Chapter 4
North Arabian Volcanic Province: Jebel el Arab–Golan–Al Harra

4.1 Geographic and Geologic Set-Up

4.1.1 Landscape and Climate

4.1.1.1 The Jebel el Arab Basalt Area

About 100 km southeast of Damascus and 100 km northeast of Aman, the volcanic mountain massif of Jebel el Arab rises above the plateaus of southern Syria and northern Jordan up to an elevation of 1,800 m asl. Jebel el Arab or Jebel Druze constitutes the core of a volcanic province, which extends from southwestern Syria across Jordan into the Al Harra basalt area of Saudi Arabia. The basalts of that North Arabian Volcanic Province originate from the regional volcanic activity which accompanied the tectonic events of the development of the Red Sea rift graben during the Tertiary to Quaternary. Further south on the Arabian Shield, volcanic rocks of comparable age extend over considerable areas in a general southeast–northwest direction along the eastern shoulder of the Red Sea graben. The basalt outcrops of the Jebel el Arab volcanic province continue the southeast–northwest trend of the Red Sea volcanics after a shift of about 200 km toward northeast. The Jebel el Arab basalt fields extend along the eastern flank of the tectonic Wadi Sirhan–Azraq depression and reach, in the northwest, the Damascus basin, the Golan heights and the rift graben at Lake Tiberias (Fig. 4.1).

The landscape of the Jebel el Arab basalt field shows two different faces: Rain-fed and irrigated agriculture on fertile soils with grain fields, vineyards and fruit trees in the west, and desert and steppe areas with bare basalt rocks and very limited vegetation in the east and south. A vast oasis adjoins the basalt field in the southwest on the Azraq plain (Qaa el Azraq).

Centres of civilization flourished in the western part of the basalt field since, at least, Nabatean times in the second century BC, and towns like Bosra, Suweida and Shahba were important provincial centres of the Roman Empire. The area owes its high level of agricultural and urban development to the relatively favourable climate conditions and to the occurrence of shallow groundwater and springs in aquiferous basalt layers.

W. Wagner, *Groundwater in the Arab Middle East*,
DOI 10.1007/978-3-642-19351-4_4, © Springer-Verlag Berlin Heidelberg 2011

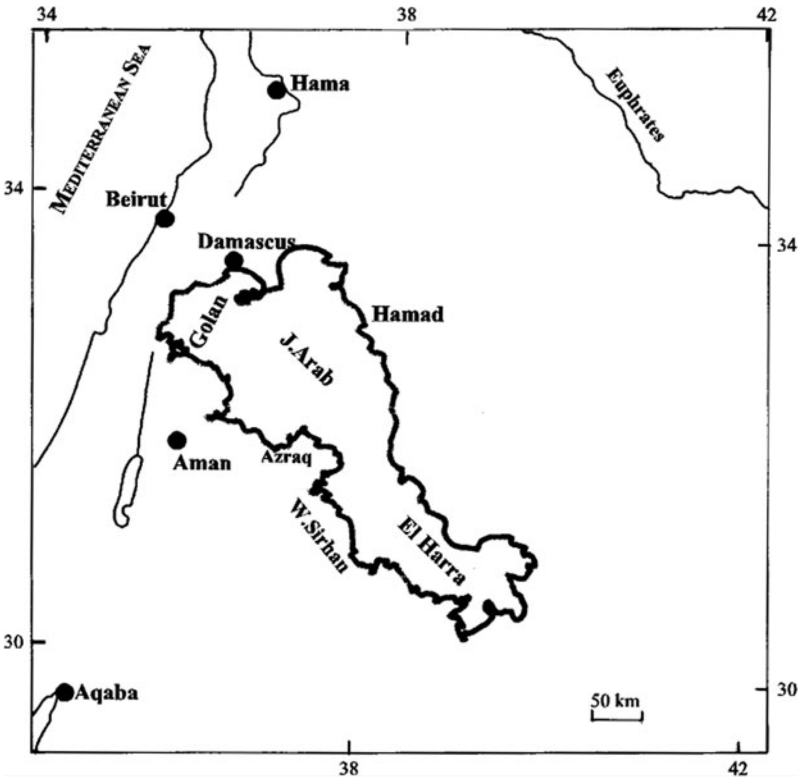

Fig. 4.1 North Arabian volcanic province ◯ basalt field

Moderately high precipitation rates originate from Mediterranean storms, which penetrate frequently until Jebel el Arab from the Lebanon–Antilebanon mountains and through the morphologic depression of Lake Tiberias–Yarmouk between Mount Hermon and the Ajloun highlands. The eastern and southeastern parts of the basalt field, situated at the lee-side of Jebel el Arab, have an arid climate and have been traditionally nomad lands.

The past few decades saw substantial agricultural developments and expansion of villages and towns, which were supported to a significant part by the construction and operation of boreholes tapping the basalt aquifer. Pipelines were built for the transport of water from springs and boreholes to urban centers within and outside the basalt area, e.g., for supplementing the city water supply of Aman and of Suweida.

A considerable number of investigations has been carried out in the basalt area of Jebel el Arab since about 1960. The author had the opportunity to participate in a study reviewing the existing information for a summary assessment of the groundwater resources of the basalt aquifer system jointly with colleagues from Jordan, Syria, Germany and the United Nations.

4.1.1.2 Morphology

The morphology of the basalt field extending over southwestern Syria and northern Jordan is dominated by the Jebel al Arab mountain massif, which is surrounded by plains and plateau like landscapes: the Hauran plain in the west, the northeastern desert of Jordan in the south, and the Hamad steppe and desert area in the east. About 2,500 km^2 of the Jebel el Arab mountain massif are situated above 1,000 m asl. Highest peaks of the basalt field are Tell Ghanie on Jebel el Arab (1,800 m), Tulul al Ashaqif in northeastern Jordan (900 m) and the top of the Golan heights with 1,199 m asl. The surrounding plains and plateaus descend with generally gentle slopes to 500 m asl in the west and south and 700 m in the east. Toward north, the basalts dip under sediments of the Damascus plain. Closed basins with seasonal lakes are located in morphological depressions at the fringes of the basalt field: lake Hijane (<600 m asl) in the Damascus plain, Manqaa ar Rahba near Zelaf (<600 m), Qaa el Azraq (<500 m), Hadhawdha in Wadi Sirhan (572 m, Fig. 3.4). In the west, the Yarmouk valley cuts into the basalt field to around 450 m asl. Prominent volcanic peaks are scattered over the Jebel el Arab mountain massif and the plateaus south and north of the massif.

The Hauran plateau grades in the west into the Golan heights, a basalt plateau which descends from an altitude of about 900 m asl on its northeastern edge to 250 m asl at the Yarmouk valley in the southwest. In the west, the Golan heights are delimited by faults with steep morphologic scarps on the boundary of the rift depression of Lake Tiberias and Houle. Along the escarpment the topographic elevation drops from 700 m asl at the edge of the Golan heights to 212 m below sea level at the shore of Lake Tiberias.

The boundary of the basalt field touches, in the west, the northwestern mountain and highland zone at Mount Hermon and the highlands of Ajloun, and, in the southwest, the east Jordanian limestone plateau. In the east, the basalts are adjoined by the sedimentary desert plateaus of the Hamad.

The surface drainage system of the Jebel el Arab basalt field comprises a network of wadis and mudpans. The wadi courses run, in general, radially from the Jebel el Arab mountain massif and Tulul al Ashaqif toward mudpans or seasonal lakes and, in the west, to tributaries of the Jordan river system. The basalt field extends over part of the Yarmouk and Zerqa river sub-basins in the west and over the catchments of several closed basins:

- The Damascus plain in the northwest
- The narrow Wadi Liwa between the Damascus and Yarmouk sub-basins
- The Azraq plain in the south
- The Hamad area in the east, where several mud pans act as local drainage centres

The eastern slopes of Jebel el Arab comprise the catchment of the extensive Wadi Sham drainage system, which ends in Manqaa ar Rahba near Zelaf.

The basalts of the Golan heights ("cover basalt") form a westward inclined plateau covering sedimentary rocks. In the southern Golan area, the basalt cover protects the soft sedimentary rocks from erosion and has led to the formation of a wide plateau. After the extrusion of the cover basalt, tectonic movements caused graben faults, lowering the erosion base by several hundred metres, incision of rivers and the formation of several gorges along the Yarmouk river and its tributaries Wadi Raqad and Wadi Hreer.

4.1.1.3 Climate

The climate of the Jebel el Arab basalt area is typical Mediterranean with a cold rainy season in winter and a dry and warm summer extending from May to October. Average annual precipitation ranges from 500 mm on the Jebel el Arab mountain massif and the Golan heights, and 250–300 mm in the Hauran plain to less than 100 mm in the south and east. Significant climate changes probably occurred about 10,000 years before present at the end of the pluvial climate phase, during which wetter climate conditions generally prevailed in the eastern Mediterranean region.

4.1.2 Geologic Structure

The geologic sequence of the Jebel el Arab basalt complex is composed of Neogene plateau basalts and Quaternary (Pleistocene–Recent) basaltic lava flows and shield volcanoes. Volcanic eruptions continued until historic times approximately 4,000 years ago.

The total thickness of Neogene to Quaternary basalts increases from less than 100 m on the fringes and in the southeastern and northeastern parts of the basalt field to more than 700 m on the foothills of Jebel el Arab.

4.1.2.1 Neogene Plateau Basalts

The Neogene plateau basalts are composed of single lava sheets of several metres thickness with intercalated soil or sedimentary layers. The lava sheets are crossed by basaltic dikes. A maximum thickness of about 1,500 m of Neogene basalt is assumed beneath the Jebel el Arab mountain massif (Krasnov et al. 1966). The unexposed feeder zones of Neogene basalt are probably located at the eastern shoulder of a rift basin structure, which may represent a northwestern prolongation of the Wadi Sirhan depression. The Neogene basalts are exposed in the southeast and east of the Jebel el Arab area and Al Harra; in the north and west of Jebel el Arab, the Neogene basalts are covered by the younger Quaternary basalts.

The Neogene basalts have prevailingly a Pliocene age. Middle Miocene effusive rocks, which are preserved in outliers in the vicinity of Damascus–Kiswe are represented mainly by basalt with some occasional tuff lenses with a visible thickness of 500 m at Kiswe. West of Zelaf, 30 m of basalt conglomerates and a 100 m thick basalt series of probable Miocene age underlie the Pliocene basalt. On the southern Golan heights, intercalations of basalt flows and intrusions of volcanic dikes are found in the Miocene Hordos formation of the Golan.

In the Lake Tiberias–Yarmouk area, the basalts overlie terrestrial deposits of lower Pliocene age, composed of conglomerates, sandstones, arenaceous marl and limestones (Ain Gev sands). The terrestrial deposits reach a thickness of 150–170 m near Lake Tiberias and thin out toward the Yarmouk river and Wadi Raqad. The thickness of the Pliocene basalts increases from a few tens of metres around Lake Tiberias to 200 m in Wadi Raqad.

A 30 to about 200 m thick sequence of basalt flows of late Pliocene age extends over wide areas of the Golan heights. The Pliocene basalts appear to originate mainly from extrusions in the Hauran–Jebel el Arab area, while secondary extrusions (plugs, small volcanoes, fissure dykes) are scattered over the Golan.

The thickness of the late Pliocene–early Pleistocene "cover basalt" increases from 30 m in the south of the Golan to 175 m toward north.

4.1.2.2 Quaternary Volcanics

The Quaternary volcanics comprise basaltic lava flows, shield basalts and basaltic cinder, scoria and tuff. Quaternary basaltic lava flows and Quaternary shield volcanoes extruded from point source feeders along NNW–SSE trending lineaments crosscutting the Neogene series. The total thickness of Quaternary lava flows varies from few metres to 150 m.

Quaternary lava flows are generally developed as narrow and relatively thin valley fillings in a pre-existing morphological relief. Quaternary shield basalts extend over larger areas and reach a maximum thickness of around 100 m. Surfaces of pahoehoe lava are frequently preserved on Quaternary lava sheets. Each of the individual shield basalts or lava flows has a thickness of about 15 m.

Recent basalts differ from the older ones by their exceptional freshness and form extensive plateaus in southwestern Syria, such as Diret et Touloul, As Safa, and the Hadar basalt sheet which extends in a wide band eastward from Mount Hermon. The Recent basalts overlie unconformably all the deposits of the Damascus depression, up to upper Quaternary limestones.

The Leja plateau in the northwest of Jebel el Arab is formed by Recent pahoehoe lavas departing from Tell Shihan volcano as a more than 45 km long and 6–12 km wide tongue. Near Shahba, block lavas of three recent volcanic cones cover an area of around 12 km^2 in a "disorderly chaotic piling of blocks of various forms and sizes" (Krasnov et al. 1966). The Recent volcanoes have well preserved volcanic cones with heights of 70–250 m.

In the area between Lake Tiberias, Yarmouk river and Wadi Raqad, middle–late Pleistocene volcanics comprise pahoehoe lavas and sheets of lava flows with a total thickness of a few metres to 25 m. On the eastern slope toward Lake Tiberias, the volcanics are overlain by detrital alluvial fans.

4.1.2.3 Subsurface of the Basalt Field

The subsurface of the Jebel el Arab mountain massif comprises probably:

- A sequence of Neogene shield basalt flows with a thickness of several hundred metres, which are covered partly by thin layers of Quaternary lava flows or basaltic tuff.
- The main feeder zone of Neogene basalts, which may constitute a thick sequence of basaltic rocks as vertical dikes or as sill-type intrusions into the sedimentary rocks.
- Layers or blocks of disturbed sedimentary rocks.

The basalt complex of the North Arabian Volcanic Province is underlain by Paleozoic to Neogene sedimentary rocks. The total thickness of sedimentary rocks above the Precambrian basement reaches in northern Jordan from 2.5 km to more than 8 km.

The sequence of Paleozoic to Jurassic rocks in northern Jordan and southern Syria is composed mainly of sandstones, siltstones, conglomerates and shales with intercalations of carbonate rocks in Syria. It can be assumed that a comparable sedimentary rock sequence underlies the basalt field at greater depth.

The Lower Cretaceous is represented by a sandstone facies in Jordan (Kurnub sandstone) and by detrital to carbonate deposits in Syria (Aptian–Albian).

Upper Cretaceous to Neogene sedimentary rocks are exposed in the surroundings of the basalt field. The Upper Cretaceous–Paleogene sedimentary sequence in northern Jordan and southern Syria can be subdivided into three major lithostratigraphic units:

- Upper Cretaceous limestones and dolomites, underlain in Jordan by an Upper Cretaceous chalk–marl formation
- Upper Cretaceous to Paleogene marls
- Paleogene chalks and marly limestones

The stratigraphic range of these units is not uniform over the area of northern Jordan and southern Syria. The deposition of carbonate rocks and of fine grained sediments, related to marine north–south transgressions, generally starts in the north at earlier stratigraphic stages than in the south.

Miocene to Recent deposits are intercalated, in some areas into the basaltic rock sequence. Neogene to Recent deposits with considerable thickness extend over the Damascus and Azraq plains at the northern and southwestern margins of the basalt field. Pliocene to Quaternary deposits, overlying the basalt in limited areas, comprise mud pan deposits, volcaniclastics and sediments in wadis and morphological depressions.

In most areas of the Jebel el Arab volcanic province, the basalts rest on Paleogene sedimentary rocks, which form the main outcrops in the areas adjoining the basalt field: the southern Syrian steppe and Hamad and the Jordanian limestone plateau. In the southwest of the Jebel el Arab basalt field, the Paleogene chalks and Upper Cretaceous–Paleogene marls are missing over a structural high, the eastern prolongation of the Ajloun dome, and the basalts lie directly above Upper Cretaceous limestones and dolomites.

References. Andrews (1992), BGR-WAJ (1994), ESCWA (1996), Krasnov et al. (1966), Michelson and Lipson-Benitah (1986), Safadi (1955), Schaeffer (1997), Wolfart (1966).

4.2 Aquifer Systems and General Groundwater Regime

4.2.1 Aquiferous Zones and Hydraulic Conditions

4.2.1.1 Major Aquiferous Sections

The sequence of Neogene to recent volcanic rocks and of Upper Cretaceous to Quaternary sedimentary rocks in the area of the Jebel el Arab basalt field comprises major aquifer sections in the following units:

- Various horizons with relatively high permeability within the basalt sequence
- Paleogene chalks and marly limestones: Rijam–Shalala (B4–B5) aquifer in Jordan, Eocene chalk and chert aquifer in Syria
- Upper Cretaceous limestones and dolomites: A7/B2 aquifer in Jordan, Cenomanian–Turonian limestone and dolomite aquifer in Syria

The Upper Cretaceous–Paleogene marls (Muwaqar formation or B3 in Jordan, Maastrichtian–Lower Eocene marls in Syria) constitute an extensive aquitard between the Upper Cretaceous and Paleogene aquifers.

Paleozoic to Lower Cretaceous formations underlying the basalt field at greater depth can be assumed to contain limited quantities of non-renewable brackish groundwater.

4.2.1.2 Productive Zones of the Aquifer System

Sections with relatively high productivity in the Jebel el Arab basalt sequence appear related to:

- The lower part of Quaternary to upper part of Pliocene volcanics in the Hauran plain (Ezraa–Deraa area)
- Parts of the Neogene and Quaternary basalts in the foothills of Jebel el Arab around Suweida, in Wadi Liwa and the Leja plateau northwest of Suweida
- The lower part of the basalt sequence, mainly Neogene basalts, which form a joint aquifer with Upper Cretaceous limestones and dolomites in the Halabat–Wadi Dhuleil areas and the northeastern desert in Jordan, and with Paleogene chalks in the Azraq area

Aquiferous horizons in the basalts with low to moderate productivity are found in wide parts of the basalt field. Of particular local importance are numerous, mainly perched, aquifers of limited extent in Neogene and Quaternary basalts of the Jebel el Arab mountain area.

The main basalt aquifer is probably related prevailingly to Neogene plateau basalts, infiltration conditions are, however, influenced in many areas by the overlying Quaternary lava flows.

The basalts and underlying Paleogene chalks and limestones (Rijam Formation) constitute, in general, one hydraulically connected aquifer system. Upper Cretaceous limestones and dolomites (Amman–Wadi Sir Formation) provide a deeper confined aquifer, but may be directly connected to the basalt aquifer in some areas, where the Paleogene has been eroded on the slope of the Ajloun anticline, such as Wadi Dhuleil.

In the eastern part of the Jebel el Arab basalt field, which extends into the Hamad steppe and desert area, Neogene plateau basalts appear to constitute a partly discontinuous aquifer in hydraulic connection with the underlying Paleogene chalk formation.

4.2.1.3 Hydraulic Conditions of Basalt Aquifers

Basalt aquifers are, in general, characterized by hydraulic anisotropy and discontinuous, heterogeneous aquifer properties. Large contrasts exist in hydraulic conductivity of different layers within the basalt aquifer systems. Relatively high permeabilities and preferential pathways are related to the boundary layers between individual basaltic flows and to joints and fractures resulting from cooling and tectonic stress. Lava flows form, after cooling, a solid mass with a coarse crust at the top. Blocky rock masses on the upper surface of lava flows, which are frequently associated with detrital stream deposits, produce a relatively high bulk porosity in most young basalts. Additional differentiation of permeability along boundaries of lava flows can be caused by buried soils and weathering at the top of basalt flows.

Porosity can be high in vesicular lava flows (10–50%), but in solid lava flows the effective porosity is generally less than 1%. Permeabilities of volcanic rocks range from very low values to 10^{-2} m/s. Young basalts have generally a higher permeability than older flows, where permeability is decreased by alterations related to weathering and deep burial and to the influx of cementing fluids (Matthess and Ubell 1983:236 f.).

In accordance with general concepts of groundwater occurrence and movement in basalts (Domenico and Schwartz 1990:70–71), the main components of groundwater flow in the basalt aquifer system in Jordan and Syria may be described schematically as follows:

- High horizontal flow along the tops of individual basalt flows
- Low vertical leakage through the interiors of basalt flows
- Leakage (vertical flow) along structural discontinuities: fractures and fissures caused by cooling and tectonic stress

Other general aspects to be considered in the study of the basalt aquifer system in Jordan and Syria is the occurrence and movement of groundwater in mountainous terrain, as altitude differences between main recharge and discharge areas reach up to 1,300 m. In mountainous terrain, the "water table may be considered a free surface whose depth and configuration depends on the interplay between infiltration and permeability distribution" (Domenico and Schwartz 1990:70). Where low-permeability materials alternate with higher-permeability units, downward percolating water in the unsaturated zone may become perched on low-permeability units (Domenico and Schwartz 1990:28–29).

4.2.1.4 Hydraulic Properties of the Jebel el Arab Basalt Aquifer

The Jebel el Arab basalt complex consists prevailingly of single sheet lava flows. The thickness of individual flows is reported to vary from 3 to 25 m, on average 5–7 m. The central parts of the basalt flows are generally constituted by well crystallized massive varieties, the upper and lower parts by coarse bubbled basaltoids. Up to 50% of individual flow sheets may be represented by porous varieties, but the pores are only to a limited extent interconnected. Permeable horizons occur prevailingly on the boundary zones between different basalt flows. Vertical hydraulic interconnections between these horizons are created by tectonic or cooling fractures.

In general, the permeability in the basalt aquifer system may decrease with depth. Water levels at more than 300 m below land surface in boreholes with significant well yields indicate, however, that productive aquiferous horizons extend to several hundred metres below surface.

Transmissivity values, obtained from single well tests, are reported to range from 1,000 to 10,000 m^2/d in the eastern part of the Hauran plain and the Leja plateau in Syria. In the area west of the road from deraa to Damascus the transmissivity decreases.

T values in the basalt aquifer in Jordan vary from 2 to 44,000 m^2/d.

Drilled wells have, in general, relatively high yields and specific capacities in the Azraq and Wadi Dhuleil areas and in the northern desert of Jordan east of Mafraq with well yields above 40 m^3/h and median Q/s values of 32–39 $m^3/h/m$. In these areas, the basalt and underlying Cretaceous limestones and dolomites or Paleogene chalks constitute a combined aquifer system. The relatively high well yields may be related to a rather high transmissivity of the aquiferous complex with a considerable thickness of carbonate rocks.

In the western part of Wadi Dhuleil and the northwestern part of Jebel el Arab, highly varying well yields are reported: <10 to >40 m^3/h. In the western Wadi Dhuleil area, the basalt constitutes only a thin top section of the aquifer complex formed mainly by Cretaceous limestones and dolomites. The median Q/s value is moderate with 11 $m^3/h/m$.

Well yields are relatively high at some locations around Suweida in the northwestern part of Jebel el Arab, which comprises a complex sequence of aquiferous sections within the basalt with one or two perched aquifer zones above the main basalt aquifer. In the area west of Jebel el Arab (Deraa–Ezra–Bosra), well yields and specific capacities are low to moderate, but relatively high specific capacities are indicated for a number of wells, in which zero drawdown is observed during operation.

Horizontal groundwater flow within the basalt aquifer system is generally restricted to horizons with significant permeability on the boundaries of individual lava sheets. These horizons may comprise about 10–20% of the total saturated thickness of the basalt aquifer. Assuming permeable layers over 20% of the saturated thickness of 100–300 m, T values of 1,000 m^2/d would correspond to permeabilities of 2×10^{-4} to 6×10^{-4} m/s. From the mean Q/s values ranging from 1 to 40 m^3/h/m for different areas of the basalt aquifer system, transmissivities of around 30–1,300 m^2/d would be expected. In areas where the basalts form a hydraulically connected aquifer with underlying carbonate rocks, the relatively high well capacities may be related to a high transmissivity of the carbonate aquifers.

The following hydraulic conditions may be assumed:

- Permeability of the basalt aquifer: 20% of the basalt aquifer consists of layers that have an average horizontal permeability of 2×10^{-4} m/s, and permeability in 80% of the aquifer is less than 1×10^{-6} m/s. The resulting average horizontal permeability is 4×10^{-5} m/s.
- The hydraulic connections between the basalt/chalk aquifer and the underlying Upper Cretaceous limestone aquifer is, in general, characterized by a downward hydraulic gradient.
- The Upper Cretaceous–Paleocene marl aquitard between the basalt/chalk aquifer and the Upper Cretaceous aquifer is saturated with groundwater and there is an average difference of in the hydraulic potential of 10–20 m between the two aquifers. The thickness of the intercalated marls is 200–300 m with an average value of 250 m. The average vertical permeability of the marls is 1×10^{-9} m/s.

4.2.2 Recharge Conditions

The pattern of groundwater recharge in the Jebel el Arab basalt field depends mainly on the climatic conditions and on factors influencing the infiltration of rain and surface water, such as morphology, outcropping geological formations, soil cover. Relatively favourable recharge conditions are related to:

- Mean annual precipitation of >300 mm on Jebel el Arab, the western part of the Hauran plain and the Golan heights
- Outcrops of Neogene and Quaternary shield basalts with very limited soil cover, e.g. on the Jebel el Arab mountain massif and the Leja plateau, where the absence of a distinct surface drainage system indicates that surface runoff is of minor importance
- Particular sections of wadi systems, where runoff collected from extensive catchments can infiltrate

Significant groundwater recharge from present-day precipitation is evident, in particular, in shallow groundwater of Jebel el Arab from:

- The immediate response of spring discharge to the seasonal precipitation
- The low salinity and hydrochemical composition of the groundwater, which reflects recently recharged water (Sect. 4.4.2.1)
- Tritium values of 8.4–21.3 TU
- A $\delta^{18}O/\delta^{2}H$ relationship characteristic for present precipitation originating from the eastern Mediterranean Sea (Sect. 4.5.2.2)

Recent recharge is indicated also at the foothills of Jebel el Arab near Suweida and in the Wadi Liwa–Leja area northwest of Suweida through the wide-spread occurrence of perched groundwater and tritium values of 3.6–16 TU in some wells. The hydrochemical and isotope composition of groundwater samples in the Hauran Plain west of Jebel el Arab reflects an impact of evaporation during the recharge process. A significant component of indirect recharge within the plain can therefore be assumed, but the quantity of present recharge may be relatively small in comparison to the stored groundwater volume.

The surface drainage system, which can be distinguished on satellite images, indicates the following infiltration characteristics on surfaces of different types of basalt:

- Miocene–Pliocene plateau basalt and Pleistocene shield basalts: poorly developed drainage pattern – relatively high direct recharge and low surface runoff
- Quaternary valley – filling lava flows and Quaternary weathered tuff terrains: differentiated drainage pattern – low direct recharge, rapid surface runoff frequently ending in mud pans which are covered by fine grained sediments with low permeability

Recharge volumes are considered to be low to insignificant, in several areas:

- The eastern and southeastern arid parts of the basalt field
- Outcrop areas of valley filling lava flows
- Plains on which a thick soil has developed, e.g. in parts of the Hauran plain

Recharge in these areas appears to be restricted mainly local indirect recharge in wadi systems.

Most of the analyzed samples from boreholes in northern Jordan – the Mafraq area, the northeastern desert of Jordan and the basalt area north of Azraq – have an isotopic signature indicating recharge on the slopes of Jebel el Arab and groundwater movement over long distances with retention periods between 6,000 and 16,000 years (Sect. 4.5.2.2).

Fossil groundwater with very high groundwater ages of more than 20,000 years and stable isotope composition characteristic for recharge during previous pluvial periods is found in boreholes in the arid northeastern parts of the basalt region. Recent recharge occurs, however, in some wadi sections in the east of Jebel el Arab, e.g. in Wadi ash Sham in the Zelaf area.

Direct and indirect recharge amounts, in general, to 6% of precipitation and, in areas with less than 90 mm of mean annual rainfall, to 3% of precipitation.

References. Al-Kharabsheh (1995), Bajbouj (1982), Domenico and Schwartz (1990), ESCWA (1996), Gibbs (1993), Krasnov et al. (1966), Schaeffer (1997), Schelkes (1997), Selkhozpromexport (1974), Wolfart (1966), files of WAJ (transmissivity values).

4.3 Hydrogeologic Sub-Basins and Groundwater Flow Systems

4.3.1 Hydrogeologic Sub-Areas

The Jebel el Arab basalt aquifer complex comprises:

- Sub-regional aquifer systems with extensive groundwater flow regimes
- Various local flow systems at shallow to intermediate depth

Hydrogeologic sub-basins with extensive groundwater flow systems are the Yarmouk sub-basin and the Azraq sub-basin in the west and southwest of the basalt field.

Wadi Dhuleil constitutes a tributary hydrogeologic area of the mainly sedimentary aquifer system of Wadi Zerqa, situated on the western margin of the basalt field between the Yarmouk and Azraq sub-basins.

The eastern part of the basalt field covers an extensive area of basalt aquifers situated above and upstream of the Mesozoic–Paleogene sedimentary aquifer system of the Hamad. The extent of continuous basalt aquifers in that area is rather limited.

The Jebel el Arab mountain massif constitutes a main water divide area between four hydrologic sub-basins – Yarmouk, Dhuleil-Zerqa, Azraq and Hamad (Fig. 4.2) – corresponding approximately to major hydrogeologic sub-areas.

4.3.2 Jebel el Arab Mountain Massif

On the high mountain plateau of Jebel el Arab, situated above 1,300 m asl, outcrops of basalt flows of Pliocene age extend over about 400 km^2. These Pliocene basalts are composed of single lava sheets of several metres thickness with intercalated soil or sedimentary layers. In parts of the high plateau, the Pliocene basalts are overlain by volcanic tuff in cinder or scoriaceous cones. Quaternary lava flows extend, in particular, over the slopes of the mountain massif.

Numerous springs discharge from the Pliocene and Quaternary basalts at various levels between 1,000 and 1,600 m asl, mainly in the western and northern parts of the high plateau and on the western mountain slope. In the eastern part of the high plateau, shallow groundwater has been explored at depths of 20–50 m below surface with water levels at around 1,300–1,400 m asl.

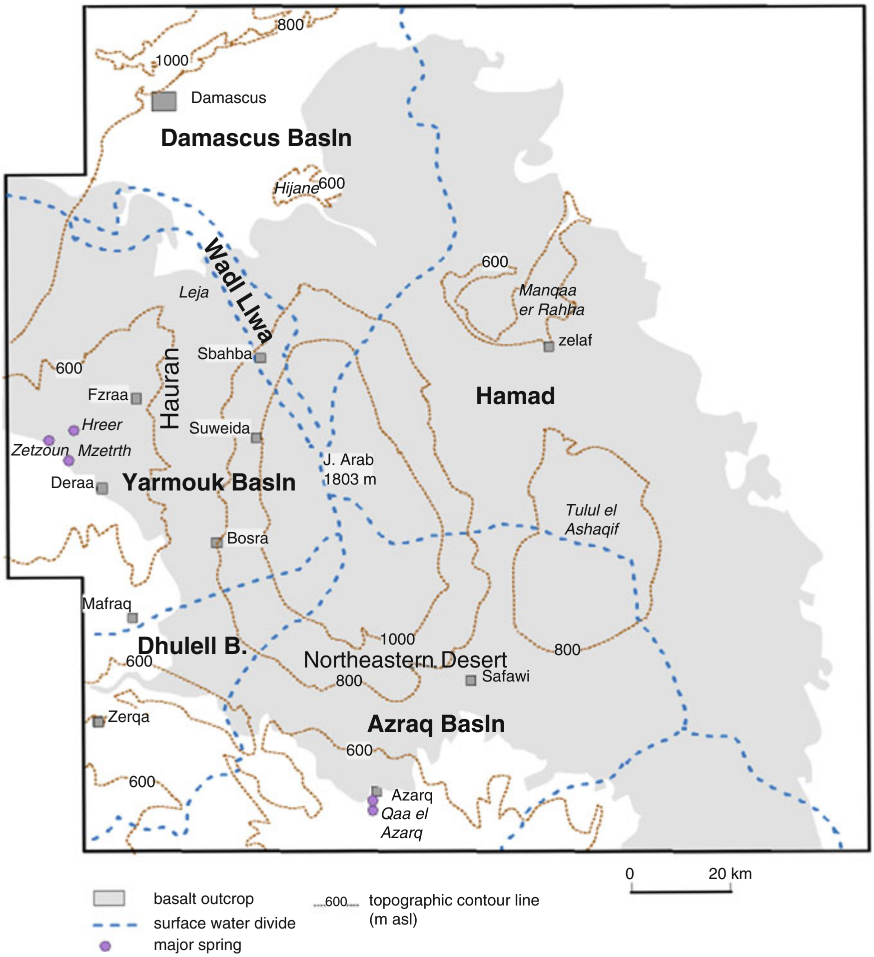

Fig. 4.2 Jebel el Arab basalt field, location map, main hydrologic basins

The springs issue at the boundary between individual lava flows. About 100 springs are observed in the Jebel el Arab area, most of which have a discharge of <1 l/s and dry up during summer. The mean discharge of larger springs is in the order of 12–20 l/s with high seasonal fluctuations. The mean total discharge of springs in the western part of Jebel el Arab and the adjoining mountain slopes in the Suweida area has been estimated at 3.6×10^6 m^3/a (Burdon 1954). The same order of magnitude of spring discharge can be assumed from reported summaries on spring discharge: 40 springs with mean discharge of 1.5 l/s and 70 springs with mean discharge of 0.5 l/s = 95 l/s or 3×10^6 m^3/a. Mean annual precipitation of 350 mm over the combined catchment areas of the springs, which extends over around 500 km^2, produces a volume of precipitation of 175×10^6 m^3/a. As spring discharge of 3×10^6 to 4×10^6 m^3/a corresponds to only about 2% of the mean annual volume of precipitation over the western Jebel el Arab mountain area, significant leakage of groundwater from shallow aquifers into deeper aquiferous horizons may be assumed.

The core of the Jebel el Arab mountain massif is probably occupied by basaltic dikes and sills of the main volcanic feeder zone and by highly disturbed blocks of sedimentary rocks. No extensive deep aquiferous zones are therefore expected in the deeper subsurface of Jebel el Arab, and no indications of deep groundwater circulation, e.g. through temperature anomalies, have been observed.

4.3.3 Yarmouk Sub-Basin

The Yarmouk sub-basin extends from the Jebel el Arab mountain massif in the east and the fringes of the Damascus basin in the north to the spring discharge zone around Mzeirib in the west. The hydrogeologic Yarmouk catchment includes the western part of the Jebel el Arab mountain massif, the foothills of Jebel el Arab around Suweida, the Hauran plain and, in the west, the Golan highlands. The basalt catchment of the Yarmouk sub-basin is adjoined in the south and west by the lower Yarmouk–upper Jordan river basin, which comprises mainly Upper Cretaceous limestone and dolomite aquifers with the main recharge areas in the Ajloun–Irbid highlands in northwestern Jordan (Fig. 4.3).

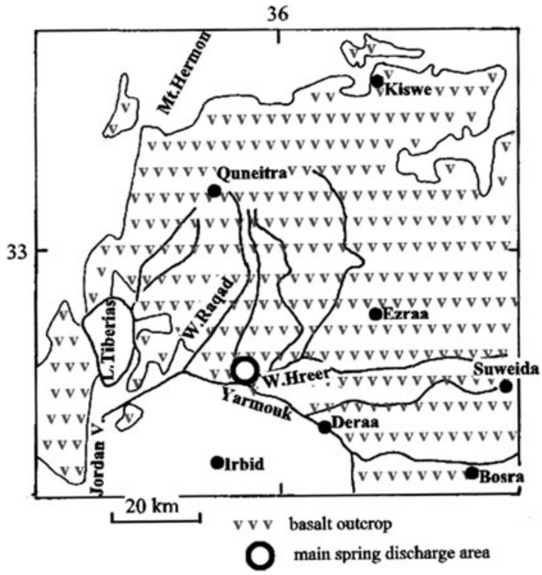

Fig. 4.3 Location map of Yarmouk catchment

4.3.3.1 Foothills of Jebel el Arab and Hauran Plain

The foothills of Jebel el Arab around Suweida are situated at altitudes between 800 and 1,000 m asl and are covered prevailingly by Lower Quaternary basalts which rest above Neogene basalts. The Hauran plain extends between the foothills of Jebel el Arab in the east and the Golan highlands in the west. Topographic elevations descend from around 800 m asl at the foothills to 500 m in the area near Deraa. West of Deraa, wadis of the Yarmouk river system are incised to elevations of less than 400 m asl. Basalt outcrops in the southern part of the Hauran plain are prevailingly represented by Lower Quaternary lava flows, which extend from volcanic eruption cones as valley fillings of a pre-existing morphologic relief. Details of the geological structure are, to a large extent, hidden under a thick soil cover. The plain is dissected by a well developed wadi system indicating a relatively important role of surface runoff.

The Pliocene–Quaternary basalts of the Deraa–Ezraa area form the principal productive aquifer system in the Syrian part of the basalt field. The water table of the main aquifer descends from around 560 m asl in the Jebel el Arab foothills near Suweida, more than 400 m below land surface, and 520 m asl in the north and east of the Hauran plain to 450 m in the southwest, where groundwater discharges in several large perennial springs. The main aquifer extends probably over the Neogene basalts and the lower section of Quaternary basalts. The thickness of the saturated main basalt aquifer decreases from 200 m in the east to around 50 m in the southwest.

4.3.3.2 Northern–Northeastern Part of the Yarmouk Sub-Basin

The northern and northeastern parts of the Yarmouk sub-basin appear to extend over surface water divides into Wadi Liwa and the Damascus plain. The northeast of the hydrogeologic Yarmouk Basin, including the Leja plateau and Wadi Liwa northwest of Jebel el Arab, comprises extensive outcrops of Quaternary shield basalts. On the Leja Plateau, which extends north of Suweida over around 300 km^2, a particularly well preserved 8–20 m thick shield basalt flow of Middle Quaternary age overlies the Lower Quaternary basalt.

Perched groundwater at some tens to some hundred metres above the main groundwater level occurs in many parts in the northeast of the Yarmouk sub-basin:

- Shallow groundwater which discharges in small springs south and northwest of Suweida
- Perched aquifers at intermediate depth in the area southwest and northwest of Suweida with water levels between 50 and 165 m below surface
- Aquifers at shallow to intermediate depth with water levels between 20 and 100 m below surface in the Leja plateau and Wadi Liwa

These local aquifers are sustained by present-day precipitation and extend in pervious layers of plateau basalts or shield basalts. Relatively favourable infiltration conditions and very limited runoff on the surface of these basalt types are indicated by a poorly developed drainage system. In particular the Leja Plateau shows no signs of significant surface runoff. Seasonal surface runoff occurs, however, in Wadi Liwa which forms a closed basin, in which surface runoff accumulates during the rainy season in a small lake near Braq. Groundwater from the local aquifers discharges, to some part, in small springs but major volumes of perched groundwater leak into deeper aquiferous layers reaching eventually the main basalt aquifer.

The main basalt aquifer in the Leja plateau and Wadi Liwa is situated between 150 and 370 m below ground surface (500–523 m asl) and groundwater flow is directed towards southwest into the hydrologic Yarmouk Basin.

In the Damascus plain adjoining the Yarmouk basin in the north, the basalts dip under aquiferous sands and gravels, which constitute a hydrogeologic system with large volumes of groundwater circulation. In pre-development state, most of the groundwater in the Neogene–Quaternary sedimentary and volcanic aquifers discharged in the area of seasonal lakes in the eastern part of the plain, Lake Hijane and Lake Ateibe. At present, the groundwater regime is dominated by artificial abstraction. To a minor part, groundwater flow in deeper aquiferous layers appears to be directed from the Damascus plain into the Yarmouk basin.

4.3.3.3 Golan Heights

The Yarmouk catchment extends in the north into the basalt area of the Golan heights. The volcanics of the Golan heights comprise mainly Neogene basalt flows. Quaternary basalts have a limited thickness of not more than 25 m and a low groundwater potential. A few springs emerge in the recharge areas of the Golan heights and numerous springs with low discharge of 0.5–1 l/s emerge in the Lake Tiberias area along the outcrop contacts between the basalt and underlying sedimentary rocks.

Groundwater flow in the aquiferous Neogene basalt is directed mainly toward south to the Mzeirib–Wadi Hreer spring discharge area and toward southeast, merging into the general groundwater flow of the Hauran plateau to the spring discharge area.

The Pliocene basalts of the Golan area comprise local aquifers at various levels. Groundwater in Lower Quaternary basalt aquifers flows toward Lake Tiberias and the Yarmouk spring discharge area.

4.3.3.4 Mzeirib–Wadi Hreer Discharge Area

Perennial springs in the Wadi Hreer–Mzeirib area rise, in general, on the boundary between Quaternary lava flows and underlying Paleogene sediments, which are represented in the Yarmouk area prevailingly by marls and marly chalks with low permeability. The discharge area comprises three major spring groups, Mzeirib and Chalalate Hreer with mean discharge of 1,400 l/s each and Zeizoun with a mean discharge of 800 l/s, and several smaller springs with mean discharge between 100 and 330 l/s. The discharge points are situated at elevations of 380–440 m asl. Total mean annual discharge of the springs is reported as 170 to 177 $\times$ 10^6 m^3.

4.3.3.5 Groundwater Balance

Groundwater balance calculations for the basalt aquifer system of the Yarmouk sub-basin lead to the following conclusions:

Subsurface flow from the eastern Yarmouk sub-basin – Jebel el Arab, Suweida foothills, Leja plateau, Wadi Liwa, Hauran plain – contributes about 60 $\times$ 10^6 m^3/a to the total spring discharge of 170 $\times$ 10^6 m^3/a in the Wadi Hreer–Mzeirib area. The calculated quantity of 60 $\times$ 10^6 m^3/a considers subsurface inflow from the Damascus basin and leakage losses of around 2.5 $\times$ 10^6 m^3/a into the deeper Upper Cretaceous aquifer.

A comparison of travel times calculated from hydraulic data with estimates of groundwater retention periods shows that the spring discharge is related to groundwater flow in the basalt aquifer as well as in the underlying Paleogene chalk aquifer. The combined saturated thickness of the basalt and chalk aquifers is 350 m, mean horizontal permeability 2.3 $\times$ 10^{-5} m/s, and travel times from different parts of the catchment to the discharge area are in the order of 3,200–9,200 years.

That groundwater flow with a mean retention period of 5,000 years is probably, to a large extent, sustained by present day recharge. Recharge is assumed, in the calculation, to correspond to 6% of the mean annual precipitation, which varies from around 250 to 500 mm in different parts of the catchment.

The calculated quantity of 60 $\times$ 10^6 m^3/a considers:

- A subsurface inflow into the Hauran plain of 35 $\times$ 10^6 m^3/a from west to northwest (Jebel el Arab, Suweida foothills and Leja plateau) and of 8.8 $\times$ 10^6 m^3/a from the north (Damascus plain and Wadi Liwa)
- Recharge of 11 $\times$ 10^6 m^3/a on the Hauran plain, or 6% of annual rainfall of 250 mm over an area of 750 km^2
- Leakage losses into the underlying Upper Cretaceous aquifer of 1.5 $\times$ 10^6 m^3/a

The remaining quantity of 110 $\times$ 10^6 m^3/a out of the total of 170 $\times$ 10^6 m^3/a of spring discharge is attributed to subsurface flow from the western part of the catchment: the Golan heights and Mount Hermon foothills.

4.3.4 Azraq Sub-Basin

4.3.4.1 Aquifer System

The Azraq sub-basin extends from the Jebel el Arab mountain massif in the north and the limestone plateau of eastern Jordan into the Azraq plain (Qaa el Azraq) in the centre of the basin. The northern part of the Azraq basin is occupied by outcropping basalts, outcrops in the southern part of the basin comprise mainly carbonate sediments of Upper Cretaceous to Paleogene age. The basalt field of the northern Azraq sub-basin descends from $>$1,000 m asl in the Jebel el Arab area in the north and around 900 m on the Tulul al Ashaqif in the east to 500 m asl in the Azraq plain.

Basalt outcrops in the Azraq catchment are Quaternary lava flows and Neogene and Quaternary shield basalts. Numerous volcanic cones are aligned in NNW–SSE trending chains in the area between the Azraq plain and Jebel el Arab. The surface drainage system in the basalt field of the Azraq basin shows major generally north–south oriented wadi systems, which extend prevailingly within the outcrops of Lower Quaternary lava flows. The wadi drainage system in the arid eastern part of the basin is directed to mudpans aligned in a morphologic depression zone between the slopes of Jebel el Arab and Tulul al Ashaqif.

Groundwater movement in the main basalt aquifer of the Azraq basin follows a general north–south direction towards the Azraq spring discharge area. Depth to groundwater exceeds 400 m in wide parts of the northeastern desert of Jordan, which is situated between Jebel el Arab and the Azraq plain. The main basalt aquifer is probably related mainly to Neogene plateau basalts, infiltration conditions are, however, influenced in many areas by the overlying Quaternary lava flows.

The basalts and underlying Paleogene chalks and limestones (Rijam formation) constitute, in general, one hydraulically connected aquifer system. Upper Cretaceous limestones and dolomites (Amman–Wadi Sir formation) provide a deeper confined aquifer, but may be directly connected to the basalt aquifer in some areas, where the Paleogene has been eroded.

4.3.4.2 Groundwater Balance

In the prevailingly semi-arid catchment of Azraq, hydrogeologic conditions are generally similar to those in the Yarmouk sub-basin, but recharge rates are lower in the dryer climate and are estimated at 2–18 mm/a on average. Spring discharge and evapotranspiration in the Qaa el Azraq was 16×10^6 m^3/a in the pre-development state and appears to have been sustained, to a substantial part, by present-day recharge, which occurs in particular in the mountainous northern parts of the catchment. An assumed infiltration of 6% of mean precipitation of 150–250 mm/a over 1,260 km^2 in the semi-arid northern parts of the catchment corresponds to an annual recharge of 13.5×10^6 m^3/a.

The spring discharge decreased significantly when operation of a well field tapping the basalt and Paleogene chalk aquifers started after 1980, and around 1991 the springs dried up completely.

In the vast arid eastern part of the catchment covering 4,500 km^2, recharge is estimated at 10.8×10^6 m^3/a from a recharge rate of 2.4 mm/a, of which around 4×10^6 m^3/a are assumed to be lost through leakage into the deeper aquifer.

Travel times of groundwater flow from recharge areas to the Azraq discharge area are calculated from hydraulic data as 5,700 to 16,000 years. These calculated travel times correspond, in general, to water ages derived from ^{14}C measurements. It can, however, not be excluded, that the groundwater of the basalt aquifer system reaching the Azraq area contains components of fossil groundwater, which is not related to present recharge and hydraulic conditions.

4.3.5 Wadi Dhuleil

The Wadi Dhuleil catchment covers a small section of the basalt field in the upstream part of the drainage system of Wadi Zerqa which is a tributary of the Jordan River. The topographic elevation of the catchment descends from >1,300 m at the Jebel el Arab mountain massif to 600 m asl in Wadi Dhuleil. The catchment is prevailingly covered by Lower Quaternary basalt flows. In the groundwater exploitation area at Wadi Dhuleil, the basalts are about 60 m thick.

The Upper Cretaceous to Paleogene marls and chalks are missing in the Dhuleil area and the aquiferous basalts are in direct contact with the Upper Cretaceous limestone–chert aquifer. The groundwater regime is highly disturbed by water extraction for irrigation and by irrigation return flow. Recharge over the catchment, which covers about 1,320 km^2, can be estimated at around 13×10^6 m^3/a. Present groundwater extraction exceeds the estimated natural recharge by about 100%. The deficit may be partly compensated by recharge from irrigation return flow, which leads, however, to serious water quality problems.

4.3.6 Hamad

In the eastern part of the Jebel el Arab basalt field, which extends into the Hamad steppe and desert area, Neogene plateau basalts appear to constitute a continuous aquifer in hydraulic connection with the underlying Paleogene chalk formation. Toward the eastern fringes of the basalt field, the basalts become unsaturated and the water level is situated in deeper carbonate formations of Mesozoic to Paleogene age. Groundwater movement is generally directed to the Euphrates–Gulf basin in the east. North of Jebel el Arab, some subsurface flow appears to occur from the Damascus basin into the basalt aquifer of the Hamad area.

References. Al-Kharabsheh (1995), Bajbouj (1982), Burdon (1954), ESCWA (1996), Krasnov et al. (1966: 37–38), Schelkes (1997), Selkhozpromexport (1974, 1986), Wolfart (1966).

4.4 Groundwater Salinity and Hydrochemistry

4.4.1 Salinity Distribution and Hydrochemical Environment

4.4.1.1 Groundwater Salinity

Salinity of the basalt groundwater is generally low to intermediate with 200–400 mg/l TDS in the Jebel el Arab area and in the basalt aquifer system west and south of Jebel el Arab. Higher groundwater salinities occur in the Hauran plain – up to 800 mg/l TDS – and in the joint volcanic–sedimentary aquifer on the southwestern fringes of the basalt field, where concentrations of total dissolved solids of up to several thousand mg/l are observed at some locations. Elevated salinities of more than 1,000 mg/l TDS appear to be caused mainly by irrigation return flow and by evaporative salt enrichment, e.g. in the Azraq plain. In the arid eastern parts of the basalt field, groundwater salinities generally range from 1,000 to 1,500 mg/l TDS, increasing to 6,000 mg/l towards southeast (Fig. 4.4).

4.4.1.2 Hydrochemical Conditions

The hydrochemical conditions of groundwater in the Jebel el Arab basalt aquifer system are, in general, characterized by the low chemical reactivity of the basaltic silicate rocks and by solution processes of carbonate and silicate minerals. Most of the groundwaters from the basalt aquifer system are Na–HCO_3 or Na–Cl type waters. Ca–HCO_3 type waters occur as spring water on Jebel el Arab.

The contribution of atmospheric input to the groundwater salinity can approximately be estimated from chemical analyses of rainwater from stations in Jordan and Syria. Shallow groundwater with low salinity (85–225 mg/l TDS) from Jebel el Arab shows an increase of Cl concentration in comparison to rainfall at Suweida and Ezraa by factors of 2–7 and of SO_4 concentrations by factors of 0–3. HCO_3 concentrations in groundwater are significantly higher than in rainwater. The hydrochemical composition of the low salinity groundwater is similar to the composition of flood waters from the Azraq area.

The increase of anion concentrations in the groundwater in comparison to rain water can be attributed to:

- Enrichment of substances dissolved in rainwater during infiltration
- Pedogenic inputs: reactions in the soil zone
- Lithogenic inputs: reactions with rock material within the aquifer or the overlying unsaturated zone

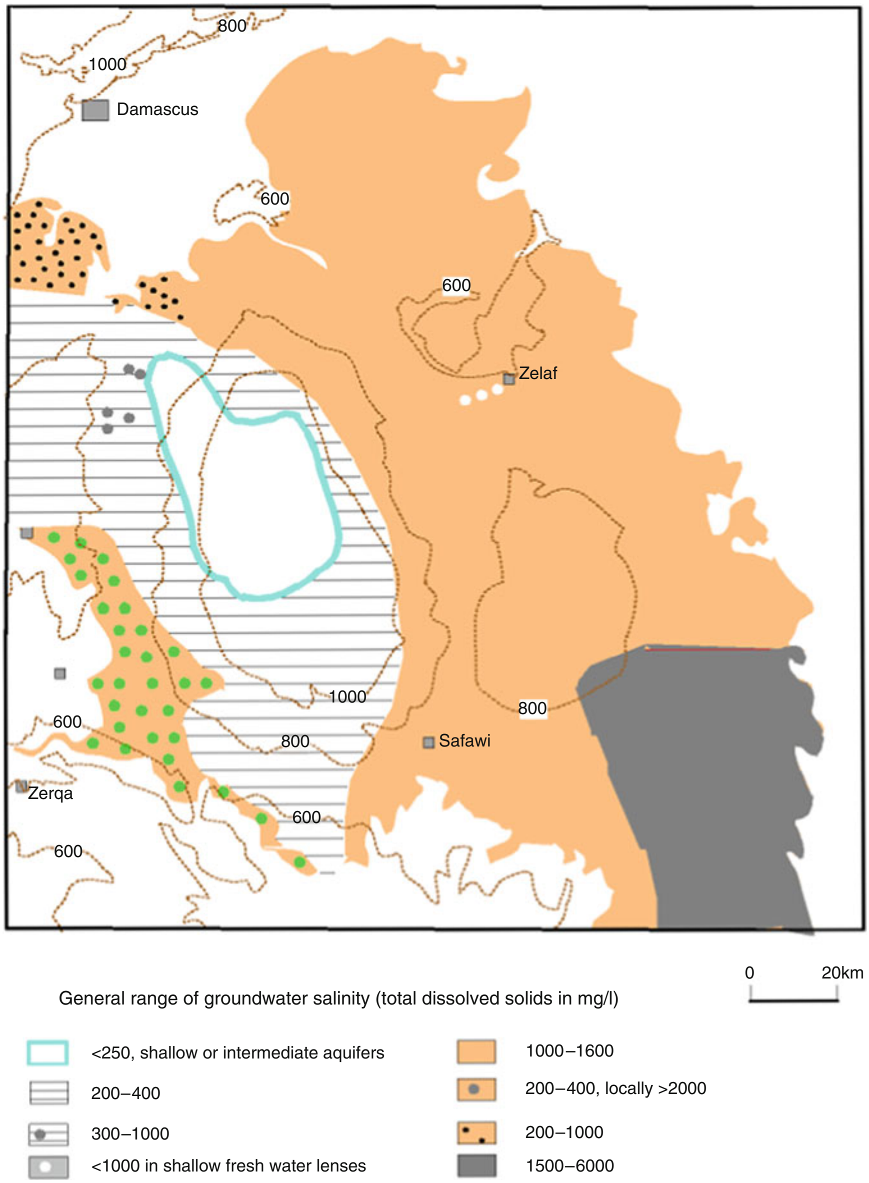

Fig. 4.4 Groundwater salinity distribution in Jebel el Arab basalt field from ESCWA (1996)

Enrichment through evaporation on the surface increases in particular Cl concentrations of the infiltrating water. Reactions of biogenic CO_2 produced in the soil zone with water and carbonate and silicate minerals leads to an increase in concentrations of HCO_3 and equivalent cations.

Solution of lithogenic components in groundwater of the basalts is predominantly controlled by reactions of water and dissolved CO_2 with rock material. Major mineral components of the basalts are silicates (plagioclase, potassium-feldspar, clinopyroxene, amphibole, biotite, olivine) and magnetite. Minor components are quartz, calcite, apatite, limonite/goethite, sulfides (pyrite, chalcopyrite) and some silicates, such as zeolite, epidote, chlorite, sericite.

A major portion of the HCO_3 concentration in the groundwater may be supplied by dissolution of calcite of volcanic origin and possibly also of carbonates of dust deposition on the surface. An additional source of dissolved HCO_3 may be provided from the process of silicate weathering, which can be formulated schematically on the example of plagioclase dissolution as follows (Appelo and Postma 1993: 204):

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^-$$

$$CaAl_2Si_2O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+}$$

Ca and HCO_3 go into solution while aluminum silicates (Kaolinite) remain as weathering products. Depending on the mineralogic composition of the basaltic rocks, release of Ca, Na, Mg, K, Si, Al and Fe as ions or molecular complexes is included in the silicate weathering reactions to a varying degree. Silicate weathering is, in general, a very slow process.

Concentrations of Cl and SO_4 show a general moderate increase in direction of groundwater flow. The increase may be related to a higher enrichment of dissolved substances during infiltration in the plain areas, where rainfall and velocity of surface runoff are lower than in the mountain area. Elevated groundwater salinity is generally correlated with elevated concentrations of Na and Cl.

4.4.2 Hydrochemical Features in Different Hydrogeologic Areas

4.4.2.1 Jebel el Arab Mountain Area

Water samples from springs and shallow wells in the Jebel el Arab mountain area are characterized by low ion concentrations and groundwater salinity between 85 and 225 mg/l TDS and are prevailingly Ca–HCO_3 type waters (Fig. 4.5). The samples represent perched groundwater in pervious zones of Pliocene basalt sheets or of Quaternary lava flows on the mountain slopes. Tritium contents of 8–21 TU indicate that the perched aquifers are replenished by recent recharge.

In general, the hydrochemical composition of shallow groundwater in the Jebel el Arab mountain area appears dominated by atmospheric inputs and evaporative enrichment of atmospheric inputs by a factor of around 5 and by reactions between soil CO_2, water and carbonate or silicate minerals.

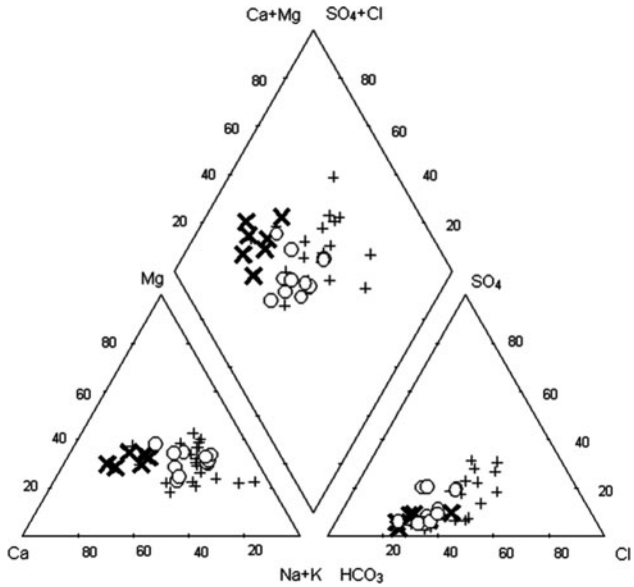

Fig. 4.5 Piper diagram: Groundwater samples from the basalt aquifer in the Jebel el Arab–Hauran–Mzeirib area, × shallow groundwater in the Jebel el Arab mountain area, + groundwater in the Hauran plain, ○ water of springs in the Mzeirib–Wadi Hreer area, data from Bajbouj (1982), ESCWA (1996)

4.4.2.2 Golan Heights

The water of springs from the Neogene and Quaternary basalt aquifers of the Golan heights is HCO_3 water with an average salinity of 475 mg/l TDS. Percentages of major cations are approximately equal with a slight predominance of Na or Ca, Na and Ca concentrations being higher than in precipitation water. Spring water from the Neogene basalt is generally Na–HCO_3 water with a Mg/Ca ratio around 1.0. The water of springs issuing from the Quaternary basalts is Ca–HCO_3 water with a Mg/Ca ratio of 0.7.

Calcium–sodium plagioclase, a major mineralogic component of the basalts, releases upon dissolution Na and Ca. Relatively high concentration of Mg in basalt waters is probably caused by the dissolution of olivine.

4.4.2.3 Hauran Plain and Mzeirib–Wadi Hreer Discharge Area

Samples from boreholes and springs from the Hauran plain and the groundwater discharge area around Wadi Hreer–Mzeirib can, in general, be characterized as Na–HCO_3 type waters with a salinity range of 250–800 mg/l TDS (Fig. 4.5). The composition of water samples shows a general zoning with:

- Relatively low Cl and SO_4 concentrations and total salinity (around 350 mg/l TDS) in boreholes in topographic higher parts of the plain (above 600 m asl) and in water from the large springs of Wadi Hreer–Mzeirib
- Moderate salinity of 500 mg/l TDS and somewhat higher Cl and SO_4 concentrations in boreholes at the topographically lower parts of the plain around Ezraa–Deraa

The rather low ion concentrations in the spring waters of Wadi Hreer–Mzeirib indicate that regional groundwater flow related to recharge in distant upstream areas of the catchment provides a major component of the spring discharge.

Comparatively high values of EC, HCO_3, Cl and NO_3 in groundwater at some locations of the Hauran plain are probably caused by anthropogenic sources of dissolved ion contents accompanied by an increase of HCO_3 and Ca contents through oxidation of organic carbon.

4.4.2.4 Mafraq–Azraq Area

On the southern and southwestern slope of Jebel el Arab, comprising the area east of Mafraq, the northeastern desert of Jordan and the Azraq area upstream of the Azraq plain, the basalt aquifer is connected with the underlying Paleogene chalk aquifer and, in the west where the Paleogene is missing, with the Upper Cretaceous limestone–chert aquifer. The basalt aquifer system here contains predominantly fresh groundwater of Na–HCO_3 to Na–Cl type with salinities of 250–700 mg/l TDS (Fig. 4.6). The fresh water is similar in its hydrochemical composition to water samples from the Ezraa area and is probably recharged prevailingly at higher parts of the catchment area. The hydrochemical composition of the groundwater appears dominated by atmospheric inputs enriched through evaporation and by dissolution of carbonate and silicate minerals. The composition of the fresh groundwater in the basalt as well as in the underlying carbonate rocks is clearly related to recharge in the basalt outcrop. No characteristics of typical carbonate rock water can be seen. A slight contribution of Na and Cl contents from the carbonate aquifer cannot be excluded.

Salinity of water extracted from the AWSA well field, situated directly upstream of the Azraq plain, is generally 300–460 mg/l TDS, with some values reaching up to 1,000 mg/l TDS. Fluctuations of the salinity and composition may be related to vertical or horizontal differentiation of the natural water quality, e.g. the occurrence of moderately higher contents of dissolved solids in water of the Paleogene chalk or in the basalt aquifer in areas surrounding the well field.

Samples from the springs Al Aura and Mustadhema, which are located at the rim of the basalt outcrop and have now dried up, show the same general hydrochemical characteristics as the water from AWSA boreholes (Fig. 4.7). Groundwater in the Azraq plain, which includes basalt water mixed with water infiltrated in the plain, has considerably higher salinity. Recent recharge and near surface groundwater in the plain are affected by evaporative enrichment of dissolved substances. The sabkha area of the Azraq plain contains saline groundwater.

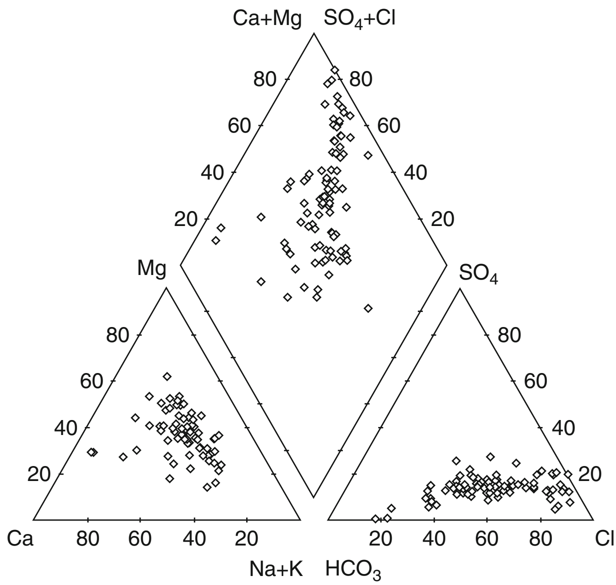

Fig. 4.6 Piper diagram: Groundwater samples from the basalt aquifer in the Mafraq area and northeastern desert of Jordan data from Rimawi (1985), Almomani (1996), ESCWA (1996)

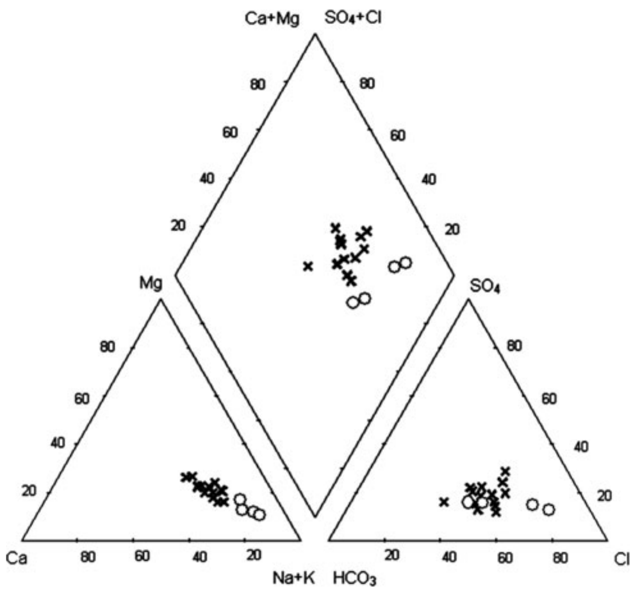

Fig. 4.7 Piper diagram: Groundwater samples from the basalt aquifer in the Azraq area, × AWSA well field, ○ springs in Azraq plain, data from Rimawi (1985), Rimawi and Udluft (1985), Al-Momani (1991), Almomani (1996)

A hydrochemical classification of groundwater in shallow aquifers of the Azraq depression has been presented by Rimawi and Udluft (1985). Four major hydrochemical groups have been distinguished:

- Typical basalt aquifer water with a mean salinity of 370 mg/l TDS
- Groundwater in carbonate and alluvial aquifers surrounding the basalt and in most parts of the Azraq plain with higher contents of dissolved solids than the basalt water and mean salinities of 800–1,200 mg/l TDS
- Hyper-saline Na–Cl water with Cl concentrations of 130 g/l in the central part of the Azraq depression, where pools of surface water evaporate

In the area east of Mafraq numerous boreholes, most of which tap aquiferous sections of the Pleistocene basalt and the underlying Upper Cretaceous carbonate aquifer (A7/B2 aquifer), extract groundwater mainly for irrigation. Salinity of samples collected from 84 boreholes between 1982 and 1992 ranges from 340 to 4,000 mg/l TDS. 70% of the evaluated water analyses are fresh water samples. The brackish groundwater, represented by 30% of the samples, is characterized by high Cl concentration and elevated Ca, Mg and Na contents. The relative cation contents are not significantly different from the fresh water of the basalt aquifer. HCO_3 concentration in a number of samples is low ($<$100 mg/l). NO_3 contents reach up to 75 mg/l in some samples; increased NO_3 contents appear to be correlated with high Cl and SO_4 concentrations, indicating that the main source of elevated ion concentrations is irrigation return flow (Fig. 4.8).

4.4.2.5 Wadi Dhuleil

In the Dhuleil area, about 80 production wells are in operation for irrigation and domestic supply. The wells tap mainly the Upper Cretaceous carbonate aquifer (A7/B2 aquifer), which is covered in part of the area by Pleistocene basalt. Depth to groundwater is generally between 50 and 100 m, the thickness of the basalt is $<$100 m.

Groundwater salinity of samples from the area with basalt cover (18 samples collected between 1985 and 1992) ranges from 400 to 6,000 mg/l TDS. Mean concentrations of all major ions, except for HCO_3, are higher than in other areas of the western part of the basalt aquifer system (Fig. 4.8). HCO_3 concentrations are generally low (around 100 mg/l). The occurrence of fresh water appears to be restricted, at present, to the more eastern – upstream – parts of the area. Historical water analysis data show that groundwater salinity and concentrations of major ions increased from low levels, before groundwater development started in 1961, to brackish water quality in many wells after 1970. Increasing NO_3 contents of the groundwater are generally correlated with high Cl and SO_4 concentration. The deteriorating quality of the irrigation water together with a diminution in the volume of the applied irrigation water led to high soil salinization. The high groundwater salinity and groundwater quality deterioration is apparently caused mainly by the rapid recycling of irrigation water: Part of the water applied for

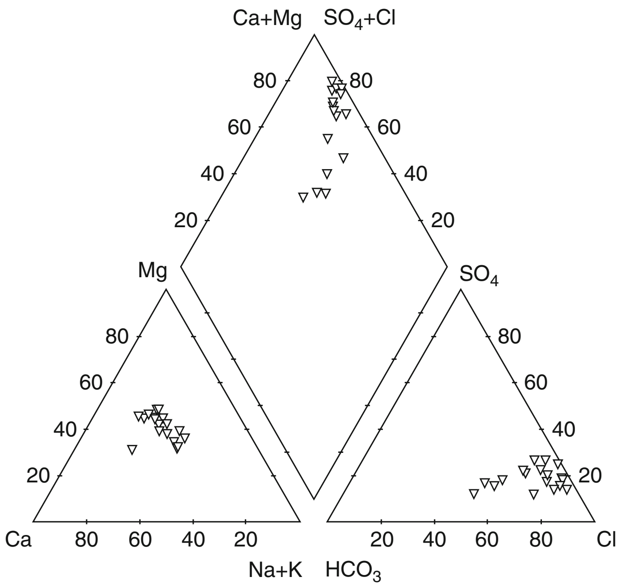

Fig. 4.8 Piper diagram: Groundwater samples from the basalt aquifer in the Dhuleil area, northern Jordan data from Rimawi (1985), ESCWA (1996)

irrigation seeps directly into the subsurface without longer retention in the soil zone. The reinfiltrating water shows no impact of reactions with soil CO_2 and has no detectable tritium. The hydrochemical composition of the reinfiltrating water is related to the dissolution of soluble salts from the saline soils and possibly to precipitation of less soluble carbonate constituents.

4.4.2.6 Hamad

The Hamad area and the eastern part of the Azraq sub-basin catchment extending northeast and east of Jebel el Arab have an arid climate with mean annual precipitation of 150 mm in the northwest decreasing to $<$70 mm southeast. The basalt thickness varies from a few tens of metres near the northern and eastern boundaries of the basalt outcrop to $>$400 m in the Tulul al Ashaqif area. In considerable parts of the northern and eastern extent of the basalt field, water levels of the main groundwater flow system are situated within the Paleogene chalk aquifer below the base of a relatively thin basalt cover.

Groundwater salinity in the basalt covered part of the Hamad area is generally $>$1,000 mg/l TDS, increasing to several 10,000 mg/l towards southeast. The groundwaters vary in their hydrochemical composition in wide ranges and include brackish water with Cl concentrations of up to 600 mg/l and SO_4 concentrations up to 950 mg/l. Fresh water to slightly brackish HCO_3 or Cl type water occurs along extensive wadi systems on the eastern and southern margin of the basalt field.

In general, the elevated groundwater salinity in the Hamad area and the eastern part of the Azraq basin can be attributed to the prevailing arid climate conditions with very low recharge rates, high evaporative enrichment of the limited quantities of infiltrating water, and low rates of groundwater circulation and flushing of aquifers. Fresh water occurrences appear to be restricted mainly to lenses along major wadi courses.

References. Abu-Sharar and Rimawi (1993), Al-Kharabsheh (1995), Almomani (1994), ESCWA (1996), Kattan (1996c), Nitsch (1990), Rimawi (1985), Rimawi and Udluft (1985), Rosenthal (1987), Salameh and Rimawi (1987a, b), Schelkes (1997), Selkhozpromexport (1974), Wolfart (1966).

4.5 Hydrogeologic Information from Isotope Data

Isotope hydrologic information on the groundwater from the basalt area is available from a number of investigations in the past decades (see references of this sub-chapter).

4.5.1 ^{3}H and ^{14}C Data

Tritium values of 5–21 TU indicate recent groundwater recharge in the Jebel el Arab mountain area, on the western Golan heights, and at some locations in the Hauran plateau. From ^{14}C ages, contemporary recharge can be assumed for the Suweida area and the eastern parts of the Hauran plateau. The mean ^{14}C ages of the groundwater increase to a few thousand years towards central and southern parts of the Hauran plateau around Ezraa–Deraa. ^{14}C ages of groundwater in the Mzeirib–Wadi Hreer spring discharge zone are around 4,000–6,000 years (Fig. 4.9). Considering mean distances of groundwater flow of 40–60 km from the recharge areas, groundwater flow velocities may be estimated to be in the order of 10 m/a.

^{14}C data show that most of the groundwater of the Jordanian part of the basalt field are between 10,000 and 28,000 years old. Retention periods of groundwater discharging in the springs at Azraq are calculated from ^{14}C data at 8,000–15,000 years. For a 60 km long flow path, these ages correspond to a mean groundwater flow velocity between 4 and 7.5 m/a.

The ^{14}C ages of groundwater samples in the Hamad area are exceptionally high (19,000–28,000 years); the samples may represent fossil groundwater mainly from the underlying Paleogene chalk aquifer.

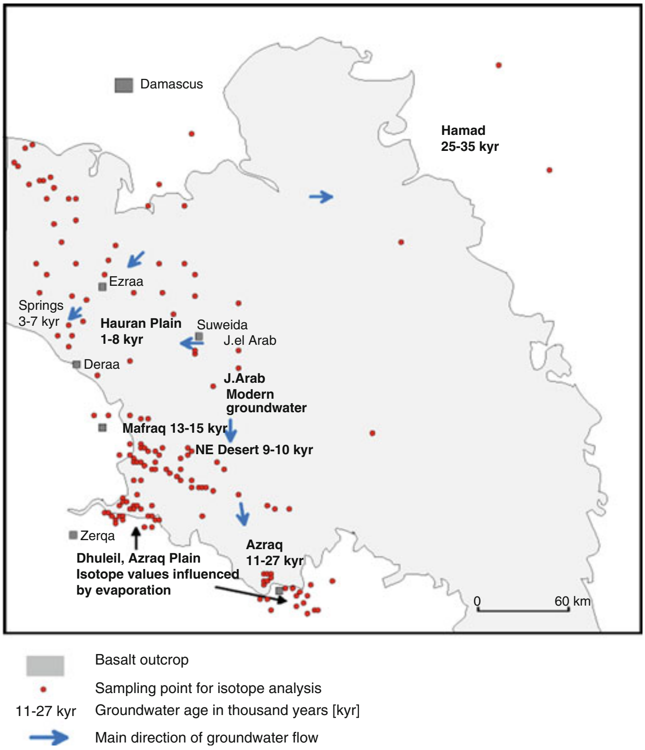

Fig. 4.9 ^{14}C water ages in the Jebel el Arab basalt field after ESCWA (1996)

4.5.2 Stable Isotopes of Oxygen and Hydrogen

4.5.2.1 Precipitation

Mean δ^{18}O and δ^2H values of precipitation water samples from the Jebel el Arab basalt area scatter close to the MMWL with d values around +20‰. δ^{18}O varies in a range of −5.27 to −7.41‰ (stations Azraq, Ezraa, Suweida, Kuneitra) (Fig. 4.10).

4.5.2.2 Groundwater

The isotopic composition of groundwater in the northwestern part of the basalt field shows a rather homogeneous development from the recharge area in Jebel el Arab over the Hauran plain to the Yarmouk spring discharge area.

The most negative δ^{18}O values between −6.5 and −8.8‰ were analyzed for samples of shallow groundwater in the Jebel el Arab mountain area. The deuterium excess of most of these samples exceeds +20‰ and corresponds to that of the present-day rainwater of Mediterranean origin.

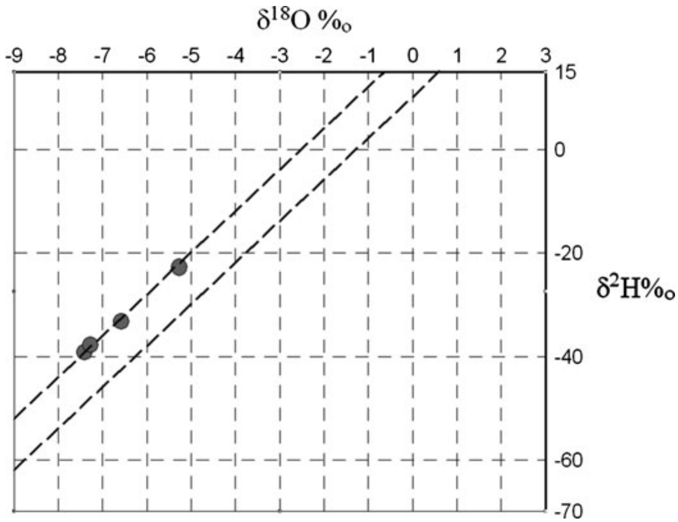

Fig. 4.10 $\delta^{18}O/\delta^{2}H$ diagram: Rain water samples from the Jebel el Arab basalt area stations Suweida, Ezraa, Azraq, data from Almomani (1996), Kattan (1996c)

The groundwater in the Jebel el Arab mountain area is similar in its isotopic composition to the groundwater of the higher ranges of Ansariye mountains and of the highlands of Jordan at Nuaime and may thus be interpreted to represent water recharged from Mediterranean rainfall at altitudes of, on average, 1,000 m asl.

In the Hauran plain and the foothills of Mount Hermon, $\delta^{18}O$ values range from −4.5 to −6‰, d values from +10 to +20‰ with a trend of increasing enrichment of heavy isotopes in direction of the groundwater flow toward south–southwest (Fig. 4.11). The trend to less negative $\delta^{18}O$ values from the Jebel el Arab mountain area and the Mount Hermon foothills toward the Hauran plain may be attributed to an altitude effect, but the increase of $\delta^{18}O$ values together with a general decrease of d values indicates a predominant impact of evaporative enrichment of heavier isotopes on the plain.

$\delta^{18}O$ values of water from springs in the Mzeirib–Wadi Hreer area vary around −5.5 to −6‰ with d values of +17‰. According to the isotopic composition, the water discharging in the springs may represent a mixture of groundwater from the Hauran plain and of groundwater recharged at higher altitudes on Jebel el Arab and on the foothills of Mount Hermon.

In the basalt field southwest and south of Jebel el Arab – areas east of Mafraq, northeastern desert of Jordan, Azraq area – $\delta^{18}O$ values range from −5.5 to −6.5‰ (Fig. 4.12). More negative values (−6.5 to −7‰) are found in some boreholes. d values show a wide scatter between +15‰ and >+20‰, values of >+18‰ were observed in particular in groundwater from the boreholes east of Mafraq, the northeastern desert of Jordan and the well field north of Azraq (AWSA well field). Water of the fresh water spring Al Aura, which has now dried up, had $\delta^{18}O$ values

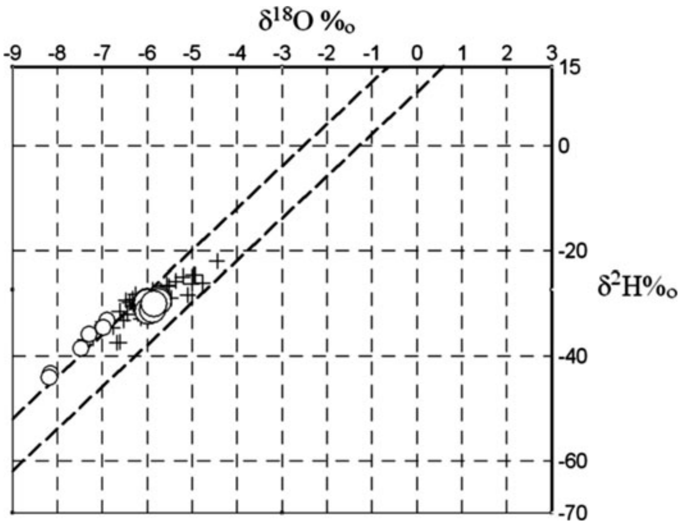

Fig. 4.11 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Jebel el Arab–Hauran–Mzeirib area data from ESCWA (1996), Kattan (1996b) ○ Jebel el Arab springs, + Hauran, ○ Mzeirib springs

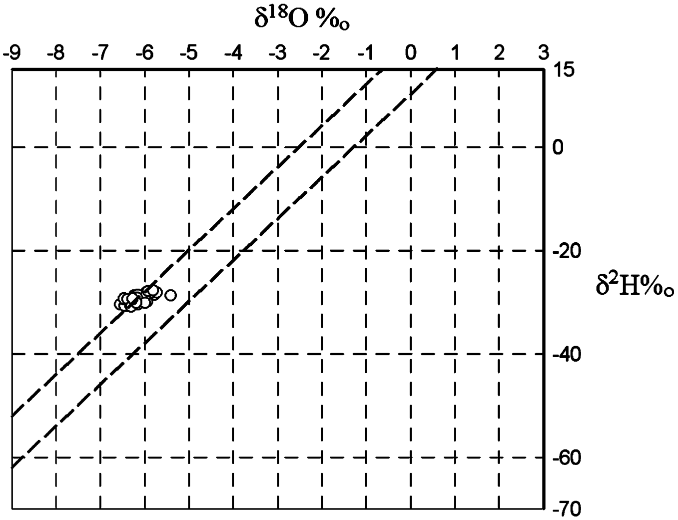

Fig. 4.12 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Mafraq–Azraq areas data from ESCWA (1996)

around −6‰ and d values around +18‰. These values are similar to the values of water of the Mzeirib springs in the Yarmouk catchment. The water discharging at Al Aura spring probably originates from recharge in various parts of the catchment area between Jebel el Arab and the northeastern desert.

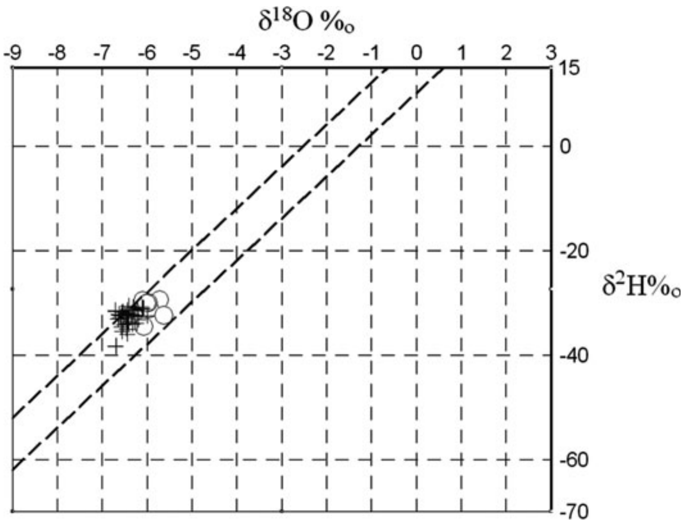

Fig. 4.13 $\delta^{18}O/\delta^{2}H$ diagram: Samples from springs and AWSA well field, + AWSA well field, ○ spring, data from Almomani (1996)

$\delta^{18}O$ values reported for the brackish springs, which issued previously in the Azraq plain (springs Souda and Kaisiye) varied in rather wide ranges with $\delta^{18}O$ between −9.4 and −19.4‰ and d values between −5.7 and −6.12‰, indicating an evaporative impact (Fig. 4.13).

In most samples of the groundwater from the basalt aquifer in the Damascus plain and the Hamad area north and northeast of Jebel el Arab, the stable isotope composition deviates significantly from that of the Jebel el Arab–Hauran areas toward more negative $\delta^{18}O$ values with d values around the GMWL.

4.5.3 Impact of Irrigation Return Flow

In several areas of the basalt aquifer system in Jordan, isotope signatures do not fit into the general picture. These deviations are, in particular, attributed to an admixture of irrigation return flow into the groundwater, which is indicated also by hydrochemical data. The agriculture area of Dhuleil appears to be particularly affected. The ^{14}C ages of 5,800–9,300 years are lower than those further north along the road between Mafraq and Safawi. The total salinity is between 400 and 6,000 mg/l TDS, HCO_3 concentrations are low, high nitrate concentrations are observed. The $\delta^{18}O/\delta^{2}H$ values reflect an influence of high evaporation rates; tritium is not found.

The admixture of irrigation return flow has a significant impact on isotope values: During flood irrigation, water evaporates and $\delta^{18}O/\delta^{2}H$ values are enriched. The evaporative moisture flux into the atmosphere prevents addition of tritium

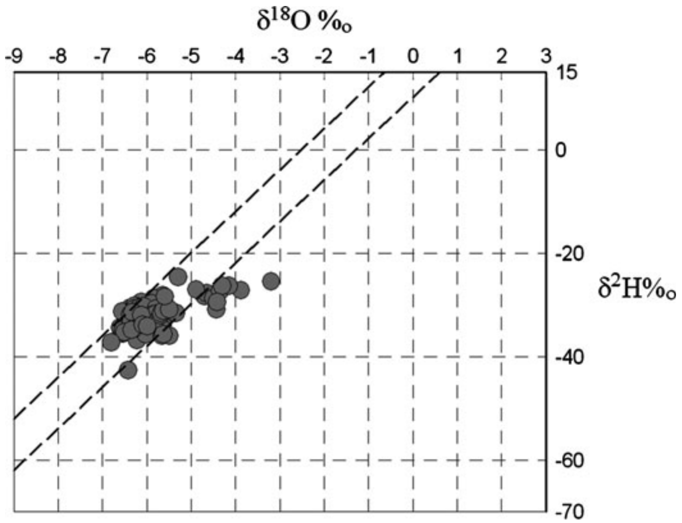

Fig. 4.14 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from Wadi Dhuleil and the Azraq plain data from Almomani (1996), ESCWA (1996)

from the atmospheric moisture, and ^{3}H remains below detection limit. During the seepage of water through the topsoil, carbon compounds are lost by the consumption of the plants while modern soil CO_2 with a high ^{14}C value from the root zone is transported into the aquifer. Accordingly, ^{14}C values in recycled groundwater of irrigation areas can be higher than values of unaffected groundwater.

In the Azraq plain (Qaa el Azraq), the isotopic composition of the groundwater is influenced by irrigation return-flow, seepage of isotopically enriched water from ponds and intensive groundwater extraction (Fig. 4.14).

4.5.4 Isotope Data and Groundwater Regime

In summary, the isotope data from the basalt aquifer system reflect the following main features:

- Significant recent recharge occurs in the Jebel el Arab Mountain area and its western foothills and on the foothills of Mount Hermon.
- Groundwater movement over large distances combined with local recent recharge shows evaporative isotope enrichment in the Hauran Plateau.
- The springs of the Yarmouk area discharge groundwater from different catchment areas with major recharge zones on the mountain zones of Jebel el Arab and the Mount Hermon foothills.

- Groundwater moves towards the Jordanian part of the basalt field over long distances from various parts of the slopes of Jebel el Arab.
- Dominant influences of irrigation return flow are evident in extensive irrigation areas.

In spring catchments on the foot of Mount Hermon, which reach into Mesozoic sedimentary aquifers adjoining the areas, an altitude gradient of $-0.23‰\ \delta^{18}O$/100 m is indicated. On flow paths from Jebel el Arab to the major spring discharge areas, altitude effects are not evident.

References. Almomani (1991, 1993, 1994, 1996), Arsalan (1976), ESCWA (1996), Kattan (1996b, c), Rimawi (1985), Rimawi and Udluft (1985), Verhagen et al. (1991: Chap. 3), Wagner and Geyh (1999), Zuppi (1986).