ORIGINAL ARTICLE

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Characterization of surface water and groundwater in the Damascus Ghotta basin: hydrochemical and environmental isotopes approaches

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Abstract The hydrochemistry of major ions and environmental isotope compositions (^{18}O, ^{2}H and tritium) of water samples have been used to investigate the characteristics of rainfalls, surface water and groundwater in the Damascus Ghotta basin. The groundwater salinity in the Damascus Ghotta basin gradually increases, as the groundwater moves from western to south-eastern and north-eastern parts of the basin. A strong relationship exists between the Barada river and the surrounded groundwaters, mainly in terms of recharge by infiltration of surface waters. The groundwater quality in the Adra region has clearly become less saline as a result of establishment of the sewage-water-treatment station in this area since 1997. The uncommon depleted stable isotope concentrations in the vicinity of Al-Ateibeh Lake and Adra valley could be interpreted as a result of sub-flow recharge from the Cenomanian–Turonian aquifer, mostly prolonged along the Damascus Fault, which forms direct contact between this complex and the Quaternary alluvium aquifers. The extensive exploitation of water from the Cenomanian–Turonian aquifer for drinking water supply would shortly be reflected by a gradual decline of the groundwater table in the Damascus Ghotta basin. Amelioration of water quality in the Damascus basin still requires further management strategies and efforts to be taken within the forthcoming years.

Keywords Hydrology · Groundwater · Hydrochemistry · Environmental isotopes · Damascus basin · Syria

Introduction

The Damascus basin, or the so-called "Barada and Aawaj basin," is one of the most important basins in Syria. This basin was subjected to accelerated anthropogenic, economic and social developments during the last three decades. In fact, as a result of a high rate of population growth (3.7%), uncontrolled immigration towards this area, together with limited water resources [700–850 million cubic metres, after the estimations of Safadi (1974) and Hadid (1989), respectively], a sharp demand of water was envisaged to cover the different uses (drinking, irrigation and industrial activities) of water.

This problem seems to be more serious when taking into account the gradual degradation of the water quality and marked drought events recorded in the country within the last few years. In a rather recent evaluation study of water resources in the country, Rasoul-Agha (1999) assumed that the Damascus basin would not only enter a phase of water deficit in the short future, but also a critical problem, if no remedial and immediate solution actions were undertaken to correct this deficit.

Based on the importance of this basin, and in a manner to follow up the previous detailed studies, that were devoted to the evaluation of available water resources in this basin (Selkhozpromexport 1986;

La-Moreaux et al. 1989), it was necessary to make new evaluation and assessment of water resources in the Damascus Ghotta basin, by using the hydrochemical and environmental isotope methods (^{18}O, ^{2}H and tritium). Such a combination has been proved to be a valuable tool for the understanding of many hydrogeological problems (Clark and Fritz 1997; Fritz and Fontes 1980; IAEA 1980a, 1983a, b, 1987, 1991, 1995; Verhagen et al. 1991). Further importance of application of isotope techniques came from the fact that these methods can easily and successfully be used to detect the sources of water pollution (IAEA 1980b, 1998). Application of such techniques was recently introduced to the country through out several investigations in different basins of Syria (Kattan 1995, 1997a, b, 2001a, b, 2002a, b, 2004a, b; Kattan and Najjar 2005).

The present work, which was initiated within the framework of the International Atomic Energy Agency (IAEA) Regional T/C Project entitled "Isotope Hydrology For Water Resources Management (RAW/8/002)," aims: (1) to characterize hydrochemically the behaviours of water resources in terms of quality patterns; (2) to determine the hydrological and hydrogeological behaviours of surface-water and groundwater resources in terms of origin, flow regimes and sources of recharge; and (3) to identify the possible hydraulic interconnection between surface water and groundwater.

General characteristics of the study area

The Damascus basin, which covers a total area of about 8,692 km^2, is located in the south-western part of Syria and lies between 32°43′ and 33°55′ of latitude N and 35°48′ and 37°05′ of longitude E (Fig. 1). As a result of a series of tectonic, volcanic and weathering events, which already started in the late Mesozoic period (Dubertret 1932; Ponikarov 1967; Selkhozpromexport 1986; La-Moreaux et al. 1989), several fold structures appeared, such as the Mt Anti.-Lebanon [up to 2,466 m above sea level (m.a.s.l.)], Mt Hermon (2,814 m), Palmyrides (1,308 m) and Mt Arab (1,790 m). The altitude of the so-called "Damascus Ghotta basin," which occupies the flat central part between the above-mentioned fold mountains, ranges between 710 m at the foothill of Mt Qassyoun and 588 m at the Al-Hijaneh area (Fig. 2).

Climatically, the Damascus basin is of Mediterranean type of climate with a mild (10–15°C) rainy winters and absolutely dry and warm (25–27°C) summers (Selkhozpromexport 1986; JICA 2001). The air temperature value could drop down during winter season to less than 0°C at high-altitude areas (1,500–2,000 m) and reaches during summer period a value of about 42°C. The mean annual air temperature decreases from east to west, and

ranges between 16 and 17°C (altitude less than 1,000 m) and 4–5°C (altitude of 2,800 m). The relative humidity values are essentially related to temperature oscillation (JICA 2001), and thus the high mean monthly values (60–70%) were registered during the rainy season (January and February), while the lowest (24–50%) values were recorded during July and August months. The long-term mean annual potential evaporation varies between 1,500 mm in the flat lands and 1,100 mm in the mountainous areas.

Rainfall occurs only during the rainy season extended from November to May, with a maximum precipitation amount (55–60%) during December to February. Snowfall occurs mostly in the high mountainous regions. The amount of precipitation decreases eastwards, and varies from 800 mm/a in the Mt Hermon to less than 90 mm/a in the vicinity of Al-Ateibeh and Al-Hijaneh region.

The hydrological features of the Damascus basin are primarily influenced by the diverse climatic, topographic, geomorphic, geological and ecological conditions prevailing in this area. Therefore, the drainage network is eventually dense on the mountain slopes, and disappears completely in the low flat lands in the southern and south-eastern part of the basin.

The Barada river with its total long rounded 65 km, and a catchment area rounded 2,400 km^2, is the major stream in the Damascus basin. This river takes its resources from the Barada spring located in the central zone of the Zabadani valley. Before joining the Figeh spring, situated on its left bank, it flows southwards within the alluvium sediment in a narrow canal of 5–10 m width, and changes its flow direction and passes through a deep and narrow valley, the so-called "Barada Wadi." At the junction point with the Figeh spring, it receives a high amount of water (>50% of its discharge), especially during the flood period. Continuing its flow towards the Damascus city, the river is subdivided near the city entrance into several irrigation canals, that all traverse cultivated flat land, the so-called "Damascus Ghotta." Barada river water seldom reaches the Al-Ateibeh Lake outside the spring and flood periods.

The Aawaj river is the second important river in the Damascus basin, which is mostly characterized by a seasonal flow regime. This stream with a total long rounded 91 km and a catchments area rounded 1,480 km^2, is formed by the junction of two main affluent (Jenani and Sebarani), which are fed from a large number of springs distributed along the slopes of Mt Hermon (Fig. 2). As the river flows towards the Damascus Ghotta, it losses, if not entirely, most of its resources by the intensive exploitation of water along its course, and thus it occasionally reaches the Al-Hijaneh area.

Fig. 1 Location map of the
Damascus basin showing the
atmospheric precipitation sam-
pling sites in Syria
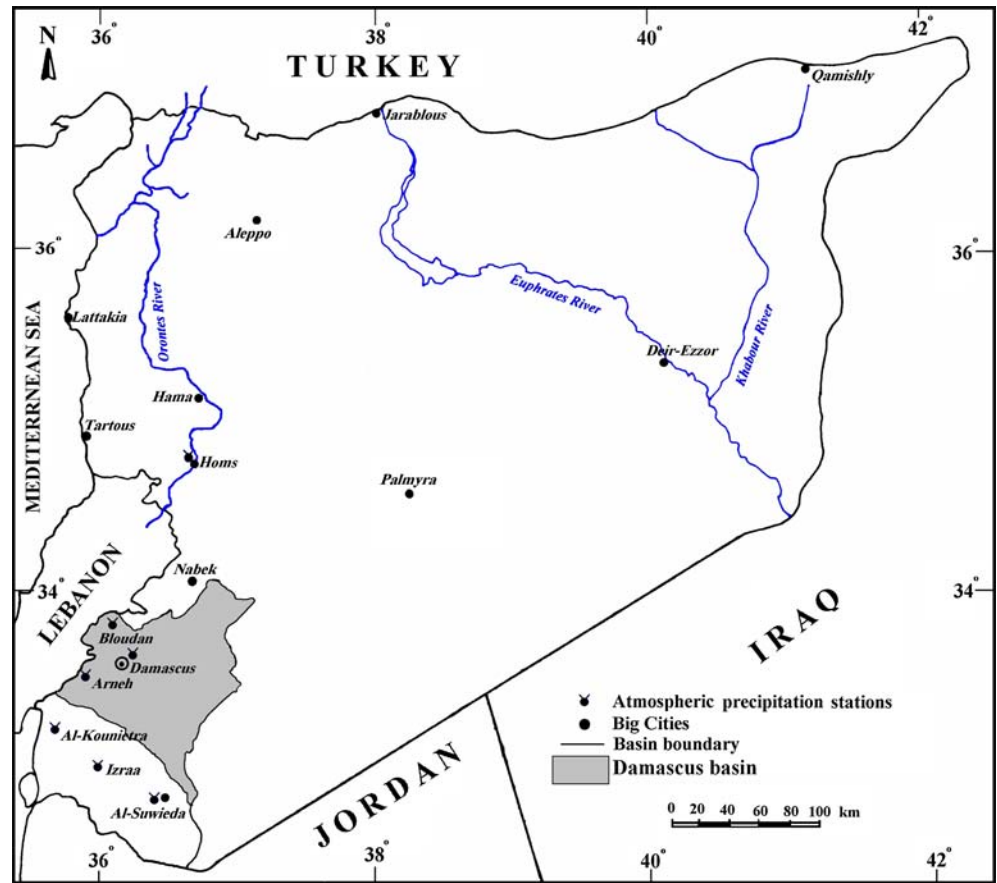
Geological and hydrogeological frameworks

From a geological point of view, the Damascus basin is
situated at the junction between two major structures:
the Mt Arab depression in the south; and the Palmy-
rides-fold system, which includes also the Mt Anti-
Lebanon, in the north and west. Consequently, the
so-called "Damascus depression," as a structure occu-
pying the central zone, forms a geologic syncline filled
with continental and lacustrine deposits and volcanic
lavas (Dubertret 1932; Ponikarov 1967; Selkhozprom-
export 1986). Accordingly, the stratigraphic sequence in
the Damascus basin is represented by the Jurassic,
Cretaceous, Paleogene, Neogene and Quaternary
deposits. Figures 3 and 4 show the geological map and
lithology of the stratigraphic column of the Damascus
basin, respectively.

The groundwater in the Damascus basin could be-
long to 14 different bearing systems (Selkhozpromexport
1986). However, as is concerned with this study, it is
pertinent to distinguish between the following major
aquifer systems.

The Jurassic aquifer

The rocks of this system are primarily encountered on
the slopes of Mt Hermon and some parts of Mt Anti-
Lebanon. They form thick layers of karstified limestone
with interbeds of dolomite, and dolomitic limestone and
marl, with a hydraulic conductivity value ranging be-
tween 2 and 99.3 m/d, and thus the transmissivity could
attain a value of about 3,085 m^2/d. The groundwater in
this aquifer is usually fresh [0.2 < total dissolved solid
(TDS) < 0.5 g/l] and characterized by a bicarbonate
calcium–magnesium type. It could be more saline
(0.6 < TDS < 0.7 g/l) and of a sulphate calcium type,
as it is the case of the Sebarani water (main affluent of
Aawaj river). The springs of Barada (average dis-
charge = 3.1 m^3/s), Bet Jin (0.84 m^3/s) and Monbouj
(0.73 m^3/s) represent the major sources emerging from
this aquifer system.

The Cenomanian–Turonian aquifer

This aquifer system (thickness 400–1,000 m), together
with that of the Jurassic, represent the most important

Fig. 2 Location map of the Damascus basin showing the sampling sites on the Barada and Aawaj rivers
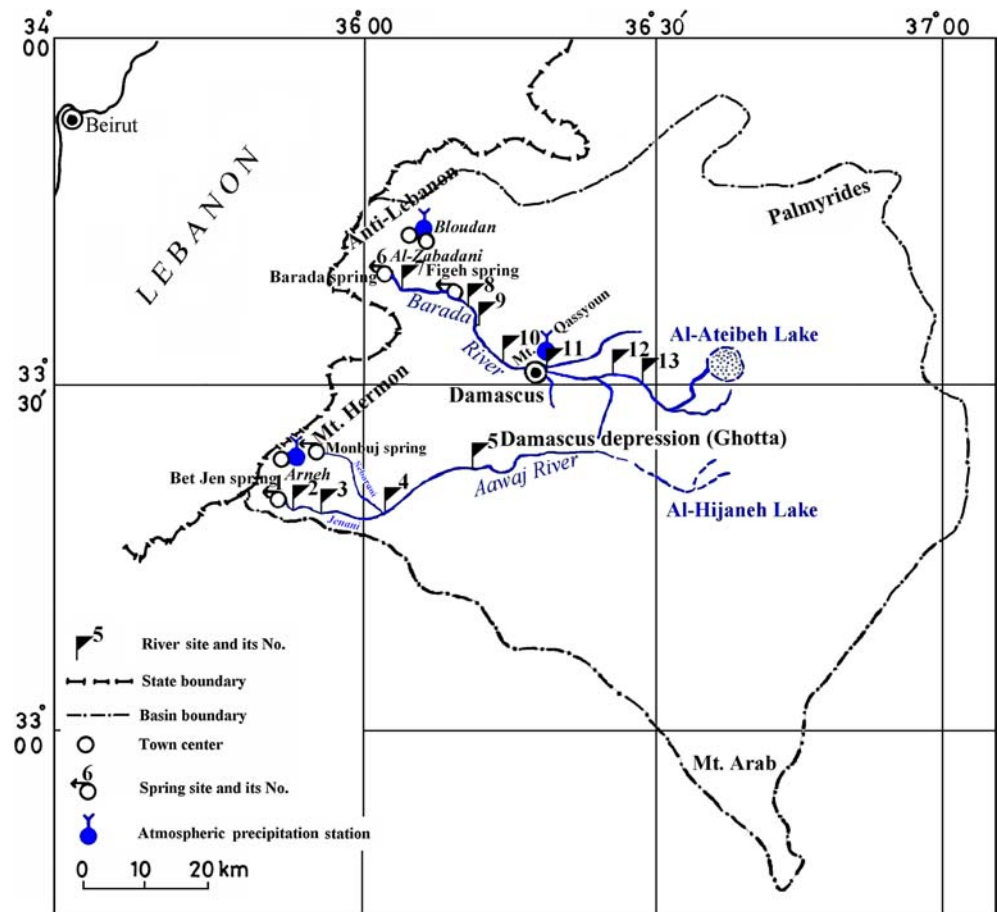
water-bearing systems in the country, in terms of storage capacity and the huge discharge of issuing springs (United Nations 1982; JICA 2001). The rocks consist of massive stratums of limestone, dolomitic limestone and crystalline dolomite with interbeds of argillaceous limestone, marl and sandstone, with a hydraulic conductivity value up to 80 m/d and a transmissivity value from 12 to 7,435 m^2/d. The importance of this aquifer system came from the high rate of fissures and large karst caves developed within this system (La-Moreaux et al. 1989). The remarkable Figeh main and side springs (average discharge = 7.7 m^3/s) represent the major sources issued from this aquifer, and could be classified as the third important large spring in the world (La-Moreaux et al. 1989). The groundwater is usually fresh (0.2 < TDS < 0.6 g/l) and of a bicarbonate calcium–magnesium type. The waters of this aquifer are intensively exploited for water supply to Damascus city.

The sedimentary Miocene–Quaternary aquifer

The rocks of this complex (thickness 140–630) are widespread on the Palmyrides slopes and the foothill of Mt Hermon. They consist of gravels and conglomerates, and associated with interbeds of clay, sandstone and limestone. As clay content increase and/or aquifer thickness decrease, the transmissivity value can drop down from 756 to 0.05 m^2/d. The groundwater quality is rather fresh (0.2 < TDS < 0.7 g/l) and the salinity level could attaint 10 g/l in some wells of Adra region.

The volcanic Middle Miocene aquifer

This aquifer (thickness up to 500 m) overlays the sedimentary Middle Miocene, and was reached in the several wells drilled in the Al-Ateibeh and Al-Hijaneh Lakes. It consists of fissured basalts associated with thin beds and lens of sand and sandstone, with a transmissivity value of about 30–60 m^2/d. The groundwater quality, which is rather fresh (0.3 < TDS < 0.8 g/l), becomes more saline in the vicinity of Al-Ateibeh and Al-Hijaneh Lakes (TDS > 2 g/l), and of a chloride or chloride-sulphate content.

Fig. 3 Geological map and cross-section of the Damascus basin. 1: Jurassic; 2: Lower Cretaceous; 3: Cenomanian-Turonian; 4: Upper Cretaceous; 5: Paleogene; 6: Neogene; 7: Neogene basalt; 8: Quaternary; 9: Quaternary basalt
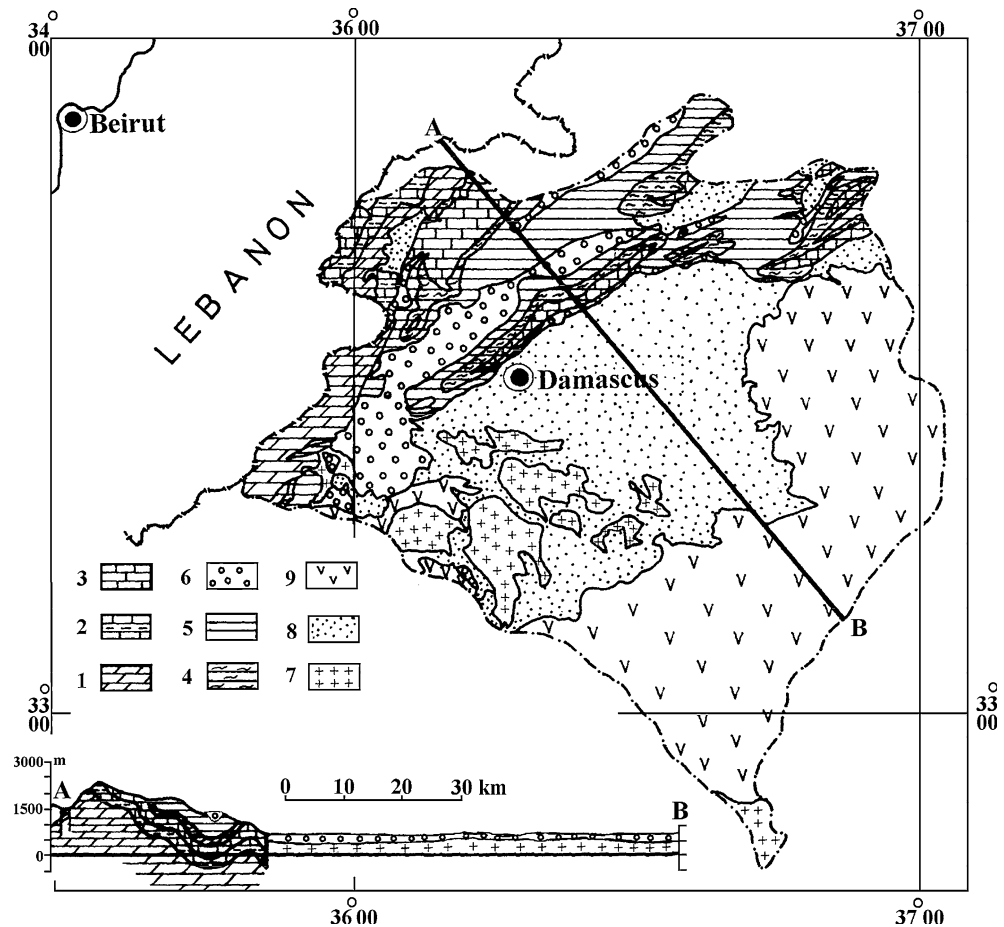
The lacustrine Upper Quaternary aquifer

This aquifer (up to 300 m) overlays the Middle Miocene basalts in the south-eastern part of Damascus depression near Al-Ateibeh and Al-Hijaneh Lakes, where it is made up of loam and clay and few beds of sand. While, in the western and northern parts it overlays the lacustrine and alluvial sediments of the Lower- and Middle-Quaternary ages, and mostly become composed of limestone and marl with beds of clays. The hydraulic conductivity ranges between 2 and 14 m/d, and occasionally could attain 88 m/d, and the transmissivity value varies from 39 to 1,485 m^2/d. This aquifer contains mostly brackish water (1 < TDS < 4 g/l) of a chloride sodium or chloride sulphate calcium–sodium content. The salinity could attain in the region of Al-Ateibeh and Al-Hijaneh a value of 10 g/l.
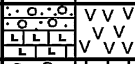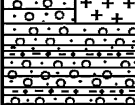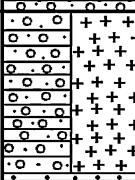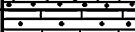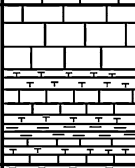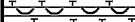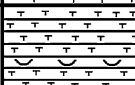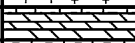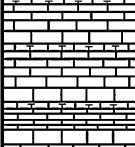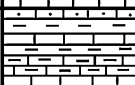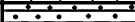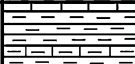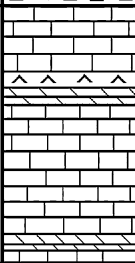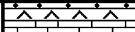
The alluvial Upper-Recent Quaternary aquifer

The sediments of this aquifer (thickness 70–90 m) are widely developed in the Damascus depression, and consist mainly of pebble, gravel, loam and sandy clays and laterally change to pebble conglomerates with carbonate and clay cement or to lenses of clayey sand of a thickness of 5–7 m. The upper part (15–20 m) of this aquifer is mostly made up of alluvial–proluvial materials, mainly of loam and clays. The aquifer is expanded along the Mt Qassyoun, and its thickness decreases in the south and south-eastern direction (i.e. towards the Al-Ateibeh and Al-Hijaneh Lakes). The deposits cover the older alluvial and lacustrine of Lower- and Middle-Quaternary ages. The hydraulic conductivity sharply varies from 3.7 to 142 m/d, and thus the transmissivity (165–3,700 m^2/d). The water quality is commonly good (TDS < 0.9 g/l), but the aquifer system is dramatically being exploited throughout the several thousands of wells drilled within the Damascus Ghotta.

Figure 5 shows the piezometric map of the shallow groundwater in the Damascus Ghotta basin during May 1992. This map, that was prepared on the basis of data covering 36 groundwater monitoring points managed by the Ministry of Irrigation, shows generally that groundwater moves from west to east, i.e. from the elevated lands near Damascus city towards the less-elevated land in the vicinity of Al-Domeir and Al-Hijaneh areas. This direction of groundwater

Fig. 4 Geological column of the Damascus Basin

GEOLOGICAL AGE			FORMATION	MAX. THICKNESS IN METERS	LITHOLOGY
QUATERNARY	QUATERNARY		RECENT	VARIABLE	LIMESTONE
			QUATERNARY	250	DOLOMITE
TERTIARY	NEOGENE		PLIOCENE	550	MARL
			MIOCENE	650	OOLITIC LIMESTONE
	PALEOGENE		OLIGOCENE	100	LACUSTRINE CARBONATE
			EOCENE	850	CLAYEY LIMESTONE
			PALEOCENE	100	SANDY CLAY
MESOZOIC	CRETACEOUS		SENONIAN	330	CLAY
			TURONIAN	120	SANDSTONE
			CENOMANIAN	570	CONGLOMERATE
			ALBIAN	270	PEBBLE, GRAVEL AND SANDY LOUM
			APTIAN	60	ANHYDRITE & GYPSUM
	JURASSIC		UPPER JURASSIC	400	CHERT
			MIDDLE JURASSIC	1700	NEOGENE BASALTS
			LOWER JURASSIC	150	QUATERNARY BASALTS

movement is identical to that of the Barada and Aawaj river flows. The hydraulic head changes from 700 m.a.s.l., near Damascus city, to less than 560 m.a.s.l. in the vicinity of Al-Hijaneh Lake, and the groundwater movement agrees well with the regional groundwater flow, previously shown by Selkhozpromexport (1986).

Sampling and analyses

Several sampling campaigns were undertaken in the study area during 1998–1999. The designed network for surface-water sampling includes 11 sites distributed along the courses of Barada and Aawaj rivers (Fig. 2),
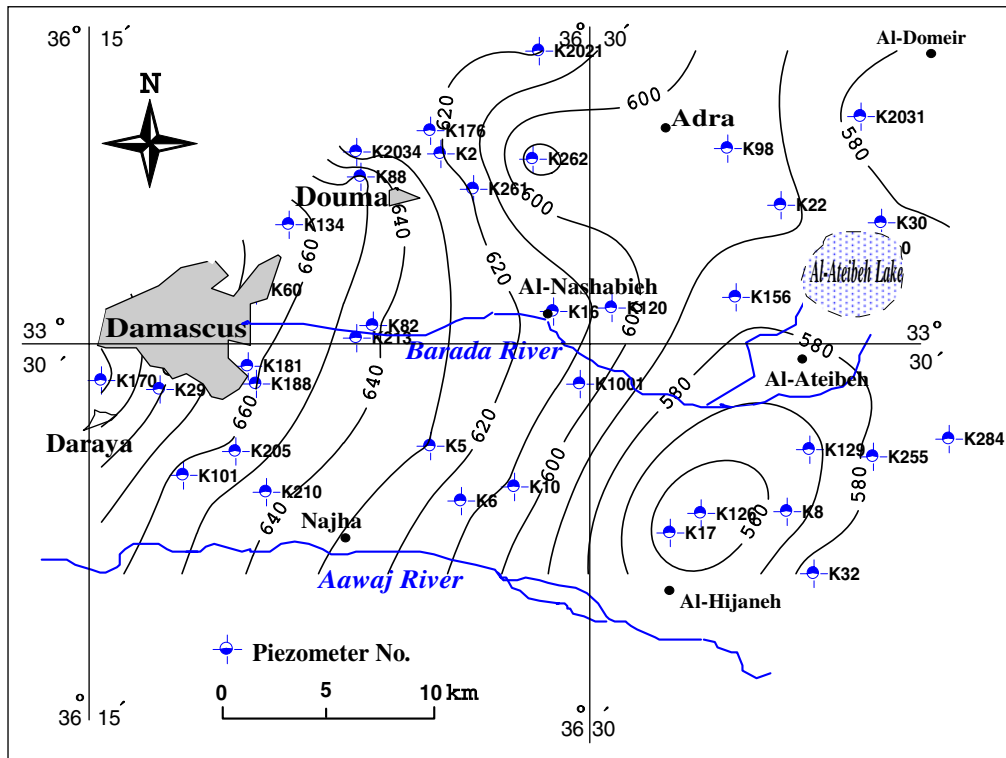
Fig. 5 Piezometric map of the shallow groundwater in the Damascus Ghotta basin during May 1992, after the Ministry of Irrigation data

while the groundwater samples were collected from 25 boreholes and dug wells of the shallow aquifers (Fig. 6), including those of the major karst springs of Barada and Bet Jin. Table 1 compiles the general characteristics of the sampling sites and collected water samples during 1998–1999.

Water samples were collected in four rinsed polyethylene bottles: one 0.5-lbottle was filled and acidified for the determination of concentrations of major cations; another 0.5-l bottle was taken for the determination of concentration of major anions, a bottle of 1-l capacity was collected for tritium measurement; and a small bottle of 50 ml was taken for the determination of stable isotopes (δ^{18}O and δ^{2}H). The geographical coordinate of the sampling sites, temperature, electrical conductivity (EC), pH, dissolved oxygen (DO$_2$) as well as total alkalinity (as HCO$_3^-$) of water samples were measured in the field during sampling.

Analyses of major cations (Ca^{2+}, Mg^{2+}, Na$^+$ and K$^+$, by atomic absorption method) together with the analyses of major anions [Cl$^-$, SO$_4^{2-}$ and NO$_3^-$, by high-pressure liquid chromatography method (HPLC) after filtration through 0.45 μm], of all water samples were performed in the Chemistry Department Labs at the Atomic Energy Commission of Syria (AECS). Analyses of stable isotopes (δ^{18}O and δ^{2}H) were performed by a Delta-E Finnigan Mat mass spectrometer in the Isotope Hydrology Lab of the Jordanian Water Authority in Amman. Analyses of tritium content were also performed (after electrolysis) in the Isotope Hydrology Lab in Amman by using a liquid scintillation counter (Packard 3253). Measurement accuracy for δ^{18}O and δ^{2}H and tritium are ± 0.1, $\pm 1.0\%$, and ± 1 TU, respectively.

Chemistry of atmospheric precipitation

Results of the weighted mean chemical composition of rainfall samples collected from a network of eight stations during the rainy seasons of 1989–1993 (Table 2) were used to interpret the chemical characteristic of meteoric water in the study area. Only three stations (Arneh, Bloudan and Damascus) belong to the Damascus basin (Fig. 1), while the remaining other stations (Al-Kounietra, Al-Suwieda, Izraa, Homs and Tartous) are located around the Damascus basin. Rainfall samples were collected on a monthly basis, and the weighted mean value was calculated by using the following equation (Yurtsever and Gat 1981):

$$C_{\mathrm{w}} = \frac{\sum_i^n [P_i C_i]}{\sum_i^n [P_i]} \tag{1}$$

where: C_w is weighted mean, P_i is amount of monthly precipitation and C_i is chemical composition of rainfall for the month i.
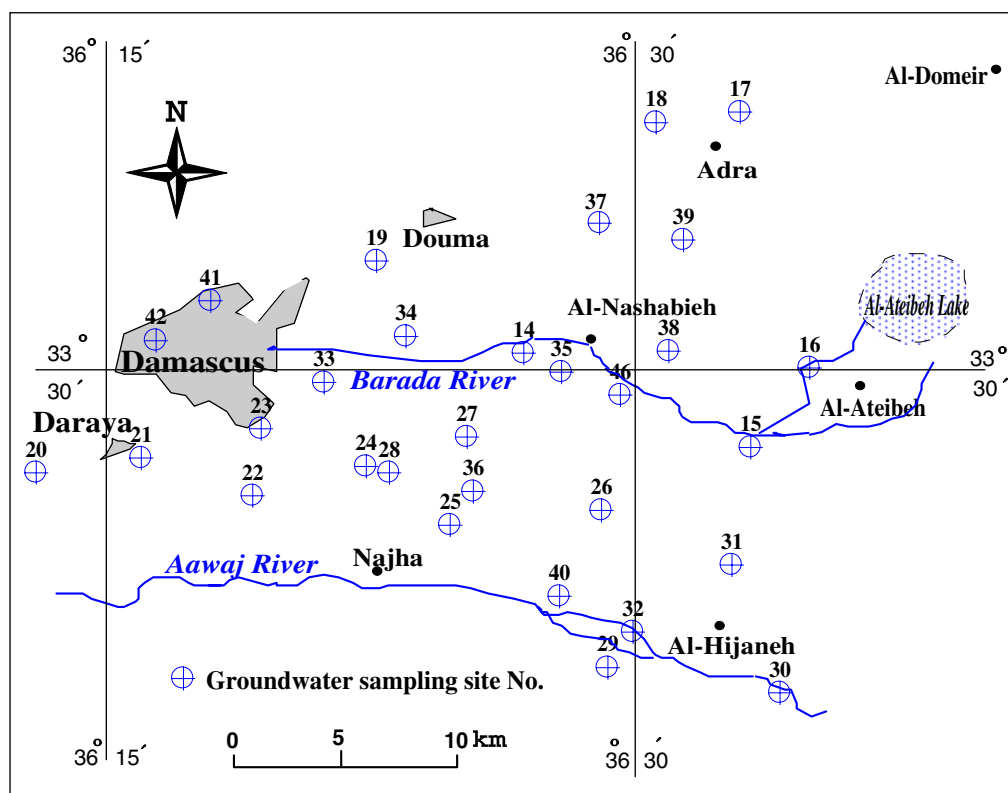
Fig. 6 Location map showing the groundwater sampling sites in the Damascus Ghotta basin during 1998. The sites nos. 39-46 correspond to groundwater sampling sites during 1993 (Kattan 2004a)

The rains of Bloudan, Izraa, Al-Suwieda, Arneh and Al-Kounietra were of low solute content (TDS < 60 mg/l) compared to those of the Damascus, Homs and Tartous (85 < TDS < 125 mg/l). The low solute content is the result of presence in low concentration of dust and combustion gases in the atmosphere (Kattan 1997a; Saad et al. 2000), while the high solute content of calcium bicarbonate in the rains of Damascus and Homs could be attributed to dissolution of carbonate dust. The rather high sulphate content in the Damascus, Homs and Tartous stations may be due to the sulphur gases derived from the combustion of petroleum materials, noting that Homs city disposes a large refinery station. The pH values are usually below neutrality (6.2 < pH < 6.9), except that of Al-Kounietra (pH > 7), which seems to be more influenced by carbonate dust. The low pH value of Al-Suwieda and Izraa rains is most probably due to their location in basaltic terrains, which can help to reduce the effect of carbonate dust (Rosenthal 1987). The effect of cement dust derived from a cement factory in the Aleppo region was behind the sharp increase of pH value (8.3 > pH > 9.5) in Aleppo rains (Kattan 1997a). The chemistry of rainwater samples is usually of the calcium bicarbonate type, with clear predominance of calcium over magnesium and sodium and sodium and bicarbonate over chloride and sulphates. The high predominance of sodium and chloride in Tartous rains is the result of marine aerosol spray (Meybeck 1983; Rosenthal 1987; Kattan 1997a; Saad et al. 2000), as indicates the molar ratio Cl/Na (1.171), very close to that of seawater (1.166).

Chemistry of surface water

Averages of the physicochemical parameters of surface-water samples collected from the Barada and Aawaj rivers during 1998, together with some characteristic ionic ratios are compiled in Table 3. The average water temperature of the Aawaj river ranges between 10 and 15°C, with a low value (9.3°C) at site no. 4, because of mixing with the cold snow melt water of the Sebarani tributary, which also drains the Mt Hermon slopes. The temperature of the Barada-river water exhibits little variations along its course, and mostly oscillates around 15°C.

The pH value changes little between 8 and 8.5 in the Aawaj river water, and it was even lower (7.8–8.1) in the case of the Barada river. The increase of pH value could be explained by the consumption of dissolved CO_2 gas by the organisms and aquatic plants (Livingstone 1963; Dermine 1985), whereas the decrease of this parameter is primarily due to oxidation of organic matter, which

**Table 1** General characteristics of samples, surface water and groundwater sampling sites

Site no.	Location	Number of samples	Sample type	Well depth	Altitude (m.a.s.l.)	Type of aquifer
1	Bet Jen spring	6	Spring		1,280	Jurassic complex
2	Bet Jen bridge	12	River		1,040	
3	Saasaa bridge	8	River		890	
4	Bet Saber bridge	4	River		870	
5	Al-Jdideh bridge	4	River		755	
6	Barada spring	6	Spring		1,100	Jurassic complex
7	Al-Tkiyeh bridge	12	River		1,090	
8	Ain Al-Khadrah bridge	7	River		850	
9	Al-Hameh bridge	8	River		845	
10	Al-Chadirwan bridge	4	River		840	
11	Al-Soufanieh bridge	7	River		690	
12	Jisreen bridge	6	River		645	
13	Al-Nashabieh bridge	4	River		620	
14	Kharabou	3	Well	40	628	Quaternary alluvial–proluvial
15	Haran Al-Awameed	3	Well	60	605	Quaternary lacustrine
16	Al-Abbadeh	2	Well	90	607	Quaternary lacustrine
17	Adra valley	3	Well	90	605	Miocene–Quaternary alluvial
18	Adra village	3	Well	90	615	Miocene–Quaternary alluvial
19	Madyara	3	Well	40	675	Quaternary alluvial–proluvial
20	Daraya	3	Well	40	705	Quaternary alluvial–proluvial
21	Housh Blasse	3	Well	30	680	Quaternary alluvial–proluvial
22	Al-Bouidah	3	Well	40	660	Quaternary alluvial–proluvial
23	Yalda	3	Well	30	665	Quaternary alluvial–proluvial
24	Al-Ghotta farm	2	Well	50	645	Quaternary alluvial–proluvial
25	Qarahta	3	Well	20	640	Quaternary alluvial–proluvial
26	Al-Ghassouleh	4	Well	30	615	Quaternary lacustrine
27	Deir Al-Assafeer	3	Well	30	635	Quaternary alluvial–proluvial
28	Al-Shabaa	3	Well	30	648	Quaternary alluvial–proluvial
29	Deir Al-Hajar	4	Well	90	625	Volcanic Middle Miocene
30	Al-Hijaneh	3	Well	110	605	Volcanic Middle Miocene
31	Jdidet al-Khasse	2	Well	65	607	Quaternary lacustrine
32	Tal Maskan	3	Well	110	615	Quaternary lacustrine
33	Jaramana	1	Well	40	660	Quaternary alluvial–proluvial
34	Jisreen	2	Well	30	647	Quaternary alluvial–proluvial
35	Marj Al-Sulttan	2	Well	25	625	Quaternary alluvial–proluvial
36	Hatitet al-Turkman	3	Well	30	635	Quaternary alluvial–proluvial
37	Haush Al-Farah	2	Well	50	615	Quaternary lacustrine
38	Al-Qasmiyeh	3	Well	40	611	Quaternary lacustrine

could lead to further amounts of HCO_3^- and H^+ species, according to the following reactions (Kempe 1984):

$$CH_2O + O_2 \Leftrightarrow CO_2 + H_2O$$

$$CO_2 + H_2O \Leftrightarrow H_2CO_3$$

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$$
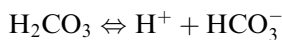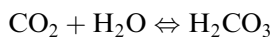
These reactions explain effectively the low pH value observed at the site no. 12, where it was likely to be linked with the visible pollution sources induced by human activity.

The DO_2 value (expressed in saturation level, %), is rather high in the Aawaj river (87–98%), compared with that of the Barada, as the Aawaj river is less subjected to

Table 2 Mean chemical composition of precipitation collected from Syrian stations during 1989–1993

Station	Altitude (m.a.s.l.)	Number of samples	T (°C)	pH	EC (µS/cm)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	HCO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	TDS (mg/l)	σ (%)
Bloudan	1,540	15	11.5	6.92	40.4	4.0	2.2	2.1	0.80	14.4	3.0	5.6	4.9	37.0	4.2
Damascus	625	13	17.5	6.90	129.0	24.0	5.2	2.9	0.60	47.4	30.8	7.3	7.0	125.2	0.9
Arneh	1,430	10	11.3	6.90	53.2	6.4	3.6	2.6	0.40	21.6	3.1	8.5	4.6	50.8	0.4
Al-Kounietra	930	4	13.8	7.58	62.6	9.2	2.1	2.8	0.30	27.3	3.8	6.0	8.0	59.5	4.0
Izraa	580	12	11.8	6.20	43.2	4.8	2.1	3.1	0.40	14.7	4.2	6.1	5.1	40.5	2.2
Al-Suwieda	1,020	12	12.2	6.40	50.2	5.4	2.4	3.5	0.40	16.9	5.9	5.9	6.2	46.6	2.8
Homs	490	14	11.6	6.71	96.7	12.2	4.6	4.1	0.96	34.9	12.7	10.3	6.2	86.0	1.5
Tartous	5	15	15.0	6.45	160.0	9.9	4.8	14.0	0.98	28.7	10.2	25.3	6.3	100.2	0.8

σ Chemical analyses error, *EC* electrical conductivity

Table 3 Mean hydrochemical data of surface water and groundwater samples collected from the Damascus Ghotta basin during 1998–1999

Site no.	T (°C)	pH	EC (µS/cm)	O_2 (%)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	HCO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	TDS (mg/l)	σ (%)	Mg/Ca (molar ratio)	Na/Cl (molar ratio)	SO$_4$/Cl (molar ratio)	SO$_4$/HCO$_3$ (molar ratio)	log pCO_2 (atm)	SI$_{cal}$	SI$_{dol}$
1	10.5	8.13	239	98	41.0	5.1	2.2	0.3	135	7.3	5.8	4.1	201	0.5	0.21	0.58	0.93	0.07	−3.089	0.251	−0.885
2	12.7	8.37	281	93	52.0	7.0	2.9	1.0	157	22.1	7.5	2.7	253	0.8	0.22	0.60	2.18	0.18	−3.266	0.657	0.012
3	15.3	8.45	337	92	53.9	7.2	8.8	2.6	159	25.5	12.4	18.4	288	0.7	0.22	1.09	1.52	0.20	−3.334	0.781	0.313
4	9.3	8.50	505	90	75.5	16.4	4.2	1.0	160	97.0	14.1	6.0	374	1.8	0.36	0.46	5.08	0.77	−3.421	0.836	0.505
5	11.5	8.40	462	87	72.0	11.3	10.3	3.6	220	45.7	24.1	10.7	398	3.3	0.26	0.66	1.40	0.26	−3.166	0.908	0.558
6	15.5	7.78	370	75	63.0	10.1	4.2	1.2	206	28.5	13.4	5.6	332	2.9	0.26	0.48	1.57	0.18	−2.536	0.304	−0.560
7	15.2	7.72	422	80	75.2	20.7	6.3	1.4	240	37.4	12.6	21.3	415	3.2	0.45	0.77	2.19	0.20	−2.417	0.357	−0.226
8	15.3	7.85	442	78	70.3	13.7	6.8	2.1	225	34.5	13.6	9.3	375	0.5	0.32	0.77	1.87	0.19	−2.573	0.441	−0.205
9	16.2	8.07	475	89	76.3	13.3	9.9	2.0	220	34.8	17.2	11.5	385	3.7	0.29	0.89	1.49	0.20	−2.804	0.689	0.262
10	13.2	8.08	477	54	72.0	13.0	11.0	2.3	245	40.1	12.1	14.0	410	2.0	0.30	1.40	2.45	0.21	−2.781	0.674	0.186
11	16.0	8.03	566	56	76.0	17.3	18.0	3.8	285	46.8	20.6	13.5	481	2.8	0.38	1.35	1.68	0.21	−2.654	0.738	0.473
12	16.1	7.76	761	34	89.3	18.1	43.2	9.3	354	98.6	43.1	6.3	642	4.6	0.33	1.55	1.69	0.38	−2.290	0.600	0.148
13	13.7	7.86	979	57	125.5	27.5	45.6	4.9	400	69.9	62.7	23.8	760	2.3	0.36	1.12	0.82	0.22	−2.359	0.847	0.628
14	19.1	7.40	925	60	124.0	41.8	33.0	1.6	453	66.4	76.3	50.7	847	2.9	0.56	0.67	0.64	0.19	−1.815	0.510	0.247
15	22.5	7.21	1,243	28	122.0	58.4	73.0	1.1	450	180.5	141	4.0	1,030	3.7	0.79	0.80	0.94	0.51	−1.612	0.314	0.066
16	22.2	7.59	785	34	53.0	44.4	65.0	2.9	340	72.6	73.4	10.2	662	0.6	1.38	1.37	0.73	0.27	−2.104	0.277	0.231
17	22.0	7.40	2,711	59	260	180	320	13.8	320	376	896	11.4	2,377	4.4	1.14	0.55	0.31	1.49	−1.995	0.539	0.671
18	20.0	7.68	1,075	52	71.0	49.1	185	2.2	398	244	109	10.2	1,069	2.8	1.14	2.62	1.65	0.78	−2.149	0.447	0.448
19	19.6	7.09	986	48	88.0	39.6	36.5	1.1	493	45.4	63.0	74.7	723	4.2	0.74	0.89	0.53	0.14	−1.458	0.113	−0.412
20	18.3	7.08	824	71	125.0	19.7	29.5	0.7	352	87.3	46.6	53.7	715	3.2	0.26	0.98	1.38	0.32	−1.601	0.094	−0.933
21	20.1	6.94	1,163	44	147	45.9	52.0	3.5	467	88.5	94	140	1,037	3.4	0.51	0.85	0.69	0.24	−1.339	0.131	−0.527
22	9.21	7.16	1,254	37	147	36.4	80.0	0.8	454	142	116	98.3	1,052	3.6	0.41	1.06	0.90	0.42	−1.576	0.313	−0.280
23	19.2	7.17	890	19	115	39.1	38.0	7.0	434	53.9	50.1	39.9	777	2.4	0.56	1.17	0.79	0.16	−1.599	0.244	−0.280
24	18.1	7.12	1,147	61	135	48.7	37.0	1.3	355	65.8	94.0	106	843	3.5	0.59	0.61	0.52	0.24	−1.647	0.147	−0.470
25	20.7	7.47	2,273	70	108	125.2	219	0.4	365	426	372	114	1,729	3.8	1.91	0.91	0.85	1.48	−1.991	0.313	0.417
26	24.8	7.52	1,478	62	88	68.5	126	1.3	398	286	168	55.3	1,070	0.6	1.28	1.15	0.82	0.59	−1.965	0.429	0.541
27	16.9	7.21	966	49	132	44.2	30.0	2.3	504	65.8	68.7	45.8	892	3.1	0.55	0.67	0.71	0.17	−1.590	0.356	−0.105
28	17.6	7.20	1,167	43	144	53.6	30.5	1.2	429	58.6	124	111	953	2.3	0.61	0.38	0.35	0.17	−1.651	0.318	−0.123
29	24.2	7.92	1,050	62	60.5	40.9	117	1.5	218	212	110	24.4	784	0.1	1.11	1.64	1.42	1.24	−2.625	0.445	0.502
30	22.1	7.52	6,493	62	150	348	1,360	3.5	419	1,997	1,792	52.4	6,122	2.3	3.83	1.17	0.82	6.05	−2.016	0.330	0.776
31	24.3	7.46	1,083	43	125	46.1	100	2.3	415	96.5	200	9.1	994	0.5	0.61	0.77	0.36	0.30	−1.889	0.581	0.519
32	23.6	7.73	3,328	64	222	270	341	13.8	387	759	950	11	2,954	0.7	2.01	0.55	0.59	2.49	−2.247	0.837	1.536
33	16.4	6.92	990	52	100	43.0	22.0	0.6	410	68.3	47.4	57.1	748	4.5	0.71	0.72	1.06	0.21	−1.386	−0.127	−0.974
34	16.8	6.87	1,248	42	162	44.1	60.8	2.8	460	79.2	108	69.1	986	3.9	0.45	0.87	0.54	0.22	−1.294	0.051	−0.809
35	17.8	7.10	1,016	52	125	52.6	31.5	2.0	490	59.3	96.8	58.6	916	3.8	0.69	0.50	0.45	0.15	−1.488	0.223	−0.256
36	17.9	7.31	1,242	45	104	68.1	78.0	2.2	459	77.4	158	85.5	1,032	2.5	1.08	0.76	0.36	0.21	−1.730	0.309	0.111
37	21.1	7.42	719	48	74	45.2	25.0	0.8	205	59.4	72.9	78.8	561	3.5	1.00	0.53	0.60	0.37	−2.160	0.033	−0.415
38	18.7	7.33	934	47	119	68.5	47.5	1.8	472	94.2	83.4	42.0	928	3.6	0.95	0.88	0.83	0.25	−1.734	0.412	0.276

σ Chemical analyses error, EC electrical conductivity

anthropogenic pollution sources. This parameter was high in the Barada upstream ($>75\%$), and gradually decreased to a value of 55% close to Damascus city, and drop down to less than 35% in site no. 12, where the surface water was intensively the most affected by urban pollution. The high DO_2 value in the Aawaj river compared with that of Barada, may also be attributed to the difference of water temperature between the two rivers, which was remarkably less of about 5°C in the case of Aawaj. The reason for this is due the thermodynamic property or DO_2 solubility, which tends to increase with decreasing temperature (Hem 1992).

The surface waters of both rivers, except that of the Barada at site no. 11, were generally fresh (TDS < 500 mg/l). The spatial evolutions of the EC, TDS and most of the major ions along the river courses, exhibit similar evolution trends, and they generally increase with the flow direction. However, these parameters progressively increase in the Barada case, as the river enters the Damascus city, and sharply rise up, as the river flows towards its estuary in the Damascus Ghotta. The EC, TDS and major ion concentrations of the Aawaj river have been approximately doubled between the river source and its estuary. The remarkable increase of Ca^{2+} and SO_4^{2-} concentrations in the Aawaj river at the junction point with the Sebarani tributary (site no. 4), could be attributed to dissolution of anhydrite or gypsum, as these minerals are partly detected in some Jurassic beds (Selkhozpromexport 1986). On the contrary, the conjunction with this affluent resulted in significant dilution of Na^+, K^+ and NO_3^- concentrations. The concentrations of Ca^{2+}, HCO_3^- and NO_3^- of the Barada river have been doubled between the river source and its estuary, those of Mg^{2+} and SO_4^{2-} become three times higher, and those of Na^+, K^+ and Cl^- were multiplied by a factor of 6–9. The NO_3^- concentration ranges between 3 and 24 mg/l in both river waters, indicating hence that these waters did not exceed the allowable level given for domestic uses (44 mg/l). The clear increase of NO_3^- in the Aawaj river at site no. 3, may be attributed to local human and pastoral activities. However, it was interesting to observe a clear decrease of nitrate content in the Barada river at site no. 12, although this site was supposed to be the most affected by urban pollution. This behaviour could be interpreted by the microbiological consumption of nitrate, with the presence of organic matter, according to the following reaction (Kempe 1984; Billen et al. 1985):

$$5CH_2O + 4NO_3^- \Leftrightarrow 4HCO_3^- + CO_2 + 2N_2 + 3H_2O$$

This later reaction explains once again the decrease of NO_3^-, DO_2 and pH, and also the increase of bicarbonate at this site. Therefore, it may be said that the deterioration of the Barada-river quality is primarily due to urban and anthropogenic pollution.

Chemistry of groundwater

The mean chemical compositions of groundwater samples collected from the study area during 1998 are reported in Table 3. The data shows that the groundwater temperature increases from 18–19°C (near Damascus city) to about 22°C (Al-Ateibeh Lake), and reaches a maximum value (24–25°C) in Al-Hijaneh region (Fig. 7). This evolution is identical to that of the groundwater movement (Fig. 5), and is more or less comparable to that of the groundwater-temperature pattern during 1993 (Kattan 2004a), with the exception that the plume of groundwater of 17°C, which was observed along the Barada river course during 1993, was reduced and shifted towards the Damascus city. The reason for this change may be attributed to the fact that the amount of infiltrated water from the Barada river towards the groundwater was largely reduced during 1998.

The spatial evolution of the groundwater pH value (Fig. 8) was also similar to that of groundwater movement, and agrees highly with that of evolution during 1993. It varies from 7–7.2 near Damascus city to 7.5–7.8 at the eastern and south-eastern border of the basin. The low pH value of the groundwater near the Barada river is the consequence of percolation or infiltration of polluted surface water, mainly deduced as a result of organic matter oxidation, and moved towards the groundwater. This mechanism explains to a large extent the spatial evolution pattern of HCO_3^-, which was highly concentrated ($\cong 480$ mg/l) in the central zone of the Damascus Ghotta (Fig. 9).

The concentration of DO_2 (expressed as %), in the Damascus Ghotta groundwater varies from 20 to 60%, and was distinctly lower than that of the river water (Fig. 10). The reason for the decrease of DO_2 content in the groundwater, compared with that of surface water, is because there is no further source of oxygen in the ground, and thus the initial amount of O_2 is limited to that quantity carried by the infiltrated water. Thus, as a result of oxygen consumption by the oxidation of organic matter, this parameter gradually decreases within the unsaturated zone and aquifer matrix. The minimum level of DO_2 (20%), which was observed south of the Damascus city, coincides with an intensive populated zone, with high industrial activity, together with wroth network of sewage water.

The spatial evolutions of major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^- and SO_4^{2}), EC and TDS in the Damascus Ghotta groundwater during 1998 were generally identical (Figs. 11, 12). All the parameters were low close to Damascus city, and gradually increase as the groundwater moves towards Al-Domeir and Al-Hijaneh areas. The comparison between the 1998 and 1993 data (Kattan 2004a) reveals that the groundwater quality in the Adra region has been ameliorated as a consequence of
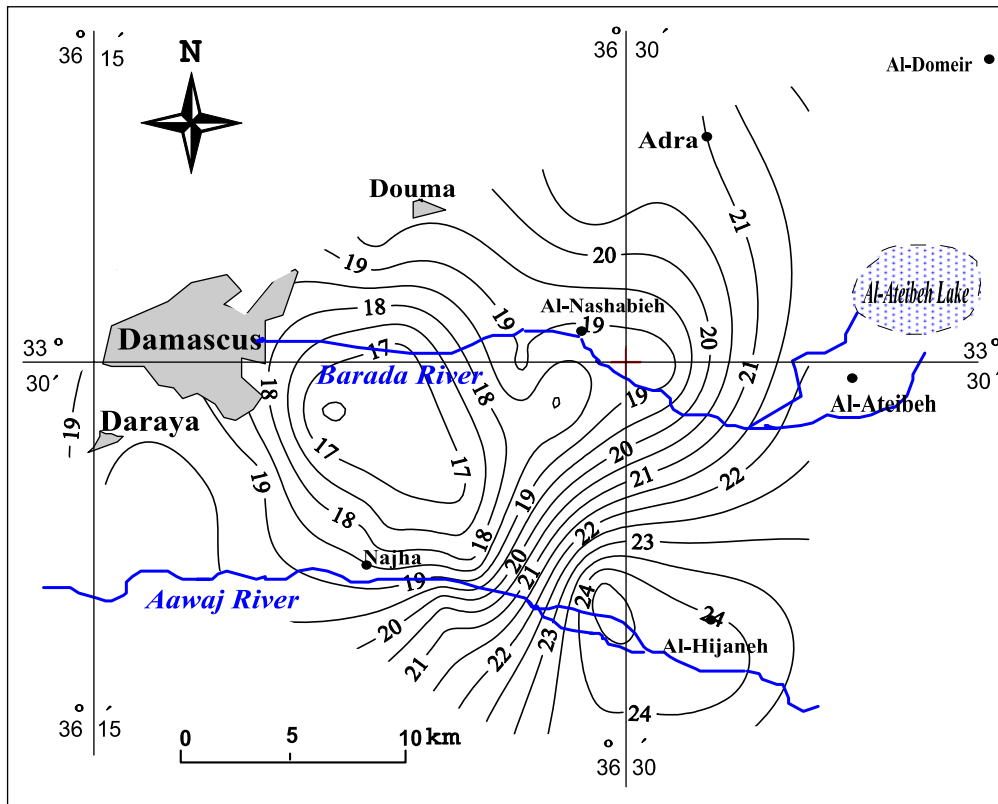
Fig. 7 Spatial distribution of the mean groundwater temperature (°C) in the Damascus Ghotta basin during 1998

establishing the water-treatment station in 1997, which was primarily designed to treat most of the sewage waters of Damascus city. Hence, the construction of this station has helped in fact to reduce the concentrations of most ions to about half the concentration recorded in 1993. It is interesting to note also that the concentrations of most ions in the groundwater along the Barada river course were relatively low, and comparable with those of the Barada river. This proves, in fact, the existence of a direct interconnection between the river and the shallow aquifer. The spatial evolution of nitrate concentration in the Ghotta groundwater was rather different from that of the other ions (Fig. 13). This parameter tends to increase southwards and decrease eastwards and largely reflects the influence of groundwater pollution, due to infiltration of sewage water, as seen above through the DO_2 distribution.

Ionic ratios of surface water and groundwater

The determination of ionic ratios (expressed in meq/l) of water samples is commonly used long time ago as a tool of distinction between the different mineralization sources (Schoeller 1956, 1977; Hsu 1963; White et al. 1963; Rosenthal 1987; Hem 1992).

The Mg/Ca ratio of the Barada and Aawaj rivers (0.2–0.45), was identical to that of rainfall water, and therefore it was rather lower than that of a carbonate aquifer (0.5–0.9). This low ratio reveals that the contact time between the infiltrated water, mainly rainfall, and hosting rocks, was rather short to dissolve enough amount of carbonate minerals, that reflects well the natural signature of this rock type.

The Na/Cl ratio is a useful tool to study contaminated water with common salts, and to differentiate between the various sources of sodium and chloride (Hem 1992). This ratio, which was about 0.6–1.09 in the Aawaj river is comparable to that of natural water (0.86–1), indicating hence the predominance of atmospheric source, as silicates rocks are completely absent (Meybeck 1986). Thus, as this ratio exceeds the unity in the Aawaj river at site no. 3 (Na/Cl = 1.09), a rather small fraction of sodium contamination by pastoral activity may be added to the river water. This ratio ranges, in the case of Barada river, between 0.5 (Barada spring) and 0.8 (site no. 9), and distinctly it becomes higher than one downstream, reaching a maximum value (1.55) at site no. 12. In fact, the river water at this site was obviously influenced by intensive domestic pollution, as seen above for pH and DO_2 parameters.

Similarly, the SO_4/Cl ratio of the Aawaj river varies between 1 and 2, with the exception that this ratio exceeds a value of 5 at the junction point with the Sebarani
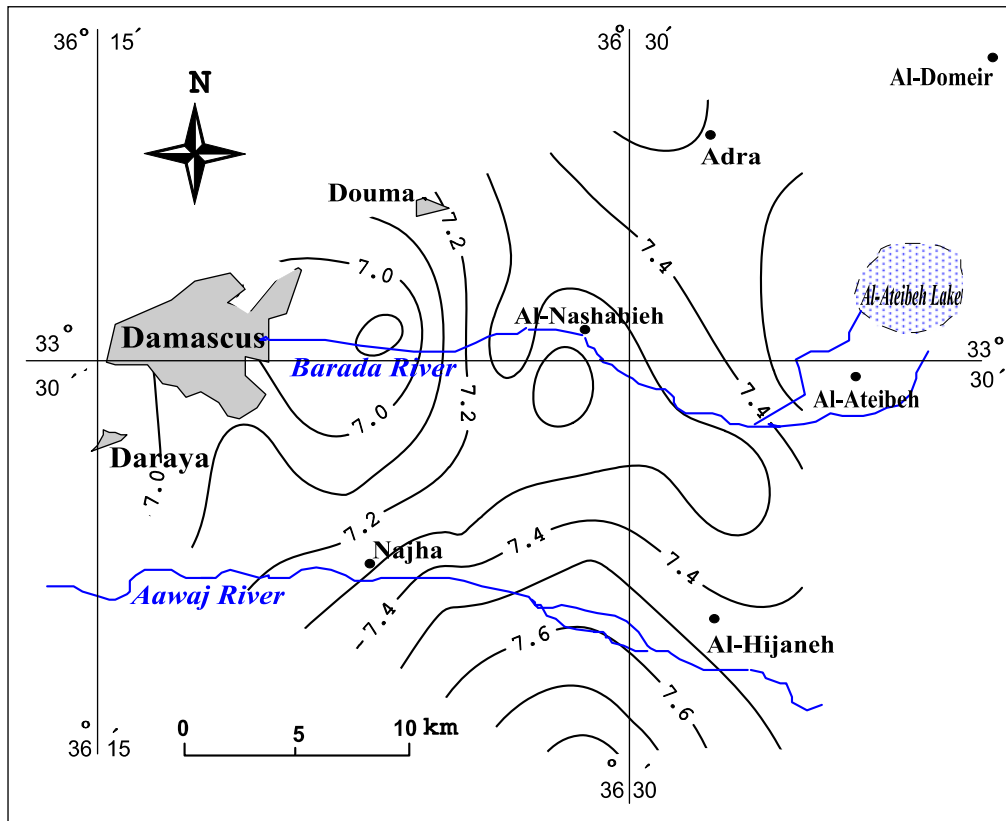
Fig. 8 Spatial distribution of the mean pH value of the groundwater in the Damascus Ghotta basin during 1998

affluent. Furthermore, the predominance of sulphate versus chloride and bicarbonate ($SO_4/HCO_3 = 0.77$) reflects clearly the effect of gypsum dissolution at this site. The low SO_4/HCO_3 ratio (< 0.4) at the remaining other sites of both rivers, together with SO_4/Cl ratios (< 2.5) for the Barada river, indicate absence of dissolution of anhydrite or gypsum.

The average chemical compositions of both rivers, compared with the average chemistry of world, arid- and semiarid-zone rivers (Meybeck 1979) are shown in Table 4. The water of Aawaj river is likely to be compared with those of the semi-arid zone, namely in terms of Ca^{2+}, Mg^{2+}, K^+ concentrations, and to some extent the HCO_3^-, as the two rivers drain carbonate rocks. The low content of Na^+, Cl^- and SO_4^{2-} in the Aawaj river, compared with that of the semi-arid-zone rivers, may be attributed to the absence of evaporite rocks. Whereas, the high concentrations of Ca^{2+}, Mg^{2+} and HCO_3^- of the Barada river, compared with those of arid and semi-arid zones, are consequently the result of predominance of limestone and dolomite rocks, the waters of both rivers are characterized by a calcium and bicarbonate type, with the following ionic trends Ca > Mg > Na > K and

$HCO_3 > SO_4 > Cl$, with a distinct predominance of calcium over magnesium and sodium and bicarbonate over sulphate and chloride, and a spatial evolution towards a sodium chloride type.

The Mg/Ca value of the groundwater varies between 0.26 (site no. 20) and 3.83 (site no. 30), and increase in the same direction of groundwater movement. This reflects the poverty of calcium over magnesium, as a result of calcite precipitation and cation-exchange. The Na/Cl ratio ranges between 0.38 (site no. 28) and 2.62 (site no. 18), with a lower Na/Cl ratio in the groundwater of the central zone of the Ghotta basin (sites nos. 14, 17, 24, 27, 28, 32, 35, 36 and 37). This low ratio, compared with those of the upstream values (0.5–0.8), may be attributed to cations exchange, which provokes depletion in sodium content. The SO_4/HCO_3 ratio ranges between less than 0.2, near Damascus city, and about 6 (site no. 30). The predominance of sulphate versus bicarbonate in site no. 30 is probably because of precipitation of carbonate minerals, as groundwater becomes oversaturated with respect calcite. The SO_4/Cl ratio of most wells was less than 1, and thus this ratio could not be used to detect any natural mineralization.

The groundwater bodies can generally be classified into two major groups:

(1) the low saline groundwater of the majority of wells, that are generally characterized by a calcium and
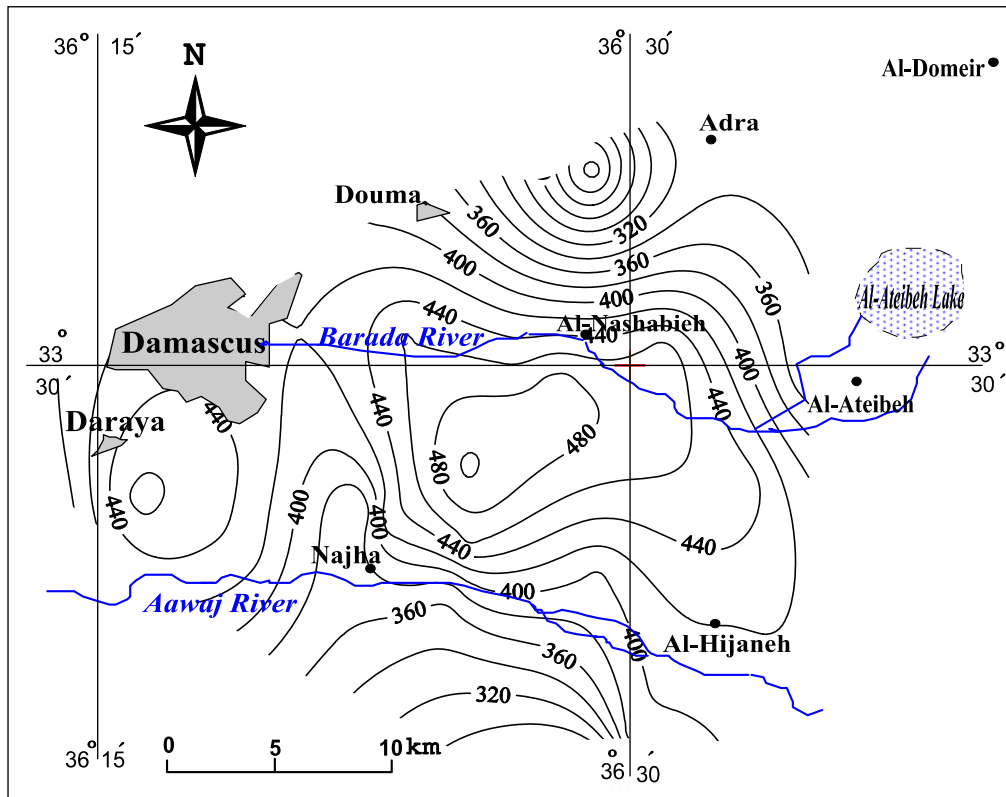
Fig. 9 Spatial distribution of the mean HCO$_3$ concentration (mg l^{-1}) of the groundwater in the Damascus Ghotta basin during 1998

bicarbonate or calcium–magnesium and bicarbonate type, with the following ionic sequence: Ca > Mg > Na > K and HCO$_3$ > SO$_4$ > Cl;

(2) the rather brackish groundwater of the wells nos. 15, 17, 18, 25, 26, 29, 30, 31 and 32, that are all situated in the eastern and south-eastern parts of the basin, and mostly characterized by a sodium–calcium–magnesium and chloride–sulphate type, with the following ionic sequence: Na + K > Ca > Mg and Cl > SO$_4$ > HCO$_3$, or a sodium–magnesium–calcium and sulphate–chloride type, with the following ionic sequence: Na + K > Mg > Ca and SO$_4$ > Cl > HCO$_3$.

The water chemistry of the first group is similar to that of both rivers, and largely reflects the influence of dissolution of limestone and dolomite rocks. Whereas, the second group reflects more the further modifications, due to recycling, evaporation, ion exchanges and precipitation of carbonates. The projection of the groundwater chemistry of the 1993 and 1998 data in the Piper diagram (Figs. 14, 15), suggests existence of small variations between the two periods, with a clear evolution from a calcium–bicarbonate type towards a sodium–chloride type.

Equilibrium condition of surface water and groundwater

The thermodynamic equilibrium conditions that control the surface-water and groundwater chemistry were studied using the WATEQF Code (Plummer et al. 1976). The saturation index (SI) of a water sample with respect to any mineral suspected to be precipitated was calculated by Stumm and Morgan (1981):

$$SI = \log \frac{IAP}{K_{SP}(T)} \tag{2}$$

where: IAP is the ion activity product of the solution, and $K_{SP}(T)$ is the equilibrium constant of the reaction considered at the temperature T (K).

Table 3 compiles the calculated partial pressure of carbon dioxide (log pCO$_2$), together with calcite and dolomite SI (respectively, SI$_{cal}$ and SI$_{dol}$). The partial pressure of dissolved CO$_2$ (pCO$_2$) of river samples was higher than that of the atmosphere (log pCO$_2$ = −3.5), meaning that these waters were capable to dissolve further amount of carbonate rocks. The spatial evolution of this parameter, which was markedly higher in the Barada river compared with that of the Aawaj, shows first a decrease between the stations nos. 7 and 9, and then an increase, reaching its maximum at site no. 12, where the river water was the most polluted (minimum pH and
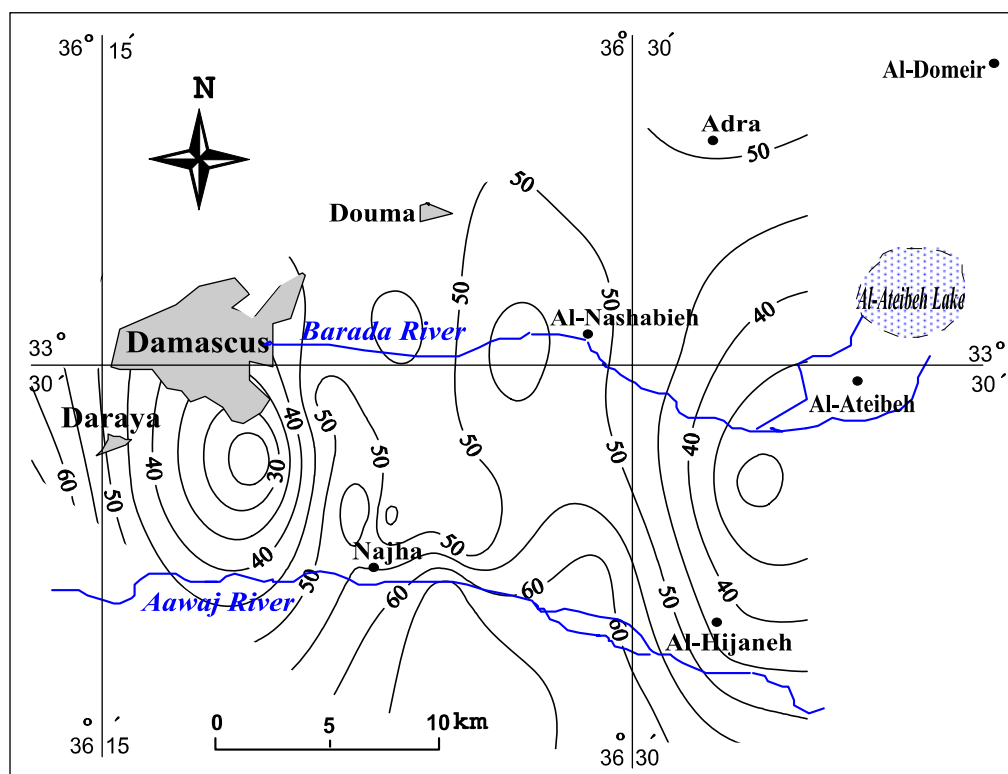
Fig. 10 Spatial distribution of the mean dissolved oxygen value (as % of saturation at measurement temperature) of the groundwater in the Damascus Ghotta basin during 1998

DO$_2$ values). The high partial pressure of CO$_2$ gas was most probably derived from the oxidation of organic matter of domestic sewage carried by the river. On the contrary, in the case of Aawaj river, this parameter tends to be in equilibrium with the atmospheric pressure at site no. 4. The spatial distribution of log pCO$_2$ values in the Damascus Ghotta groundwater gradually decreases in the direction of groundwater movement (Fig. 16). This evolution pattern is opposite to the pattern of the pH, as these two parameters are thermodynamically combined (Stumm and Morgan 1991). Although, most of the water sample were kinetically oversaturated with respect to calcite, only some water samples were undersaturated with respect to dolomite, and entirely all the samples were below the equilibrium state with gypsum. The comparison between the 1993 and 1998 data shows a rather good accordance between the two records.

Stable isotope composition of atmospheric precipitation

The isotopic composition of meteoric water has been extensively monitored in several continents on regional and global scales (Dansgaard 1964; Gat 1980; IAEA 1992; Rosanski et al. 1993; Gonfiantini et al. 2001; Kendall and Coplen 2001). The knowledge on the spatial and temporal evolution of the isotopic composition of atmospheric waters, as a major input function of most of the hydrological and hydrogeological systems, was successfully used to characterize the behaviours of water bodies, in terms of recharge origin, replenishment rate, mixing process, interconnection between aquifers and evaporation (Fritz 1981; Rosanski 1985; Rosanski et al. 1992; Gat 1996; Kendall and McDonnell 1998), as well as to predict the climatic variations (Rosanski et al. 1992, 1993).

The results of the weighted mean isotopic compositions of rainfall samples collected from eight stations: Al-Kounietra, Al-Suwieda, Arneh, Bloudan, Damascus, Homs, Izraa and Tartous (Fig. 1) during the period 1989–1993 are reported in Table 5. The data shows that the stable isotope composition is primarily affected by the altitude effect. Thus, the rainfalls of Bloudan, as the highest station (altitude = 1,540 m.a.s.l.) were the most depleted in heavy stable isotopes (δ^{18}O = −8.58‰ and δ^2H = −48.5‰). On the contrary, the rains of the coastal station (Tartous) were the most enriched in heavy stable isotopes (weighted means about −6.23 and −30.6‰ for δ^{18}O and δ^2H, respectively). However, because of recycling of humid moisture, a similar isotopic composition can be observed for the rains of Damascus and Arneh stations, although there is a difference of about 800 m in their altitude. Another reason for this difference is
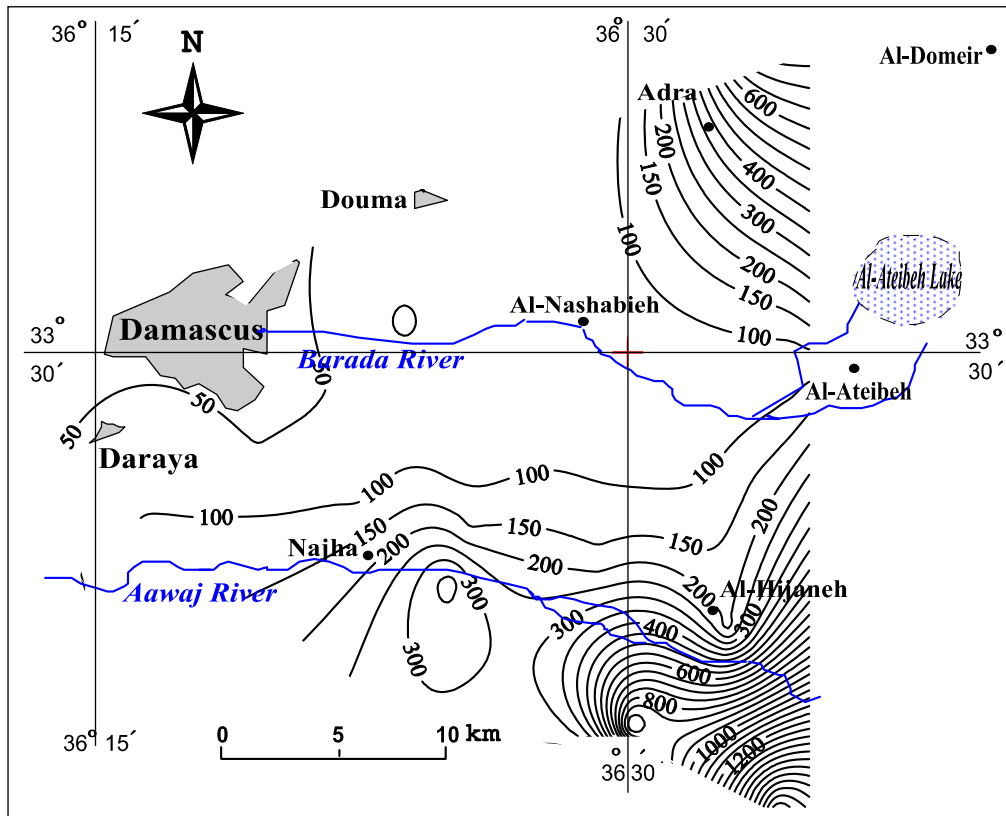
Fig. 11 Spatial distribution of the mean Cl⁻ concentration (mg l⁻¹) of the groundwater in the Damascus Ghotta basin during 1998

probably due to the fact that Damascus station may receive more continental (Khamasin) rains compared with the mountainous stations of Arneh and Bloudan (Kattan 1997a).

The deuterium excess (*d* or *d*-excess) value, which was defined by Dansgaard (1964) as

$$d = \delta^2\text{H} - 8\delta^{18}\text{O} \tag{3}$$

and highly depends on the relative humidity of air masses at their origin and kinetic effects during evaporation (Merlivat and Jouzel 1979; Gat and Matsui 1991), can be used as an indicator of fractionation by evaporation (low *d*-excess value). The data shows that this parameter ranges from 19.3 (Tartous) to 23.9‰ (Al-Suwieda), and varies in the remaining stations between 20.1 and 21.6‰. It was significantly higher than 10‰, the value estimated by Craig (1961) for global meteoric waters, but clearly close to the value of 22‰, given by Nir (1967) for eastern Mediterranean rains. The reason behind this increase of the *d*-excess value in this region is because of the interaction between the humid marine air masses and the dry continental air masses by additional moisture originating from the Mediterranean sea (Nir 1967; Gat and Carmi 1970; Dincer and Payne 1971;

Yurtsever and Gat 1981). On the other hand, the estimated mean weighted *d*-excess value (≅21‰) seems to be slightly higher than that value of 19.3‰, which was given by Kattan (1997a) for the Syrian rains during the single rainy season of 1989–1990. Regionally, this parameter becomes higher than 22‰ in southwards Syria (Izraa and Al-Suwieda) and in northern Jordan (W. Bajjali, unpublished).

Stable isotope composition of surface water and groundwater

The average stable isotope compositions of surface and groundwater samples collected from the Damascus Ghotta basin during 1998, together with those of the *d*-excess values are compiled in Table 6. The data permits to observe first a rather slight enrichment of $\delta^{18}\text{O}$ concentration in the Aawaj river water as water moves downstream from Bet Jen spring (−7.9 ± 0.1‰) towards the site no. 5 (−7.1 ± 0.4‰), which was most probably due to evaporation. At the conjunction point between the Aawaj river with its affluent, the Sebarani (site no. 4), a marked depletion of stable isotope compositions can also be observed, likely because this affluent is generally fed by several springs of higher recharge altitude compared with that of the Bet Jen spring. The
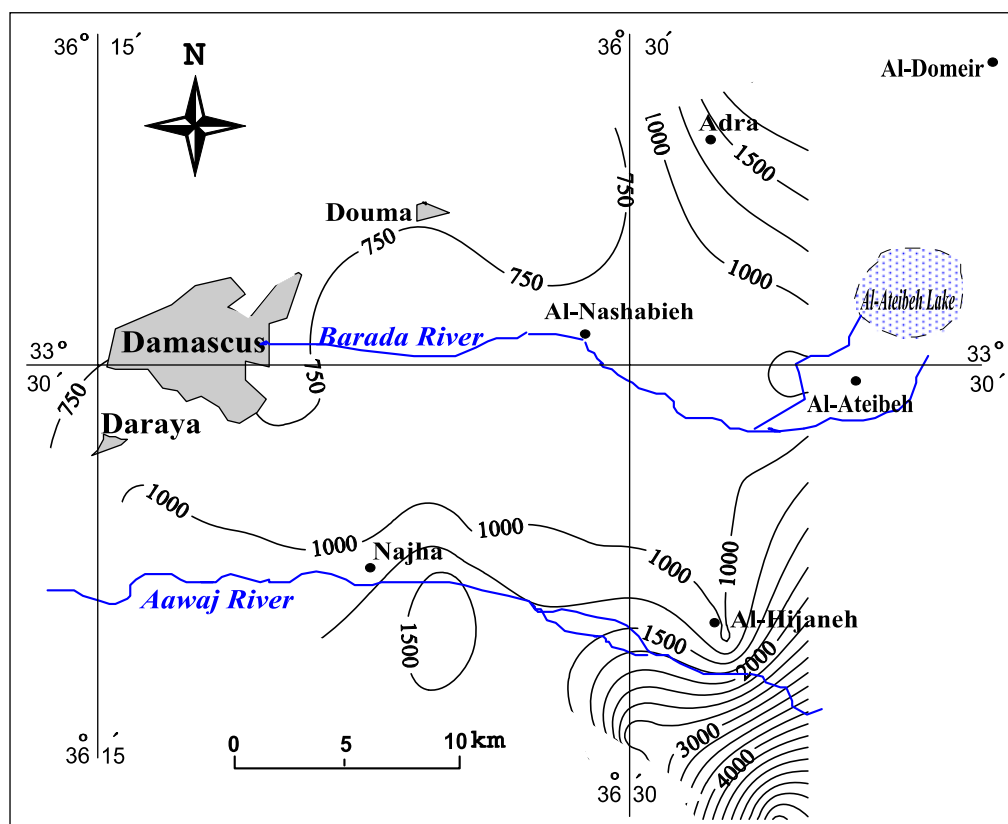
Fig. 12 Spatial distribution of the mean TDS content (mg l^{-1}) of the groundwater in the Damascus Ghotta basin during 1998

evolution of $\delta^{18}O$ and δ^2H values along the Aawaj river were identical, and slight differences in the stable isotope concentrations (± 0.1 and $\pm 0.3\%$ for $\delta^{18}O$ and δ^2H, respectively) can be observed for the water of Bet Jen spring, while comparing the data of 1993 with that of 1998.

The stable isotope concentrations scatter slightly (-7.4 to -7.9%, and -41 to -45% for $\delta^{18}O$ and δ^2H, respectively) in the case of Barada river. However, it is noteworthy to observe an important isotopic enrichment of water along this river course, as one could suppose because of evaporation, which should not be excluded entirely. The tendency of depletion of the isotopic composition was first marked at site no. 8, where the river takes commonly a large portion of water from the Figeh spring (Selkhozpromexport 1986; La-Moreaux et al. 1989; Kattan 1997b). The second progressive depletion can be marked after site no. 9, indicating that the river is gradually fed or mixed with isotopically depleted water, identical to that of the Figeh spring (-8.5 to -9.1% and -47.8 to -52.5% for $\delta^{18}O$ and δ^2H, respectively), as it was previously given by Kattan (1997b). The explanation of this phenomenon is due to the fact that Barada river receives in many locations

along its course different amounts of sewage waters, which were also isotopically depleted, as Damascus city and its suburbs depend for their water supply on the Figeh spring and some other wells (site nos. 41 and 42) having similar isotopic composition. On the other hand, it can be observed in the Barada river data of 1993 a gradual enrichment of the stable isotope compositions, especially downstream the site no. 10. This enrichment proves that the river water has undergone reasonable evaporation, and/or less fed by isotopically depleted water, similar to that of the Figeh spring.

The d-excess value of the Aawaj river decreases downstream, and varies between 20.7 ± 1.0 (site no. 2) and $17.4 \pm 0.1\%$ (site no. 5), meaning that the river water downstream was more affected by evaporation. Although, only one sample was taken from the Bet Jen spring during 1993, the earlier d-excess (21.9‰) value is still comparable with that of 1998 ($19.6 \pm 2.3\%$).

The d-excess value of the Barada river water ranges between 20.6 ± 0.4 (Barada spring) and $16.1 \pm 2.9\%$ (site no. 7), indicating also that river water has undergone a rather important evaporation processes, within a small distance (less than 10 km). Downstream, this parameter progressively increases, reaching a value of about 20.6 ± 3.9 at site no. 13. Although, this evolution proves that the river water was upstream affected by gradual mixing with isotopically depleted water, there is no
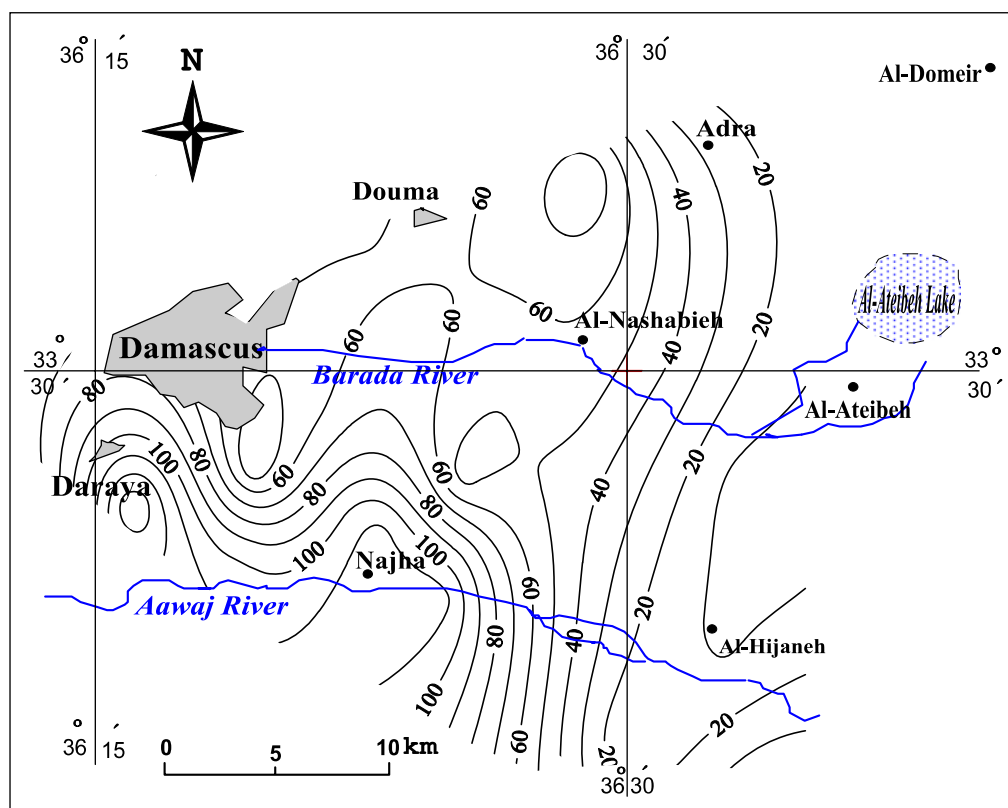
Fig. 13 Spatial distribution of the mean NO$_3$ concentration (mg l^{-1}) of the groundwater in the Damascus Ghotta basin during 1998

doubt that this river was also subjected to evaporation. Comparison between the 1993 and 1998 data reveals that the river water during 1993 was perhaps more alimented by water from the Barada spring than from the Figeh spring.

The δ^{18}O concentration in the groundwater of Damascus Ghotta basin ranges from -8.75 to $-5.84‰$ during 1998, and from -8.89 to $-6.08‰$ during 1993, indicating hence the existence of a slight difference between these two periods. As a result of fractionation by evaporation, the spatial distribution of δ^{18}O values of the groundwater during 1998 was represented by a progressive enrichment from west towards Al-Hijaneh area (Fig. 17), but with a marked progressive depletion towards Al-Ateibeh Lake. This later depletion towards Al-Ateibeh Lake seems to be strange, as it does not

coincide well with the regional groundwater movement. Similarly, the concentration of δ^2H in well no. 16 was also depleted (-52.4 and $-51.4‰$ for the data of 1998 and 1993, respectively). The concentration of deuterium in well no. 30 was, in the opposite, the most enriched (-35.9 and $-35.6‰$ for the data of 1998 and 1993, respectively). Here again, one can find an identical spatial evolution by enrichment of deuterium content towards Al-Hijaneh area, and depletion towards the Al-Ateibeh Lake, similar to that of the δ^{18}O concentration. The similarity of the stable isotope composition of the groundwater located between the Barada and Aawaj rivers with that of the Barada river, indicates the existence of an important relationship between this river and the groundwater, mainly in terms of infiltration and recycling of irrigation water.

Because of evaporation, it can be observed that the d-excess value of the groundwater of 1998 data was rather low in Al-Hijaneh area ($10–10.8‰$), and significantly

Table 4 Mean chemical composition of world, arid-zone and semiarid-zone rivers (adapted from Meybeck 1979)

Major ions	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na$^+$ (mg/l)	K$^+$ (mg/l)	HCO$_3^-$ (mg/l)	Cl$^-$ (mg/l)	SO$_4^{2-}$ (mg/l)	TDS (mg/l)
Average of world rivers	13.4	3.35	5.15	1.3	52	5.72	8.25	89.2
Average of arid zone rivers	38.3	13.5	64.5	5.5	153	63.4	54.4	393
Average of semi-arid zone rivers	54.0	10.8	24.8	1.85	140	26.2	74.5	332
Average of Aawaj river	59.0	9.4	5.7	1.7	166	12.8	39.5	303
Average of Barada river	81.0	16.7	18.1	3.4	269	24.4	48.4	475

Fig. 14 Piper diagram of the chemical composition of groundwater samples collected from the Damascus basin during 1998
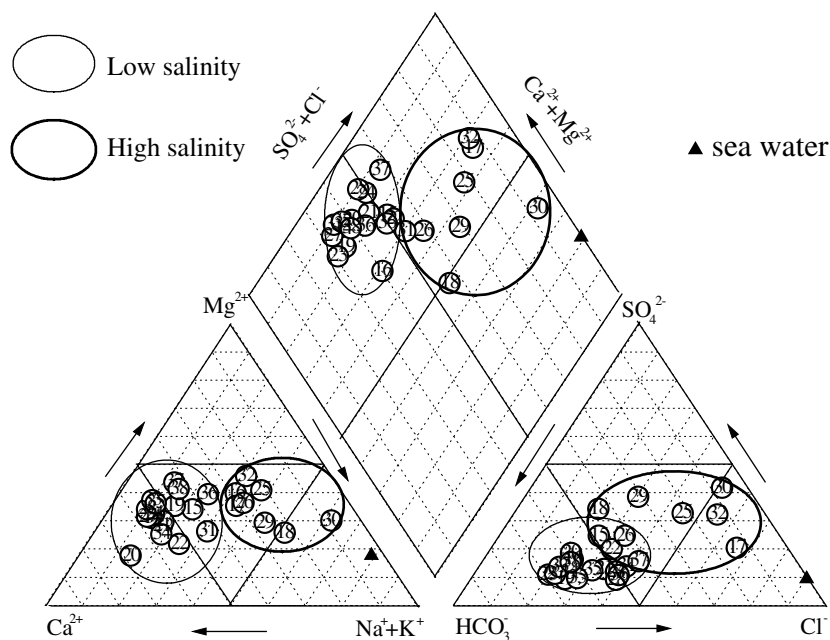
high (up to 18.5‰) in well no. 23 (Fig. 18). This parameter ranges in the case of 1993 data between 11.9 and 13‰ in Al-Hijaneh region and 21.9‰ in several wells close to Damascus city (site nos. 14, 19, 24 and 36). The similarity of the evolution patterns of $\delta^{18}O$, δ^2H and d-excess in the basin, mainly towards Adra region, is effectively a good argument for the importance of groundwater recharge by infiltration of isotopically depleted water, identical to that of the Figeh spring, which should have emerged from the Cenomanian–Turonian aquifer.

δ^2H–$\delta^{18}O$ relationships of rainfall, surface water and groundwater

Figure 19 shows the relationship between $\delta^{18}O$ and δ^2H of all the rainfall samples collected from the eight sta-

Fig. 15 Piper diagram of the chemical composition of groundwater samples collected from the Damascus basin during 1993

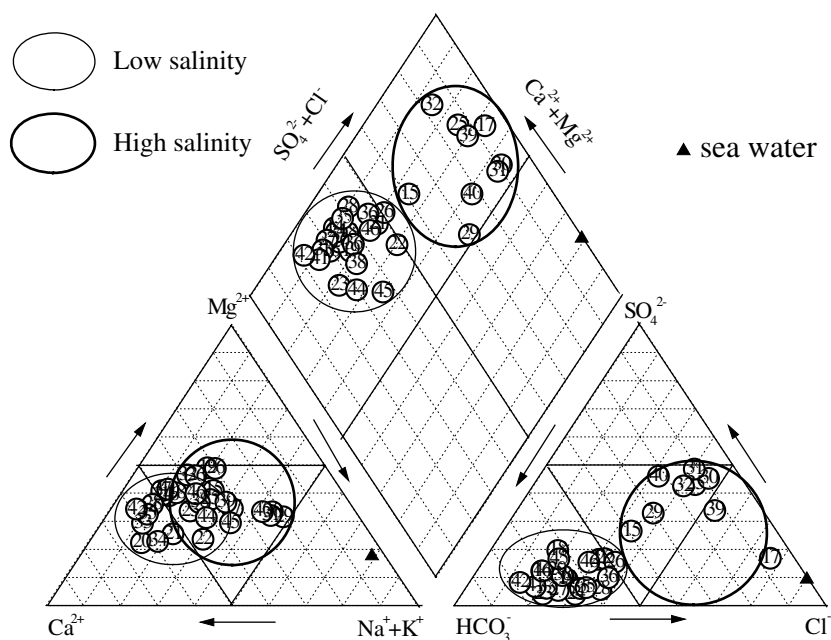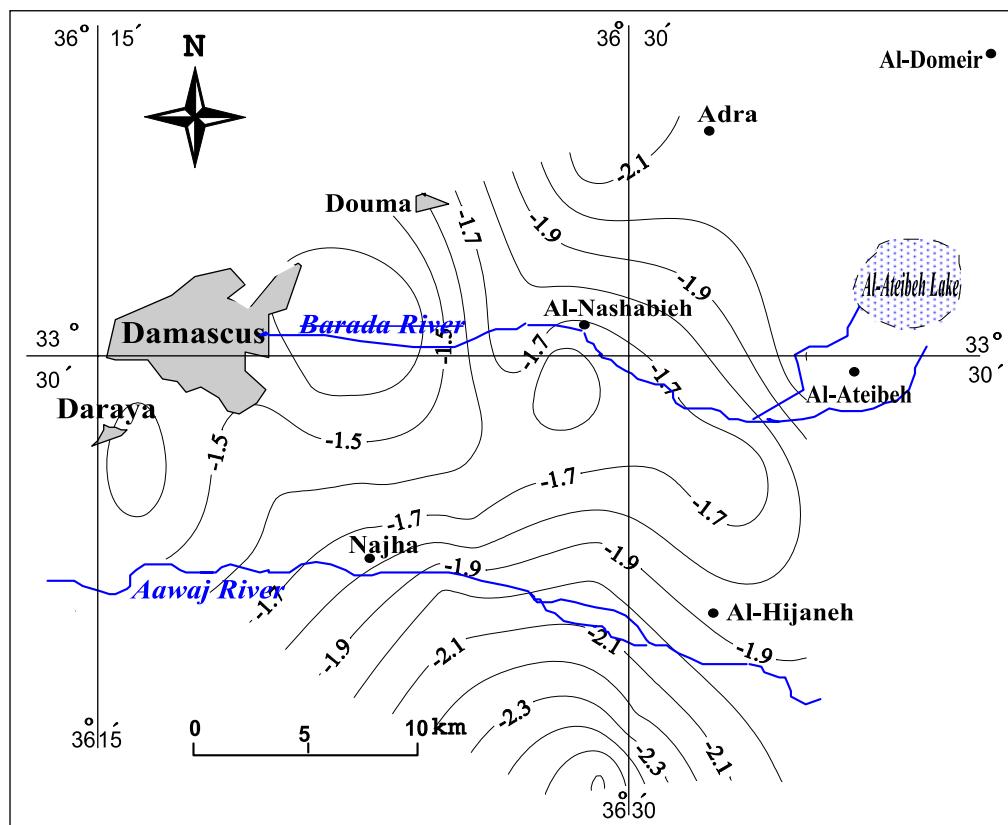**Fig. 16** Spatial distribution of the mean log pCO_2 (atm.) of the groundwater in the Damascus Ghotta basin during 1998

tions in Syria during 1989–1993. This plot shows that most of the sample points match the Mediterranean meteoric water line (MMWL):

$$\delta^2H = 8\delta^{18}O + 22 \tag{4}$$

The equation of the least-squares regression line, fitting all of the precipitation data points of all the monitored Syrian stations is given by:

$$\delta^2H = (6.35 \pm 0.19)\delta^{18}O + (7.18 \pm 1.33)$$
$$(R^2 = 0.92 \text{ and } N = 103) \tag{5}$$

This equation is somewhat different from that established by Kattan (1997a) for the Syrian meteoric water line (SMWL), given by:

$$\delta^2H = (8.26 \pm 0.37)\delta^{18}O + (19.30 \pm 2.7)$$
$$(R^2 = 0.96 \text{ and } N = 43) \tag{6}$$

The slope of this line (6.35) is lower than that (8.17) of the unweighted global meteoric water line (GMWL), given by Rosanski et al. (1993) as:

$$\delta^2H = 8.17\delta^{18}O + 10.35 \quad (N = 583) \tag{7}$$

The low slope (6.35) may commonly be related to low humidity and evaporation (Yurtsever and Gat 1981), as few samples were highly enriched in heavy stable iso-

Table 5 Mean isotopic composition of precipitation collected from Syrian stations during 1989–1993

Station	Altitude (m.a.s.l.)	Number of samples	$\delta^{18}O$ (‰, VSMOW)	δ^2H (‰, VSMOW)	^3H (TU)	d (‰, VSMOW)
Bloudan	1,540	15	−8.58	−48.5	6.3	20.1
Damascus	625	13	−8.23	−45.4	7.1	20.5
Arneh	1,430	10	−8.27	−44.5	6.0	21.6
Al-Kounietra	930	5	−7.41	−39.1	7.1	20.2
Izraa	580	13	−7.55	−37.0	6.3	23.4
Al-Suwieda	1,020	12	−7.35	−34.9	6.9	23.9
Homs	490	14	−6.64	−33.3	6.1	19.8
Tartous	5	15	−6.23	−30.6	5.5	19.3

d Deuterium excess

Table 6 Mean isotopic composition of surface water and groundwater samples collected from the Damascus Ghotta basin during 1998–1999

Site no.	Altitude (m.a.s.l.)	Number of samples	$\delta^{18}O$ (‰, VSMOW)	δ^2H (‰, VSMOW)	^3H (TU)	d (‰, VSMOW)
1	1,280	2	−7.90	−43.7	5.7	19.6
2	1,040	4	−7.72	−41.1	5.3	20.7
3	890	2	−7.36	−41.9	5.6	17.0
4	870	2	−7.58	−42.4	5.7	18.2
5	755	2	−7.10	−39.4	5.8	17.4
6	1,100	2	−7.67	−40.8	6.8	20.6
7	1,090	4	−7.49	−43.8	6.9	16.1
8	850	2	−7.73	−43.7	6.3	18.1
9	845	2	−7.42	−41.7	6.3	17.7
10	840	2	−7.57	−41.9	5.8	18.7
11	690	2	−7.80	−43.9	6.1	18.5
12	645	2	−7.92	−44.5	6.2	18.9
13	620	2	−7.78	−41.6	5.7	20.6
14	628	1	−7.65	−44.2	4.9	17.0
15	605	1	−7.44	−42.8	1.1	16.7
16	607	1	−8.75	−52.4	< 1	17.6
17	605	1	−8.16	−51.8	< 1	13.5
18	615	1	−7.8	−46.8	< 1	15.6
19	675	1	−7.56	−44.1	6.3	16.4
20	705	1	−6.6	−38.0	5.2	14.8
21	680	1	−6.93	−41.1	7.9	14.3
22	660	1	−7.36	−42.9	6.1	16.0
23	665	1	−8.14	−46.6	7.1	18.5
24	645	1	−7.72	−44.7	6.9	17.1
25	640	1	−6.68	−39.3	4.5	14.1
26	615	1	−7.55	−44.1	4.3	16.3
27	635	1	−7.56	−43.8	7	16.7
28	648	1	−7.53	−43.2	7.4	17.0
29	625	1	−5.85	−36.8	< 1	10.0
30	605	1	−5.84	−35.9	< 1	10.8
31	607	1	−7.9	−48.0	< 1	15.2
32	615	1	−6.82	−41.1	< 1	13.5
33	660	1	−7.88	−44.9	6.5	18.1
34	647	1	−7.76	−45.0	7.9	17.1
35	625	1	−7.72	−43.9	7.3	17.9
36	635	1	−7.42	−42.5	7.8	16.9
37	615	1	−8.45	−50.1	< 1	17.5
38	611	1	−7.66	−44.3	6.9	17.0

d Deuterium excess

topes ($\delta^{18}O$ up to 4‰ and δ^2H up to 30‰). By dropping out or filtering the data points of $\delta^{18}O > −4$‰ and $\delta^2H > −15$‰, a line of a closer slope to the value (8) could be obtained. The most depleted rainfall samples ($\delta^{18}O < −10$ and $\delta^2H < −60$‰) coincide with the Khamasin rains, that reflect the effect of continental air masses crossing the North African deserts (Eriksson 1983), which better fit the GMWL with an intercept of 10‰.

The altitude effect, as a tendency for a systematic decrease of stable isotope composition with increasing altitude, is theoretically associated with the concept that this parameter is a function of the cooling of air masses as they rise to higher elevation. This effect has been largely used by several authors around the world as a tool to determine groundwater-recharge zones (Payne and Yurtsever 1974; Fontes and Olivry 1976; Gonfiantini et al. 1976, 2001; Yurtsever and Gat 1981; Gasparini et al. 1990; Kattan 1997b). Based on the correlations between the weighted means of both $\delta^{18}O$ and δ^2H and the corresponding altitude for all the meteoric stations, the least-squares regression lines were calculated, but by dropping out those of the Damascus station. The reason was that rains of this station were isotopically depleted as a result of receiving more Khamasin rains, and also because of the local recycling of depleted humid moisture over the city atmosphere.

The calculated altitude effect is shown by a gradual lapse rate of heavy stable isotopes of about −0.14 and −1.1‰ per 100 m for $\delta^{18}O$ and δ^2H, respectively. This effect fits well in the range given by Yurtsever and Gat (1981), in which the $\delta^{18}O$ laps rate is between −0.15 and −0.5‰ per 100 m and the δ^2H lapse rate is between −1.5 and −4‰ per 100 m. These values are slightly lower than those estimated by Kattan (1997a), in which the gradient was of about −0.23 and −1.6‰ per 100 m, for $\delta^{18}O$ and the δ^2H, respectively. However, it seems that the $\delta^{18}O$ gradient (−0.19‰ per 100 m), which was given by Prizgonov et al. (1988) was practically closer.

Figure 20 shows the δ^2H–$\delta^{18}O$ relationship of surface-water samples collected from the Damascus Ghotta basin during the two periods of 1993 and 1998. This plot indicates that all the surface-water samples fit a least-square regression line of the following equation:

$$\delta^2H = (6.04 \pm 1.16)\delta\delta^{18}O + (3.48 \pm 8.96)$$
$$\text{with } (R^2 = 0.79 \text{ and } N = 19) \tag{8}$$

The slope of this line (6.04), which is lower than that of the local rainfall line (6.35), and likely to be compared with arid and semi-arid regions, in which the slope could drop down as low as 5–6 (Gat 1974; Gat and Tzur 1967; Gat and Carmi 1970; Gat and Dansgaard 1972; Friedman et al. 1992; Kendall and Coplen 2001), is a good indicator that the evaporation of surface occurred after rainfall, mostly in the stream during water flow. The fitted evaporation line or "evaporation-mixing" line matches the representative point that reflects the depleted composition of the Figeh spring (−9.1 and 52.5‰ for $\delta^{18}O$ and δ^2H, respectively), and intersects with the MMWL at a point having the following isotope composition: −9.4 and −53.4‰ for $\delta^{18}O$ and δ^2H, respectively, which is also very close to that of the Figeh water. This means that the Figeh water should be considered as the initial water before any evaporation, and also as a depleted end-member of any mixing suspected to take place.

The progressive isotopic enrichment in the Aawaj river along its course means clearly that the water of the river was entirely derived from resources identical to that of its source (Bet Jen spring). On the contrary, the
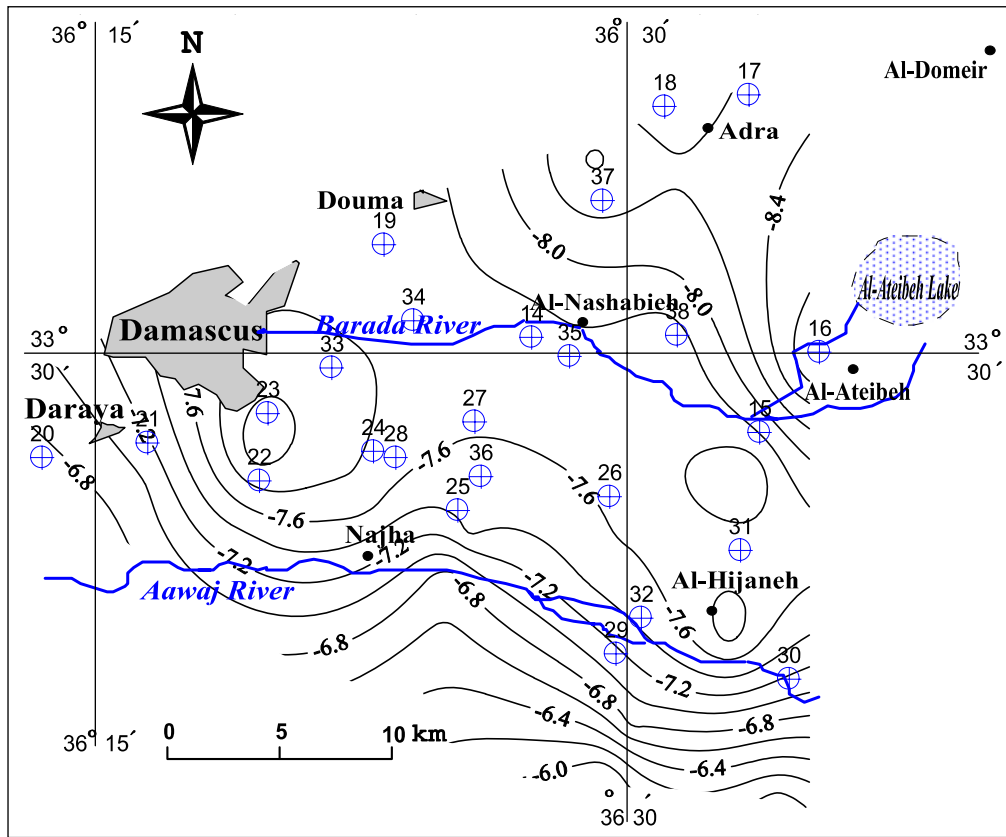
Fig. 17 Spatial distribution of the mean $\delta^{18}O$ content (‰) of the groundwater in the Damascus Ghotta basin during 1998

$$\delta^2 H = (5.1 \pm 0.32)\delta\delta^{18}O - (4.94 \pm 2.44)$$
$$\text{with } (R^2 = 0.90 \text{ and } N = 60) \tag{9}$$

distribution of the Barada river sampling points, most of which were depleted compared with that of the Barada spring, means that it is impossible to have been derived from the Barada spring only. This evidently proves that the river water was produced by mixing of other water resources very close to that of the Figeh spring.

Based on a mixing hypothesis using the interactive Netpath Code (Plummer et al. 1991), the contribution of such fraction, of isotopically depleted water (Figeh water), could represent at least 35%, and this portion could be even higher by taking into consideration evaporation process. By referring to the 1993 data, a further argument for the importance of isotopically depleted water in feeding the Barada river can be detected, as reflects the isotopic composition of the Barada river at site no. 10, where more than 65% of river flow could be related to the Figeh spring. By considering the isotopic composition of the river at site no. 11, this portion could be reduced to around 50%.

Figure 21 shows the $\delta^2 H$–$\delta^{18}O$ relationship of the groundwater samples collected from the Damascus Ghotta basin during two periods of 1993 and 1998. This plot shows that the groundwater samples fit a least-square regression line of the following equation:

Although, the slope of this line (5.1) can be compared with that (4–6) of the groundwater in arid and semiarid-zones (Gat and Tzur 1967; Gat and Carmi 1970; Gat and Dansgaard 1972; Fontes 1983b), it is even lower than that of the local rainfall (6.35) and surface water (6.04), indicating hence an argument for further fractionation by evaporation, mostly during water infiltration within the unsaturated zone.

The stable isotope compositions of groundwater in the well no. 16, located close to Al-Ateibeh Lake, were the most depleted, and clearly close to that of the Figeh spring, with rather a slight evaporation. The possible explanation for such a case is to consider a recharge component of isotopically depleted water, identical to that of the Figeh spring, as the infiltration of surface-river waters should be completely excluded. It is likely to suppose existence of subsurface-flow movement of groundwater, recharged at sufficiently high elevation ($> 1{,}750 \pm 100$ m.a.s.l), as previously given for the Figeh spring by Kattan (1997b), on the basis of altitude effect of meteoric waters. Therefore, such a groundwater component could be derived form the Cenomanian–Turonian aquifer as the unique aquifer in the area that disposes such constraints. Accordingly, the water
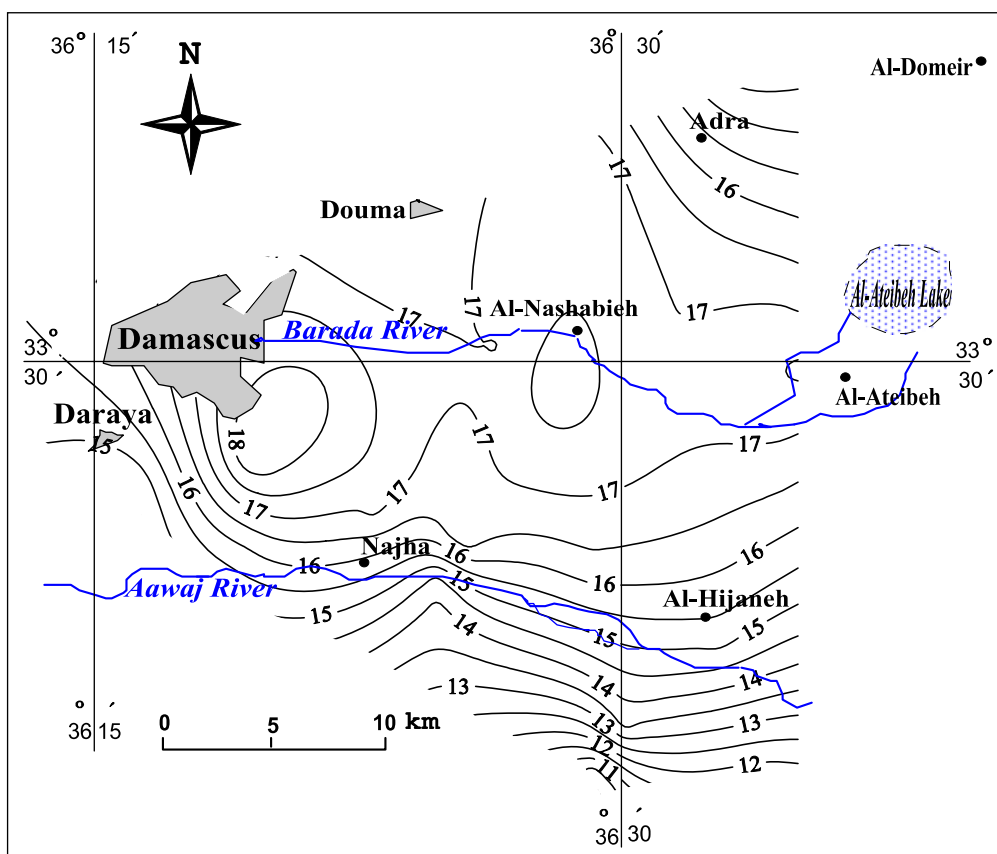
Fig. 18 Spatial distribution of the mean deuterium excess value (‰) of the groundwater in the Damascus Ghotta basin during 1998

movement may probably be facilitated along the Damascus Fault, that permits a direct contact between the Cenomanian–Turonian rocks and the Quaternary alluvium aquifers, as geologically noticed long ago

Fig. 19 Relationship between $\delta^{18}O$ and δ^2H values of precipitation in Syria during 1989–1993
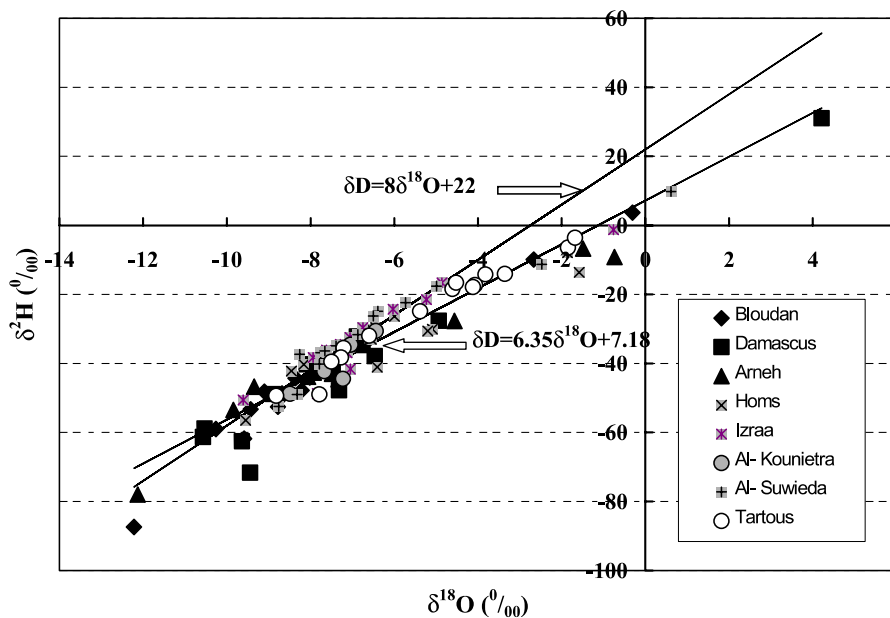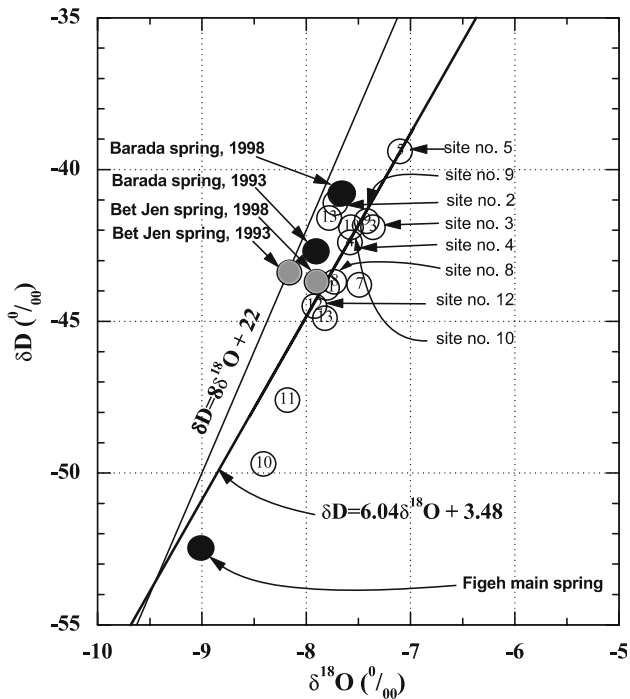
Fig. 20 Relationship between $\delta^{18}O$ and δ^2H values of surface water samples collected from the Damascus Ghotta basin during 1993 and 1998

(Dubertret 1932; Ponikarov 1967; Selkhozpromexport 1986). The isotopically depleted values of groundwaters in the wells nos. 17 and 37, located in the Adra area also support the above-mentioned explanations.

The groundwater in the wells nos. 30 and 29 were isotopically the most enriched, because their location in the marginal border of the basin, where the recharge process is absolutely null. Another remarkable observation is related to the isotopic composition of the groundwater in well no. 20, which also seems to have undergone higher evaporation effect, although it is located in the western part of the basin. The reason for this is due to fact that the groundwater in the Daraya area is mainly recharged by recycling and infiltration of evaporated surface water from the Aawaj river, as is clearly indicated by the similarity of the isotopic composition between this groundwater and the Aawaj river water at site no. 5.

Tritium content in rainfall, surface water and groundwater

Tritium with its half-life of about 12.43 years is the only radioactive environmental isotope that constitutes part of the water molecule. For this reason, it has been largely used as a natural tracer in many hydrological and

mathematical simulation studies (Fontes 1983a; Yurtsever 1983; Zuber 1994; Kattan 1997b, 2002b). Tritium is naturally produced (up to 5 TU) in the upper atmosphere by nuclear reactions between cosmic neutrons and nitrogen (Payne 1983). However, as a result of several nuclear explosions and weapon tests, mainly in the northern pole of the globe (Eriksson 1983), the maximum tritium content attainted a value of about 7,000 TU in the Ottawa rains during 1962–1963 (IAEA 1981, 1992). Since then, a gradual decrease of tritium content in the atmospheric precipitation was observed as a consequence of ceasing up of nuclear tests. The actual tritium content approaches to that prior to 1950s (5 TU), and hence the necessity for tritium enrichment by electrolysis was postulated to arise in the analysis detection limit of tritium (Wagner and Geyh 1999).

The weighted mean tritium concentrations in the atmospheric precipitation during the period 1989–1993 are reported in Table 5. The tritium content ranges from 5.5 (Tartous) to 7.1 TU (Damascus and Al-Kounietra). A build-up of tritium content with increasing distance form the Mediterranean coast can be detected (Kattan 1997a). Hence, the low tritium content in Tartous, Arneh, Homs and Bloudan rains compared with the other stations, is most probably the result of modification of the isotopic composition by mixing process with Mediterranean air masses, generally characterized by low tritium content (Carmi and Gat 1973). Comparison of tritium concentrations of the two data records (1993 and 1989–1990) suggests, approximately, a reduction of the tritium content of about 0.5 TU per year.

The tritium content in the Aawaj river during 1998 was about 5.3–5.8 TU, and about 13.7 TU in Bet Jen spring during 1993 (Table 6), and thus it was two times higher than that of the rainfall of both Arneh and Bloudan during the period 1989–1993. This means that the tritium decreased in the spring waters by about 1.6 TU per year, which is three times higher than that of tritium in rainfall ($\cong$0.5 TU/a).

The tritium content of the Barada river during 1998 (Table 6) was close to 6 TU at all the river sites, and about 10.5 ± 0.9 TU in the Barada river at site no. 10 during 1989–1990 (Kattan 1997b). It was about 13.2 TU in the Barada spring during 1993, and hence it decreases by about 0.6–0.7 TU per year. The tritium content, which was in the range of 8–9 TU during 1993 at the stations nos. 10, 11 and 13, and lower of about 3–4 TU compared with that of the Barada spring, seems to be closer to that of the Figeh spring (9.6–10.8 TU), proving hence that a considerable amount of river water belongs to such a similar enriched water.

The tritium content of groundwaters in the Damascus Ghotta basin during 1998 (Table 6) ranges from less than the detection limit of 1 TU in the south-eastern and north-eastern parts of the basin to 7.9 TU in the wells nos. 21 and 34. This content was also very low
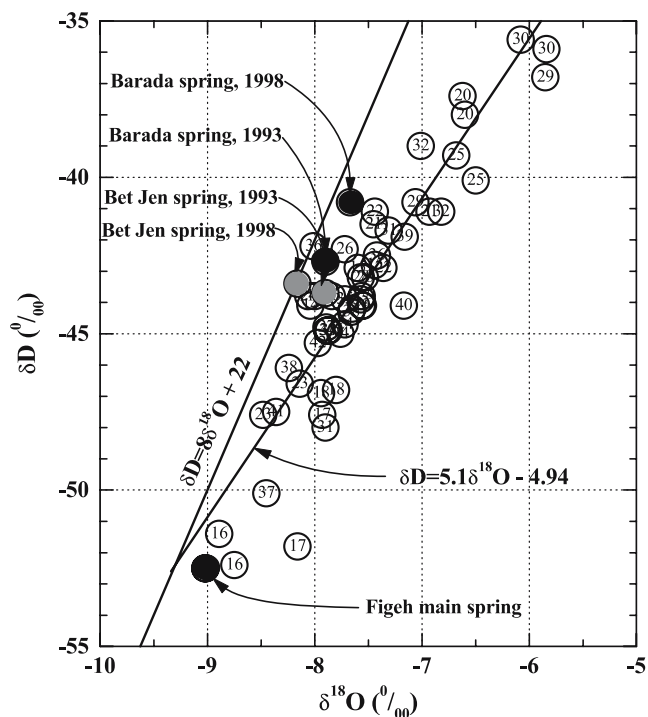
Fig. 21 Relationship between $\delta^{18}O$ and $\delta^{2}H$ values of groundwater samples collected from the Damascus Ghotta basin during 1993 and 1998

(< 1 TU) in the groundwater of the south-eastern and north-eastern parts of the Damascus Ghotta basin during 1993 (Fig. 22), and higher than 10 TU in several wells close to Damascus city (wells nos. 27, 34, 36 and 41). The decline of tritium content between the two periods, which can be evaluated approximately as 0.5–1 TU per year, is mainly the result of decrease of tritium content in the atmospheric precipitation. The plot of the spatial distribution of tritium content in the Damascus Ghotta groundwater during 1998 (Fig. 23) agrees well with the evolution patterns of groundwater temperature, most of the major ions and the stable isotope concentrations, which all increase in the same direction of groundwater movement. Although, the groundwater velocity is relatively homogenous all over the basin, as it can be learned from the piezometric map (Fig. 5), it is however interesting to observe that the sheet of cultivable lands in the central Damascus Ghotta basin, which is generally irrigated by water from the Barada river and its effluents, disposes groundwater highly enriched with tritium (7–8 TU), identical to that of surface waters. Furthermore, it is noteworthy to observe a sharp regular decline of tritium content within the basin borders, as is indicated by the dense contour lines. This observation proves without any doubt the excellent role that can play the Barada river and its effluents, as a major source of groundwater recharge, especially for the shallow alluvium aquifer of the above-mentioned sheet.

Conclusions

The conjunctional use of hydrochemistry and environmental isotope methods to investigate the characteristic of rainfall, surface water and groundwater in the Damascus Ghotta basin, has so far permitted to extract the following major conclusions:

- The chemical and isotopic characteristics of the atmospheric precipitation in the country in terms of salinity levels, altitude effect, continental effect and fractionation by evaporation are in a good agreement with the behaviours of meteoric rainfall of the eastern Mediterranean region.
- The water quality of Barada and Aawaj rivers was generally fresh, less saline upstream and progressively becomes more saline, as rivers flow inside the lands of Damascus Ghotta. The difference of water temperature between the two rivers is not only the result of variation of the altitude of recharge zones of feeding sources, but also because of the high portion of snow-melt water coming from slopes of the Mt Hermon and received by the Aawaj river. The waters of both rivers were of calcium and bicarbonate type, with relative increase of the Ca^{2+} and Mg^{2+}, which primarily reflects the predominance of dissolution of limestone and dolomite rocks, and the salinity levels coincide well with those of the arid and semi-arid rivers.
- The decrease of the pH, NO_3^- and DO_2 values in the Barada river water, accompanied with significant increases in K^+, Na^+, SO_4^{2-} and Cl^-, especially at the site no. 12, is likely to be linked with the anthropogenic pollution, which can be explained by the oxidation of the organic matters of sewage water injected in the river. The relatively high SO_4^2 concentration in the Sebarani effluent is simply related to anhydrite and gypsum dissolution, locally detected in the Mt Hermon.
- The groundwaters emerging from the Barada and Bet Jen springs, and both issued from the Jurassic aquifer; dispose the best water quality in the Damascus basin. However, as groundwater moves in the Damascus Ghotta from west to south-east and north-east, the water temperature, pH and EC values, together with the concentrations of most major ions, TDS, the saturation indices versus carbonate minerals (calcite and dolomite) and stable isotope concentrations, progressively increase, reaching their maximum values in the vicinity of Al-Hijaneh area. On the contrary, the tritium content, partial pCO_2 pressure and d-excess values in the Damascus Ghotta basin show inverse spatial evolutions, with gradual decrease in the direction of groundwater movement.
- Two groundwater groups can be distinguished: (1) the low-saline groundwater of calcium-bicarbonate or calcium–magnesium and bicarbonate type of the
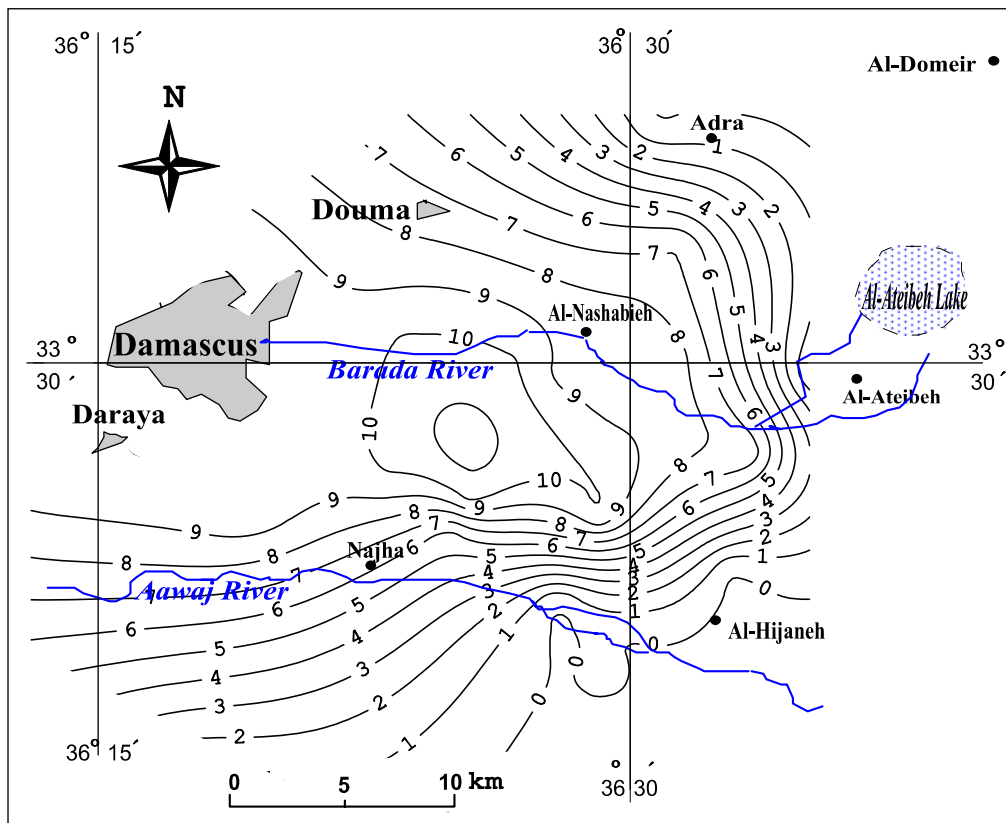
Fig. 22 Spatial distribution of the tritium content (TU) of the groundwater in the Damascus Ghotta basin during 1993

majority of wells and (2) the rather brackish groundwater of chloride–sulphate and sodium–calcium–magnesium type of wells located in the marginal border of the basin.

- The low DO_2 and high nitrate concentrations detected in the groundwater south of Damascus city are most probably due to groundwater pollution, by the infiltration of urban sewage water in the area. Whereas, the establishment of the water-treatment station of sewage water in the Adra region has been reflected by a sensible amelioration of the groundwater quality in that area.
- The high concentration of bicarbonate, high partial pressure values of pCO2, high tritium content, accompanied with low pH value and depleted stable isotope compositions of the groundwater in the vicinity of Barada river, especially the sheet of cultivable land occupying the central zone of the Damascus Ghotta, reflect the strong relationship existing between the Barada river and the groundwater, not only in terms of groundwater recharge by direct infiltration of river waters, but also through penetration and recycling of irrigation water, predominantly from of the Barada river.

- While, the Aawaj river is uniquely fed from springs issued form the Jurassic aquifer of Mt Hermon, the Barada river is oppositely formed by a mixed origin: (1) from the Jurassic aquifer of the Mt Anti-Lebanon and (2) from the Cenomanian–Turonian bearing system, which should be treated as the primary contributor, not only for the Barada river, but also for the groundwaters in the Damascus Ghotta basin.
- The isotopically depleted groundwaters in Al-Ateibeh and Adra area, which are supposed to be regionally enriched by evaporation as the surface water and the groundwater move towards this area, is a clear evidence of the existence of subsurface flow movement of groundwater bodies of sufficiently high recharge elevation, and thus most presumably from the Cenomanian–Turonian aquifer. Such a water movement may probably be facilitated by the presence of the famous Damascus Fault, which could help to put in a direct contact the Cenomanian–Turonian rocks with the Quaternary alluvium aquifers.
- As the Cenomanian–Turonian aquifer represents the major water resource of Barada river (35–70%), and consequently that of groundwater in the Damascus region, the extensive exploitation of water from this aquifer for long-term water supply would dramatically be reflected by a gradual decline of the groundwater

Fig. 23 Spatial distribution of the mean tritium content (TU) of the groundwater in the Damascus Ghotta basin during 1998
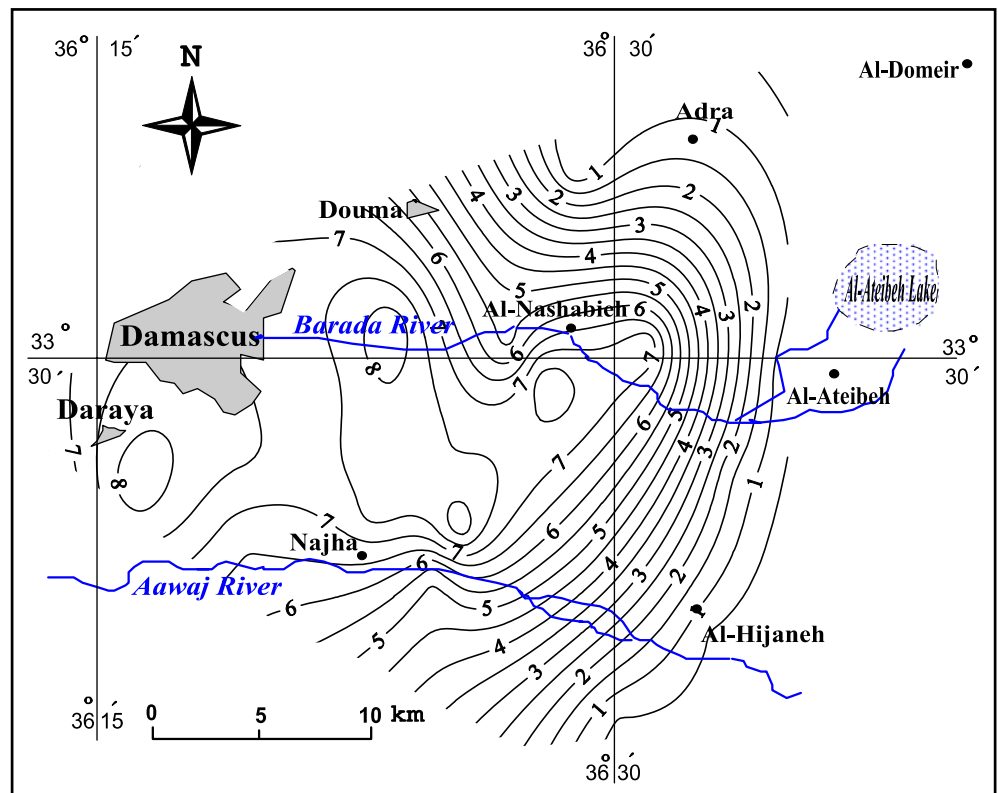

table in the Damascus Ghotta, as it was envisaged during the last few years.

- The water resources in the Damascus area are limited and insufficient to host the most accentuated domestic, agricultural and industrial activities in this part of the country. Hence, the development and amelioration of water resources in terms of quantity and quality would require further management strategies to be considered, together with establishing additional sewage-water-treatment stations.

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