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Isotopic composition of rainfall and ground-water recharge in the western province of Saudi Arabia

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The oxygen-18 and deuterium isotopic compositions of rainfall from eight meteorological stations are discussed. The results show that the stable isotope distribution of the rainfall over the western province display a difference in isotopic ratios, which can be attributed to the altitude effect and water vapour sources, and to some extent, to rainfall amount. The changes of $\delta^{18}O$ and δD contents with altitude are $-0{\cdot}08$ and $-0{\cdot}38‰$ per 100 m respectively. Comparison of the isotopic analyses of rainfall and local ground-water and springs indicates that the monsoon derived rainfall that prevails during the autumn season plays a crucial role in alluvial aquifer recharge. Although Atlantic water vapour can arrive virtually throughout the area in winter months, its influence seems to be of minor importance to the water balance in the study area.

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Introduction

Data on isotopic composition of rainfall are very scarce in Saudi Arabia. Previous isotopic investigations for several basins (deep and shallow aquifers) in the country were mainly carried out for studying ground-water recharge mechanisms and age determination (e.g. Dincer *et al*., 1974*a*, *b*; Shampine *et al*., 1978; Lloyd *et al*., 1980; Jado & Zotl, 1984; Alkabir, 1985), with no particular attention given to the study of the isotopic content of rainfall. Such work, can provide additional valuable information on ground-water conditions.

In the present study, an isotopic investigation of rainfall in the western province was undertaken as a part of a comprehensive study to investigate and characterize the ground-water system in the selected major wadis in terms of general hydrogeology using hydrochemistry and environmental isotopes.

This work presents preliminary results that will be very useful for any future study regarding the hydrochemical and isotopic evaluation of the ground-water and rainfall conditions, and to some extent, to describe and delineate a proposed local meteoric water line of the region.

Area description

The research area lies between latitude 21° 15′ and 22°15′ N and longitude 39°00′ and 40°30′ E (Fig. 1). This area is considered physiographically as a part of the Arabian

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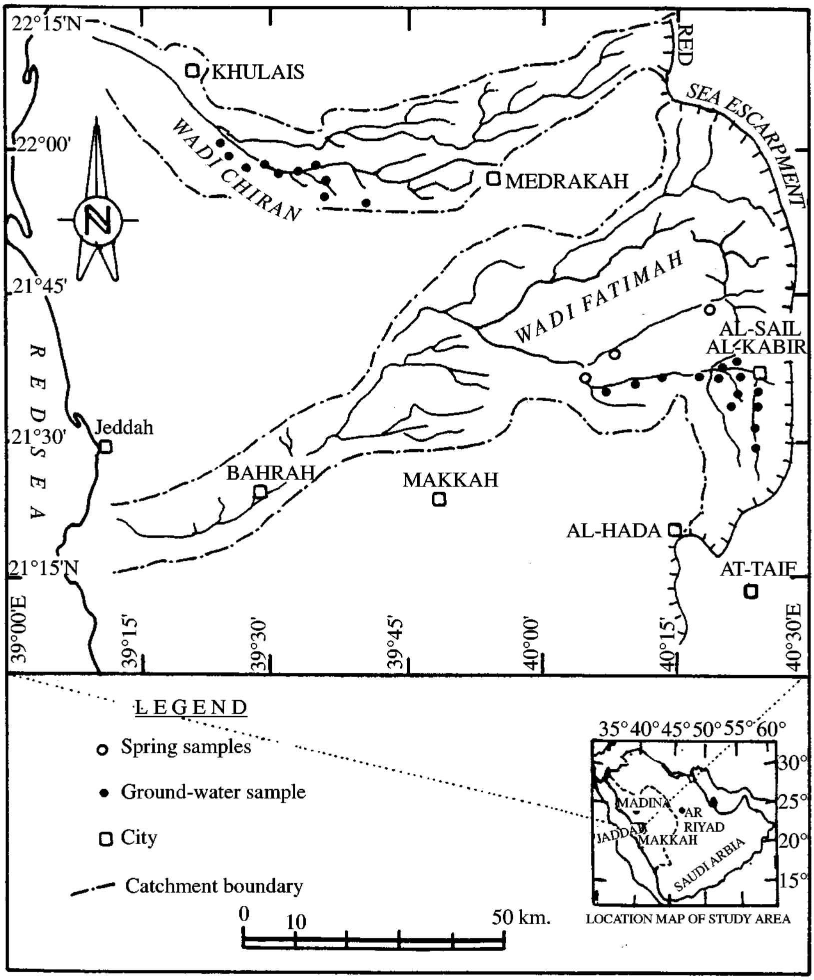

Figure 1. Location of the study area.

Shield. The elevation increases from the coastal area towards the Red Sea escarpment and sharp peaks reach a maximum elevation of 2000 m in the Alhada area. The escarpment is considered to be the most important recharge zone for the alluvial aquifers in the western province, which provide considerable amounts of water to the major districts of Jeddah, Makkah and Al Taif, as well as the surrounding towns.

The climate is typically arid. The coastal plain is among the driest parts in the region, with an average annual rainfall of about 70 mm. To the east, rainfall may be substantially higher with an average of more than 280 mm annually. Such a variation in the rainfall amounts can be attributed to topographic effects. In most cases, however, rainfall occurs locally and often in the form of violent storms of short durations.

The climatic pattern over the study area can best be described by considering the various air mass movements that affect the rainfall distribution over the region. The influence of the various air masses (Fig. 2) on the climatic pattern of Saudi Arabia was discussed and mapped by several investigators (MacLaren, 1979; Al Qurashi, 1981;

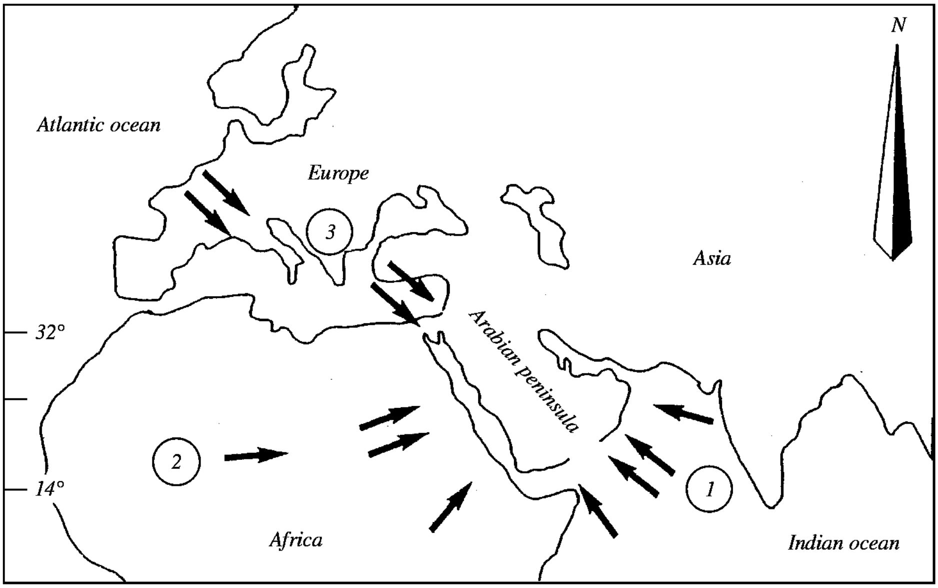

Figure 2. Air mass movements over the Arabian Peninsula. (1) Maritime tropical air mass (monsoon type); (2) continental tropical air mass (warm and moist); and (3) maritime polar air mass (Mediterranean type).

Sen, 1983; Alyamani & Sen, 1993). The air mass movements map shows that there are three major fronts of moisture flowing into the Kingdom:

(1) The retreating monsoon front during late autumn (maritime tropical air masses) that reaches the area from the southern Arabian Peninsula. This front originates from the Indian Ocean and Arabian Sea and contains warm and moist air. Autumn rains become more frequent and are characterized by medium to high intensity over the western and north-western regions of the country. This front often picks up further moisture as it is moving through the Red Sea trough.
(2) The warm and moist continental tropical air masses coming from the Atlantic Ocean through the middle and north African continent.
(3) The maritime polar air masses originated from the eastern Mediterranean Sea. Both (2) and (3) prevail in the winter season.

Although these different air masses have an influence on various parts of the country, the climatic pattern over the western region might be described as developing in a transitional zone between the southerly monsoon front and the Mediterranean and Atlantic effects, both of which are greatly modified by the Red Sea and the escarpment (Alkabir, 1985).

Sampling and analytical methods

Saudi Arabia in an arid region, and hence displays a high variability in rainfall frequency and intensity. This restricted the number of rainfall events to 51 for a period between January 1989 and December 1992. All the rainfall samples were collected as individual event samples during the expected rainy period (October–March). These samples were collected in 500-ml screw-top plastic bottles. They were sealed and kept in a temperature of about 6°C to avoid isotope fractionation by evaporation.

Twenty-seven additional isotopic analyses were made on samples of ground- and spring waters from other sources, are used in this study to provide a clear picture of the ground-water recharge mechanism (Bazuhair *et al.*, 1991, 1994). Ten out of 27 were collected from Wadi Ghiran in May 1991, while 14 ground- and three spring-water samples were taken from Wadi Fatimah during spring periods of 1988 and 1993. These samples were collected from upper reaches of the two basins to minimize changes that may take place in their isotopic compositions throughout traveling of the ground-water along the flowpath (Fig. 1). The isotopic samples were analysed at the IAEA Isotopic Hydrology Laboratory in Vienna. The results are expressed as per mille deviation from the internationally accepted standard V-SMOW.

Results and discussion

Because the isotopic data of rainfall are insufficient to construct the regression lines of the $\delta^{18}O/\delta D$ relationship for individual stations. Figure 3 offers a graphical comparison of $\delta^{18}O$ and δD for all stations. From the $\delta^{18}O/\delta D$ diagram, it can be seen that many samples plot above the global meteoric water line (GMWL), where some samples show a strong evaporation effect during rainfall, with $\delta^{18}O$ enrichment.

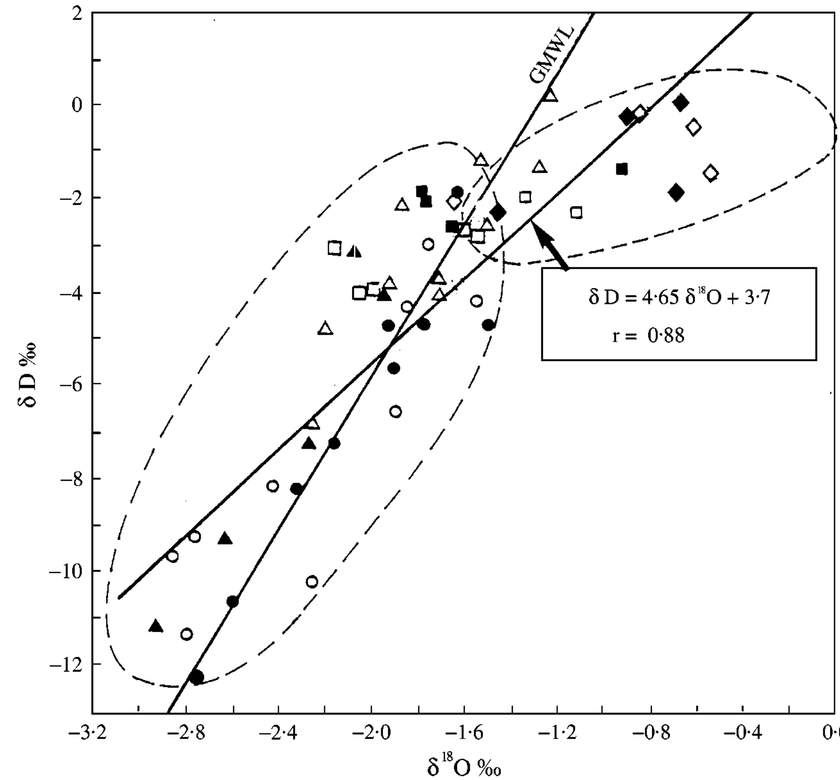

Figure 3. Deuterium-oxygen-18 relation in the rainfall. Alhada (○); Alsail Alkabir (●); Medrakah (△); Al Taif (▲); Makkah (□); Bahrah (■); Jeddah (◇); Khulais (◆).

The values range between $-0{\cdot}53$ and $-2{\cdot}9‰$ in $\delta^{18}O$ and zero to $-11{\cdot}1‰$ for δ D concentrations.

The regression equation ($\delta D = 4{\cdot}65\ \delta^{18}O + 3{\cdot}7$) with a correlation coefficient 0·88 shows that the isotopic rainfall composition does not reflect a true global meteoric behaviour ($\delta D = 8\delta^{18}O + 10$). A systematic isotopic shift in the rainfall could be attributed to a number of factors such as altitude effects, partial evaporation of the falling rain, rainfall amount, and changes in the source of the air masses. All of these are important for variations in the isotopic composition of the rainfall.

Seasonal variation

Seasonal changes in the isotopic composition are clearly observed if autumn (September–November) data are compared with winter (December–February) results for the majority of sites (Fig. 4). The isotopic compositions of the rain waters show that autumn storms are isotopically enriched in $\delta^{18}O$ and δD compared with winter storms (Table 1). This is possibly due to the fact that they originate from warm bodies of water (such as Indian Ocean, Arabian Sea and Red Sea) mobilized by the monsoon front; and due to higher ambient air temperature, and enrichment caused by evaporation. When a storm reaches the area, the rate of evaporation from raindrops is enhanced by the high autumn temperatures and the relatively low humidity of the air, facilitated isotope enrichment. In the lowland areas (Jeddah and Khulais stations), it was not possible to distinguish seasonal trends in the isotopic contents of the rainfall, nor was it possible to discern a relationship between rainfall amount and its $\delta^{18}O$ and δD values. There were, however, considerable variations in the $\delta^{18}O$ and δD composition of rainfall samples between events. This might be attributed to two different processes that operated either individually or concurrently: (1) the air masses derived from the Atlantic Ocean in winter season that crossed the Red Sea probably reloaded with moisture characterized by relatively heavy isotopes originating from the Red Sea although the travel distance over the Red Sea was rather short and produced rainfall on the coastal area; (2) the isotopic contents of the rain waters was probably evaporated during rainfall. Accordingly, both processes would lower the value of d-excess below 10‰ (Fig. 4 and Table 1).

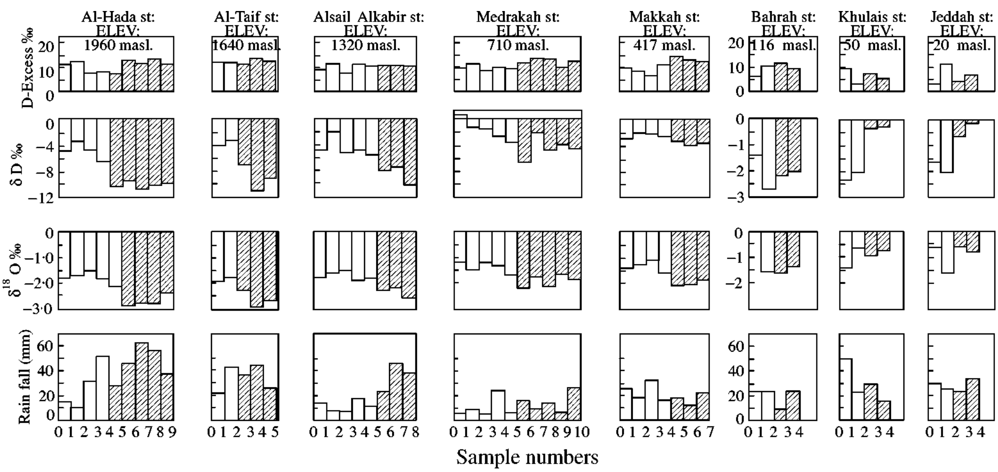

Figure 4. Isotopic composition and seasonal pattern of the rainfall in the eight stations. Winter season (▨), autunm season (□).

Table 1. *Summary statistics of the isotopic compositions of the rainfall*

Station name		Autumn rainfall No. of samples	Autumn rainfall $\delta^{18}O$ (‰)	Autumn rainfall δD (‰)	Autumn rainfall d-excess (‰)	Winter rainfall No. of samples	Winter rainfall $\delta^{18}O$ (‰)	Winter rainfall δD (‰)	Winter rainfall d-excess (‰)
	Max		−1·50	−3·11	10·60		−2·22	−8·20	13·10
Alhada	Min	4	−1·78	−6·60	7·70	5	−2·84	−11·10	7·60
	Mean		−1·73	−4·60	9·24		−2·61	−9·64	11·20
	Max		−1·78	−3·12	11·10		−2·25	−7·30	12·10
Al Taif	Min	2	−1·90	−4·10	11·10	3	−2·90	−11·10	10·70
	Mean		−1·84	−3·61	11·10		−2·59	−9·20	11·53
Alsail	Max		−1·47	−2·00	10·80		−2·18	−7·40	10·22
Alkabir	Min	5	−1·91	−5·50	6·96	3	−2·59	−10·50	10·04
	Mean		−1·72	−4·30	9·48		−2·40	−8·70	10·15
Medrakah	Max		−1·20	0·20	10·80		−1·71	−2·00	12·60
	Min	5	−1·68	−3·70	8·30	5	−2·25	−6·80	9·68
	Mean		−1·41	−1·73	9·50		−1·97	−4·30	11·49
	Max		−1·10	−2·00	10·00		−1·91	−3·30	13·60
Makkah	Min	4	−1·60	−2·80	6·40	3	−2·11	−4·00	11·60
	Mean		−1·37	−2·47	8·48		−2·02	−3·66	12·50
	Max		−0·90	−1·40	10·02		−1·37	−2·00	11·70
Bahrah	Min	2	−1·59	−2·70	5·80	2	−1·74	−2·20	8·96
	Mean		−1·24	−2·05	7·91		−1·56	−2·10	10·33
	Max		−0·64	−2·00	9·14		−0·68	0·00	6·66
Khulais	Min	2	−1·43	−2·30	3·12	2	−0·87	−0·30	5·44
	Mean		−1·04	−2·15	6·13		−0·78	−0·15	6·04
	Max		−0·53	−1·60	10·80		−0·56	−0·20	6·12
Jeddah	Min	2	−1·60	−2·00	1·64	2	−0·79	−0·60	3·88
	Mean		−1·07	−1·80	6·22		−0·68	−0·40	5·00

d-excess ($d = \delta D - 8\delta^{18}O$).

Altitude effect

A good relationship exists between the weighted means of the $\delta^{18}O$ and δD ratios and altitude (Fig. 5). It shows continuing depletion of the heavy isotope of atmospheric moisture with increasing elevation of the sample site in west-east direction, which is explained mainly by gradual rainout from orographically uplifted air masses. The slopes of the relationship of $\delta^{18}O$ and δD with altitude are $-0{\cdot}08$ and $-0{\cdot}38‰$ per 100 m respectively.

Rainfall amount effect

The relationships between the weighted mean of the rainfall amount and the weighted means of the $\delta^{18}O$ and δD ratios are shown in Fig. 5. It is seen that $\delta^{18}O$ and δD are to

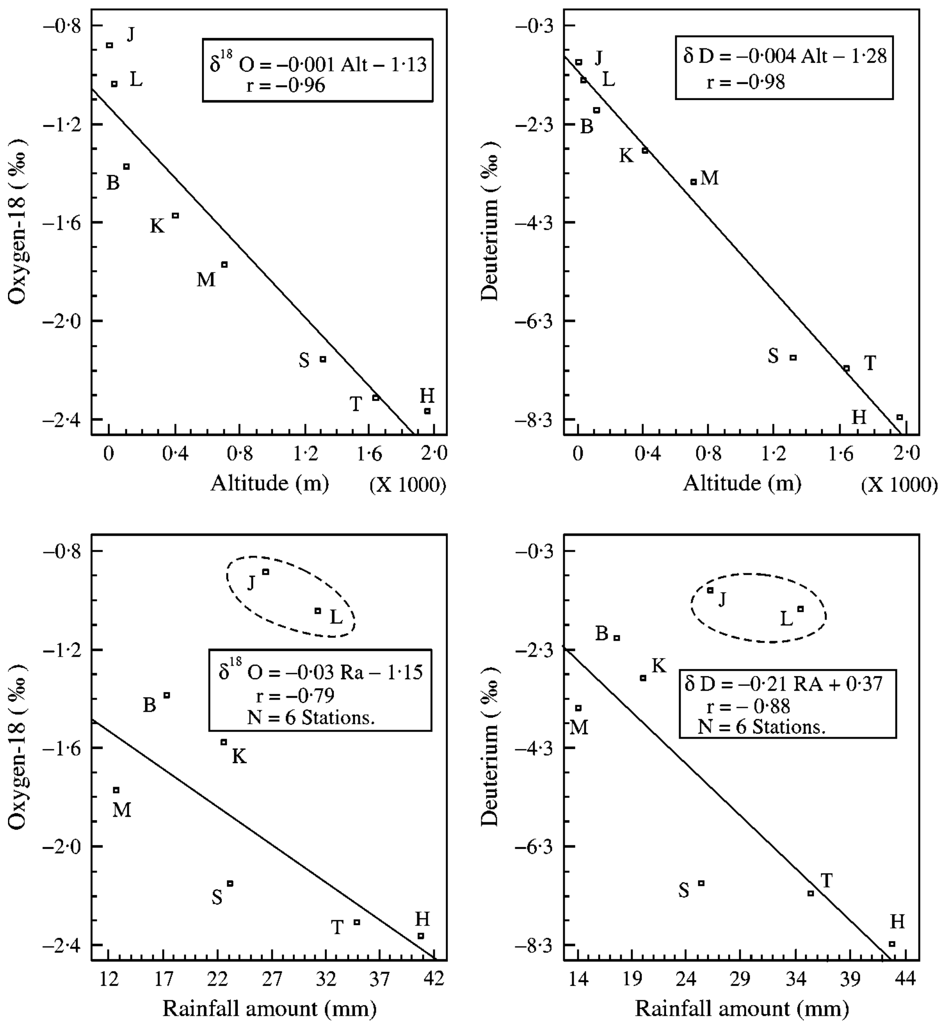

Figure 5. Altitude and rainfall amount effects on oxygen-18 and deuterium, and the eight stations denoted as; Alhada (H), Al Taif (T), Alsail Alkabir (S), Medrakah (M), Makkah (K), Bahrah (B), Khulais (L) and Jeddah (J).

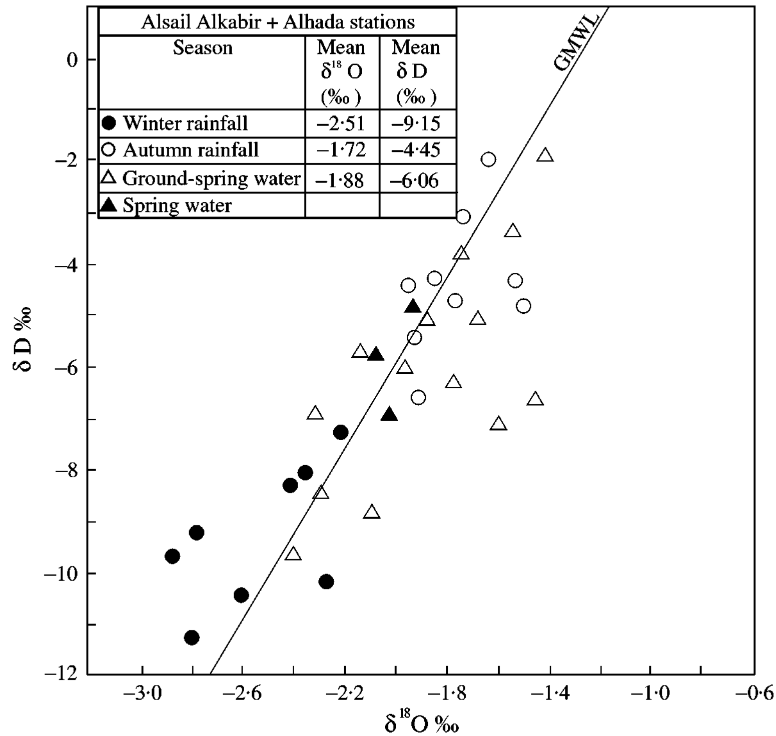

Figure 6. Deuterium-oxygen-18 relation in the ground-water and springs of Wadi Fatimah basin.

some extent, correlated with the amount of rainfall with correlation coefficients of − 0·33 and − 0·53 respectively. However, the low correlation occurred probably as a result of the poor relationship found between rainfall amount and its isotopic composition in Khulais (L) and Jeddah (J) stations due to the reasons mentioned above. When the results of the two mentioned stations are omitted, the correlation coefficients between − 0·79 and − 0·88 respectively.

Sources of rainfall over the study area

It has been noted in earlier that the study area is under the influence of three types of moisture influx, namely from the Mediterranean and Atlantic Ocean (winter season, Dec.–Feb.) and the monsoon front (autumn season, Sept.–Nov.). The results of environmental isotopic analyses of rain waters have shed some clues on the relative weights of each moisture source producing rain over the area.

Dansgaard (1964) defined the d-parameter ($d = \delta D - 8\delta^{18}O$), which is used to identify the origin of the vapour masses producing rainfall. Different studies have used the d-excess parameter to investigate the sources of the water vapour over the Middle East region (e.g. Gat & Carmi, 1970; Leguy *et al.*, 1983).

In order to study the effect of the above three water vapour sources on the ground-water recharge, 24 ground-water and three spring-water samples were used. Their isotopic contents were compared to that measured from the rain water samples. The rain water samples from Alsail Alkabir and Alhada stations were considered to represent the recharge area of Wadi Fatimah, and these from Medrakah station- to represent the recharge zone of Wadi Ghiran (see Fig. 1).

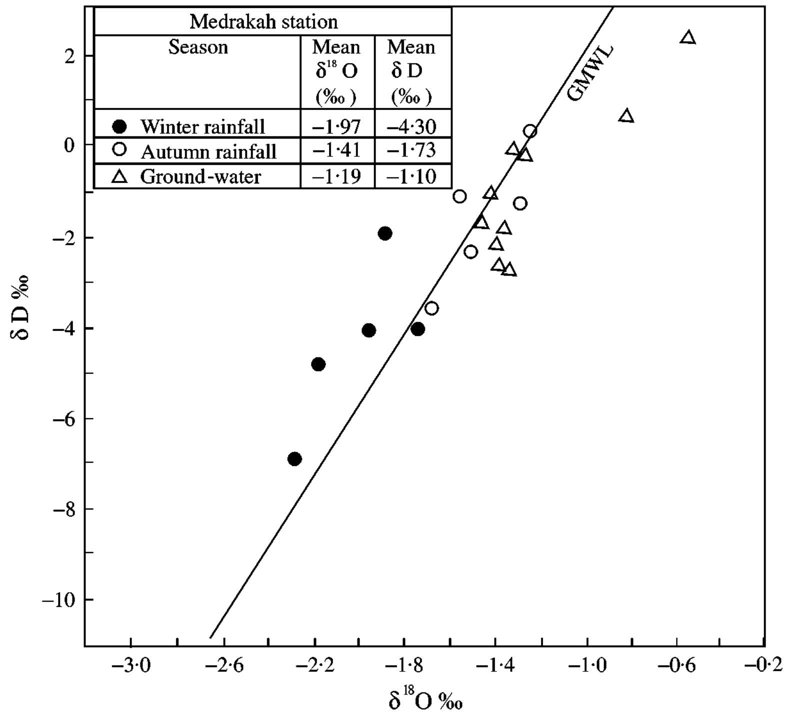

Figure 7. Deuterium-oxygen-18 relation in the ground-water of Wadi Ghiran basin.

Considering the d-excess values obtained for the local rainfall, as shown in Table 1, it is evident that most of the values are close to or less than 10‰. Since the Mediterranean winter rains are mainly characterized by relatively large d-excess (d = 22‰), (Gat & Carmi 1970, Leguy *et al.*, 1983), the possibility of the Mediterranean rainfall being an effective factor in the recharge process of the ground-water aquifers of the area, may be excluded. This may suggest that the two warming air masses with an entirely different origin of atmospheric moisture might have contributed to the formation of rainfall over the western region. The first and one represents continental tropical air masses of Atlantic origin, which circulate and travel long distances and bring water vapour during the winter season. The other one is dominated by monsoon air stream, that brings the water vapour during autumn season.

From the $\delta^{18}O/\delta D$ diagrams (Figs 6 & 7) it can be seen that in most cases the ground-water and springs fall on or close to the GMWL, showing that these samples have not been subjected to significant evaporation before or during infiltration into the aquifers. This suggests that storm water infiltrates rapidly throughout fractured zones of the rocks and the highly permeable deposits in the recharge areas of the two basins. A few points, especially those located in downstream areas of Wadi Ghiran (Fig. 7) show relative deviation from the isotopic composition of the rainfall. This probably indicates that either the infiltrating rain water undergoes some evaporation while passing through the soil zone and, as a result, the residual descending water gets slightly enriched in the heavy isotopes; and/or, the evaporation occurs from the sheet flow over the wadi sediments. However, the ground-water and the springs are isotopically enriched compared to the Atlantic rainfall taking place in winter season, but they are closer to the composition of rainfall storms observed in autumn season at Alhada, Alsail Alkabir and Medrakah stations (Figs 6 & 7). This in fact implies that the local recharge is produced mainly by monsoon-derived autumn rainfall. Winter stroms, on the other hand, might partially contribute to ground-water recharge in Wadi Fatimah (Fig. 6).

Conclusions

Based on the aforementioned findings one can postulate that the variations in the stable isotope ratios in the rainfall are due primarily to altitude effects and the air masses of different origin. The changes of $\delta^{18}O$ and δD with altitude were $-0{\cdot}08$ and $-0{\cdot}38‰$ per 100 m respectively. A small seasonal variation in the rainfall isotopes was noted, and the winter rainfall was depleted compared to that of autumn. Stable isotope contents in the ground-water and springs indicate their recharge sources to be the seasonal monsoon air masses originating from Indian Ocean and Arabian Sea, whereas winter storms originating from the Atlantic Ocean might be less important for the ground-water balance.

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