HYDROLOGICAL PROCESSES
Hydrol. Process. **21**, 2112–2123 (2007)
Published online 27 March 2007 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6390

Chloride, hydrochemical and isotope methods of groundwater recharge estimation in eastern Mediterranean areas: a case study in Jordan

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Abstract:

Jordan is classified as an arid to semi-arid country with a population according to 1999 estimates of 4·8 millions inhabitants and a growth rate of 3·4%. Efficient use of Jordan's scarce water is becoming increasingly important as the urban population grows. This study was carried out within the framework of the joint European Research project 'Groundwater recharge in the eastern Mediterranean' and describes a combined methodology for groundwater recharge estimation in Jordan, the chloride method, as well as isotopic and hydrochemical approaches. Recharge estimations using the chloride method range from 14 mm year^{-1} (mean annual precipitation of 500 mm) for a shallow and stony soil to values of 3·7 mm year^{-1} for a thick desert soil (mean annual precipitation of 100 mm) and values of well below 1 mm year^{-1} for thick alluvial deposits (mean annual rainfall of 250 mm). Isotopically, most of the groundwater in the Hammad basin, east Jordan, falls below the global meteoric water line and far away from the Mediterranean meteoric water line, suggesting that the waters are ancient and were recharged in a climate different than Mediterranean. Tritium levels in the groundwater of the Hammad basin are less than the detection limit (<1·3 TU). However, three samples in east Hammad, where the aquifer is unconfined, present tritium values between 1 and 4 TU. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS groundwater recharge; chloride method; hydrochemistry; isotopes; Jordan

Received 20 September 2005; Accepted 26 January 2006

INTRODUCTION

Groundwater recharge studies can be made in a more adequate way if different types of recharge mechanism are distinguished conceptually and if their relative importance in the climatic realm of the investigation is assessed from the beginning (Balek, 1988; Lerner *et al*., 1990; Simmers *et al*., 1997). A typical feature of dryland hydrology and a major bifurcation (Figure 1, bold circle), with respect to the regional distribution of groundwater recharge, is the sporadic development of Hortonian (Horton, 1940) overland flow. Rainfall dynamics, antecedent moisture conditions, surface and soil properties and the type of vegetation determine the onset and extent of overland flow generation. Special features, such as soil crusts, biotic films and cracks, may act as additional controls on the infiltration properties of a given soil. Once overland flow has developed, its concentration (i.e. down-slope, along streams, in pans) becomes the driving factor for the spatial distribution of recharge within the river basin (Kuells, 2003). Therefore, a major distinction is made between *direct* and *indirect* recharge mechanisms.

Figure 2 shows four major processes that contribute to groundwater recharge in semi-arid and arid regions: (A) recharge on hard-rock outcrops through fissures, cracks and large karst conduits (fracture recharge); (B) colluvial infiltration at the bottom of hill slopes, where the upper part of the hill slope acts as a 'micro-catchment' to concentrate the water; (C) streambed infiltration; (D) direct recharge by flow through the soil matrix. Commonly, (A), (B) and (C) are termed *indirect* recharge, since the prior generation of runoff is required, and (D) is called *direct* recharge. Fracture recharge (A) has been studied in the Kalahari (Mainardy, 1999; Kuells, 2003), and colluvial infiltration (B) studies have been carried out in an experimental basin in the Negev Desert, Israel (Doby *et al*., 1995; Adar *et al*., 1998; Yakirevich *et al*., 1998).

The relative importance of direct and indirect recharge mechanisms is a major criterion for the choice of adequate estimation methods. If direct recharge is the dominant recharge mechanism, then numerical or experimental analysis of vertical moisture flow is a suitable approach. Also, water balance methods or the chloride profile method can be applied. However, if indirect recharge mechanisms are dominant, then completely different approaches need to be applied. Runoff generation and distribution become important, controlling

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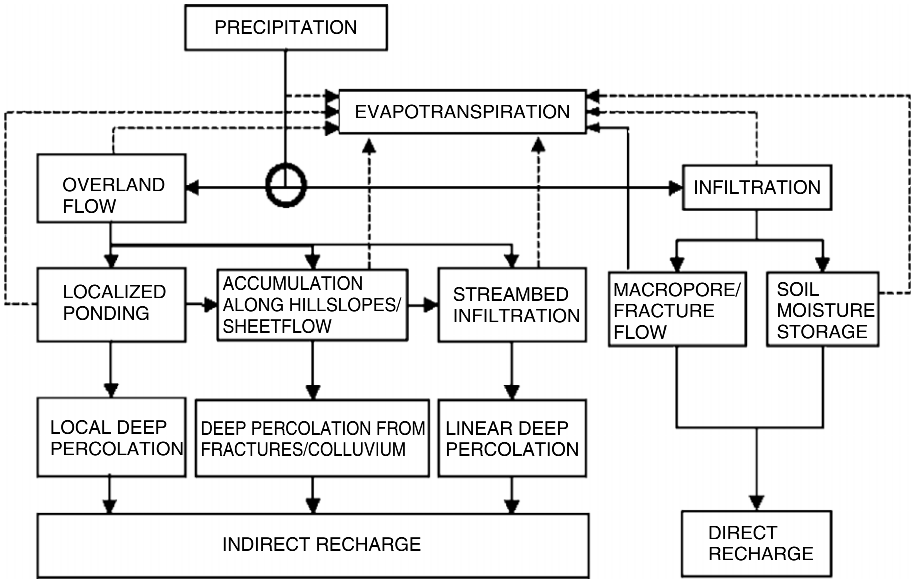

Figure 1. Flow chart of hydrological processes controlling direct and indirect recharge in arid and semi-arid environments (Lloyd, 1986, modified)

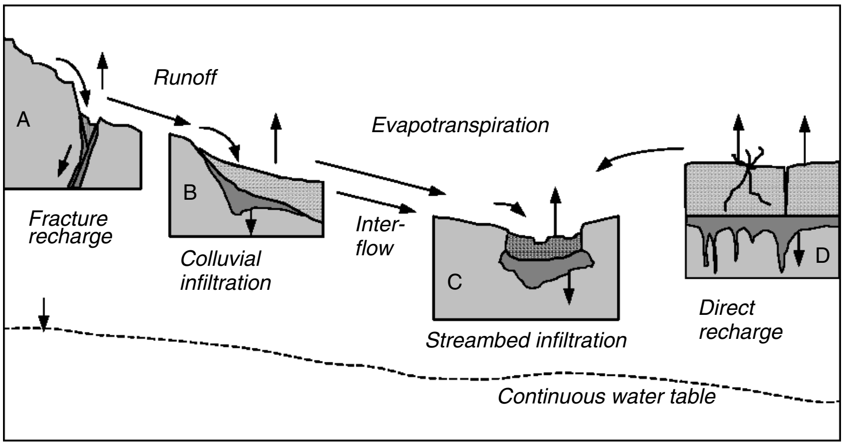

Figure 2. Conceptual model or recharge processes (Kuells, 2003)

pan recharge, transmission losses and colluvial infiltration. Preferential recharge areas need to be identified regionally. In this context, isotope and hydrochemical indicators become helpful tools and have been used for the delineation of favourable recharge areas in complex terrain. Within this study the research concentrates mainly on direct recharge through soils. As a working hypothesis, it is assumed that direct recharge processes are largely controlled by climatological conditions and by soil properties that can be quantified, such as soil texture and thickness. The main objectives of the study were to understand the relationships between climate and soil texture that govern direct groundwater recharge in Jordan. However, this concept has been combined with another direction of research. The assessment of indirect recharge components, which are controlled by complex local conditions, has been involved in the study. At the Hammad basin, east Jordan (Figure 3), an attempt is made to address the indirect recharge processes at a smaller scale by isotopic and hydrochemical studies.

STUDY AREA

Jordan

Jordan is situated at the northwestern part of the Arabian Peninsula and is bordered by the Mediterranean Sea, the Red Sea, the Indian Ocean and the Persian Gulf. It is classified as an arid to semi-arid country and has an area of about 90 000 km^2.

Owing to the topographic features of Jordan, the annual rainfall distribution varies considerably from around 600 mm in the northwest to less than 50 mm in the eastern and southeastern parts. More than 80% of Jordan receives an annual average rainfall of less than 100 mm (WAJ, 1989). Thus, the country suffers from both water scarcity and maldistribution. Surface water in Jordan is limited and depends on rainfall as the major water source. Therefore, groundwater resources are the major reliable source of water supply. Jordan's surface water is distributed in many basins, as shown in Figure 3.

In order to study recharge processes through the soil matrix under semi-arid and arid conditions, a number of stations representing a wide range of climatological and

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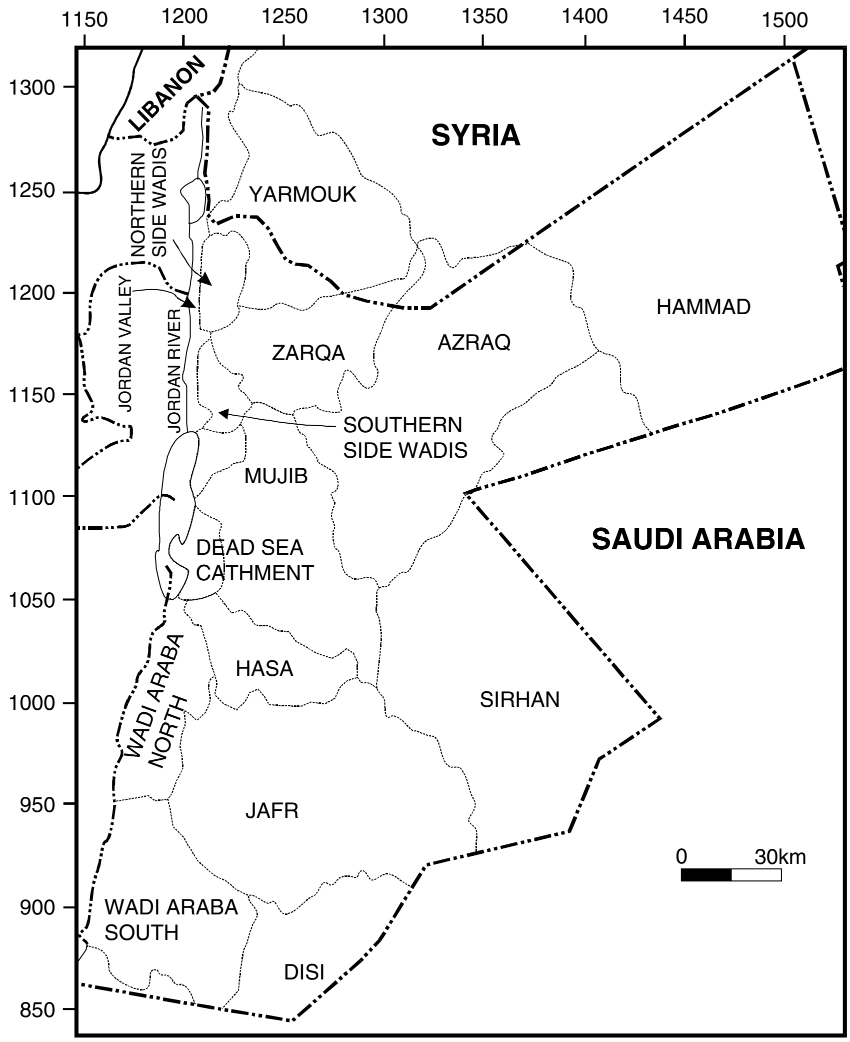

Figure 3. Surface water basins in Jordan

pedological conditions have been chosen. The study area in Jordan extends from Deir Alla near the River Jordan at an elevation of 235 m below sea level (b.s.l.) with an average precipitation of 250 mm year^{-1}, through Salt at an elevation of 1000 m above sea level (a.s.l.) with an average precipitation of 500 mm year^{-1}, through Al Zarqa/Mafraq at an elevation of 600–700 m a.s.l. and an average precipitation of 180–220 mm year^{-1}, to Safawi in the east at an elevation of 700 m a.s.l. with an average precipitation as low as 100 mm year^{-1}. These stations are shown in the context of a soil map describing the genetic properties of soils in Jordan (Figure 4). The main soil types described by Moorman (1959) are as follows:

1. Grey desert soils are developed in areas with mean rainfall ranging between 25 and 100 mm year^{-1}. They are formed in east Jordan (northeast and southeast) on lacustrine limestone of Pleistocene age, sandstone and conglomerates of Oligocene–Neogene age, and on limestone with chert layers of Palaeocene–Eocene age. They cover also basaltic rocks of Neogene and Pleistocene age in northeast Jordan (Bender, 1974).
2. Brown soils (yellow soils of Jordan) are developed in areas with mean rainfall ranging between 150 and 300 mm year^{-1}, mainly on chalk, marls and bituminous limestone of Cretaceous age.
3. Red and yellow Mediterranean soils are found in areas with higher rainfall. Yellow types are formed in areas with rainfall ranging between 250 and 350 mm year^{-1}, whereas red soils are formed in areas with rainfall above 350 mm year^{-1}. The red Mediterranean soil differs from typical terra rossa in that it is developed not only on limestone (sandy limestone and dolomite marl of lower Cretaceous age), but also on basalts and sandstones (varicoloured argillaceous sandstone, white sandstone of lower Cretaceous age) (Bender, 1974). Red soils of Jordan are rich in the calcareous content and show a very high saturation of clay complex.
4. Alluvial soils occur all over Jordan, in wadis or streambeds or flood basin areas. Their main presence is the Jordan Valley.

Deir Alla station is located in the Jordan Valley, where Lisan formations (marls, gypsum, oolitic limestone) and alluvial deposits (flood deposits) form the sediments

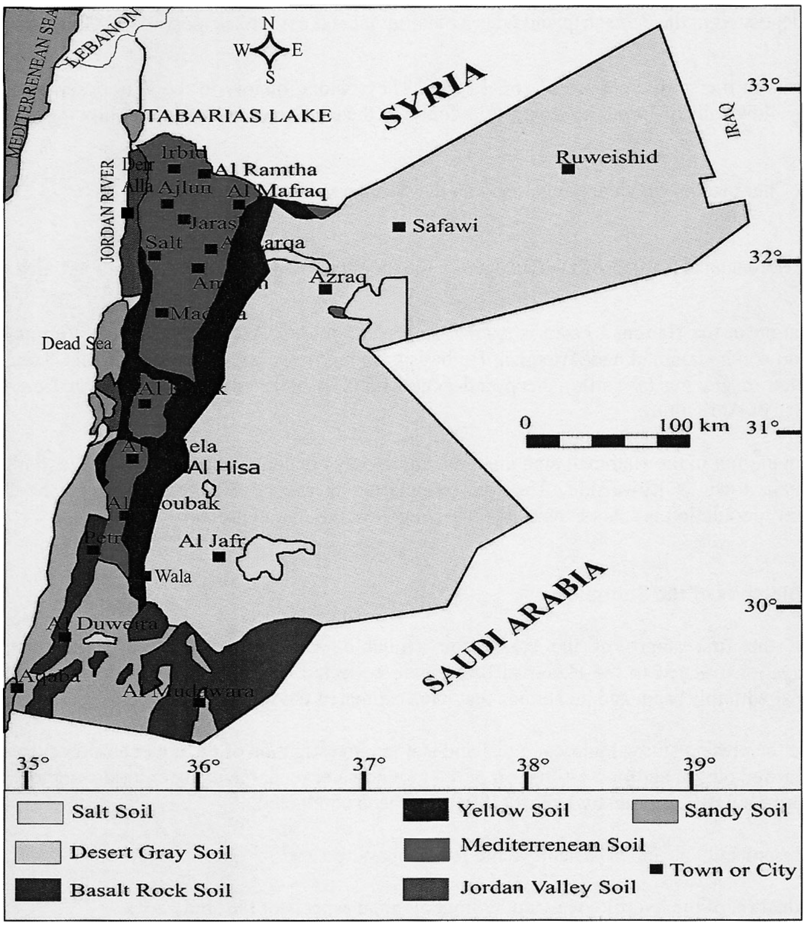

Figure 4. Map showing the study area and the soil types in Jordan (Royal Jordanian Geographic Centre (1999)), modified by (Obeidat 2001)

on which soils develop. Salt and Al Zarqa are located within or at the border of the area belonging to the Mediterranean-type soil area. Al Mafraq is located in a transition zone with basaltic bedrock; Safawi belongs to the realm of desert soils that are dominated by dust and salt accumulation.

Hammad basin

The Hammad basin is a flat plateau covering a very large area, which includes the southern part of Syria, the westernmost part of Iraq, a part of northwest Saudi Arabia, the panhandle of Jordan and a part of the Jordanian Sirhan. In the course of the present study, the Hammad basin is taken to cover the northeastern part of Jordan, east of the Azraq–Hammad catchment divide comprising an area of 18 250 km^2 (Figure 3). The western Hammad is a part of the basalt plateau, whereas the eastern Hammad is a part of the limestone plateau, with the floodplain area of the converging wadis in-between (Bender, 1974). The outcropping formations in the Hammad basin are the Rijam and Shallala in the central and eastern parts, both of Eocene age. The west Hammad is dominated by Neogene and Pleistocene basalts (see Figure 6). The Rijam formation consists of limestone, chalk and chert, and the Shallala formation consists of chalk, marl and limestone with some chert. The aquifer system in the Hammad basin comprises three complexes: the upper aquifer system, represented by the Cainozoic formations (basalt, Rijam formation, Shallala formation), the middle aquifer system, represented by the Mesozoic formations (Amman–Ajlun, the Lower Cretaceous Kurnub sandstone aquifer, Azab–Ramtha aquifer of the Jurassic–Triassic), and the lower aquifer system, represented by the Palaeozoic formations (Disi Sandstone) (WAJ, 1989). The aquifer systems are separated from each other by an aquitard/aquiclude.

METHODOLOGY

The chloride method

Environmental tracers such as chloride (Cl^-) are produced naturally in the Earth's atmosphere and are used to estimate recharge rates (Allison and Hughes, 1978; Phillips, 1994). Chloride is deposited as dry and as wet (dissolved in rainwater) fallout. Most plants do not take up chloride; therefore, it is concentrated in the soil in proportion to the actual evapotranspiration. Chloride in the soil can hence be used as an indicator of evaporative enrichment and groundwater recharge. If certain assumptions are met, then it can be stated that the lower the enrichment of chloride the higher the groundwater recharge rate. These criteria are:

1. Analysis should be made near watershed boundaries in order to avoid runoff effects.
2. No geogenic chloride should be in the soil or aquifer.
3. Enough chloride must be available in the rain.

For longer periods and steady conditions, the flux of chloride must be equal at the soil surface and below the root zone; hence, $\overline{PC_P} + \overline{D} = \overline{RC_S}$, where $\overline{P}$ is mean annual rainfall, $\overline{C_P}$ is the mean chloride concentration of rainfall, $\overline{D}$ is dry deposition, $\overline{R}$ is the mean annual recharge rate and $\overline{C_S}$ is the mean chloride concentration of soil water. The flow below the root zone can be rewritten as $\overline{RC_S} = \overline{R}\overline{C_S} + \overline{\Delta R \Delta C_S}$, where the last term is the mean of the product of respective deviations from $\overline{R}$ and $\overline{C_S}$. In general, it is assumed that this term cancels out or that there is no correlation between these variables; hence (Allison *et al.*, 1985, 1994):

$$\overline{R} = \frac{\overline{PC_P} + \overline{D}}{\overline{C_S}} \quad (1)$$

According to the model assumptions, chloride should increase in the soil and reach a steady-state value at the lower end of the root zone. Still, chloride profiles do not always have that ideal shape. Bulge-like profiles might be found, which are more difficult to explain. Such a shape can be the result of (a) non-steady conditions, (b) preferred flow paths, (c) past climatic variability—changes in the recharge rate. Diffusion wipes out vertical variability to a significant extent only with high chloride contents (>8000 g m^{-3}). Profile techniques using chloride in the unsaturated zone for groundwater recharge estimations have been successfully applied in Africa (Edmunds *et al.*, 1988), the Middle East (Edmunds and Walton, 1980), Australia (Allison and Hughes, 1978), India (Sukhija *et al.*, 1988) and North America (Stone and McGurk, 1985). The chloride technique has the important feature of integrating recharge at a given site over many years. The main source of uncertainty in applying the technique, however, lies in knowing the chemistry of rain for the antecedent period (Edmunds and Gaye, 1994). In the present study, for the Salt and Deir Alla areas, 3 years' data have been averaged (Salameh, 2001); for the Al Zarqa and Safawi areas, 2 years' data have been averaged (Obeidat, 2001). However, ideally, longer runs of data are considered necessary to calculate C_P. In this study, it is also assumed that dry deposition of chloride is zero; hence:

$$\overline{R} = \frac{\overline{PC_P}}{\overline{C_S}} \quad (2)$$

In order to study chloride fluxes and to estimate groundwater recharge within the frame of this study, soil lysimeters have been prepared. The sketch map (Figure 5) shows the major features of the experimental set-up. The soil is filled into a cylinder of 25·4 cm diameter; an outer cylinder surrounds this cylinder in order to reduce external (thermal) influences. The cylinder has a height (corresponding to a soil depth) of 50, 75 or 100 cm. This cylinder is exposed to the normal meteorological conditions, i.e. to rainfall, evaporation, and dry and wet deposition. The leachate of the lysimeter is sampled and analysed for major chemical elements. A total of 150 soil samples were taken at 10 cm intervals from different depths (up to 80 cm where conditions allowed) and analysed for Ca, Mg, Na, K, HCO_3, SO_4^{2-}, NO_3^-, Cl^- and water content. For the stations at Deir Alla, Salt, Zarqa and Safawi, sampling was obtained during summer and winter.

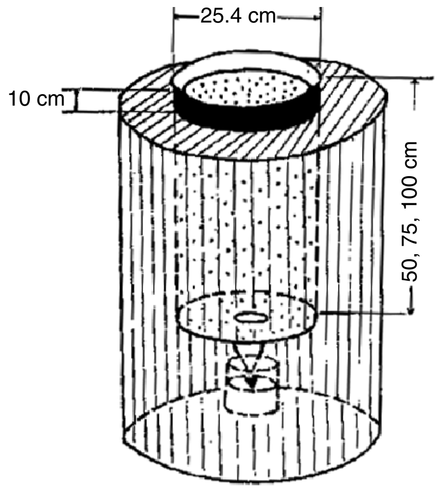

Figure 5. Lysimeter for analysis of soil water chemistry

Hydrochemical and isotopes measurements

The methods of isotope hydrology are useful and essential tools for hydrogeologists working in arid and semi-arid regions, particularly when questions have to be answered concerning the origin, mixing, residence time of the groundwater and the transport of dissolved constituents (Verhagen *et al.*, 1991). Variations in the isotopic composition of rainfall and groundwater have been mainly used in order to identify the provenance of groundwater, likely mechanisms of groundwater recharge, or recharge conditions such as altitude and degree of evaporative enrichment. In this study, hydrochemical data have been applied for delineating recharge areas and isotopes have been used for the investigation of indirect recharge processes and recharge environments.

Groundwater samples from the upper aquifer system have been collected from the Hammad basin in the eastern part of Jordan. Figure 6 shows the locations of sampling points. The water samples were analysed in the laboratory of the Department of the Hydrogeology and Environment at the University of Würzburg for their chemical and physical characteristics. Compositions of the stable isotopes (^2H, ^{18}O) and the activity of the radioactive isotope tritium (^3H) in groundwater samples were also determined. Stable isotope compositions of the groundwater were measured in the GSF (Forschungszentrum für Umwelt und Gesundheit) in Munich, whereas the activities of the radioactive tritium were measured in the Niedersächsisches Landesamt für Bodenforschung in Hannover.

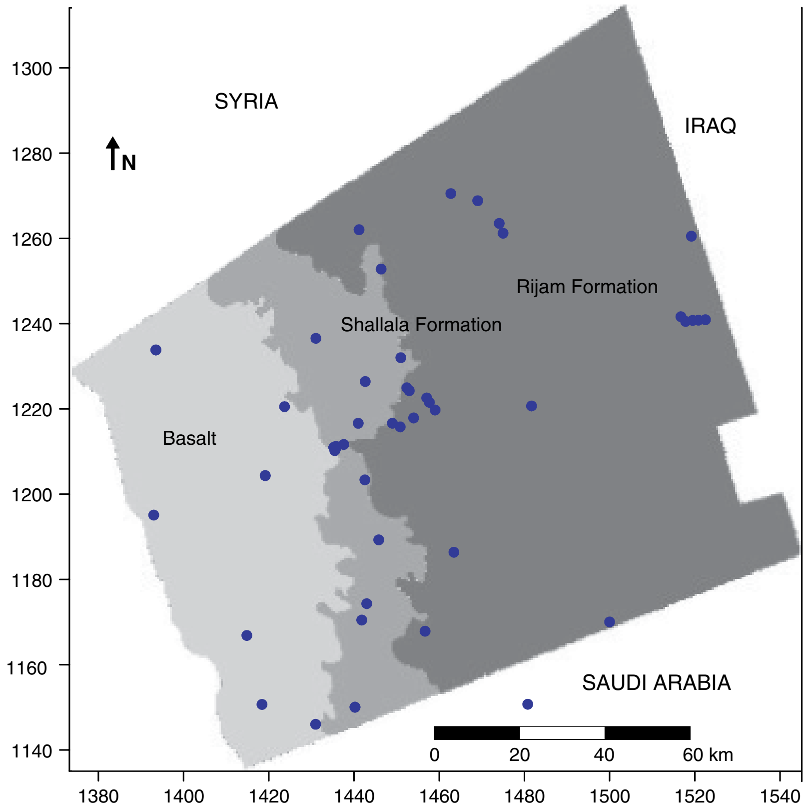

Figure 6. Location map of groundwater sampling points

Monthly rainfall samples from 11 rainfall stations from different parts of Jordan were collected and analysed for their stable isotope compositions of hydrogen and oxygen by the laboratories of the Ministry of Water and Irrigation, Jordan (Bajjali, 1990). Tritium data of precipitation from Jordan were obtained from the International Atomic Energy Authority for the period 1965–1969 and from Bajjali (1990) for the period 1987–1989. Jordan lacks long-term tritium measurements. In contrast, Bet Dagan Station, Israel, has relatively long-term measurements, which can be used as a reference for the tritium values for Jordan.

RESULTS AND DISCUSSION

Soil profiles

Figures 7–10 present the soil profiles. The analyses of chloride and solute profiles show a strong seasonal variability of solute concentrations. These variations reflect the annual infiltration/wetting and evaporation/drying cycle of soils in the study area. These observations stress the importance of the timing of sampling and monitoring over longer periods.

At Salt, the strong variation in soil water content between winter and summer can be observed (Figure 7). Although the soil water content is more or less similar with depth in winter (about 20 vol.%), it decreases down to about 3 vol.% during summer. This leads to a strong increase in chloride content within the profile. In contrast to the expected increase with depth, there is an enrichment of solute in the uppermost 2 dm. This points to upwards migration of solutes because of capillary and evaporation at the soil surface (in contrast to moisture removal by roots only). The mean rain chloride concentration in the Salt area amounts to 15 mg l^{-1} (Salameh, 2001). This would lead to an estimation of groundwater recharge of 2·7% of mean annual rainfall (14 mm year^{-1}).

The other extreme is represented by the samples taken from Zarqa. Here, a similar variation in soil moisture is found (Figure 8). However, a very strong enrichment of solutes, especially chloride, compared with known chloride input in the rainfall (25 mg l^{-1}; Obeidat, 2001) is observed. This may indicate high concentration factors and an estimated recharge rate of below 1 mm year^{-1} (i.e. 0·21 mm year^{-1}) by soil matrix flow only for an area where mean annual rainfall amounts to 180 mm year^{-1}.

In the Deir Alla area the strong variation in soil water content between winter and summer can be observed (Figure 9). Whereas the soil water content is more or less similar with depth in winter, it increases during summer (wetting by winter rainfall and drying in the upper soil horizon by drainage and evaporation during summer). A very strong enrichment of chloride within the profile during summer can also be observed. Compared with rainfall chloride concentration (16·7 mg l^{-1}; Salameh, 2001) an estimated recharge rate of below 1 mm year^{-1} (i.e. 0·31 mm year^{-1}) results. At Safawi (Hammad basin), an area where the mean annual rainfall amounts to 100 mm year^{-1} and the mean chloride concentration in rain is 31·9 mg l^{-1} (Obeidat, 2001), the estimated recharge rate

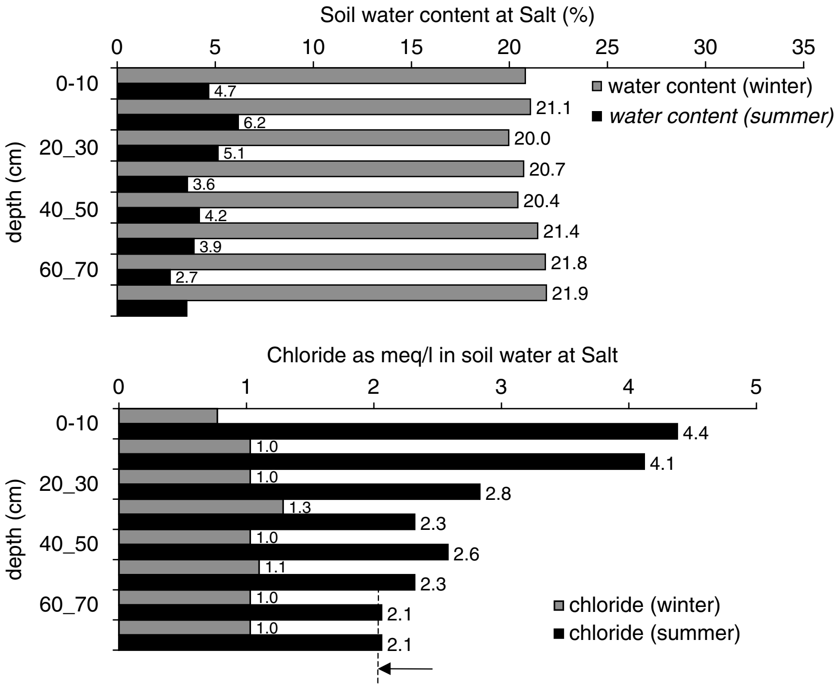

Figure 7. Soil water content and chloride concentration at different depths at Salt in winter and summer

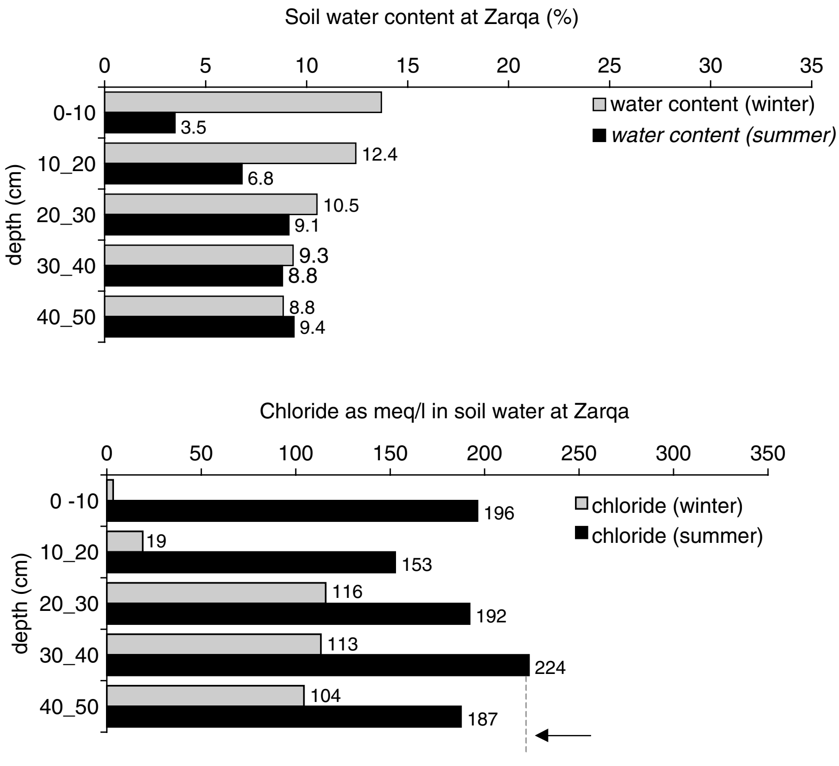

Figure 8. Soil water content and chloride concentration at different depths at Zarqa in winter and summer

amounts to 3·7 mm year^{-1}. Table I presents the estimated recharge rates in different localities in north Jordan.

The effect of different soil thickness for different climatic conditions in Jordan is summarized in Figure 11. The range of measured electrical conductivity (as a rough indicator of evaporative enrichment or reciprocal recharge) is shown as a parallel bar for soils of different depths (*y*-axis) and for different climatic groups (350–450, 200–350 and 100–200 mm year^{-1} mean annual precipitation). These results indicate that recharge through the soil matrix seems to be mainly controlled by climatology and soil thickness and that these relationships are valid over large distances in Jordan.

Hydrochemistry

The total dissolved solids (TDS) of groundwater in the Hammad basin vary from 390 to ~4000 mg l^{-1}. Groundwater samples in the southwest part of Hammad

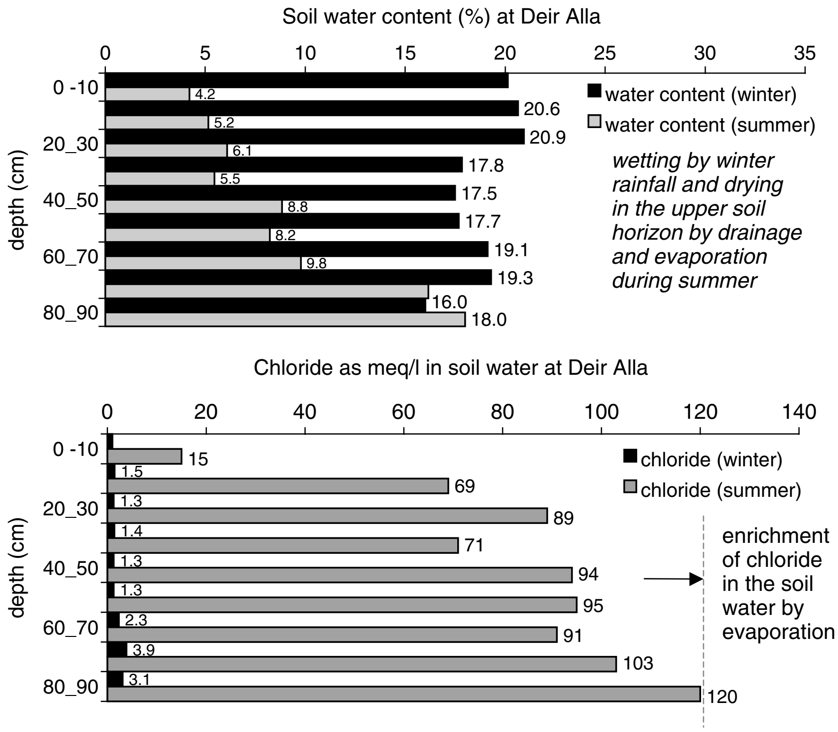

Figure 9. Soil water content and chloride concentration in different depths at Deir Alla in winter and summer

Table I. Groundwater recharge estimated using chloride method

	Salt	Zarqa	Safawi	Deir Alla
Average rainfall (mm year^{-1})	500	180	100	250
Mean Cl^- concentration of rainfall (mg l^{-1})	15	25	31·9	16·7
Mean Cl^- concentration of soil water (mg l^{-1})	539	21 700	856	13 550
Groundwater recharge (mm year^{-1})	14	0·21	3·7	0·31

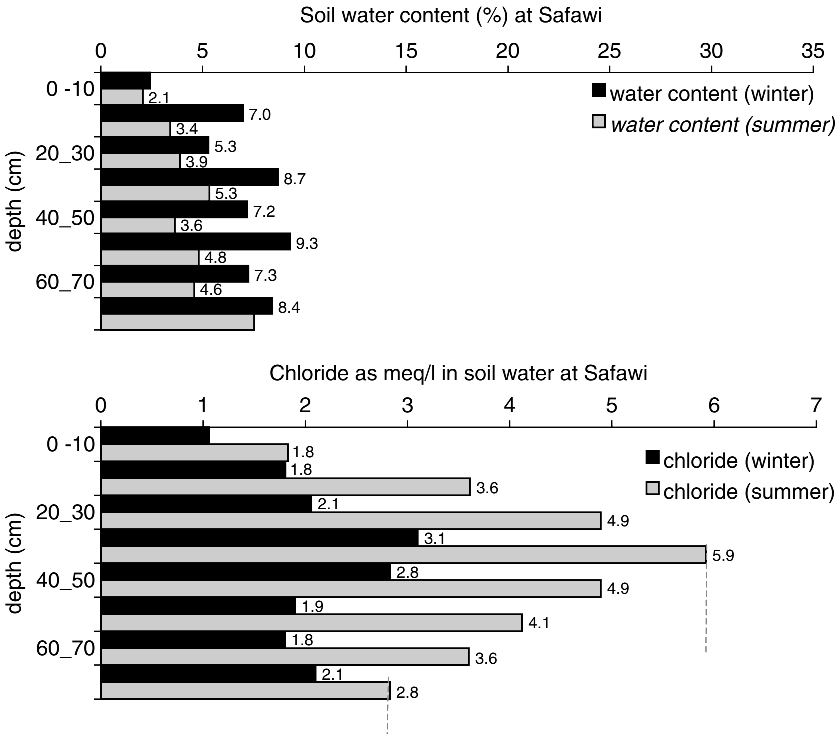

Figure 10. Soil water content and chloride concentration at different depths at Safawi in winter and summer

DOI: 10.1002/hyp

have the highest TDS values. The calculated temperature gradient is 3·7 °C per 100 m. Wells with the highest temperature are located in the basalt area in the west and southwest of Hammad basin. Chloride concentrations in groundwater range between 71 and 950 mg l^{-1}, with an average of 393 mg l^{-1}. The highest values are present in the southwest, north and east of Hammad basin. Figure 12 shows the Piper diagram of groundwater in the Hammad basin. It allows water classification into four types:

1. Alkaline earth water with increased portions of alkalis, and chloride prevailing; about 80% of the water samples belongs to this type.
2. Alkaline earth water with bicarbonate–chloride type; two samples belong to this type.
3. Alkaline water with prevailing chloride; one sample belongs to this type.
4. Alkaline earth water with prevailing chloride; one sample belongs to this type.

The first type represents fresh–brackish water of non-contemporary and almost ancient water recharge (Gat and Dansgaard, 1972; Mazor *et al*, 1973; Gat and Issar, 1974; Salameh and Rimawi, 1984) ascending from deep aquifers along major faults or it corresponds to fresh water mixed with saline water or fresh water that has passed through evaporites (Rimawi and Udluft, 1985). The second type could be interpreted as fresh groundwater of contemporary recharge (Rimawi and Udluft, 1985) and sometimes as fresh water with short percolation within the aquifer or it represents unpolluted water (Abdelnoor and Salameh, 1981).

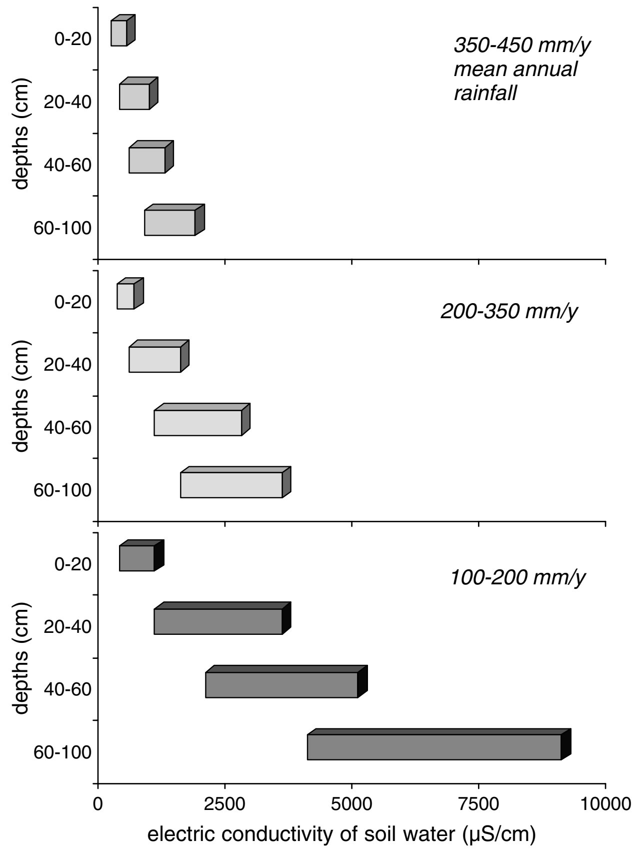

Figure 11. The effect of soil thickness to the salinity of soil water in different localities in Jordan

Isotopes

Stable isotopes $\delta^{18}O$ and δ^2H in precipitation. Table II presents the average stable isotope composition of precipitation in Jordan. By plotting the values in an ^{18}O–^2H

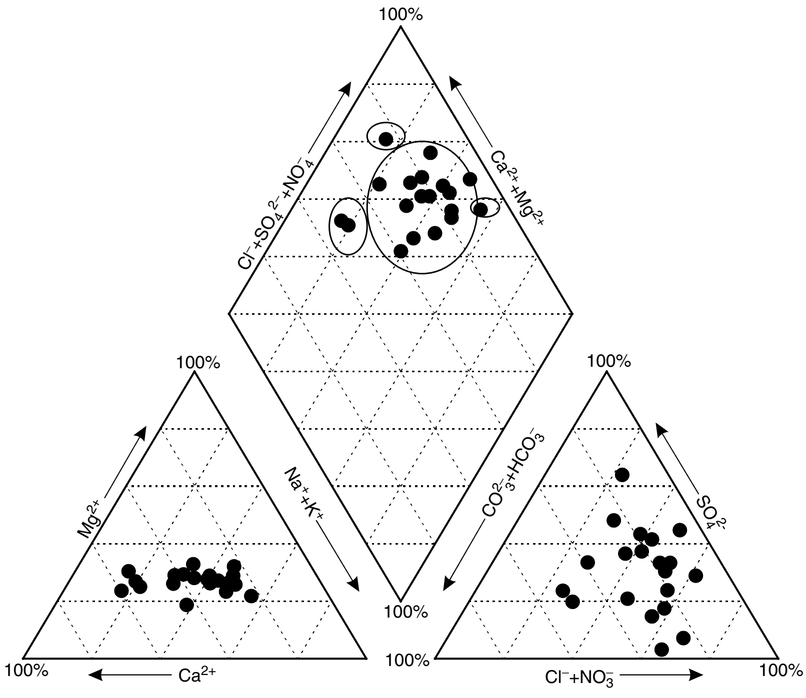

Figure 12. Piper diagram of groundwater samples in Hammad basin

diagram (Figure 13) it was observed that most of precipitation follows the Mediterranean meteoric water line (MMWL) with deuterium excess of 22‰. However, Azraq, Aqaba and Deir Alla stations lie between the MMWL and global meteoric water line (GMWL), which may indicate mixing of two moisture fluxes. These stations have low elevation and low rainfall amounts, whereas Ras Munif station presents high elevation and high amounts of rainfall and lies at the end of the line. Precipitation from Deir Alla has a δ^{18}O value of −4·04‰, whereas precipitation from Ras Munif has δ^{18}O value of −7·26‰, indicating a continental effect. The high values of the Deir Alla precipitation station could also be a result of the altitude effect.

Stable isotopes $\delta^{18}O$ and δ^2H in groundwater. Figure 14 shows the locations of groundwater samples collected from Hammad basin for isotope analyses and the contours of equal isotopic composition of groundwater. The results of the analyses are compiled in Table III. The δ^2H and δ^{18}O compositions of groundwater are plotted in a ^{2}H–^{18}O diagram and shown in Figure 15. The GMWL, the MMWL and the precipitation of Jordan are also presented. Most of the Hammad basin groundwater falls below the GMWL, suggesting that the waters are ancient and were recharged in a different climate than Mediterranean. A distinguishing feature also is that they are depleted in their δ^{18}O and δ^2H compositions with respect to the modern water of the Mediterranean. This indicates that they are fossil groundwater. Two samples are located between the GMWL and MMWL (wells H2015 and H1012), indicating that these samples are a mixture of two water types. This is supported by the tritium content of these samples. These wells are located in east Hammad, where the aquifer is unconfined. Groundwater in Hammad basin presents values of δ^{18}O ranging between −4·97 and −9·4‰ and values of δ^2H ranging between −27·3 and −71‰. Comparison of the δ^2H and δ^{18}O values of the upper aquifer system in Hammad basin with those of the upper aquifer in the neighbouring Azraq basin recorded by Rimawi (1985) and Verhagen *et al.* (1991) show that the δ^{18}O values in both basins are similar to each other, whereas the δ^2H data in Hammad basin shows relatively depleted values compared with those in Azraq basin. Deep Hammad has the most depleted values ever recorded in Jordan, being equivalent to the isotopic values of groundwater in Libya and Sudan recorded by Sonntag *et al.* (1979).

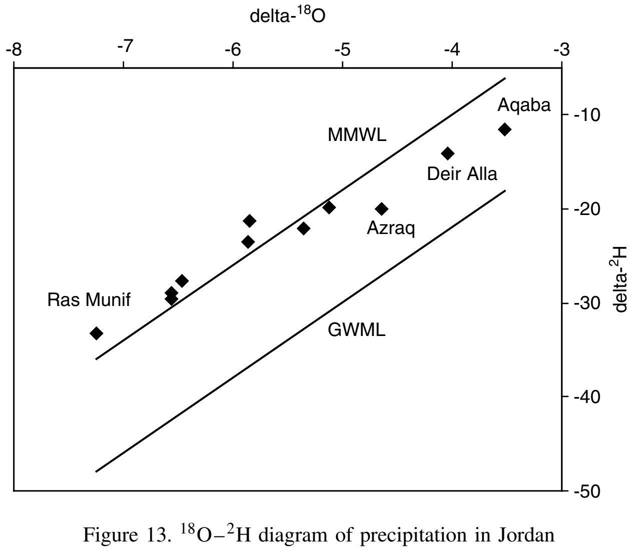

Figure 13. ^{18}O–^{2}H diagram of precipitation in Jordan

Table II. Stable isotope composition of precipitation in Jordan (Bajjali, 1990)

Station	δ^{18}O	δ^2H	Deuterium excess d (δ^2H − 8δ^{18}O)	No. of samples
Amman	−6·47	−27·72	24·04	40
Aqaba	−3·52	−11·52	16·64	4
Azraq	−4·64	−20·02	17·10	20
Baqa'	−5·85	−21·24	25·56	12
Deir Alla	−4·04	−14·05	18·27	11
Irbid	−6·56	−29·51	22·97	25
Q.A. Airport	−5·86	−23·57	23·31	13
Rabba	−5·13	−19·9	21·14	28
Ras Munif	−7·25	−33·19	24·81	15
Shobak	−6·56	−28·92	23·56	21
Walla	−5·35	−22·07	20·73	13

Tritium in precipitation. Tritium concentrations in precipitation ranges from 8·2 TU in Irbid in north Jordan to 19·6 TU in Rabba in the southeast of the Dead Sea, with an average value of about 11 TU for the period 1987–1989 (Bajjali, 1990). In Bet Dagan station in Israel,

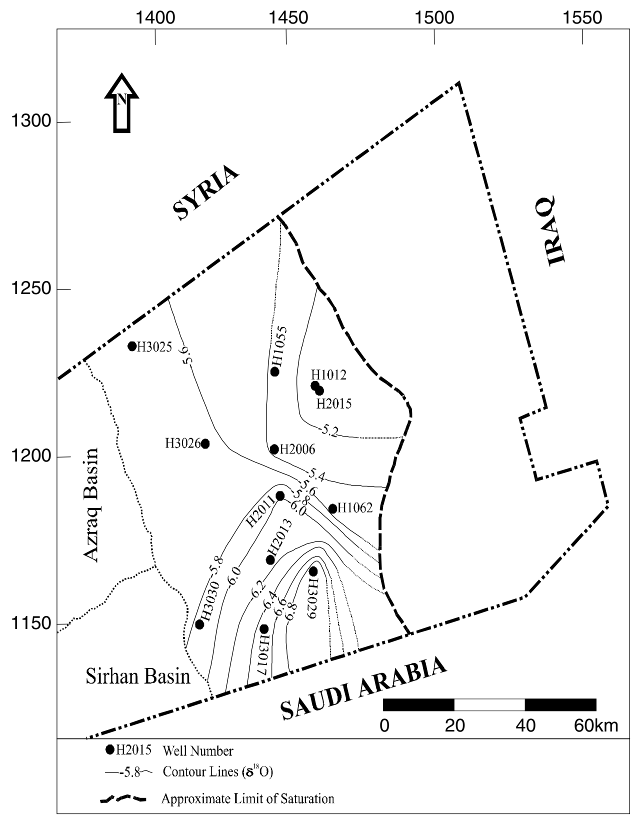

Figure 14. Location of groundwater samples for isotope analysis and contours of equal isotopic composition of groundwater in Hammad basin

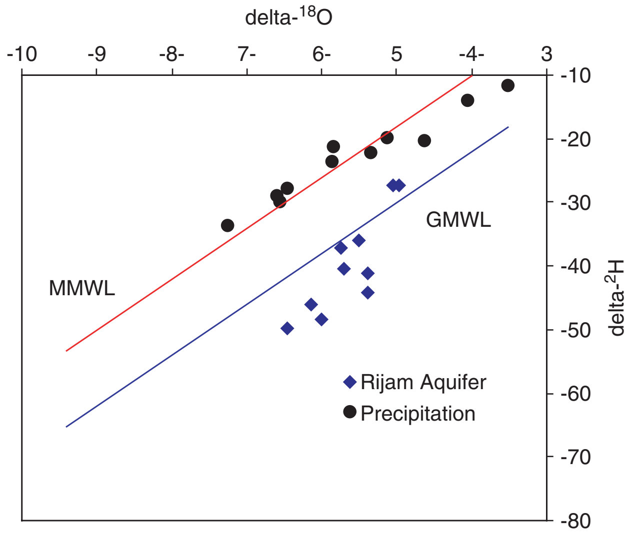

Figure 15. ^{18}O–^{2}H diagram of groundwater in the study area

Table III. Isotope composition of groundwater in Hammad basin

Sample no.	δ^2H	$\delta^{18}O$	$d = \delta^2H - 8\delta^{18}O$
H1012	−27·3	−4·97	12·46
H1055	−44·0	−5·38	−1·00
H1062	−36	−5·51	8·10
H2011	−48·4	−6·01	0
H2013	−46	−6·15	3·20
H2006	−41·1	−5·38	1·94
H1097	−32·4	−5·4	10·80
H2015	−27·3	−5·05	13·10
H3026	−40·4	−5·7	5·20
H3025[a]	−37·2	−5·74	8·72
H3017[a]	−49·7	−6·47	2·10
H3029[a]		−7·11	
H3030[a]		−5·83	
H1102	−60·2	−7·41	−1·0
H1053 (Deep H1)	−71	−9·4	4·20

[a] IAEA (1996).

the tritium concentration in precipitation reached its maximum in April 1963 with a value of 1940 TU (IAEA, 1996). Thereafter, the tritium concentration at that station has decreased, reaching a value of 7 TU.

Tritium in groundwater. Most of groundwater in Hammad basin contains tritium below the detection limit. This means that the water infiltrated prior to the atom bomb test of 1952. Only three samples contain tritium in the range of 1–4 TU, which means that a part of these wells' water infiltrated after 1952. These wells are located in the unconfined section of the Rijam aquifer, east of the Hammad basin near Wadi Ruweishid and Wadi Abu Hifna with wadi bottoms composed of sand and gravel, which may drive rapid infiltration of the wadi flow to the underlying Rijam aquifer. Excluding the three samples with detected tritium values and providing that the natural production of the tritium is 7·5 TU, the groundwater of the Rijam aquifer contains a portion of young water of less than 17·3%.

CONCLUSIONS

In Jordan, direct groundwater recharge rates have been estimated from soil chloride profiles. However, isotopic and hydrochemical approaches have been applied in Hammad basin, east Jordan, in order to address the indirect recharge processes. The result of applying these methods yields the following conclusions:

- Recharge estimations using the chloride method range from 14 mm year^{-1} (mean annual precipitation 500 mm year^{-1}) for a shallow and stony soil to values of 3·7 mm year^{-1} for a thick desert soil (mean annual precipitation of 100 m year^{-1}) and values of well below 1 mm year^{-1} for thick alluvial deposits (mean annual rainfall of 250 mm year^{-1}).
- In general, the thicker the soil profiles the higher the salinity of the infiltration water. Even in the low-precipitation regimes, the salinity of the infiltrating water remains low if the soil cover is thin (10–20 cm) or if it is missing, i.e. if rocks are outcropping.
- Based on the stable isotope compositions and radioactive isotopes, most of the Hammad basin groundwater is considered to be palaeowater (fossil groundwater) recharged during past pluvials, under conditions other than those prevailing in Jordan nowadays. It is not a part of an actively recharged flow system. Therefore, mining of groundwater resources is taking place in the Hammad basin. Present-day recharge is taking place in east Hammad, where the Rijam aquifer is unconfined, and most probably as indirect recharge.

ACKNOWLEDGEMENTS

We wish to thank Professor E. Salameh from Department of Geology, Jordan University, Amman, for helping during the 'Groundwater recharge in the eastern Mediterranean' (GREM) project.

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