Using hydrochemistry and environmental isotopes to define the groundwater system of the Ain Maghara Spring, Jordan

H. El-Naser & A. Subah

Ministry of Water and Irrigation/Jordan, PO Box 2412, Amman 11183, Jordan

Abstract

Ain Maghara spring is an important historical water supply for agriculture in the Jordan Valley region near the Dead Sea, and is of increasing importance for industry. In the last decade, a number of deep wells have been drilled in the area to supplement industrial needs. There is concern that exploitation of the deep aquifer system (Disi/Kurnub) and shallower alluvial aquifer may adversely affect the discharge or water quality of Ain Maghara spring. Stable isotope data, geochemistry, and ^{14}C age dating all suggest that current water abstraction does not have a strong impact on the quantity or quality of water discharging from the spring. However, due to the increasing industrial demand for water, it would be prudent to continue the monitoring of geochemistry and isotope hydrology of the spring and surrounding wells to permit early identification of any changes in the hydrogeology of Ain Maghara spring.

Keywords: aquifers, case studies, geochemistry, hydrogeological controls, water resources

Introduction

The country of Jordan experiences either arid or semi-arid climatic conditions and thus has limited water resources. The dominant resource, groundwater, is coming under increasing stress from population growth and urbanization (Salameh 1996). Long-term water resource planning in Jordan requires a thorough understanding of groundwater supplies. Environmental isotope techniques in hydrological investigations have been increasingly applied in Jordan for water resources development and management. In this study, hydrogeological investigations using environmental isotope techniques and water quality data were employed to improve the understanding and identification of a possible hydraulic connection between the Ain Maghara spring, and deep and shallow aquifer systems.

The study area includes the southeastern part of the Dead Sea from Wadi Mujib in the north to Wadi Hasa in the south, and from the Dead Sea in the west to Karak in the east (Fig. 1). The main feature of this area is the eastern escarpment of the north–south trending Dead Sea Rift Valley. The Dead Sea is approximately 400 m below mean sea level (−400 m msl). The mountains at the top of the escarpment rise to +1100 m msl. The Lisan peninsula is composed of alluvial and sea bed deposits of hundreds of metres thickness at the mouth of Wadi Karak. Average precipitation in the study area ranges from less than 150 mm per year in the Jordan Valley to more than 300 mm per year for the surrounding escarpment (Fig. 2).

The potential for water quality degradation in the area is high due to many factors, including dissolution of evaporite minerals in the playa sediments of the area, the presence of and intrusion from other high salinity waters in the subsurface, and the depletion of water caused by over-exploitation (Abu Jaber & Wafa 1995). Therefore, it is important to understand the relationship between the different water resources in the area to allow for proper resource management and protection of water supplies.

Geology and aquifer systems

The study area forms part of the Dead Sea geological province. From Wadi Mujib in the north to Wadi Hasa in the south, a wide variety of rocks are exposed, ranging in age from Precambrian to Recent (Fig. 3). Close to the Dead Sea Rift, the geological structure is very complex and, in some places, the faulting in the Quaternary deposits provides evidence of continuing tectonic instability (Bender 1968).

The main geological outcrop in the study area is the Ram Group, which consists of fine to medium-grained sandstone, micaceous siltstone and silty claystone, interbedded with limestone and dolomite. The Ram Group outcrops at the lower slopes of the rift escarpment, east of the Dead Sea.

The lower Cretaceous Kurnub (K) aquifer unconformably overlies the Ram Group in the study area. The Kurnub consists of sandstone, mostly medium to coarse grained, with thin beds of siltstone and sandy dolomite. The outcrop of the Kurnub extends along the slope of the rift escarpment in the area east of the Dead Sea. This formation combines with the Ram Group to form one of the main aquifers in Jordan (WAJ-BGR 1994).

The lower Ajloun Group (A1/A6) unconformably overlies the Kurnub Group. It comprises a late

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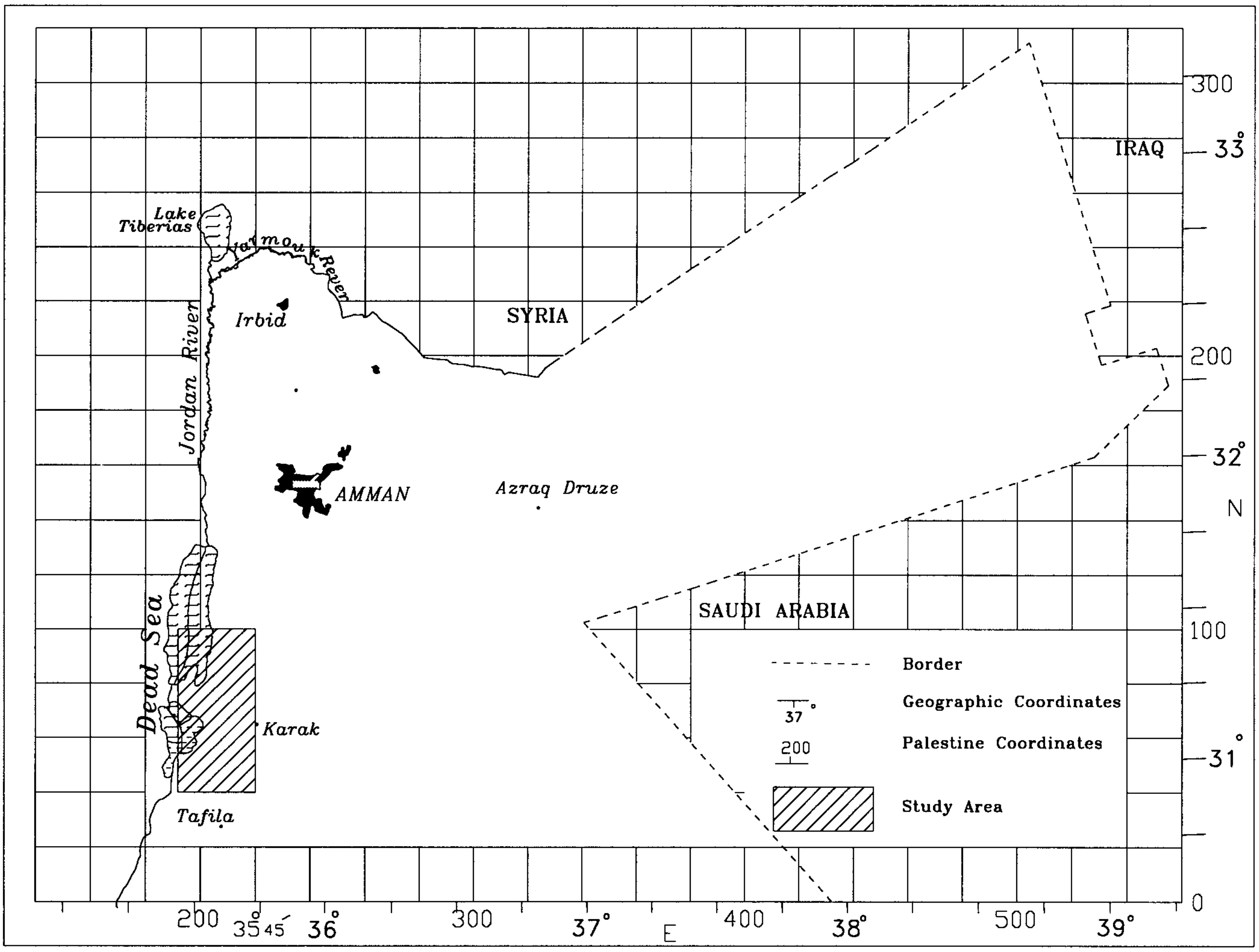

Fig. 1. Location map of the study area.

Cretaceous sequence dominated by marl, limestone, dolomite and shale.

The uppermost member of the Ajlun Group and the lower part of the Belqa Group are considered as one hydrogeological unit (B2/A7). It consists of massive limestone, dolomitic limestone and dolomite with intercalated beds of marl, gypsum and chert. The B2/A7 unit forms the most important aquifer in Jordan because of its vast extent and relatively high permeability.

The overlying Muwaqqar formation (B3) aquitard is dominated by marl, typically bituminous, chalky marl and chalky limestone.

Lisan marls are present in the area of the Ibn Hammad, Karak and Isal wadis. They are restricted to the rift area and are composed of clay aragonite laminites interbedded with gypsum, sand and gravel.

Quaternary deposits are composed of soil, calcrete, alluvium and beach or salt flats.

The hydrogeological units outcropping in the study area are shown on Fig. 3. Three main aquifers were studied in the area: the deep Kurnub Ram aquifer, the B2/A7 aquifer and shallow alluvium.

Two wells in the study area penetrate the deep Kurnub aquifer. The static water level in the first of these, CA3025, is 150 m below ground level. However, the second of these, CA3026, is flowing and has a temperature about 5°C higher than CA3025.

The Ain Maghara spring (CA0502) is believed to originate from the A7 (B2/A7) aquifer, in the study area. A shallow alluvial fan aquifer in the Safi and Mazra'a area is fed by subsurface flow and suspected leakage from the deep Cretaceous aquifer (Kurnub sandstone), which has different hydrogeological and hydrochemical properties (El-Naser & Rimawi 1995). The static water level in the Safi and Mazra'a areas (wells CA3005, CA3006, CA1045 and CA3019; in alluvial aquifer, Table 1) varies from 20–35 m below ground level (Ministry of Water and Irrigation 1998).

Sampling and analyses

Water samples were collected for chemical and isotopic analysis on three occasions in 1997. Samples for ^{14}C and

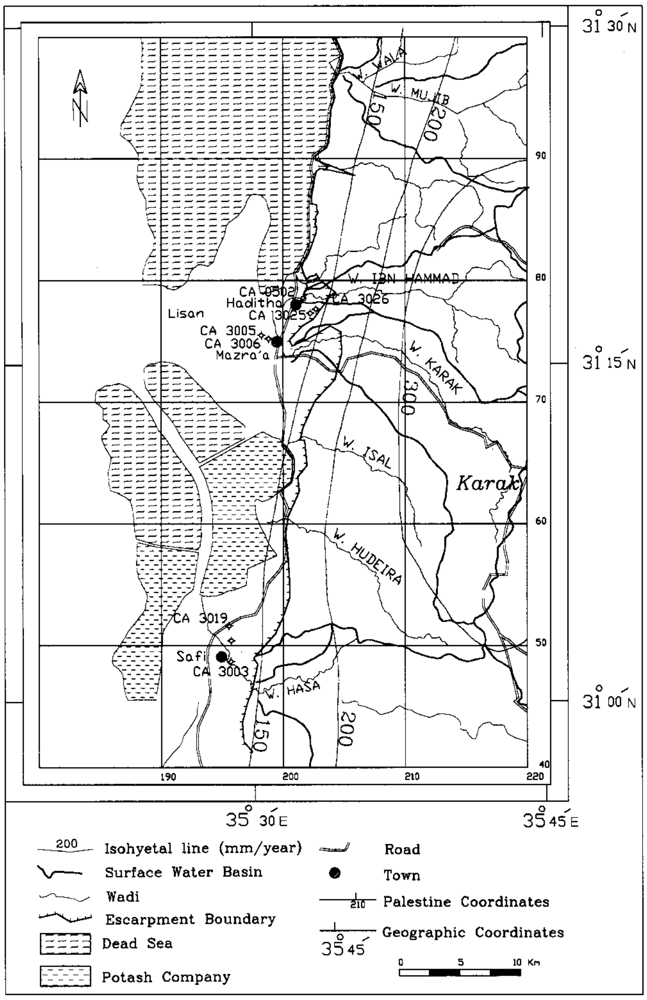

Fig. 2. Well location and isohyetal map.

^{13}C analysis were only collected once. All analyses, including oxygen-18, deuterium, tritium and ^{14}C were performed in the Laboratory of the Water Authority of Jordan. The results are presented in Table 2.

Results and discussion

During the past two decades, the Ain Maghara spring has been used extensively for irrigation in support of the thriving agricultural activity in the area. Discharge from this spring has been relatively constant from the 1970s to the present (Fig. 4). In Fig. 4, there is evidence of seasonal flow. This seasonal flow could reflect seasonal pressure responses in the confined karst or fractured rock B2/A7 aquifer, which feeds Ain Maghara spring, or it may reflect an increasing and decreasing contribution of young run-off water from Wadi Ibn Hammad. It is important for water quality and resource management of this spring that the sources of water are identified. Therefore, the stable isotopic composition of groundwater and Ain Maghara spring water was studied to identify water sources that may be related.

Since 1987, monthly precipitation has been sampled for isotope analysis, from 11 precipitation stations representing both the arid and semi-arid climates in Jordan.

The local meteoric water line for the Al Rabba station (approximately 25 km from the study area) is given by equation 1 (Laboratory of Water Authority of Jordan files):

$$\delta D = 6 \times \delta^{18}O + 9.3. \tag{1}$$

Figure 5 shows the stable isotopic composition of groundwater from the Kurnub and Alluvial aquifers, along with the stable isotopic composition of the Ain Maghara spring water. The very light stable isotopic composition of groundwater in the Kurnub formation indicates water that was recharged during the last glacial period. The groundwater in the alluvial aquifer generally falls along the local meteoric water line. It is interesting to note that the stable isotopic composition of water from Ain Maghara spring falls between these two sources of water. This may be an indication of mixing between the two sources of water. To further investigate this hypothesis, the hydrochemistry of the water was used to support or refute this possibility.

Figure 6 shows all of the water samples plotted on a Piper diagram. The water of Maghara spring has a salinity of about 1050 mg/l. It is classified as sodium bicarbonate water with prevailing SO_4 and Cl, with the following ionic sequences: $r\text{HCO}_3 > r\text{Cl} > r\text{SO}_4$. The groundwater from the Kurnub sandstone aquifer in wells CA3025 and CA3026 has a good quality, but it is interesting to note that both the chemistry and the temperature differs between these two wells. The groundwater of well CA3025 is characterized as sodium chloride water with prevailing SO_4 and Cl, with the following ionic sequences: $r\text{Cl} > r\text{HCO}_3 > r\text{SO}_4$. The groundwater of well CA3026 is classified as sodium bicarbonate water with prevailing SO_4 and Cl, with the following ionic ratio: $r\text{HCO}_3 > r\text{Cl} > r\text{SO}_4$.

The quality of groundwater of the shallow alluvial fan aquifer quickly degrades away from the core of the fan. This degradation may indicate that, as the amount of fan material decreases, the water in the aquifer is in longer contact with surrounding sediments. The main Lisan Marl contains soluble evaporite minerals such as aragonite and gypsum, which easily dissolve into groundwater. The groundwater in the Mazra'a area (CA3005, CA3006) is classified as sodium chloride with prevailing SO_4 and Cl, with the following ionic sequences $r\text{Cl} > r\text{SO}_4 > r\text{HCO}_3$. The groundwater in the Safi area (CA3019, CA1045, CA3003) is characterized as Na–Ca–HCO_3–Cl with prevailing SO_4 and Cl, with the following ionic sequences $r\text{Cl} > r\text{HCO}_3 > r\text{SO}_4$. The salinity in the Haditha area varies from 550 to 1500 mg/l. The salinity of the water in Mazra'a and Safi

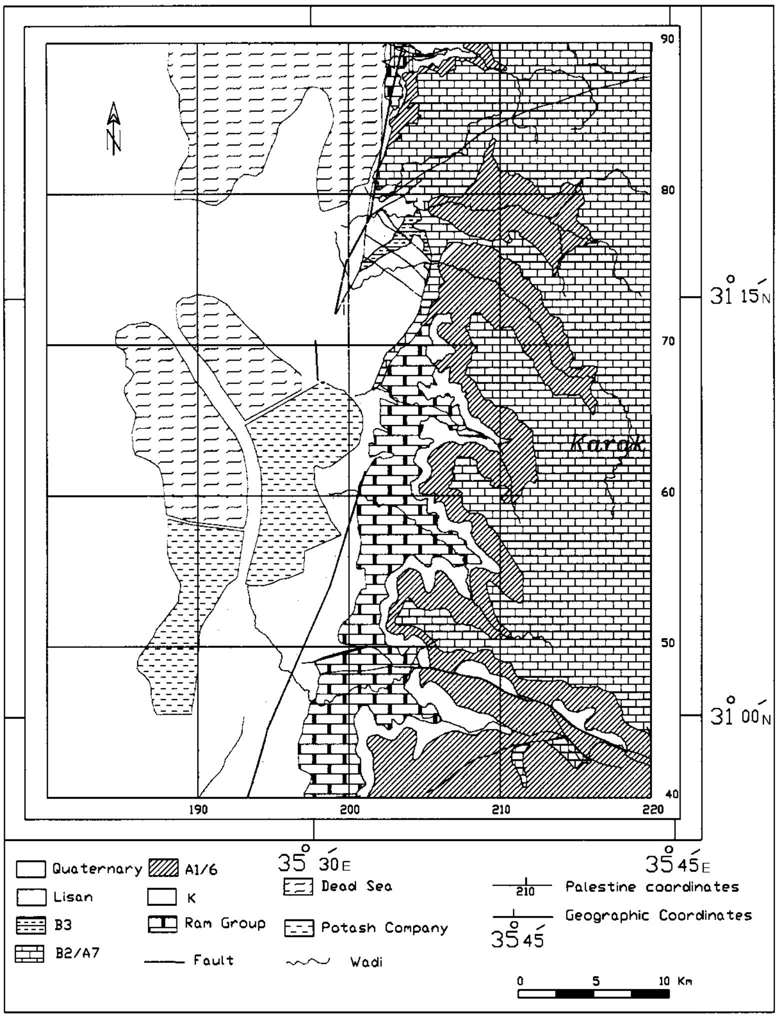

Fig. 3. Distribution of hydrogeological units.

areas ranges from 1500 to 2400 mg/l. The value of NO_3 in Mazra'a wells is around 50 mg/l; this high value is due to agricultural activities in the area (Table 2).

The difference in water types shown in Fig. 6 indicates that the water coming from Ain Maghara spring cannot be a mixture of water from the shallow alluvial aquifer and the deeper Kurnub sandstone aquifer (CA3025). However, from the Piper diagram (Fig. 6), the difference in water quality between groundwater from the Kurnub aquifer well CA3026 and either the shallow alluvial aquifer may be possible end-members for mixing which result in the composition of Ain Maghara spring. If this were the case, there should be a significant component of young (<50 years) water in the Ain Maghara spring water. Table 2 shows that most of the water samples collected from shallow wells had significant levels of tritium (^3H) which indicate some component of young water. However, none of the water samples analysed from the Ain Maghara spring had detectable tritium. Therefore, there is likely to be little (<20% by

Table 1. *Identification of wells*

Identification No.	Name	Altitude (msl)	Aquifer	Well depth (m)
CA0502	Ain Maghara Spring	− 325	A7	
CA3025	Ta1	− 231	Kurnub	782
CA3026	Ta2	− 183	Kurnub	828
CA3006	MPB3	− 390	Alluvial	37
CA3005	MPB1	− 370	Alluvial	40
CA1045	SPB5	− 361	Alluvial	165
CA3019	SPB17	− 390	Alluvial	56

Table 2. *Chemical and environmental isotopes analysis*

IDN	Symbols	Date	T (TU)	D (per mil)	O-18 (per mil)	C-14 (per mil)	C-13	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	HCO_3 (mg/l)	SO_4 (mg/l)	Cl (mg/l)	NO_3 (mg/l)	EC (µS/cm)	pH	*T* (°C)
Ca0502	1	29.12.97	0	− 39.6	− 7.08	23.3	− 6.1	68	27	103	11	203	116	157	2	1052	7.56	
Ca0502	2	7.7.97	0.7	− 39.4	− 6.45			61	29	103	11	209	103	167	0	1065	7.4	28.2
Ca0502	3	21.9.97	0.5	− 41.1	− 6			61	27	107	11	193	101	158	36	1056	7.4	
Ca0502	D	7.8.96						73	29	53	7	172	144	93	0	854	7.6	
Ca3025	F	17.12.97	0.8	− 50.7	− 6.9	0.55	− 4.1	139	52	164	26	244	79	468	2	1944	7.4	
Ca3025	G	7.7.97	0	− 51	− 6.96			114	47	145	23	227	61	412	0	1769	7.2	42.3
Ca3025	E	1.9.93						70	32	130	5	305	150	182	0	1100		
Ca3026	H	17.12.97	0	− 51.5	− 6.86	0.74	− 4.1	71	21	101	14	229	89	162	1	1005	7.31	
Ca3026	I	7.7.97	0.2	− 50.85	− 6.98			74	24	97	13	253	87	155	0	1063	7.3	47.2
Ca3026	J	21.9.97	0.3	− 51	− 6.85			76	20	100	14	227	96	159	1	1040	6.91	
Ca3005	4	7.7.97	1.8	− 31.95	− 5.66			151	69	124	18	268	253	323	11	1933	7.3	28.7
Ca3005	5	21.9.97	1.8	− 31.4	− 5.18			152	82	130	18	256	288	356	16	2110	7.33	
Ca3006	6	17.12.97	0.7	− 33.4	− 5.22	58.01	− 7.7	206	93	180	20	272	405	443	49	2410	7.22	
Ca3006	7	7.7.97	2.2	− 32.75	− 5.25			188	83	164	16	260	321	433	50	2390	7.2	29
Ca3006	8	21.9.97	2.2	− 33	− 5.42			184	93	171	17	234	387	433	50	2500	7.33	
Ca3019	9	7.7.97	0.7	− 34.6	− 5.54			88	55	134	13	240	193	253	2	1524	7.61	26.8
Ca3019	A	21.9.97	0.6	− 33.5	− 5.29			99	53	130	13	256	173	276	2	1590	7.67	
Ca1045	B	15.7.97	1.7	− 34.9	− 5.66			126	60	126	13	218	190	310	42	1732	7.4	26.1
Ca1045	C	21.9.97	1.6	− 35	− 5.41			126	59	122	12	189	227	296	41	1735	7.41	

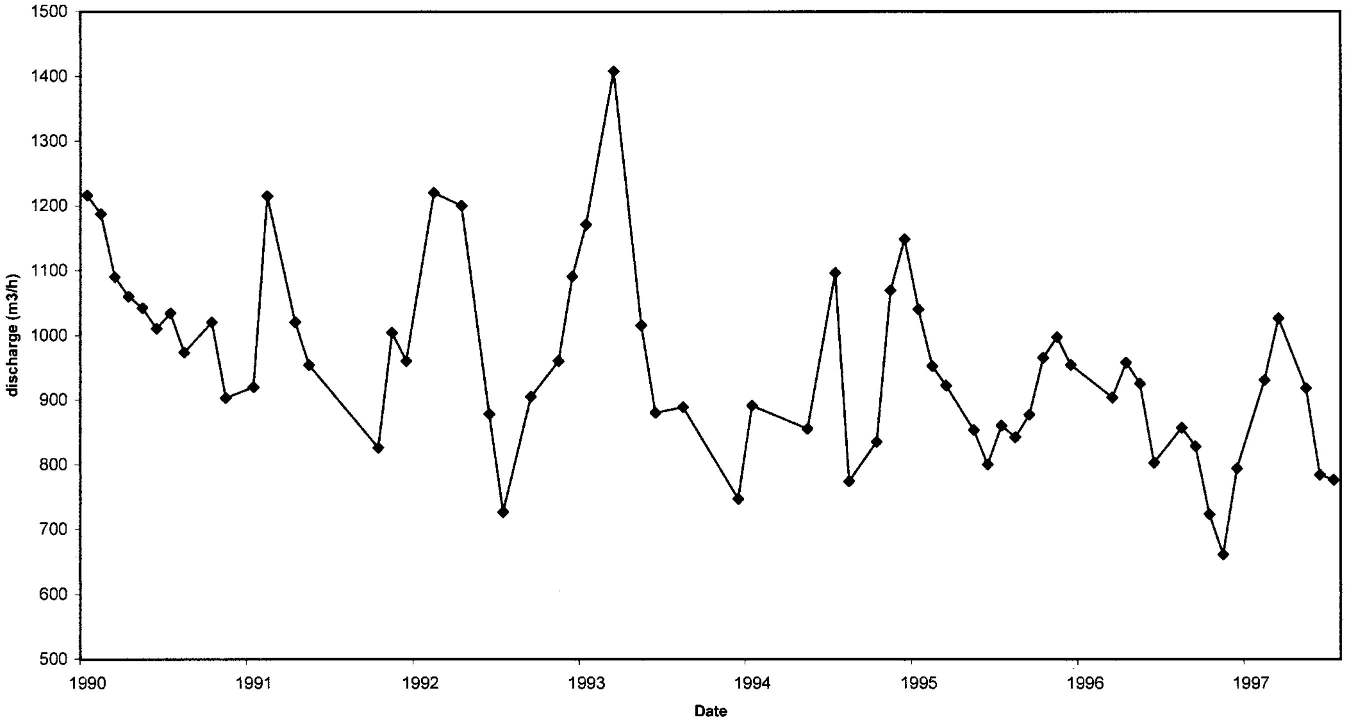

Fig. 4. Maghara Spring discharge.

volume) young water, either wadi recharge or alluvial groundwater, as a component of Ain Maghara spring water. Thus, a combination of tritium and hydrochemistry data suggest that an alternative hypothesis for the stable isotopic composition of Ain Maghara spring water should be considered.

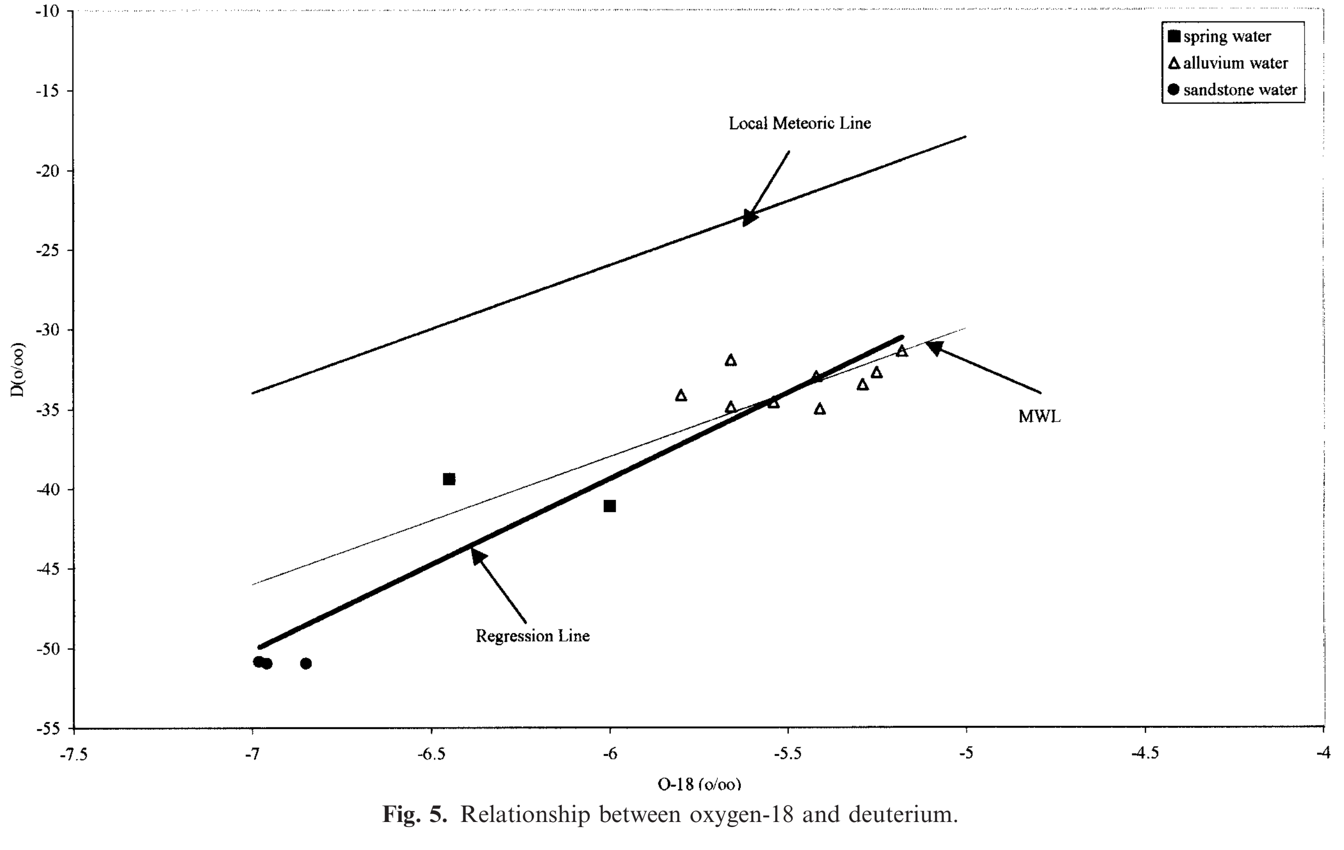

Fig. 5. Relationship between oxygen-18 and deuterium.

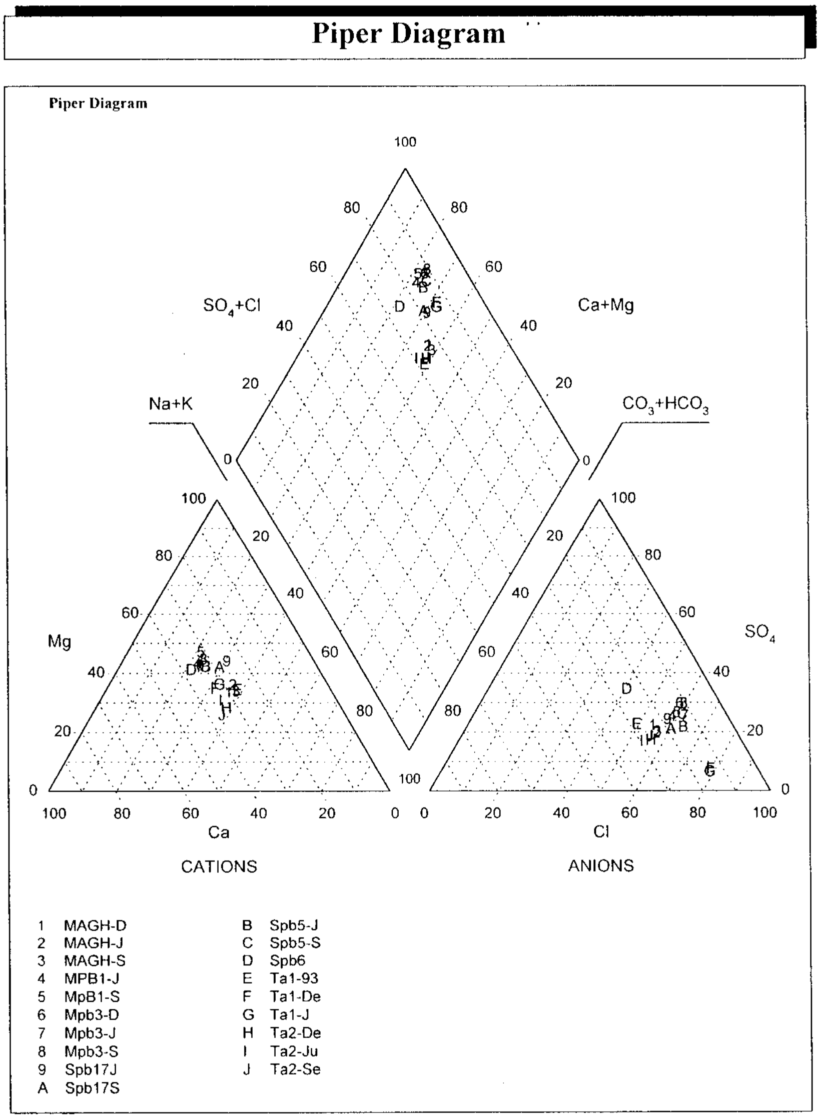

Fig. 6. Trilinear plot of the major ions.

The ten precipitation stations that were used to determine the local (Jordan) meteoric water line range in elevation from − 220 to 1500 msl, Table 3.

Using the weighted mean δD and $\delta^{18}O$ data for precipitation samples collected from these sites allows a regression relationship to be calculated between δD or $\delta^{18}O$ data and the elevation of the precipitation stations. These relationships are given by:

$$\delta D = 0.84 \text{ permil}/100 \text{ m} \qquad (2a)$$

$$\delta^{18}O = 0.18 \text{ permil}/100 \text{ m}. \qquad (2b)$$

Given that the average elevation of the recharge zone for the alluvial aquifer is approximately − 200 m (msl), equations (2*a*) and (2*b*) can be used to estimate the average elevation of precipitation which recharges the B2/A7 aquifer and provides flow to the Ain Maghara

Table 3. *Regression lines for the main rainfall stations in Jordan*

Precipitation site	Approximate distance from spring (km)	Elevation (msl)	Slope
Yarmouk University	140	555	6.63
Ras Munif	125	1150	7.47
Al Baqaa	90	700	8.61
Deir Alla	100	− 224	6.12
Lab Amman	80	900	6.87
Al Azraq	140	533	6.23
Al Wala	45	350	7.18
Al Rabba	25	970	8.51
Shobak	80	1475	5.95
Queen Alia Airport	65	715	7.94
		Avg	7.151

Source: Ministry of Water and Irrigation Data Base.

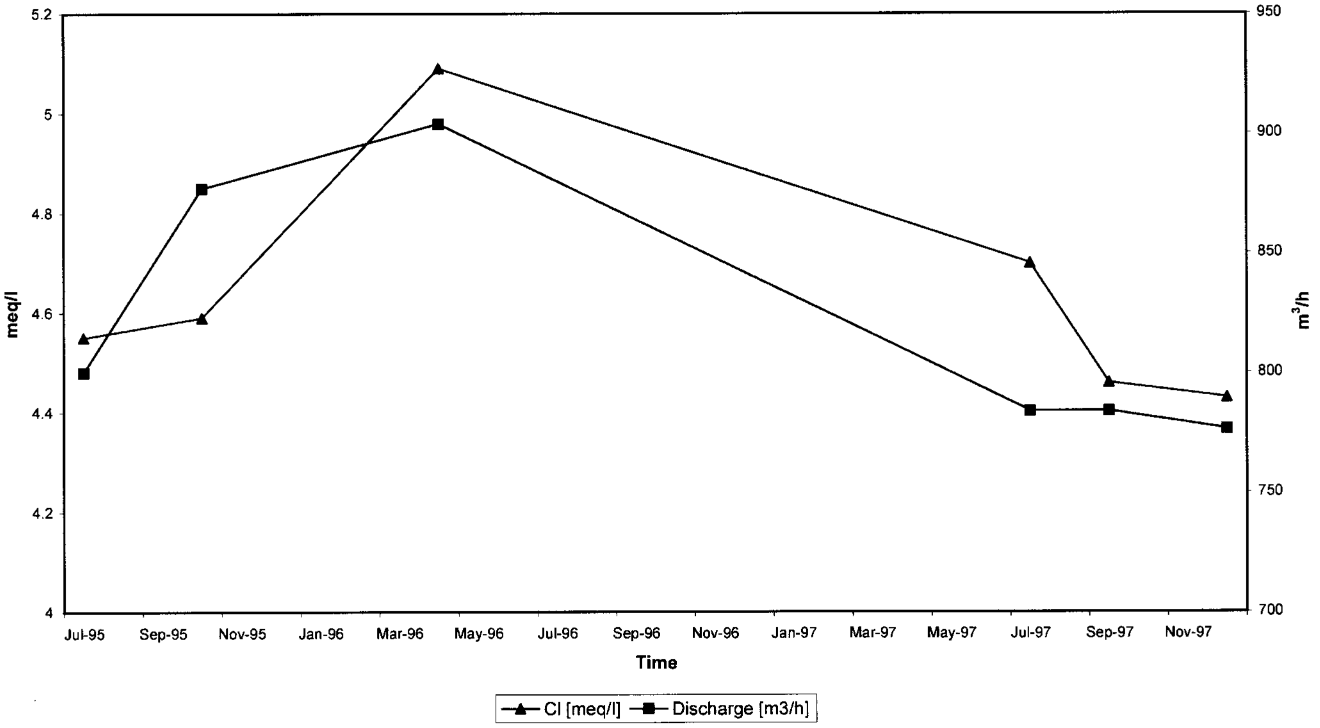

Fig. 7. Relationship between discharge and chloride.

spring. This elevation of +500 m (msl) (700 m above −200 m) indicates that recharge is occurring along the flanks of the Jordan Valley escarpment. Recharge likely increases with increasing elevation, and thus it is logical that the recharge water for Ain Maghara spring originates in the upper elevations of the Jordan valley escarpment. This hypothesis is logical and suggests that groundwater flow from recharge zone to the spring is not a simple open karst system from recharge to discharge, as there is no young water containing tritium, but rather piston flow through a complex, confined, fractured aquifer.

This hypothesis is further confirmed when consideration is given to the radiocarbon activity measured in the alluvial aquifer, Kurnub aquifer and the Ain Maghara spring. Cursory interpretation of the ^{14}C activity of these samples could suggest a confirmation of mixing between a younger (alluvial) aquifer water and very old, deep Kurnub groundwater as seen in the stable isotope data (Fig. 5). The geochemical model NETPATH (Plummer *et al.* 1991) was used to inversely model groundwater water-rock and mixing reactions, and to interpret the ^{14}C ages of groundwater (after Kalin 1996). All potential mixing models to support the hypothesis of mixing between deep and shallow water violate the phase constraint of NaCl due to low Cl concentrations in the Ain Maghara spring water. Therefore based on geochemical modelling, mixing between shallow and deep groundwater appears to be impossible.

However, some thought should be given to direct wadi recharge to the B2/A7 aquifer up-gradient of the Ain Maghara spring but, without chemical or isotopic analysis, it is not possible to consider this hypothesis. It should be noted again that the lack of tritium in the Ain Maghara spring water indicates that any young component would only be a small contribution. Figure 7 shows chloride concentrations and discharge of Ain Maghara spring. It is interesting to note there is an apparent relationship between discharge and chloride, where chloride increases with a corresponding increase in discharge. However, the magnitude of the chloride change is relatively small which most likely indicates that during higher discharge, some component of water with higher chloride concentration accentuates the base flow of Ain Maghara spring. At this time, it is not possible to identify the source of this water, however it is possible that changes in the karstic flow in the aquifer are affected by seasonal recharge.

Even though the limited ^{3}H measurements do not support a very young component, further study with other 'young water' tracers such as chloro-flouro-carbon (CFC) (Plummer *et al.* 1991) is warranted.

To interpret the ^{14}C ages of groundwater in the shallow alluvial aquifer, the deep Kurnub sandstone aquifer and the Ain Maghara spring, NETPATH was used to determine the mass transfer of minerals during the geochemical evolution of groundwater from rainfall chemistry to final sample. Much is known about the mineralogy of these units. Table 4 gives the dominant minerals, which play a role in mass transfer control of groundwater chemistry of these units, and the $\delta^{13}C$ and ^{14}C values used in calculation of ^{14}C age.

Table 4. *Minerals used in calculation of mass transfer and age calculations with NETPATH*

Aquifer	Mineral	Assumed isotopic composition	
Kurnub	Calcite	$^{13}C=+1$	$^{14}C=0$
	Dolomite	$^{13}C=+1$	$^{14}C=0$
	Halite		
	Sylvite		
	Ca/Na		
	Ion exchange		
	Gypsum		
	H_2S		
Alluvial	Calcite	$^{13}C=+1$	$^{14}C=5$
	Dolomite	$^{13}C=+1$	$^{14}C=5$
	CO_2	$^{13}C=-16$	$^{14}C=100$
	Halite		
	Sylvite		
	Ca/Na		
	Ion exchange		
	Gypsum		
B2/A7	Calcite	$^{13}C=0$	$^{14}C=0$
	Dolomite	$^{13}C=0$	$^{14}C=0$
	Gypsum		
	Halite		
	CO_2	$^{13}C=-12$ to -19	$^{14}C=100$
	Sepiolite		
	Ion exchange		

The $\delta^{13}C$ of carbonates in the sediments around the Dead Sea averages +1 permil PEE DEE Formation Belemnoid (PDB) (R. Kalin, pers comm). Therefore this value was used for geochemical modelling of the alluvial aquifer. A value of +1 permil also was assumed for the Kurnub aquifer carbonates, because the sandstone in the study area has a calcareous cement, and further study is planned to validate these assumptions. The $\delta^{13}C$ of soil CO_2 in this semi-arid region was estimated at between −12 and −16‰ (Kalin 1996, Kalin, pers comm). As expected, the groundwater in the Kurnub aquifer is very old, approximately 31 000 years in samples collected from both CA3025 and CA3026. Because tritium was found in most wells of the alluvial aquifer, it was expected that geochemical modelling and mass transfer modelling of the ^{14}C for well CA3006 would confirm a modern water. This was the case where the initial activity (A_0) calculated by mass transfer was less than the measured 58% modern carbon (MC).

The radiocarbon age of the Ain Maghara spring water was complicated by uncertainty in the initial carbon isotopic composition of CO_2. Here, a range of initial $\delta^{13}C$ values for CO_2 in the recharge zone was used, along with variable isotope exchange as mass transfer at equilibrium along the flow path. These parameters were adjusted such that the modelled and observed $\delta^{13}C$ in the Ain Maghara spring converged on the same value. Because there is uncertainty in isotopic composition of the dominant carbonate minerals and CO_2, there is a large uncertainty in the final age of the Ain Maghara spring water as modelled with NETPATH. In reality, this age represents an average age of the water and may represent water of different ages that change in ratio depending on the discharge of the spring (Table 5).

Table 5. *Ages of groundwater as modelled with NETPATH*

Aquifer	^{14}C Measured	^{14}C Age
Alluvial	58%	Modern
B2/A7	23%	2000–5000*
Kurnub	0.6%	31 000

*Dependent on assumed $\delta^{13}C$ of CO_2.

Unfortunately, there is no other local source of water originating from the aquifer (B2/A7) to be used for comparison purposes.

Conclusions and recommendations

Results of hydrochemistry and isotope hydrology data suggest that there is little or no relationship between groundwater from the deep Kurnub and shallow alluvial aquifers, and the water discharging from Ain Maghara spring. The lack of measurable tritium in the spring water suggests that the component of recent water is less than 20%. The results of stable isotope samples collected from the spring suggest an average recharge elevation of 700 m above the Jordan Valley. The range of modelled ^{14}C ages for Ain Maghara spring water (2000 to 5000 years) also supports a long residence time and flow path consistent with recharge at higher elevations and confined flow to the Jordan Valley. This, however, indicates that the water source feeding the Ain Maghara spring has a renewable origin.

Further work is needed to measure the chemistry and isotopic composition of water discharging from the spring throughout the year, and to evaluate changes in the mean water age in relation to changes in discharge and other measures of young water (such as CFC). Additional study of the water chemistry and isotopic composition of wadi flow would allow for a more complete interpretation of the influence of this water type on the discharge of Ain Maghara spring. These additional studies would further constrain the understanding of the spring for long-term management of this resource.

Acknowledgements. This study was conducted within the framework of the ongoing International Atomic Energy Agency Regional Technical Cooperation Project entitled ‘Isotope Hydrology Techniques in Water Resources Management’, RAW/8/002. The isotope samples were analysed in the isotope laboratory of the Water Authority of Jordan, and we thank the staff of that laboratory. We are grateful to Dr Yurtsever for his assistance and support, and to Eng. M. Almomani for the continuing support and valuable discussions related to application of isotope studies. We also thank Dr Kalin for assistance and discussions related to the interpretation of the data using geochemical models and geological and hydrogeological background. Eng. Mohammed Abu Ajamiyah and Dr Rakad Taani for discussions, and the staff of the Ministry of Water and Irrigation for their comments.

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Received 8 January 1999; accepted 31 August 1999