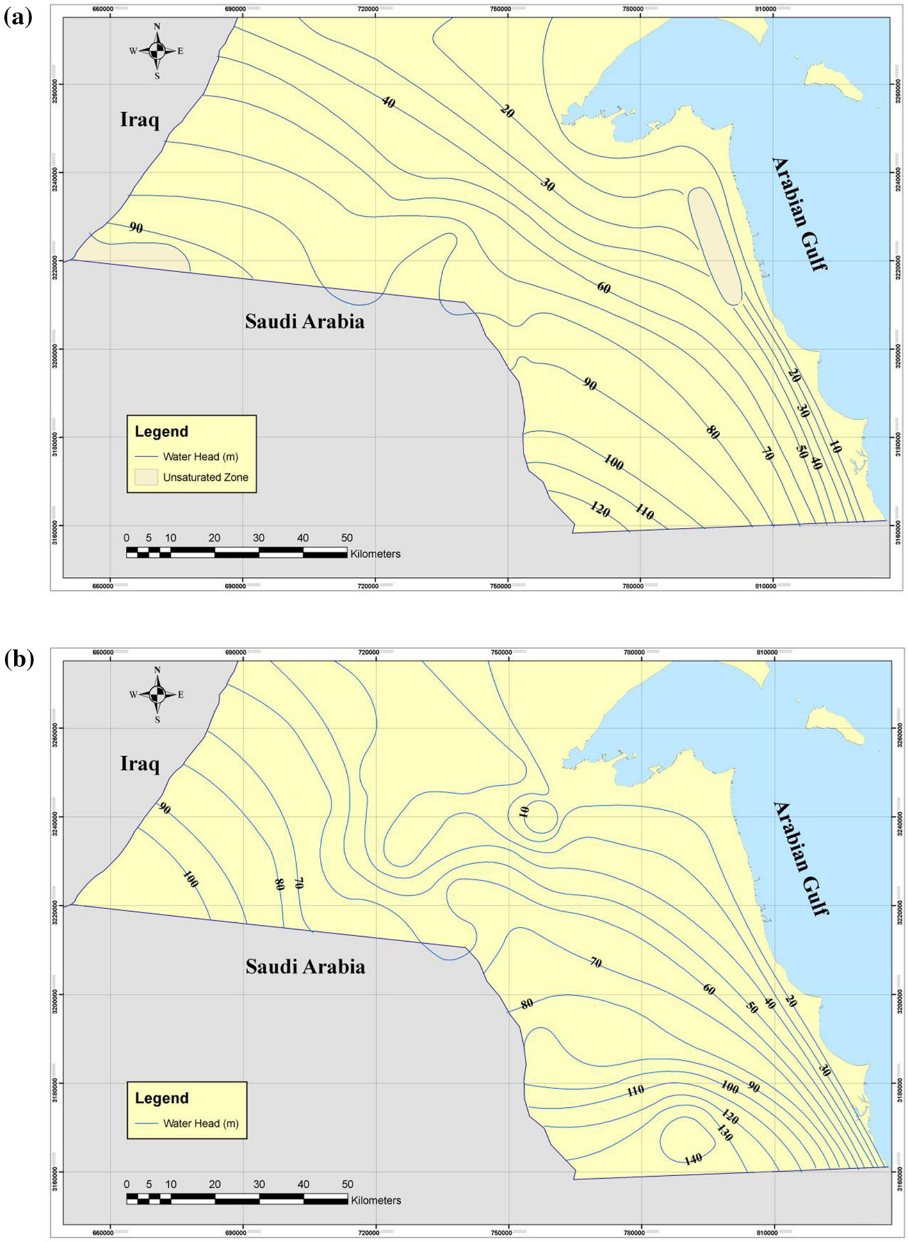


Fig. 4 Potentiometric head (m, above mean sea level) of **a** Kuwait Group and **b** Dammam Formation aquifers

constituents. Several mass balance correction models have been proposed in the literature. The most popular correction models are the ^{13}C-based Pearson's model (Pearson 1992), the chemistry-based Tamer's model (Tamer 1967), and the Fontes and Garnier model (Fontes 1992), a combination of chemistry and ^{13}C.

Kuwait Group and Dammam Formation aquifers showed decrease in ^{14}C values with enrichment in δ^{13}C along the flow path (Fig. 8). Dissolution of carbonate-bearing minerals (calcite, aragonite, dolomite, etc.) and oxidation of organic matter through bacterial reduction are the two dominant processes that govern the $^{13}C_{DIC}$ systematics of a sedimentary aquifer system. While the first process enriches $\delta^{13}C_{DIC}$, the second depletes it by producing HCO_3 (depleted in ^{13}C) from the oxidation of organic matter along the flow paths. Pearson's model and Tamers' model take into account carbonate dissolution and soil gas CO_2 dissolution.

Hence in the present study, Pearson's model and Tamers' model were used to obtain the ^{14}C ages of the groundwater samples, along with other models (Vogel's model and statistical model) (Table 4). As shown in the table, the Pearson's model ages are relatively higher compared to the other models except for two sampling sites. Tamer's model ages for Kuwait Group aquifer range from 5069 to 23,976 a, B.P, and that for the Dammam

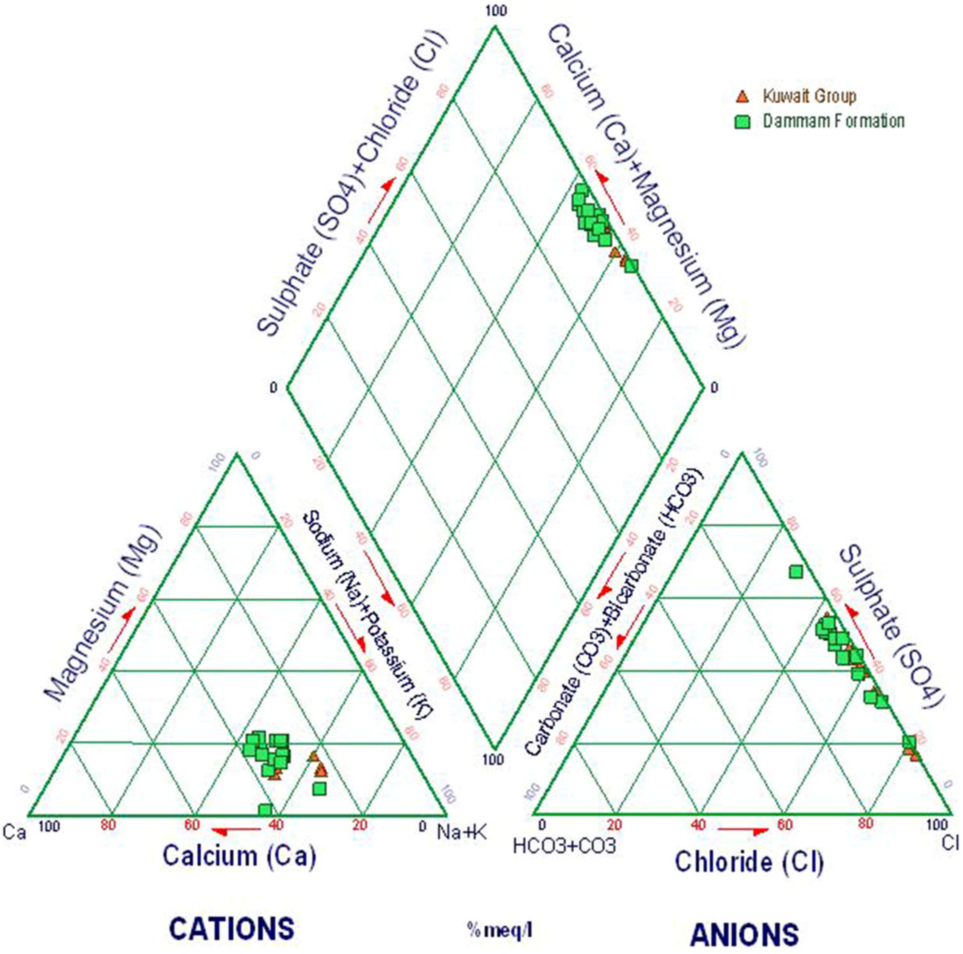


Fig. 5 Piper diagram of groundwater samples

Fig. 6 $\delta^{18}O$ versus $\delta^{2}H$ of rainwater samples ($\delta^{18}O$ vs. *d*-excess given in *inset*)

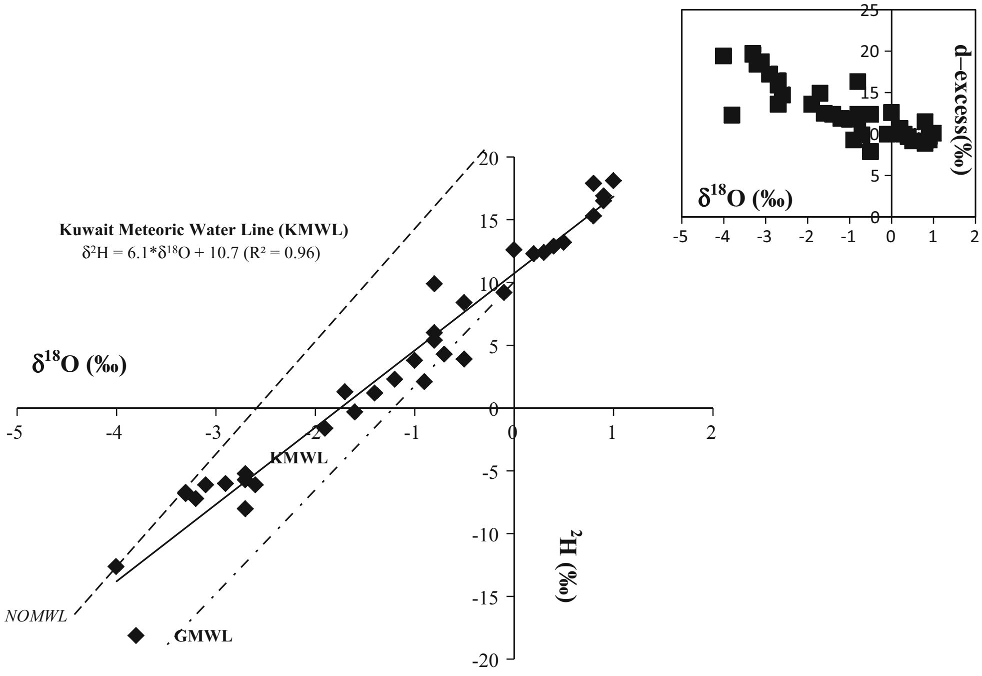
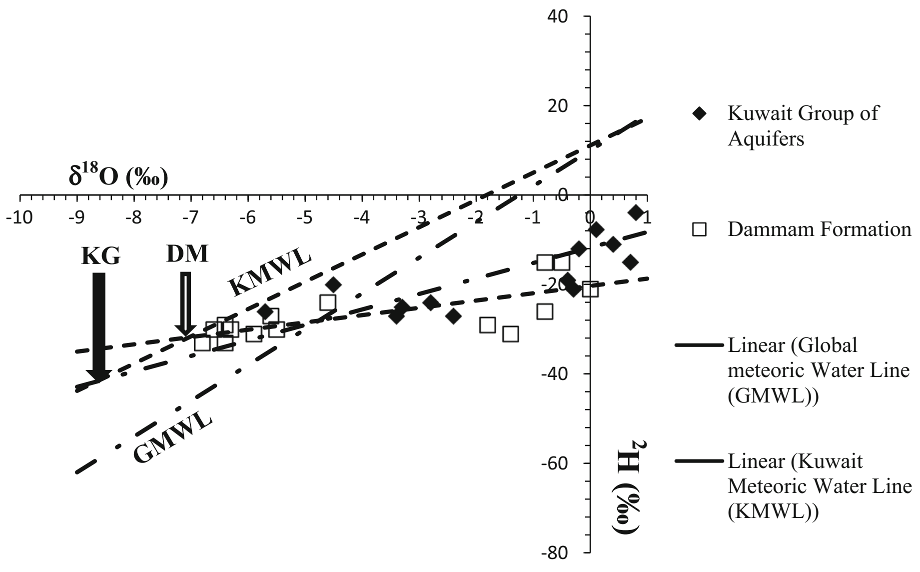


Fig. 7 $\delta^{18}O$ versus $\delta^{2}H$ of groundwater samples



Formation aquifer range from 5874 to 20,074 a, B.P [^{14}C radioactivity at time *t*, $A_t = A_o\, e^{-\lambda t}$, where '$\lambda$' is its radioactive decay constant (=1.2097 × 10^{-4} a^{-1})].

Discussion

Origin of cloud mass

The large variation seen in the $\delta^{2}H$ and $\delta^{18}O$ of rainwater of Kuwait (Fig. 6) is a typical characteristic seen in arid and semi-arid regions. Comparatively, a higher intercept of KMWL (~11.1) than GMWL indicates the difference in climatic conditions (relative humidity and temperature) under which the cloud is formed at its source. A lesser slope of the KMWL (~6.1) in Eq. (1), compared to the Global Meteoric water Line (GMWL), along with positive δ-values of the rainwater samples, indicates evaporation of falling raindrops (i.e. secondary evaporation) of the less intense rains occurring under dry atmospheric conditions. Owing to the fact that Kuwait receives scanty rain (118 mm annual) with very low intensity, a clear amount effect in the isotopic composition of the precipitation was not observed. Thus, the observed large variation in the isotope composition of precipitation is attributed to the varying moisture sources and thus the associated continental effect not due to amount effect.

Dansgaard (1964) defined the *d*-excess as *d*-excess = $\delta^{2}H - 8 * \delta^{18}O$. The *d*-excess is a useful tracer of vapour source and has been related to meteorological conditions at vapour source regions and to vapour recycling over the continents. The *d*-excess indicates the effect of secondary evaporation. The global mean value of *d*-excess is approximately +10 ‰. Different studies have used the *d*-excess parameter to investigate the sources of water vapour over the Middle East region (Celle-Jeanton et al. 2001).

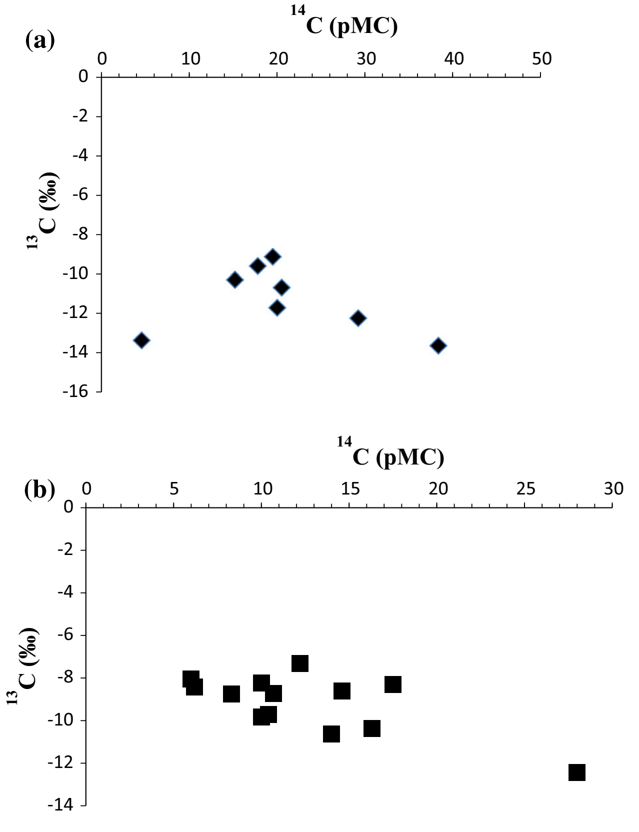


Fig. 8 $\delta^{18}O$ versus *d*-excess of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

Table 4 Corrected ^{14}C ages of groundwater samples

Sample ID	*T* (°C)	pH	^{14}C activity (pMC)	Apparent age (a, B.P)	Corrected ages (a, B.P) (Tamer's model)	Corrected ages (a, B.P) (Pearson's model)	Corrected ages (a, B.P) (Vogel's model)	Corrected ages (a, B.P) (statistical model)
Kuwait Group aquifer								
SH-A-13	30.9	7.23	15.2	15,573	10,705	9162	14,230	12,625
SU-85A	32.9	7.18	38.3	7934	3138	3976	6590	4985
UG-62	31.8	7.48	20	13,305	8090	8099	11,961	10,356
UG-65	31.4	7.39	29.2	10,176	5069	5336	8833	7228
HS-16	30.5	6.01	4.6	25,454	23,976	–	24,111	22,506
KB-3K	33.0	7.18	20.5	13,101	8305	7134	11,757	10,152
KB-4K	32.5	7.14	19.5	13,514	8795	6253	12,170	10,565
WT-03	29.0	6.71	17.8	14,268	10,668	7421	12,925	11,319
WT-04	28.4	6.62	15	15,683	12,372	–	14,339	12,734
WFW-1	31.1	6.97	8.2	20,675	16,335	13,091	19,332	17,727
WFW-2	29.6	6.54	16	15,149	12,079	6869	13,806	12,201
Dammam Formation aquifer								
SH-B-15	41.4	6.54	6	23,257	20,074	14,946	21,914	20,309
SH-B-36	31.9	6.58	10	19,035	15,805	12,383	17,691	16,086
SH-C-1	32.0	7.41	17.5	14,409	9274	6360	13,065	1146
SH-C-32	34.0	7.18	8.3	20,575	15,773	12,963	19,232	17,627
SH-D-6	33.3	7.32	10.7	18,475	13,453	10,825	17,132	15,527
SH-D-19	32.9	6.68	10.4	18,710	15,154	11,958	17,367	15,762
SH-E-25	33.9	7.19	10	19,035	14,216	10,916	17,691	16,086
SU-18	35.0	7.23	14	16,253	11,360	10,233	14,910	13,305
SU-106	31.0	7.11	28	10,523	5874	5817	9180	7574
SU-123	34.4	6.96	6.2	22,986	18,641	15,057	21,643	20,038
WW-D-1	35.4	7.12	14.6	15,906	11,207	8142	14,563	12,958
WW-92	31.8	7.12	16.3	14,996	10,321	8786	13,652	12,047
WF-10L	33.5	7.07	12.2	17,391	12,805	8294	16,048	14,442

As mentioned before, the Middle East region is under the influence of three types of moisture influx, namely the Mediterranean, Atlantic Ocean, and the monsoon front. The *d*-excess value of the rainwater samples was computed (Table 2) and found to range between +19.7 ‰ (November–December) and +7.9 ‰ (February–May). The low values of *d*-excess during February–May probably indicate that the source of moisture could be the nearby Arabian Gulf with a component of recycled water through secondary evaporation during condensation under dry atmospheric conditions. A high *d*-excess value (+19.7 ‰) with depleted isotopic values in December rainwater samples at Kuwait Oil Company (KOC)—North Kuwait ($\delta^{18}O = -3.3$ ‰ and $\delta^{2}H = -6.8$ ‰)—suggests Mediterranean rains, as the air mass originating from the Mediterranean Sea is generally characterized by relatively large *d*-excess ($d = +22$ ‰) (Gat and Carmi 1970).

As the cloud mass moves from a source area towards the continent, depletion in the isotopic composition of rainwater occurs (continental effect). Also, the rainwater samples collected during November–December showed a decreasing trend in their *d*-excess values from north to south, possibly reflecting the direction of the Mediterranean moisture-bearing winds in those months or indicating the multiple sources of the atmospheric moisture or both. During February–May, *d*-excess of the rainwater samples does not change significantly across the country and the source of moisture could be nearby Arabian Gulf with a component of recycled water through secondary evaporation during condensation under dry atmospheric conditions. The higher *d*-excess in case of NOMWL is attributed to the Mediterranean source.

δ^{2}H and δ^{18}O composition of the initial recharge waters

Figure 7 shows that the regression (evaporation) lines of Kuwait Group and Dammam Formation aquifer, respectively, intersect the $\delta^{18}O$ and $\delta^{2}H$ axis (shown as vertical arrows with KG and DM) at $\delta^{18}O = -8.8$ ‰ and $\delta^{2}H = -40$ ‰ and $\delta^{18}O = -7.2$ ‰ and $\delta^{2}H = -32$ ‰. The intersected values represent the isotopic composition of initial waters at the recharge area, and hence, the same can be used to confirm the location of the recharge areas in the highlands of Saudi Arabia and to estimate volumetric mixing between the two aquifers.

It is interesting to note in the figure that the initial recharge waters of the underlying Dammam Formation aquifer are relatively less depleted than that of the overlying Kuwait Group aquifer. This suggests that the Kuwait Group aquifer was recharged relatively during more humid period than the Dammam Formation aquifer. Also, the regression lines for the Kuwait Group and Dammam Formation aquifers intersect each other on the GMWL.

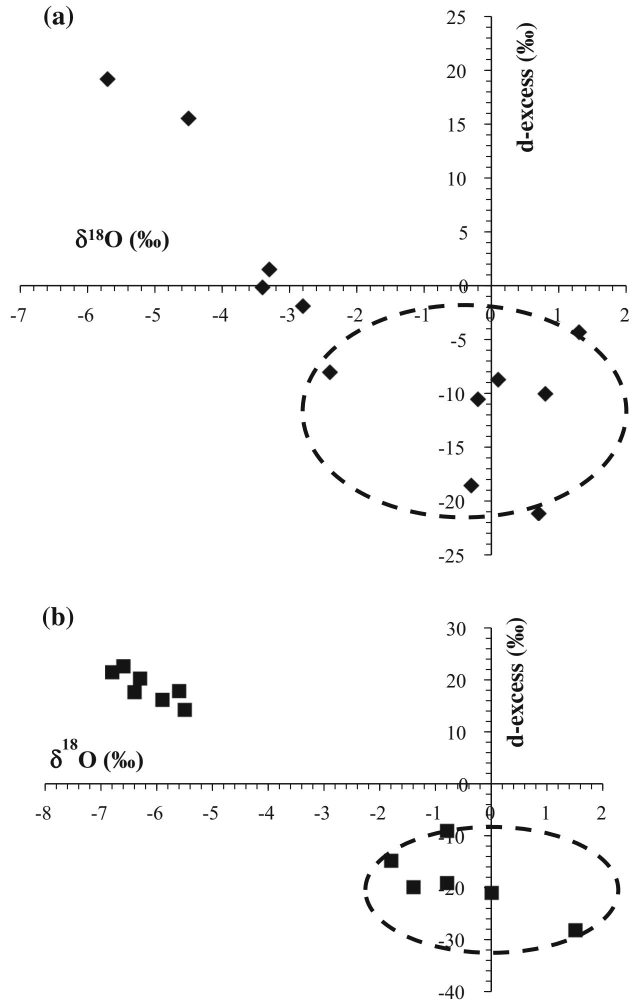


Fig. 9 $\delta^{13}C$ versus ^{14}C plot of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

Interrelationship between the aquifers

The knowledge of possible interconnection between different aquifers in a multi-aquifer system is very essential for groundwater resource evaluation as well as for forecasting water-quality issues (increase or decrease) by leakage from above or below, particularly in case of carbonate aquifers, as the interconnection may be difficult to establish by piezometric studies alone owing to highly heterogeneous and non-isotropic nature of the geology. Stable isotopes such as ^{2}H and ^{18}O along with radioactive ^{3}H and ^{14}C can be used to establish interconnection between the various aquifers.

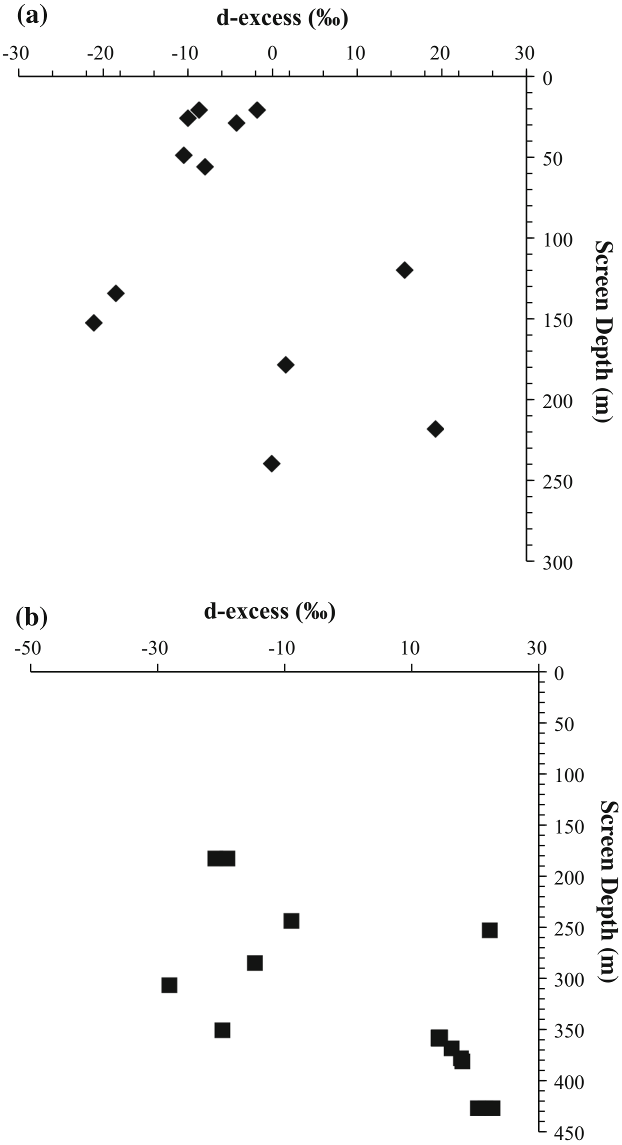


Fig. 10 *d*-Excess versus screen depth of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

The Kuwait Group groundwaters near the coast (HS-116, WT03), at the central parts (SU-85A), and near the south-west border (UG 62) fall on regression line for the Dammam Formation aquifer (Fig. 7), indicating that possibly the two aquifers are interconnected at those places. Similarly, the groundwaters of the Dammam Formation at the south (near Al-Wafra) fall on the regression line for the Kuwait Group aquifer, indicating the interconnection between the two aquifers. The piezometric study of the two aquifers also corroborates the same.

Groundwater ages and recharge processes

Highly lesser slopes of the δ^2H–δ^{18}O regression lines of the groundwater samples of both Kuwait Group and Dammam Formation aquifers (Eqs. 2, 3), in comparison with that of the KMWL, indicate an evaporation effect in their stable isotopic composition. The evaporation effect could be due to either near-surface evaporation in the unsaturated zone during recharge or a secondary evaporation of falling raindrops or both.

Although most of the groundwater samples from both the aquifers indicate evaporation effect (Fig. 7), the samples from the Kuwait Group aquifer at sites SU-85A (in the central part) and UG-65 (near the Saudi Arabia border in the south-west) fall on the KMWL with depleted isotopic values. This indicates that these groundwaters are non-evaporated precipitational recharge. Similarly, some of the groundwater samples of the Dammam Formation aquifer located in the south-west border (SH-C-32, SH-D-6, SH-E-25, SW-4) fall close to the KMWL with depleted values, which again possibly indicates that they are non-evaporated precipitational recharge.

The conversion of stable isotopes to *d*-excess is also being exploited as a complementary tool to understand the processes of recharge (Abass et al. 2010). The calculated *d*-excess values of the groundwater samples are given in Table 3 and Fig. 9. A wide range of *d*-excess of the groundwater samples is seen (Kuwait Group aquifer: +16.0 to −20.6 ‰; Dammam Formation aquifer: +22.8 to −19.6 ‰). Most of the groundwater samples from the Kuwait Group aquifer (Fig. 9a) have *d*-excess value less than the global mean value (∼+10 ‰). This indicates the evaporation of recharging rainwaters prior to infiltration. However, since the KMWL (Fig. 6) shows a lesser slope (6.1) than that of the GMWL (∼8), the raindrops undergoing evaporation during their fall could also be another contributing factor to the lesser *d*-excess of groundwater.

In the Dammam Formation aquifer, some of the groundwater samples have *d*-excess value close to a value of 20 (Fig. 9b), which is a typical value for moisture sources from Mediterranean Sea. There is no correlation between *d*-excess and the screen depth of the wells (Fig. 10). It is also interesting to note that the samples from central, south, and along the coast (i.e. away from the recharge area located at Saudi Arabia) of both the aquifers showed negative *d*-excess values with heavier ^{18}O and ^{2}H (shown in eclipse in the figure) indicating greater degree of evaporation prior to recharge. Thus, the *d*-excess of the groundwater samples indicates that the groundwater system is a mixture of so many types of water with different origin (recharge source) and history (time, evaporation, climate).

The corrected ^{14}C ages showed large variation for both the Kuwait Group and Dammam Formation aquifers (Fig. 11). The ^{14}C age of a groundwater system is governed by its flow paths through the geological formation and the distance from the recharge area. From the ^{14}C versus δ^{18}O plot, it can be seen that in the case of Kuwait Group aquifer, three different groups of groundwater are discerned: Group 1 (samples at intermediate depths in the south-west and central parts)—low ^{14}C ages (∼5000 B.P)

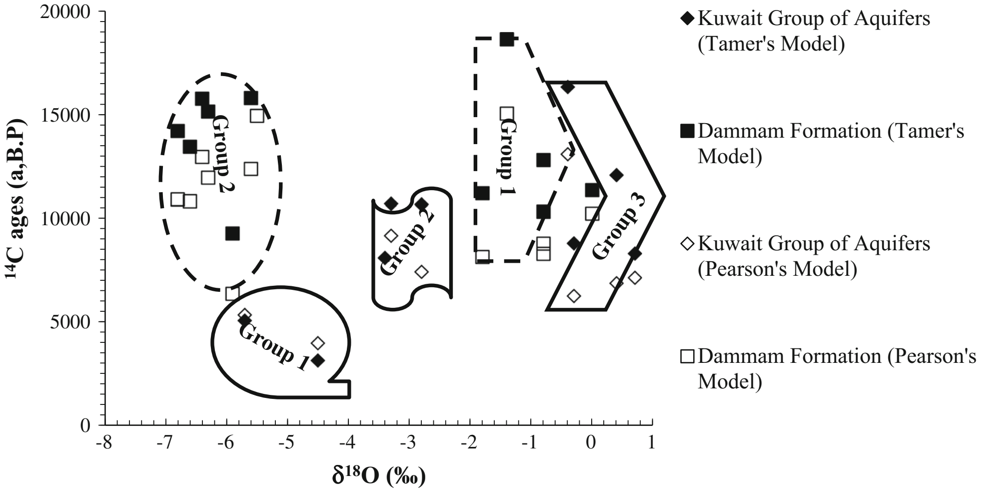


Fig. 11 ^{14}C versus δ^{18}O of groundwater samples

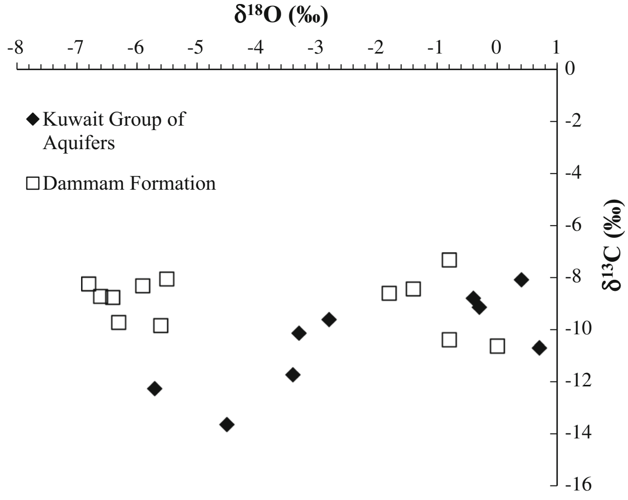


Fig. 12 δ^{18}O versus δ^{13}C of groundwater samples

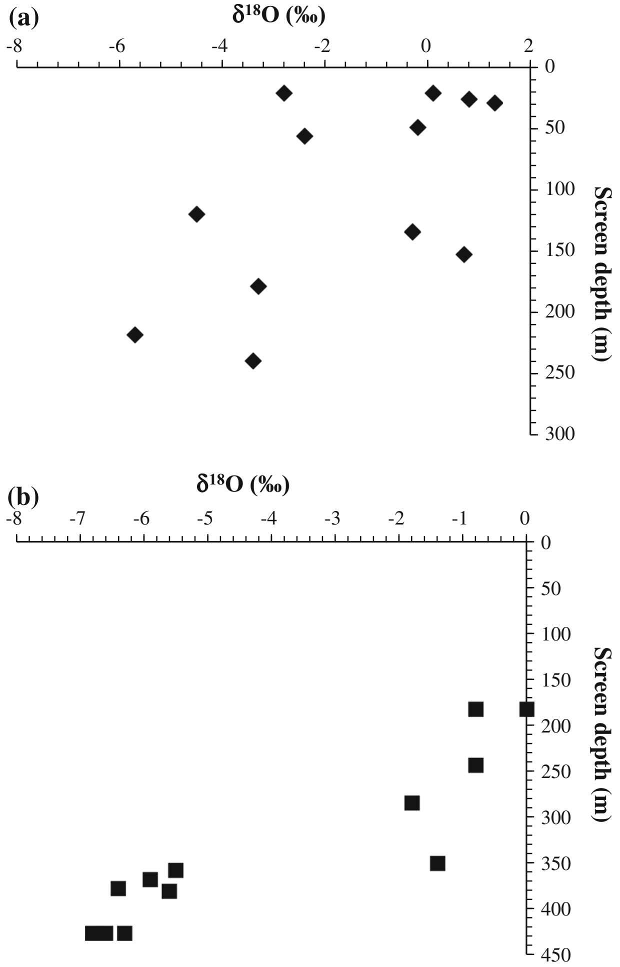


Fig. 13 ^{18}O versus screen depth of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

and depleted δ^{18}O isotopic values (−4.5 to −5.7 ‰); Group 2 (samples at deeper depths in the south-western part and at shallow depths along the coast)—intermediate ^{14}C ages (∼8000–10,000 B.P) and intermediate δ^{18}O isotopic values (−2.5 to −3.5 ‰); and Group 3 (deeper (>300 m) samples from the south—higher ^{14}C ages (∼9000–16,000 B.P) and enriched δ^{18}O isotopic values (∼0–1 ‰). This suggests that the deeper groundwater in the south is recharged during arid phase, whereas the intermediate groundwater in the south-west and central parts is recharged during the humid phase. The deeper groundwater in the south-western part and the shallow groundwater along the coast are of mixed water of several origins.

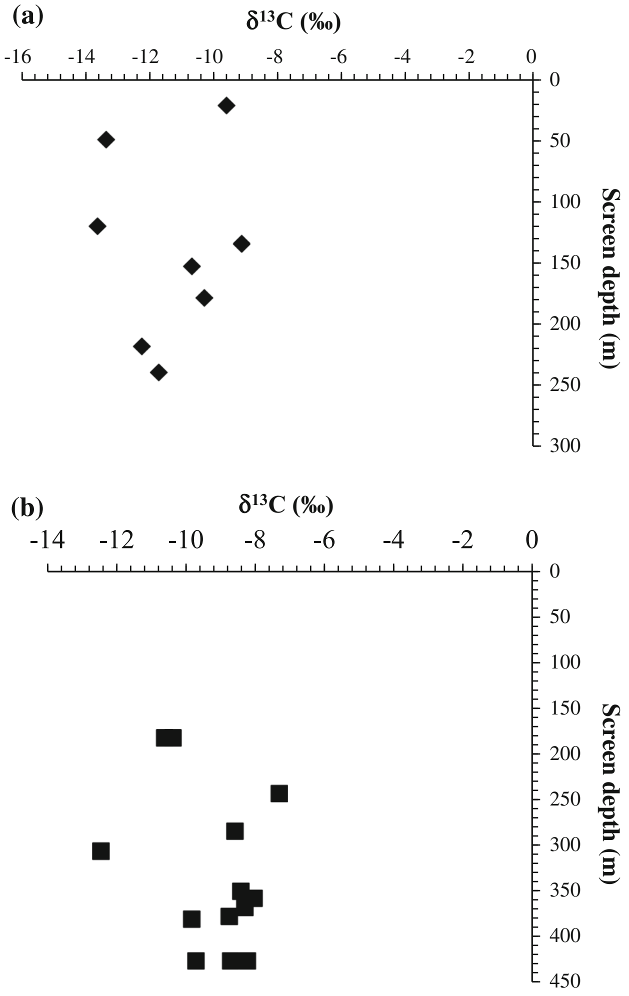


Fig. 14 δ^{13}C versus screen depth of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

The samples from the Kuwait Group aquifer at sites SU-85A (in the central part) and UG-65 (near the Saudi Arabia border in the south-west) (ref. Figure 3), falling on the KMWL with depleted isotopic values and having low ^{14}C values (38.3 and 29.2 pMC, respectively) and measurable tritium content (0.51 and 0.75 TU, respectively) (ref. Table 3), possibly indicate a mixing between (young) recent non-evaporated precipitational recharge and old waters in the aquifer system.

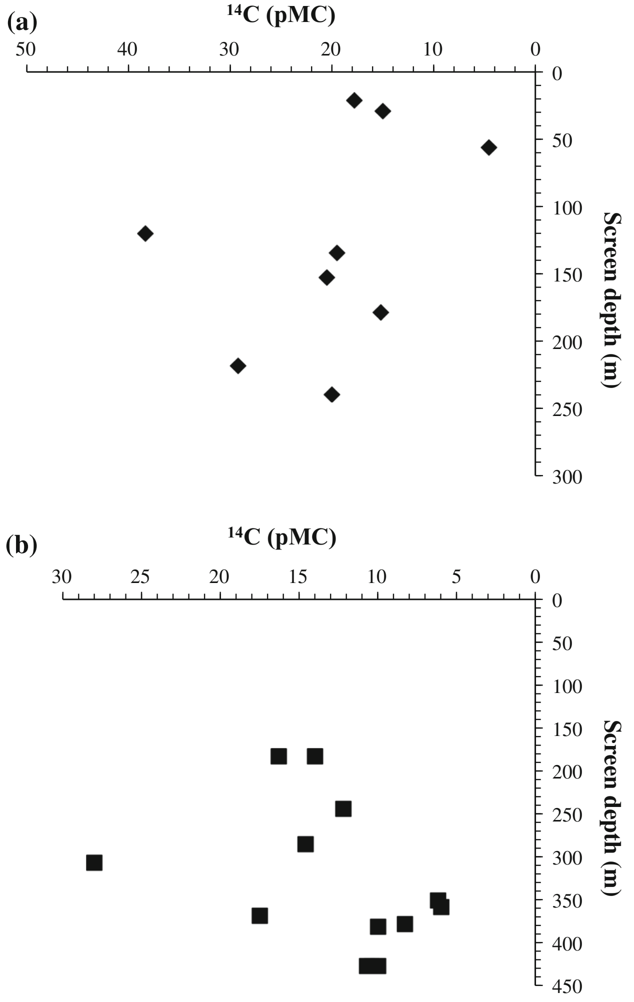


Fig. 15 ^{14}C versus screen depth of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

In the Dammam Formation aquifer, there are two groups of groundwater, namely Group 1 (wells in the central part and with depth less than 350 m)—enriched δ^{18}O isotopic values (0 to −2 ‰)—and Group 2 (wells in the south-western part and with depth more than 350 m)—depleted δ^{18}O isotopic values (−5 to −7 ‰), although the range of ^{14}C ages of both the groups are the same. Out of the two groups, Group 2 samples do not show evaporation effect, as they fall on the KMWL (Fig. 7) and they are very old waters (>8000 a, B.P). Highly depleted δ^{18}O values and higher ^{14}C model ages of the deeper groundwater in the south-western part suggest that they were recharged in the past at cooler climatic conditions (humid phase). Since the Group 2 samples fall close to the intercept between the KMWL and the regression line for the Dammam Formation, it appears that the recharge to the Dammam Formation significantly occurred during over 8000 a, B.P.

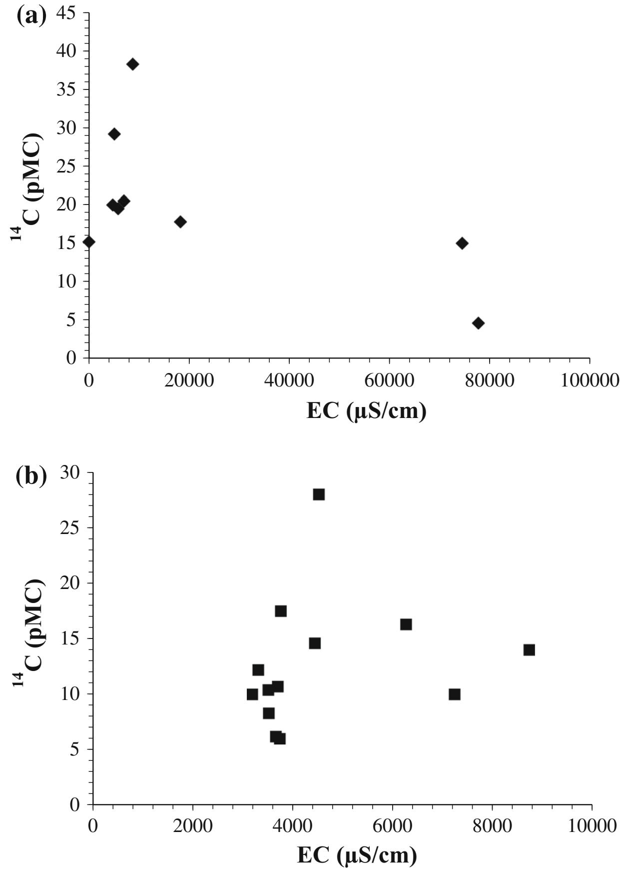


Fig. 16 ^{14}C versus EC of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

The δ^{18}O versus δ^{13}C (Fig. 12) showed that both isotopically (δ^{2}H and δ^{18}O) enriched and depleted groundwater contained similar range of enriched δ^{13}C values (−6 to −12 ‰), which is indicative of samples away from the recharge areas.

The plot of well depth (screen depth) versus δ^{18}O and δ^{2}H of the groundwater samples of Kuwait Group aquifer (Fig. 13a) revealed no good correlation in the shallow depths (0–50 m), but at deeper depths (>50 m) a fairly good correlation is observed. This suggests that the groundwater of Kuwait Group aquifer at shallow depths is fairly well mixed (no stratification), whereas at deeper depths they are probably stratified. At deeper depths, the groundwaters are isotopically depleted compared to the shallower depths. The variations in δ^{18}O and δ^{2}H isotopic values at shallow and deeper zones reflect the recharge histories and the associated isotopic content of the initial recharging rainwaters at the recharge area.

In the Dammam Formation aquifer, there are two groups of groundwater seen (Fig. 13b): Group 1—located at a depth less than 350 m and with enriched δ^{18}O and δ^{2}H isotopic values (0 to −2 ‰) and Group 2—located at a

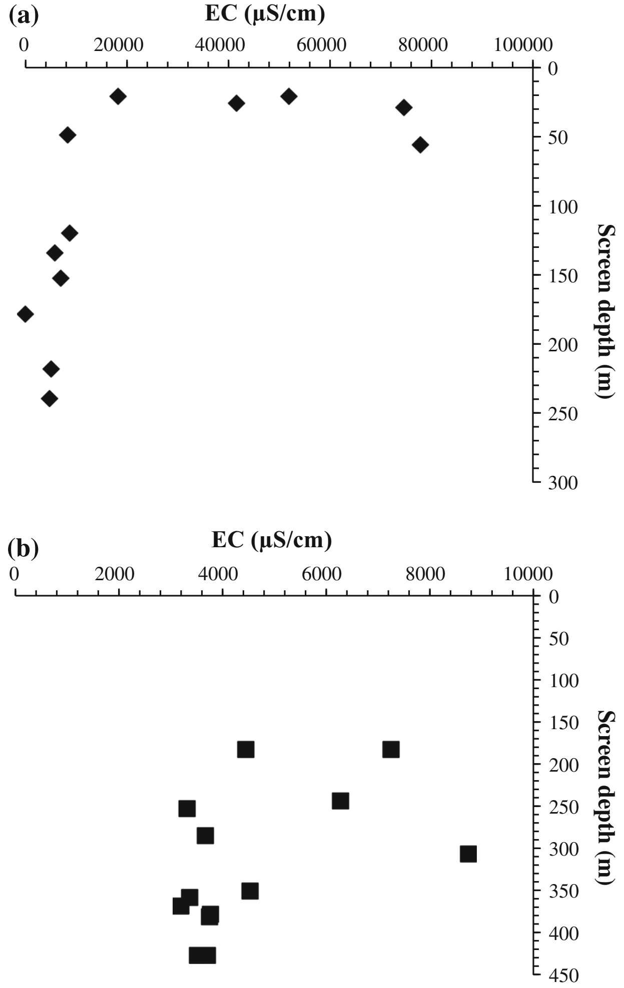


Fig. 17 EC versus screen depth of groundwater samples of **a** Kuwait Group and **b** Dammam Formation aquifers

depth more than 350 m and with depleted $\delta^{18}O$ and $\delta^{2}H$ isotopic values (−5 to −7 ‰), corroborating the findings from ^{14}C versus $\delta^{18}O$ (Fig. 11).

A plot of $\delta^{13}C$ versus screen depth (Fig. 14) and ^{14}C versus screen depth (Fig. 15) also corroborates the aforementioned discussions on, stratification, or otherwise of the aquifers, recharge during older periods and climatic conditions, different flow paths, etc. Also, as seen from ^{14}C versus screen depth (Fig. 15a) in the Kuwait Group aquifer, samples located along the coast at shallow depths (<57 m) are very old (^{14}C <20 pMC), compared to some of the deeper groundwater. These groundwater contains much higher EC (41,600–77,730 µS/cm), compared to other Kuwait Group aquifer samples (4550–8730 µS/cm; Fig. 16a) and the underlying Dammam Formation aquifer samples (3200–8730 µS/cm; Fig. 16b). As substantiated by $\delta^{18}O$ (Fig. 11; Group 2), this indicates possibly mixed nature of groundwater with several origins along the coast.

The Dammam Formation aquifer samples contain low ^{14}C values: 6–28 pMC (Fig. 15b). The ^{14}C versus EC for both the Kuwait Group (Fig. 16a) and Dammam Formation (Fig. 16b) aquifers does not indicate any correlation, which is possibly due to various intermixing processes occurring between various formations along the flow.

A plot of EC versus depth of sample of the Kuwait Group aquifer (Fig. 17a) indicates that, except for the shallow groundwater along the coast (Group 2; Fig. 11) which shows large variation in EC (18,330–77,730 µS/cm), the others show relatively lesser EC (50–8780 µS/cm). In case of the underlying Dammam Formation aquifer (Fig. 17b), the groundwater samples below 350 m show similar EC (4530–3710), indicating probably the well-mixed condition.

Based on the above results and discussion, a refined conceptual flow model of the groundwater system is given in Fig. 18.

Conclusions

A detailed environmental isotopic characterization of the one of the important shared aquifer systems in the region has been carried out for the first time. The aquifer system mostly contains palaeo-groundwaters, i.e. not part of the actively recharged systems, and hence, the resources may be finite and their exploitation is mining.

The aquifer system is quite complex, containing several types of water having different origin (recharge area) and history (time, evaporation, climate). The groundwater flow direction is rather quite complex and not distinct, although the general direction is from south-west to north-east towards the discharge zones near the Arabian Gulf where the water becomes almost stagnant or of very slow movement. Interconnection between the two main aquifers (Kuwait Group and Dammam Formation) established near the coast and south-west border of the country. The isotopic signatures of the initial recharge waters of the groundwater aquifer system deciphered which can be used for the confirmation of the location of recharge area which lies in the Saudi Arabia. Palaeo-climatic excursions between arid (~9000–16,000 a, B.P) and humid phases (~5000–10,000 a, B.P) during the Holocene and Late Pleistocene in this Gulf region has been obtained based on isotopic composition of deeper groundwaters (Tertiary sediments) as proxies from the present investigation and reported for the first time.

From the present study, the existing conceptual groundwater flow model for the aquifer system has been refined. The updated conceptual model will lead to a more precise numerical model that will help in devising plans to ensure the sustainable exploitation of the two aquifers without jeopardizing the quality and/or the volume of the

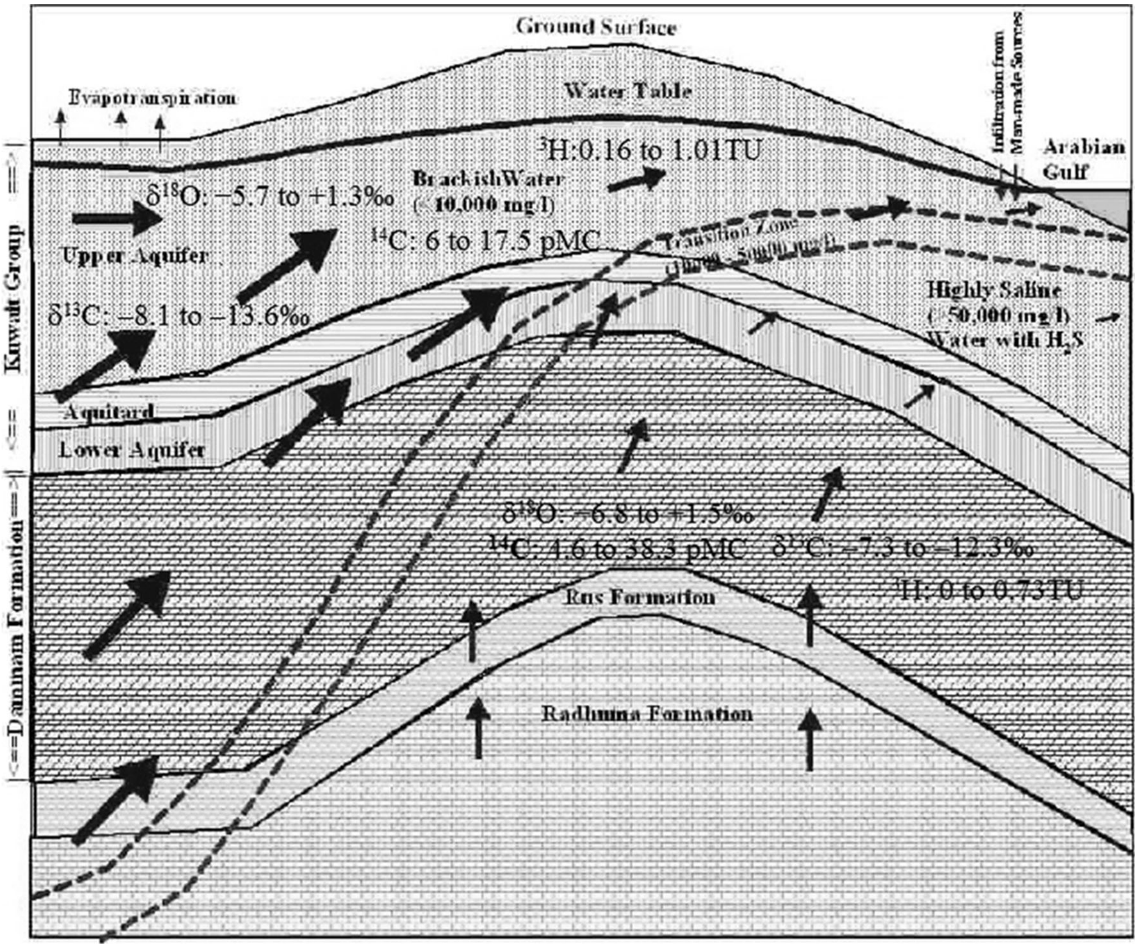


Fig. 18 Refined conceptual groundwater flow model of the aquifer system (modified after Senay et al. 1987)

water produced. Also, as not abundant information on the isotopic characteristics of one of the shared aquifer systems in the region is available, the data generated from the present study will benefit water researchers and managers in the region.

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References

Abass G, Shiloh O, Tetteh TA, Dickson A, Samuel YG, Edward PKB, Alhassan H (2010) Origin of dissolve ions in groundwaters in the Northern Densu River Basin of Ghana using stable isotopes of ^{18}O and ^2H. J Water Resour Prot 2:1010–1019

Al-Awadi E, Mukhopadhyay A, Al-Senafy MN (1998) Geology and hydrogeology of the Dammam Formation in Kuwait. Hydrogeol J 6(2):302–314

Celle-Jeanton H, Travy Y, Blavoux B (2001) Isotopic typology of the precipitation in the Western Mediterranean region at three different time scales. Geophys Res Lett 28:1215–1218

Craig H (1961) Isotopic variations in meteoric waters. Science 133:1702–1703

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16:436–468

Fontes J-C (1992) Chemical and isotopic constraints on ^{14}C dating of groundwater (Chap 17). In: Taylor R, Long A, Kra R, (eds) Radiocarbon after four decades: an interdisciplinary perspective. Springer, New York, pp 242–261

Gat JR, Carmi I (1970) Evolution of the isotopic composition of atmospheric waters in the Mediterranean Sea area. J Geophys Res 75:3039–3048

Michelsen N, Reshid M, Siebert C, Schulz S, Rausch R, Knöller K, Weise S, Al-Saud M, et al (2015) Isotopic composition of Riyadh rainfall, Saudi Arabia, Geophysical Research Abstracts, 17, EGU General Assembly 2015-12839-1

Milewski A, Sultan M, Al-Dosari A, Yan E (2014) Geologic and hydrologic settings for development of freshwater lenses in arid lands. Hydrol Process 7:3185–3194

Mukhopadhyay A, Al-Sulaimi J, Al-Awadi E, Al-Ruwaih F (1996) An overview of the Tertiary geology and hydrogeology of the northern part of the Arabian Gulf region with special reference to Kuwait. Earth-Sci Rev 40:259–295

Pearson FJ (1992) Effects of parameter uncertainty in modeling ^{14}C in groundwater (Chap 18). In: Taylor R, LongA, Kra R (eds) Radiocarbon after four decades: an interdisciplinary perspective. Springer, New York, pp 262–275

Senay Y, Hamdan L, Yacoubi A (1987) Study of the subsurface water rise in the residential areas of Kuwait, vol 3: hydrogeology. Kuwait Institute for Scientific Research, Report No. KISR2227, Kuwait

Tamers MA (1967) Radiocarbon ages of groundwater in an arid zone unconfined aquifer. In: Isotope techniques in the hydrological cycle. American Geophysical Union Monograph, Washington DC, USA, vol 11, pp. 143–152