Chapter 3
Eastern Part of the Northern Arabian Platform

3.1 Al Badiye, Hamad and the Transitional Zone

3.1.1 Morphology, Hydrography, Climate and Land Use

3.1.1.1 Morphology

The mountain and highland chains of the northwestern mountain and rift zone grade, in the east, into plateau landscapes of the steppe and desert areas of Syria and Jordan. Semi-arid to arid plateaus extend, over the eastern parts of the northern Arabian platform, from the foreland of the Taurus mountains in the north into the steppe areas of Syria, Jordan and southwestern Iraq. The dry zones of central and eastern Syria, eastern Jordan and southwestern Iraq are generally known as Al Badiye, the land of the bedouins. Toward southeast, the steppe areas of Al Badiye change into a stony desert landscape, the Hamad.

In the east, the northern Arabian platform is separated from the eastern Arabian platform by a geologic uplift structure (Hail–Rutba arch). The distance from the western mountain zone to the eastern boundary of the northern Arabian platform at the Euphrates valley and the Rutba uplift ranges from around 140 km in northern Syria to 350 km in Jordan–Iraq. In the northeast, a zone of plains marks the margin between the Arabian Platform and the alpidic Taurus and Zagros mountain chains.

Most of the Badiye and Hamad is occupied by undulating to flat morphology with moderately incised wadi systems. Two types of mountain landscapes rise above the plateaus: the southern and northern Palmyrean mountain chains and volcanic mountains or hills, the most prominent of which are Jebel el Arab in southern Syria and northeastern Jordan and Jebel el Hass southeast of Aleppo.

The eastern part of the northern Arabian platform comprises – from north to south – the following main geographic units (Fig. 3.1):

- The northern Syrian steppe or Aleppo plateau and, northwest of the Euphrates river, Al Jezire
- The Palmyrean mountain zone
- The southern Syrian steppe grading into the Hamad desert

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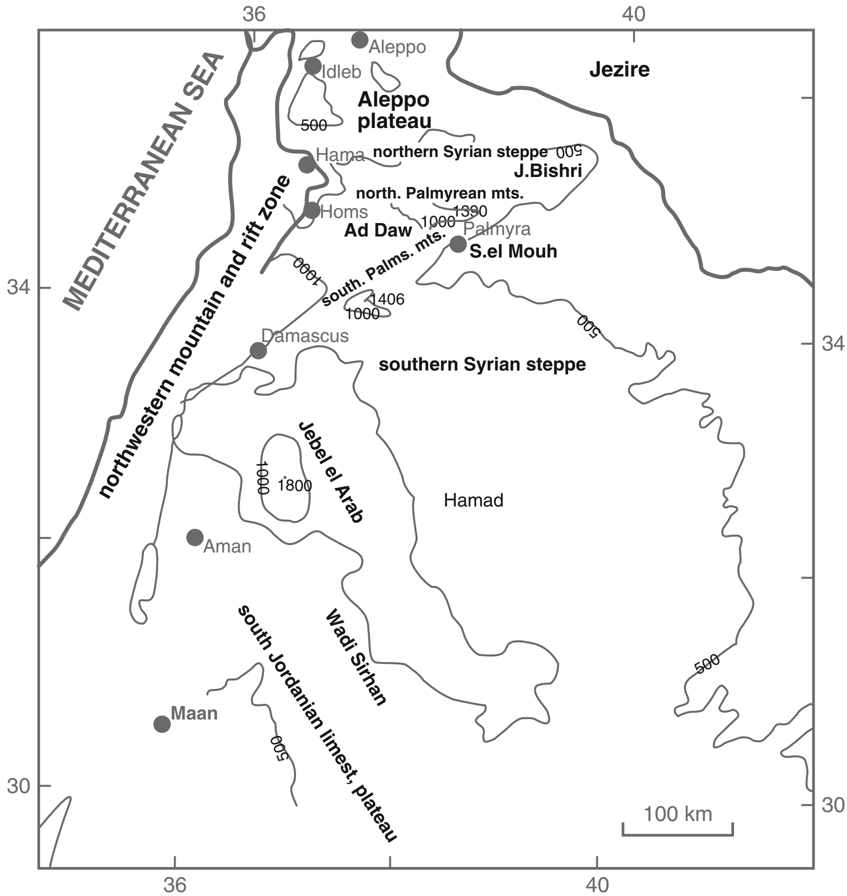

Fig. 3.1 Main orographic–geographic units of the eastern part of the northern Arabian platform. __600__ topographic contour line 600 m asl

- The east Jordanian limestone plateau, separated from the Hamad by the Jebel el Arab volcanic massive

The southwest–northeast to west–east trending southern and northern Palmyrean mountains interrupt the plateau landscapes of the northern Arabian platform. The Palmyrean mountains branch out, in the Damascus area, from the S–N to SSW–NNE directed Antilebanon mountains in three generally NNE to NE trending chains:

- The western mountain zone of Jebel Abu Ata–Jebel Nebek–Jebel Deir Atiye with peak altitudes around 1,400–500 m asl, which is separated from the Antilebanon mountains by the Qalamoun high plain.
- An up to 1,218 m high mountain zone further east, separated from Jebel Nebek by the morphologic depression of Jayroud.
- The southern Palmyrean mountains extending as a 160-km long chain from the Damascus plain at Dmeir until Palmyra.

The main mountain massifs of the southern Palmyrean chains – Jebel Dmeir, Jebel Mghara, Jebel Manqoura, Jebel Ghantous, Jebel Basiri – reach peak altitudes of 1,100–1,390 m asl.

The northern Palmyrean mountains extend in general west–east direction between the Homs depression and the Palmyra area, where they converge with the southern Palmyrean mountains into one chain, which continues toward east into Jebel el Bishri (851 m). Individual mountain massifs of the northern Palmyrean chain – Jebel Shoumariye, Jebel Bilas (1,098 m), Jebel Chaar, Jebel Mraa, Jebel Bouaida (1,390 m) – have a general southwest–northeast trend.

The southern and northern Palmyrean mountains enclose a vast plain, the Ad Daw or Dawwa plain, situated at an altitude of around 600 m asl. To the southeast, the Palmyrean mountain chains are adjoined by the Sabkhet el Mouh salt flat at 370 m asl.

The plateau area north of the Palmyrean mountain zone is occupied by the northern Syrian steppe or Aleppo plateau. The plateau comprises mainly flat to hilly landscapes at topographic elevations around 400 m asl, descending gently to salt flats in the morphologic depressions of Al Matah and Jaboul.

In the north and south, the Aleppo plateau is bordered by mountain uplifts: the eastern Taurus mountains north of Adiyaman and the northern Palmyrean mountains with elevations of up to 2,550 m and 1,060 m asl, respectively. In the west, the plateau is adjoined by the hydrologic Orontes sub-basin in the northwestern mountain and rift zone with elevations between 400 m in the Orontes valley and on the Homs plain, 100 m in the Karasu graben and up to 870 m in Jebel ez Zaouiye. In the northwest, the Aleppo plateau continues into the Idleb plateau and, in the northeast, the plateau is adjoined by the Euphrates valley, which is situated at an elevation of around 300 m asl.

The Euphrates river separates Al Jezire from the Syrian Badiye. Al Jezire, the "island" between Euphrates and Tigris rivers, occupies the northeastern edge of Syria and extends into western Iraq. The topography of the Jezire is dominated by plains and flat valleys at altitudes between 340 and 400 m asl. An approximately west–east oriented series of morphologic elevations interrupts the flat plain landscape and rises up to 950 m asl in Jebel Abd el Aziz and 1,640 m in Jebel Sinjar.

The plateau areas south of the Palmyrean mountain zones extends from the southern Syrian steppe into the Hamad desert. The centre of the Hamad comprises a high plateau with internal surface drainage toward local sabkhas. The plateau with a gently undulating morphology is situated at 700–900 m asl with highest elevations of 940 m at Jebel Aneiza (border triangle of Jordan, Iraq, Saudi Arabia) and more than 1,000 m near Khawr Um Wual in Saudi Arabia. The surface of the plateau is a generally flat, stony semi-desert. To the west, the Hamad plateau is bordered by hill to mountain chains of the Jebel el Arab–Al Harra basalt field.

The southern Syrian steppe and the Rutba and Al Widyan areas north and east of the Hamad comprise undulating plains, which are dissected by mainly shallow wadis with courses toward the Euphrates valley in the northeast.

The east Jordanian limestone plateau occupies a southeastern segment of the northern Arabian platform. The plateau descends from altitudes of 600–900 m asl in the south, on its boundaries with the highlands of Jordan and the Interior Shelf, to about 500 m asl in the morphologic depressions of Wadi Sirhan and Qaa el Azraq in the east. In the northeast, the limestone plateau disappears under the basalt cover of Jebel el Arab field, which separates the Jordanian limestone plateau from the Hamad.

3.1.1.2 Hydrography

The eastern part of the northern Arabian platform comprises a vast zone of internal drainage and, in the northeast, a network of wadis directed toward the Euphrates valley. The by far largest volumes of river flow of the Arabian Plate are concentrated in the Euphrates–Tigris river system. The river system receives its major flow volume in the Anatolian highlands and the mountain chains of Taurus and Zagros, and discharges through the Shatt el Arab into the Gulf. Average flow in the Euphrates river in Syria is in the order of 800 m^3/s; the river flow is, at present, controlled by several large reservoirs.

The Euphrates river enters Syrian territory at Jerablus in the eastern part of the Aleppo plateau. After an about 100 km long north–south stretch the river course turns toward east into the Neogene Euphrates depression. Main tributaries of the Euphrates river in the Syrian Jezire are the Balikh and Khabour rivers. Nahr el Khabour is the main internal river of the Syrian Jezire with a length of 486 km and a mean discharge of 42 m^3/s. The river takes most of its flow from karst springs emerging at Ras el Ain.

Most of the eastern part of the northern Arabian platform is situated in the zone of internal drainage, which extends between the hydrologic basins of the Mediterranean Sea and of the Euphrates river. Wadis in the inland drainage zone are directed to closed basins, generally flat morphologic depressions with seasonal lakes or salt flats.

The large depressions act as groundwater discharge zones: Jaboul and Matah in northern Syria, Sabkhet el Mouh near Palmyra in central Syria, Manqaa ar Rahba and Qaa al Azraq on the fringes of the Jebel el Arab basalt field in Syria and Jordan, Wadi Sirhan on the eastern boundary of the Jordanian limestone plateau. Various smaller depressions without surface outflow are dispersed over the Badiye and Hamad at elevations of up to some hundred meters above the present level of the groundwater surface of the upper aquifer system.

Flow in the wadis of the internal drainage zone is only sporadic after major rain events. In the Queiq river on the Aleppo plateau, seasonal flow drains into the Matah depression.

The southern Syrian steppe and the adjoining Widyan area comprise distinctly incised wadi systems, which are directed toward the Euphrates valley: Wadi el Murabaa and Wadi Miyah in Syria, Wadi Sawab in the Syrian–Iraqian border area, Wadi Akash and Wadi Hauran in Iraq. The hydrography of the Hamad plateau is characterized by mostly short wadis, which end in shallow sabkha depressions. A relatively extensive wadi system, Wadi Ruweishid, is developed on the plateau in northeastern Jordan. Larger sabkhas are Khabra et Tenf and Khabra Hraith in Syria, an extended system of sabkhas at the western border of the plateau in northeastern Jordan and the sabkha in the Khawr Um Wual graben in Saudi Arabia.

The east Jordanian plateau is dissected by a network of wadis, which drain toward closed basins in morphological depressions or to the Dead Sea valley. The catchments of the Dead Sea tributaries Wadi Mujib and Wadi Hasa reach more than 80 km toward east into the limestone plateau. Major closed basins are the Wadi Sirhan and Azraq basins on the eastern border of the plateau, with lowest topographic levels at around 500 m asl, and the Jafr basin, the centre of which is formed by a depression within the limestone plateau situated at around 800 m asl.

Wadi Sirhan comprises a morphologic depression elongated in southeast–northwest direction with a low lying zone of salt pans, lakes and mud flats in northwestern Saudi Arabia; Al Hadhawdha, the largest salt lake, extends over an area of approximately 400 km^2.

The major wadi courses draining toward the basin centres are relatively well defined, have wide channels (50–100 m) and an average slope of 2–5 m/km.

3.1.1.3 Climate

The eastern part of the north Arabian platform has semi-arid to arid climate conditions. The relatively humid climate of the western highlands and mountains of Jordan and Syria changes rapidly to dry climate conditions toward the steppe and desert areas of Al Badiye in the east. The change of the sub-humid climate of the highlands to dry climate conditions of the Badiye takes place in a transitional zone of 50–100 km width. Within the transitional zone, mean precipitation is decreasing toward east and south, the rain season becomes shorter and rainfall more erratic. In the steppe and desert areas of southern Syria and eastern Jordan, mean annual precipitation is less than 50 mm.

Slightly more humid climate conditions in some parts of the sub-region may be related to morphological features: relatively high altitudes (northern Palmyrean mountains) and gaps in the mountain barriers (Homs depression). In northern and northeastern Syria, the dry climate is modified by inflow of moist air masses from the north. Precipitation during the winter season on the Aleppo plateau and the Jezire is associated with Mediterranean fronts or intrusions of cold fronts reaching the area from the continental Anatolian highlands. Mean annual precipitation in the Jezire varies from 300 mm in the northwest to 200 mm in the southeast.

3.1.1.4 Land Use

Al Badiye with mean annual precipitation of <200 mm has been traditionally an area of nomadic tribes. Most of Al Badiye and the adjoining Hamad desert, which extend from the Great Nefud desert in Saudi Arabia to the Euphrates river in the north, is located on Jordanian and Syrian territory. Living conditions have changed considerably over the past few decades. In the Badiye of Jordan, only 5% of the population are still nomadic, the majority has been settled, though livestock production is still a major activity of the area.

Local occurrences of fresh groundwater have been used since antiquity for water supply of towns like Palmyra and Resafe or of isolated settlements like the Umayad desert castles.

A few oases form green spots in the vast steppe and desert landscape of Al Badiye: Palmyra in central Syria, Azraq in Jordan, Qurayat in Wadi Sirhan in northwestern Saudi Arabia.

Palmyra was the centre of a large state, which extended between the Roman and Persian Empires under its rulers Odeinat and Zenobia in the third century AD. The ruins of the splendid Syrian–Hellenistic Palmyra are now a major tourist attraction at the modern small town Tudmor. Other architectonic remains of the Hellenistic and medieval periods are found at isolated locations of Al Badiye: Resafe and Qasr Ibn Wardan in northern Syria, and Umayad desert castles dispersed over the Badiye of Syria and Jordan.

Brackish water was used for irrigation of oases. Through modern drilling techniques, groundwater from deeper aquifers has been exploited in the Badiye in recent decades for watering points of nomadic herds, for irrigation developments, for phosphate mining and domestic supply.

3.1.1.5 Transitional Zone

On the margins between the western highlands and mountains of Jordan and Syria and the dry plateaus in the east, the seasonally or year-round cultivated lands grade into the steppe areas of Al Badiye. In a transitional zone, sufficient precipitation for rain fed agriculture is received, in average and wet years, from winter storms advancing from the western mountain chains and from the Taurus mountains in the north. The high variability of rainfall with frequent occurrence of dry years creates, however, high hazards of agricultural cultivation.

In the transitional zone, the vegetation changes from the highlands covered by perennial trees and plantations to rainfed cereal cultivation in limited areas and to steppe areas with prevailing seasonal pastoral grazing. Production of winter crops relies in the transitional belt on supplementary irrigation, as far as surface or subsurface water resources are available.

The transitional zone has been classified in Syria into agricultural stability zones from:

- Zone 1 with a mean annual precipitation of >350 mm and probability of at least 350 mm in 2 out of 3 years to
- Zone 4 with a mean annual precipitation of 200–250 mm and probability of not less than 200 mm in 1 out of 2 years and
- Zone 5 a mean annual precipitation of <200 mm

The cropping pattern on the irrigated areas depends on the salinity of the irrigation water. Winter legumes are generally not salt tolerant and accept a maximum salinity equal to an electrical conductivity of 1,200 μS/cm. Salt accumulation in the soil can build up rapidly under summer irrigation. Brackish water is therefore applied prevailingly for supplementary irrigation of cereals with a tendency of mono-cropping of wheat.

Supplementary irrigation in the transitional belt is practised, in particular, along perennial rivers: Euphrates, Khabur, and Tigris rivers. Groundwater is extracted for supplementary irrigation in several areas in the eastern part of the northern Arabian platform: in the areas of Aleppo–Idleb and Selemiye in northern Syria, Hauran in southwestern Syria and Mafraq – northeastern desert in Jordan, and in the transitional zone between the highlands and the east Jordanian limestone plateau.

References. ACSAD (1981), Al-Homoud et al. (1995), Khouri (1982), Ponikarov et al. (1967a), Wakil (1994).

3.2 Geology

3.2.1 General Geologic Structure

The eastern part of the northern platform constitutes a relatively mobile zone of the Arabian Shelf, but was less intensively affected by the Neogene rift tectonics than the western mountain and rift zone. The sub-region comprises prevailingly plateau areas with a nearly horizontal or gently dipping sedimentary cover. The anticlinal southern and northern Palmyrean mountains form a major structural element with more intensive tectonic displacements. Basin and graben structures, accompanied by major flexure and fault zones, extend along the northeastern boundary of the platform – the boundary to the Mesopotamian–Euphrates basin – and in the southwest in the Wadi Sirhan–Azraq depression. Toward east–southeast, the platform grades into the paleogeographic uplift zone of the Rutba arch. The western border area corresponds to the zone, where the south–north oriented anticlinal uplifts of the Jordan–Antilebanon highland chains change eastward into flat plateau areas and the mainly southwest–northeast directed Palmyrean mountains (Figs. 3.2–3.4).

The plateaus of the eastern part of the platform are subdivided by the massifs of the Palmyrean mountain and Jebel el Arab into a few major geologic blocks:

- The Aleppo plateau including the northern steppe of Syria
- The Palmyrean fold belt with the basins of Ad Daw and Sabkhet el Mouh
- The southern Syrian steppe and the Hamad
- The Jordanian limestone plateau with the adjoining Wadi Sirhan and surrounding areas in northwestern Saudi Arabia

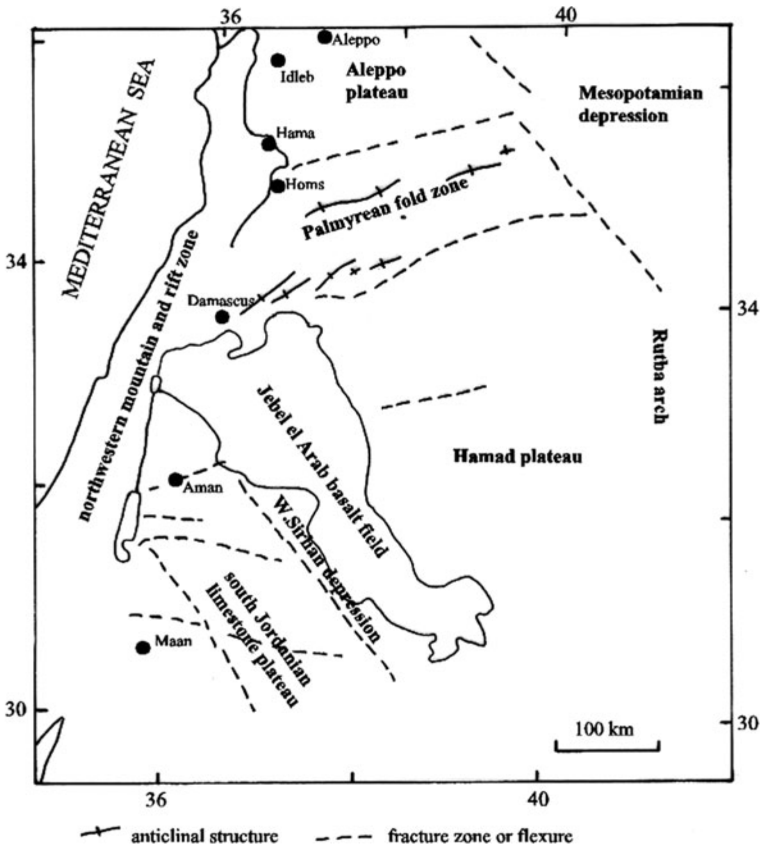

Fig. 3.2 Main structural geologic units of the eastern part of the northern Arabian platform. After Lovelock (1984), Sunna (1995), Wiesemann (1969), Wolfart (1966)

The Arabian Plate dips in the northeast, on the boundary between the Arabian Shelf and the alpidic mountain chains, under the Mesopotamian foredeep. The foredeep, which was formed during the final phase of the alpidic tectonic movements mainly in the Pliocene–Quaternary, extends as a vast plain area in a wide belt along the Taurus–Zagros folded zone and is filled with thick molasse sediments. An intermediate zone between the Arabian platform and the Mesopotamian foredeep is occupied by the Euphrates plain, which covers a structural depression (Al Furatian depression, Ponikarov et al. 1967a) on the northeastern margin of the plateau areas of the northern Arabian platform. Mesopotamian foredeep and Euphrates plain are separated along an approximately west–east trending system of faults and flexures and a series of anticlinal structures: Tuwal el Aba – Jebel Abd el Aziz – Jebel Sinjar (Figs. 3.2–3.4).

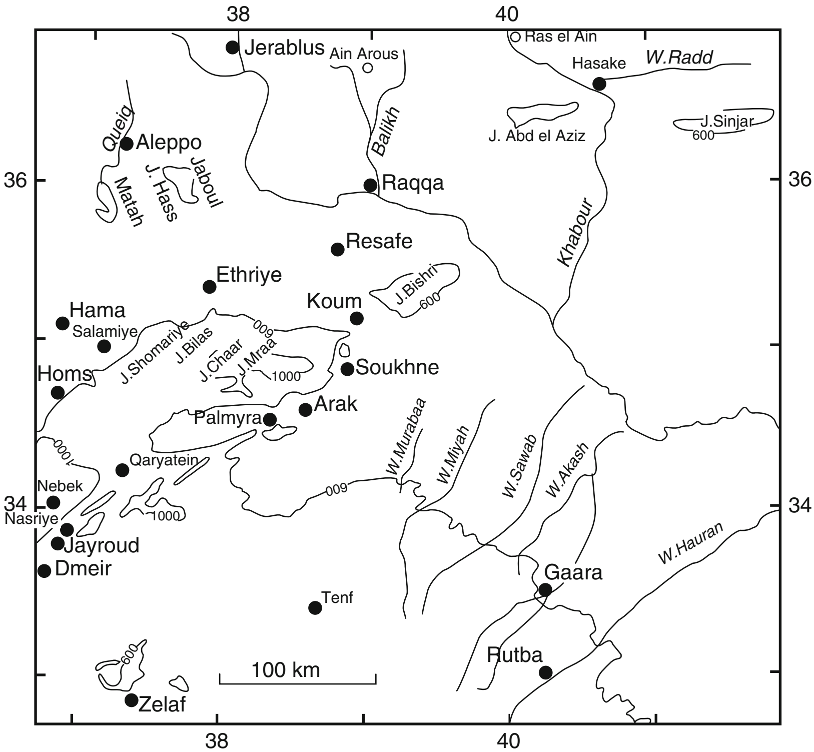

Fig. 3.3 Location map of the northeastern part of the north Arabian platform. __600__ topographic contour line 600 m asl, ○ spring

3.2.2 Litho-Stratigraphic Sequence

The eastern parts of the northern Arabian platform are covered, to a large extent, by Paleogene–Neogene deposits. Mesozoic formations are exposed in uplift structures, such as the Palmyrean mountain chains. Accumulations of terrigenous Neogene–Quaternary sediments are found in major structural depressions: the Euphrates–Mesopotamian basin, Ad Daw plain, Wadi Sirhan (Table 3.1).

3.2.2.1 Aleppo Plateau and Mesopotamian Foredeep

The Aleppo plateau is underlain by a several kilometres thick sequence of sedimentary rocks. The main units in the upper few hundred metres of the sequence are (from bottom to top):

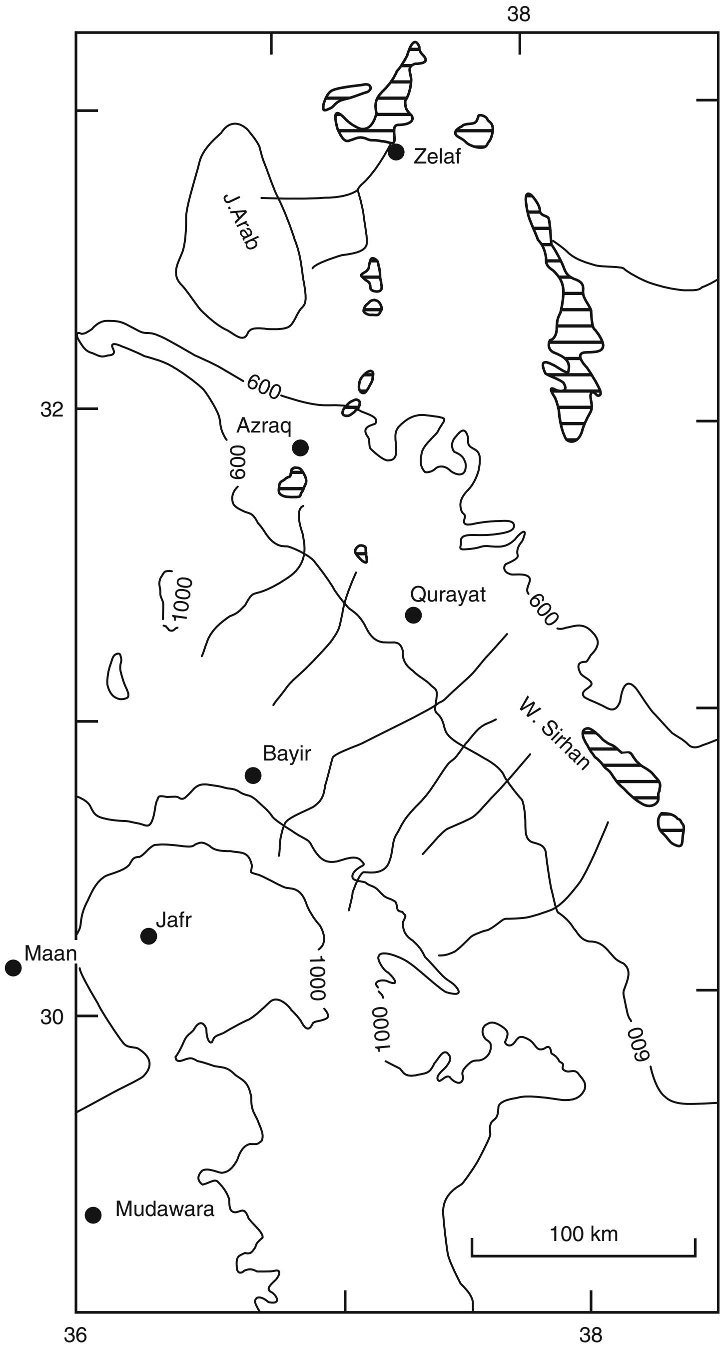

Fig. 3.4 Location map of the southeastern part of the north Arabian platform. __600__ topographic contour line 600 m asl, hatched fields sabkha

Upper Cretaceous:

Limestones and dolomites (Cenomanian–Turonian, in some areas possibly reaching into higher stages of the Upper Cretaceous).

Chalky and marly limestones with chert and phosphoritic intercalations, partly bituminous (Coniacian–Santonian–Campanian)

Upper Cretaceous to Paleogene:

Marls and argillaceous limestones (Maastrichtian–Paleocene)

Paleogene:

Eocene chalks and nummulitic limestones

Neogene:

Helvetian limestones

Tortonian limestones, marls, conglomerates, sandstones

Miocene basalts

Pliocene continental deposits

Pliocene basalts

Quaternary:

Flood plain, terrace and lacustrine deposits

Data of deep drillings near Aleppo and Khanaser indicate the following thickness of Paleozoic–Mesozoic formations:

- Upper Cretaceous carbonate rocks and marls: around 900 m
- Lower Cretaceous–Triassic: 140–300 m
- Paleozoic: >2,900 m

The Aleppo plateau is covered prevailingly by Paleogene to Neogene deposits with some outcrops of Miocene–Pliocene basalts. Exposures of Upper Cretaceous (Campanian–Maastrichtian) formations are limited to Jebel Shbith near Esriye and the southwestern rim of the plateau.

In the depressions of Al Jaboul and Matah–Harayeq, Pliocene lacustrine deposits – sandstones, conglomerates and gypsum layers – overlie Helvetian or Paleogene carbonate formations.

In the Selemiye plain in the southwest of the northern Syrian steppe, the Paleogene is partly covered by Pliocene terrigenous sandstones, clays and conglomerates.

The Mesopotamian foredeep and the Euphrates depression comprise a large Neogene basin, which was temporarily flooded by a marine invasion from the east. During the Miocene, the northern shelf area of the Arabian Platform was divided into two basins with different type of sedimentation. The Mediterranean basin in the west was connected to the ocean and sedimentation occurred under normal saline sea water conditions. The Mesopotamian basin in the east was isolated from the open ocean over considerable periods and the deposits include sediments of varying environments: salt, gypsum, marine, lagoonal and fresh water carbonates, marls and clays. The western and southwestern boundaries of the Euphrates depression follow approximately the shore line of the Neogene basin on the fringes of the Aleppo plateau, the Palmyrean zone and the Hamad plateau.

The Mesopotamian and Euphrates plains are covered prevailingly by Neogene–Quaternary detrital deposits. The thickness of these molasse sediments reaches

500 m in northern Syria, increasing to several thousand metres in the adjoining areas of Turkey and Iraq.

The Jezire includes, on its western boundary, a narrow strip of Paleogene outcrops of the Aleppo plateau on the left bank of the Euphrates river. Cretaceous–Paleogene and Miocene formations are exposed on the hill chain, which separates the Euphrates and Mesopotamian plains.

The underground of the Euphrates depression comprises, above the crystalline rocks of the basement, the following geological sequence:

- About 1,200 m Paleozoic deposits (Ordovician–Permian): mainly mudstones with interbedded sandstone, shale, limestone, sandy shale and clay
- Triassic–Jurassic dolomitic sandstone, shale, dolomite, anhydrite with a total thickness of around 700 m
- 400–600 m Cretaceous sandstones, limestones, marls and chalks
- Paleocene prevailingly argillaceous limestone and bituminous shale
- Eocene argillaceous limestone with chert, nummulitic limestone with interbedded marl, 200–300 m
- Oligocene marls, limestone, dolomite, 20–160 m
- Neogene marl, lacustrine and terrestrial deposits, up to 1,000 m
- Quaternary proluvial, alluvial, lacustrine formations, basalt, gravel, loam, clay, sand

In western Iraq, the Miocene sediments are subdivided into three stratigraphic units:

- Upper Fars (Upper Miocene): continental deposits, clays, sandstones, conglomerates
- Lower Fars (Middle Miocene): clays, marls, shales, limestones, gypsum
- Lower Miocene: reef limestones (Euphrates limestone)

3.2.2.2 Palmyrean Fold Belt

The Palmyrean fold belt constituted a marine sedimentary basin from the Upper Jurassic to Campanian with an up to more than 400 m thick accumulation of Cenomanian–Turonian carbonate rocks. Limestones and marls of up to 300 m thickness were deposited in the basin during the Coniacian, Santonian and Campanian. The Campanian contains abundant chert beds and, in the central part of the Palmyrean zone, thick beds of phosphate rocks.

The Mesozoic stratigraphic sequence of the Palmyrean zone comprises:

- Triassic–Middle Jurassic littoral – lagoonal carbonate and clay sediments with evaporite intercalations
- Upper Jurassic limestones, clayey limestones and marls
- Lower Cretaceous sandstones with beds of marls, dolomite and gypsum
- Cenomanian–Santonian limestones and dolomites
- Campanian limestones and marls with chert bands and thick layers of phosphate rocks
- Maastrichtian marls and marly limestones

Paleogene chalks cover wide areas on the outer parts of the Ad Daw plain, of the surroundings of Sabkhet el Mouh and of the anticline of Jebel Bishri. Jebel Bishri, the northeastern continuation of the Palmyrean chains, dips as a broad anticline toward east to northeast into the Euphrates depression.

The Ad Daw plain is filled by an up to more than 250 m thick sequence of Pliocene–Pleistocene lacustrine and fluviatile deposits: alternations of conglomerates, sandstones, marl, clay, gypsum. Coarse detrital deposits occur mainly at the periphery of the plain.

The Sabkhet el Mouh plain east of Palmyra is underlain by varying Neogene deposits: marl, clay, conglomerates, limestones, sand and sandstones.

In the plain around Jayroud lake, the Paleogene outcrops are partly covered by gypsum sands, which form low dunes.

3.2.2.3 Southern Syrian Steppe, Hamad and East Jordanian Limestone Plateau

The vast plateau areas of the southern Syrian steppe and the Hamad are mainly covered by Paleogene carbonate and chert formations.

In the subsurface, the following sequence of sedimentary formations is found:

- Paleozoic sandstones, which crop out in the Rutba arch east of the Hamad (Gaara sandstone) and are situated at greater depth in the plateau areas.
- Triassic–Jurassic carbonate rocks, in some areas with sandstone intercalations, which are exposed on the Rutba uplift (Upper Triassic Mulussa formation) and have been reached in boreholes in the At Tenf area (Syria) and H5 area (Jordan).
- Lower Cretaceous sandstones (Kurnub sandstone in Jordan, Rutba sandstone in the Rutba area in Iraq).
- Upper Cretaceous limestones, dolomites and cherts (Cenomanian to Campanian), which extend, in general, at a few hundred metres depth below the plateau areas.
- Marls and marly limestones of Maastrichtian–Paleocene–lower Eocene age, grading into limestones and dolomites on the flanks of the Rutba uplift.
- Paleogene chalks and limestones with marl and chert intercalations.

Neogene–Quaternary terrestrial deposits occur in structural and morphologic depressions. Veils of wind blown sand cover some parts of the desert plateaus in the south of the Hamad. Mesozoic sedimentary rocks crop out in a belt on the south-eastern margin of the Hamad along the transition to the Widyan plateau as well as in the southern Palmyrean mountains north of the southern Syrian steppe.

The east Jordanian limestone plateau lies in a paleogeographic situation between the western highlands of Jordan and the Hamad. The geologic development during the Mesozoic to Tertiary is dominated by the Upper Cretaceous and Paleogene marine transgressions over older prevailingly clastic shelf deposits. The transition from the limestone plateau to the Hamad is masked by the Neogene–Quaternary basalt field of Jebel el Arab.

The limestone plateau is, to a wide extent, covered by sedimentary rocks of the Paleogene Rijam and Shalala formations:

- Chalky limestone, chalk, chert with phosphatic and bituminous layers of the lower Eocene "Umm Rijam chert–limestone formation"
- Chalk, chalky marl, marly limestone of the middle Eocene "Wadi Shalala formation"

The Paleogene carbonate formations are exposed, in particular, on the western slope of the Sirhan depression and the central part of the Jafr syncline. In the central and southern parts of Wadi Sirhan and on the Hamza graben structure southeast of Azraq, the Paleogene is covered by Neogene to Quaternary sediments. On the eastern slope of Wadi Sirhan and in the northern and eastern parts of the Azraq basin, Neogene–Quaternary basalts overlie the Paleogene.

The thickness of the Rijam formation is generally 100 m and increases to 300 m in tectonic depressions at the eastern margin of the plateau: at Qurayat in Wadi Sirhan and in the Hamza graben structure southeast of Azraq. The Shalala formation has a general thickness of 70 m, increasing to more than 500 m at Qurayat and in the Hamza graben.

On the western slopes of Wadi Sirhan, the Shalala formation comprises an upper unit, consisting of chalky limestone with chert, and a lower unit, composed mainly of bituminous marl with layers of marly limestone.

The Paleogene is underlain by:

Upper Cretaceous marls (Muwaqar formation, B3)
Upper Cretaceous limestones and dolomites (Cenomanian–Campanian, B2/A7)
Paleozoic–Cretaceous sandstones (Disi sandstone, Kurnub sandstone)

The Upper Cretaceous comprises, in the Jordanian limestone plateau, the Lower Ajloun (A1–A6), Aman–Wadi Sir (A7–B2) and Muwaqar marl (B3) formations. The Lower Ajloun formation is composed mainly of marls and marly limestones. To the south, the deposits of the formation become increasingly sandy. The Aman–Wadi Sir (B2/A7) formation consists of limestones and dolomites with intercalated beds of sandy limestones, chalk, marl, gypsum, chert and phosphorite. The Muwaqar formation comprises prevailingly marls and, in some areas, chalks and chalky limestones.

In the tectonic depressions of the Hamza graben and the northern Wadi Sirhan, the Wadi Sir and Aman formations are separated by a sequence of limestones, dolomites, claystones and sandstones. In the southern part of Wadi Sirhan, the Aman formation rests directly on Lower Cretaceous sandstones or on shales of the Paleozoic Khreim group.

3.2.3 Lithologic Features of the Upper Cretaceous - Paleogene Sequence

During some stages of the late Upper Cretaceous - Paleogene, differentiated sedimentation conditions caused considerable lithologic variations. The sediments deposited during that period comprise, apart from limestones, dolomites and marl, considerable amounts of chalk, siliceous and phosphatic rocks. A particular feature of the lithologic sequence from the Campanian to Eocene is the abundance of chalk deposits, which act as important aquifers with particular hydrogeologic characteristics in various areas of the platform (Sect. 3.4.2).

Chalk is a sediment composed mainly of skeletal calcite protozoa: coccolithophorida with minor amounts of foraminifera and other biogenic fragments and originates from "planktonic rain" settling as carbonate ooze on the sea bottom. Extensive accumulations of chalk are normally limited to the open ocean but can develop on shelf areas, if sea levels are exceptionally high and erosion on adjoining land areas is very limited. The depth of deposition of chalk on shelf areas below sea level is estimated at 100–250 m. Low erosional activity can be related, in particular, to a non-seasonal arid climate and to times of exceptional tectonic stability. In areas or periods with increasing transport of detrital material, pure chalk deposits generally pass into an alternation of chalk, marl, clays or silty clays.

In addition to the abundance of chalky sediments, the lithology of the late Upper Cretaceous–Paleogene formations is characterized in the eastern parts of the northern Arabian platform by a relatively high percentage of siliceous rocks and the occurrence of phosphates. Siliceous oozes can be deposited in an environment controlled significantly by upwelling ocean water, which is cold and rich in nutrients and silica and has a low oxygen content. Zones of mixing of upwelling ocean water with oxygen rich near-surface water are characterized by rapid organic growth. Decaying organic material, sinking down in the sea water of these zones, consumes the available oxygen and produces CO_2, which dissolves the calcareous plankton, leaving siliceous components of the "planktonic rain" (radiolarians, diatoms) to settle on the sea floor.

3.2.4 Tectonic Structure of the Geologic Sub-units

3.2.4.1 Aleppo Plateau

The Aleppo plateau constitutes a relatively undisturbed block in the northeast of the northern Arabian platform. The plateau is delimited by flexure and fault zones against the Palmyrean fold belt in the south, the allochthonous Basit complex in the northwest and the Euphrates–Mesopotamian depression in the east. Most of the platform is covered by flat to gently sloping Paleogene to Neogene deposits. Outcrops of Maastrichtian rocks are found in the central part of the plateau (Jebel Shbith).

The internal structure of the plateau comprises gentle anticlinal and synclinal structures. Major synclinal zones correspond to the morphologic depressions of Al Jaboul and Matah–Harayeq.

Major fracture zones appear to cross the plateau mainly in southwest–northeast, southeast–northwest and SSW–NNE directions. The plateau area includes several Neogene–Quaternary mainly basaltic volcanic complexes, which may be related to

Pliocene–Pleistocene tensional reactivation of deep seated lineaments within the craton area.

3.2.4.2 Mesopotamian Foredeep

The Arabian Plate dips in the northeast, on the boundary between the Arabian Shelf and the alpidic mountain chains, under the Mesopotamian foredeep. The foredeep, which was formed during the final phase of the alpidic tectonic movements mainly in the Pliocene–Quaternary, extends as a vast plain area in a wide belt along the Taurus–Zagros folded zone and is filled with thick molasse sediments.

An intermediate zone between the Arabian platform and the Mesopotamian foredeep is occupied by the Euphrates plain, which covers a structural depression (Al Furatian depression, Ponikarov et al. 1967a) on the northeastern margin of the plateau areas of the northern Arabian platform. Mesopotamian foredeep and Euphrates plain are separated along an approximately west–east trending system of faults and flexures and a series of anticlinal structures: Tuwal el Aba – Jebel Abd el Aziz – Jebel Sinjar.

The Euphrates plain is filled mainly with marine, lagoonal and continental rocks of Neogene age.

3.2.4.3 Palmyrean Fold Belt

The Palmyrean fold belt (Palmyrean aulacogen, Ponikarov et al. 1967a) comprises a zone of intensively folded dislocations. The zone represents an early Mesozoic rift basin, that was later folded and faulted, and is seen as an intracratonic fold belt isolated within relatively undeformed sectors of the platform. The belt constituted a marine sedimentary basin from the Upper Jurassic to Campanian with accumulations of limestones and dolomites with abundant chert beds and phosphate intercalations in the upper part of the sequence.

Most of the tectonic deformations in the Palmyride belt were produced during the Neogene. The general southwest–northeast trending tectonic structure of the Palmyrean fold belt is cut off, in the southwest, by the longitudinal Dead Sea–Jordan rift system and, in the northeast, by the northwest–southeast oriented Euphrates graben. In a regional view, the Palmyride belt appears as a northeast plunging anticlinorium, upon which complex folds are superimposed. The zone of anticlinal and synclinal deformations of Mesozoic and Cenozoic strata can be traced to a depth of at least 5 km below surface.

The tectonic forces causing the fold and fault structure of the Palmyrean belt are attributed to the Cenozoic movements of the Dead Sea–Jordan rift system and to the shortening of a zone of intraplate weakness between more rigid blocks of the platform.

The fold belt is demarcated in the south and north by systems of deep faults against the southern and northern sectors of the northern Arabian platform. The south Palmyrean flexure between the southern Palmyrean chains and the southern Syrian steppe divides the northern Arabian platform into a stable southern part and a more mobile northern sector, in which displacements surpass 1,000 m. In the northwest, the Palmyrides are also delimited by a series of large fractures, separating the fold belt from the Aleppo plateau and from the Homs–Beqaa depression zone, in which the fault system is covered by Neogene–Quaternary sediments.

The overall structure of the Palmyride belt is a complex composite of uplifted blocks and depressions.

The individual mountain massifs of the southern and northern Palmyrean chains correspond to anticlinal structures with outcrops of Upper Cretaceous limestones and dolomites in the cores of the anticlines and, in some areas, of Lower Cretaceous to Jurassic rocks. The mountain slopes are generally covered by Maastrichtian marls and argillaceous limestones and Paleogene chalks, chalky limestones and marls.

The southern Palmyrean mountain chain comprises prevailingly narrow asymmetrical anticlines of 10–25-km length with steep faulted southern flanks and more gentle slopes in the north. The northern Palmyrean chains are characterized by generally SSW–NNE trending fold structures. In the Pliocene–Quaternary basins of Ad Daw and Sabkhet el Mouh, the Upper Cretaceous formations are situated at depths of several hundred metres below surface.

3.2.4.4 Southern Syrian Steppe and Hamad

The plateau areas of the Hamad and the southern Syrian steppe are subdivided by tectonic movements of prevailingly block-faulting type into structural depressions and arch-like uplifts. The sub-region is bordered by major fault zones:

- The southwest–northeast oriented south Palmyrean fault in the north
- The southeast–northwest trending Faidat fault in the northeast on the boundary of the Euphrates basin

The Hail–Rutba arch is a dominating structural element on the eastern border of the Hamad, which appears as a broad swell in Cretaceous to Paleogene formations. The structural high passes from the Rutba area in SSE direction to Jebel Unaiza (Iraq–Jordan–Saudi Arabia border triangle) and into Khawr Um Wual, a narrow zone of grabens and synclinal depressions along the crest of the arch.

The plateau area west of the Rutba arch is tectonically subdivided into mainly SSE–NNW oriented anticlinal structures and graben or synclinal structures which are occupied by small morphologic depressions (swells of At Tenf and Al Owered, Khabret et Tenf, Kahbret Mashqouqa, Khabret et Tnefat, Ponikarov et al. 1967a). A belt of generally WSW–ENE directed structures marks the northern rim of the southern Syrian steppe; the belt merges in the east into the Euphrates basin and in the southwest into the structural depression of Al Juwef.

South of Rutba, the Hamad is adjoined in the east by the Widyan sector of the eastern Arabian platform. The uplift structure of the Rutba arch, which forms the southeastern border of the northern Arabian platform, is here hidden under a cover of Upper Cretaceous sedimentary rocks.

3.2.4.5 East Jordanian Limestone Plateau

The strata of the Jordanian limestone plateau dip from the western highlands gently to the east; the monoclinal structure is modified by local anticlines, synclines and basin-like depressions.

The base of the Rijam (B4) formation is located at around 1,200 m asl in the western highlands, 950–1,000 m asl in the south of Jordan (south of Bayir) and descends to 766 m below sea level in Wadi Sirhan in Saudi Arabia.

The Paleogene outcrops in the Jordanian limestone plateau are crossed by major fault systems, which extend in east–west, northwest–southeast and NNW–SSE direction over lengths of 50 km to more than 300 km (Kerak–Wadi Fiha fault, Hasa fault zone, Siwaqa fault, Wiesemann 1969; Sunna 1995).

The Jafr depression corresponds to a WNW–ESE oriented tectonic trough within the limestone plateau. The eastern margin of the limestone plateau is formed by the southeast–northwest trending Wadi Sirhan fault zone (Ramtha–Wadi Sirhan trend), which is marked morphologically by the Wadi Sirhan and Azraq depressions. The Hamza graben southeast of Azraq constitutes a particularly deep structural depression, in which Upper Cretaceous sediments reach a thickness of more than 3,000 m.

References. Ahmed and Kraft (1972), Al Ejel and Abderahim (1974), Bender (1974a), Buday (1980), Downing et al. (1993), ESCWA (1999b), GITEC and HSI (1995), GTZ and NRA (1977), Hobler et al. (1991: 49), Kemper (1980), Krasheninikov et al. (1996), Kruck et al. (1981), Litak et al. (1998), Lovelock (1984), McBride et al. (1990), Ponikarov et al. (1967a), Powers et al. (1966a: 104), Razvalayev (1966), Soulidi-Kondratiev (1966), Sunna (1995), Wagner and Kruck (1982), Wiesemann (1969), Wolfart (1966).

3.3 Aquifers and Groundwater Regimes

3.3.1 Main Aquifers

3.3.1.1 Aquifers and Groundwater Flow Systems

A continuous aquifer system at shallow to intermediate depth extends in the Paleogene chalk formations over wide parts of the plateau landscapes of the eastern part of the northern Arabian platform. Zones with increased erosion and with relatively high secondary permeability of aquiferous carbonate rocks have developed along fracture systems. Wadi courses on the rigid blocks largely follow the pattern of the fracture systems and zones with relatively favourable aquifer potential are found preferentially along the fracture and wadi systems.

The Paleogene aquifers are underlain, in general, by a deeper aquifer system in Upper Cretaceous (Cenomanian–Coniacian) carbonate rocks and are separated from that deeper aquifer by an aquitard composed of Upper Cretaceous–Paleogene (Maastrichtian–Lower Eocene) marls, chalks and argillaceous limestones (Table 3.1).

Toward structural uplifts of the Rutba area and the Palmyrean chains, the continuous upper aquifer disappears since:

- The Paleogene sediments are located above the level of saturated aquifers.
- The Paleogene chalk formation and/or the Maastrichtian–Paleogene marl aquiclude are missing because of paleogeographic or erosional gaps.

In the uplift areas, the upper aquifer system is either connected to the deeper Mesozoic carbonate aquifers or becomes unsaturated or discontinuous.

In structural basins and some plateau areas, the upper aquifer system includes Oligocene or Neogene–Quaternary aquiferous sediments, which are generally in hydraulic connection with the Paleogene chalk aquifer.

The Paleogene aquifer system on the eastern part of the northern Arabian platform is separated by structural geologic features into several groundwater flow systems. Major flow systems enclose:

- The northeastern part of the northern platform around Aleppo
- The southeastern part of the northern platform between the southern Palmyrean mountains and the Rutba high
- The east Jordanian limestone plateau

3.3.1.2 Aleppo Plateau

The Paleogene chalk aquifer system and the deeper Upper Cretaceous aquifer system extend continuously over most of the Aleppo plateau. The upper aquifer system is formed by Middle to Upper Eocene chalks and limestones in wide areas around Aleppo and east of Hama and Homs. In some parts of the area, the Eocene rocks form a connected aquifer system with overlying rocks: Helvetian limestones, Pliocene–Quaternary unconsolidated sediments, Neogene basalts. The deeper aquifer comprises Upper Cretaceous (Cenomanian–Turonian) limestone and dolomites.

The upper aquifer system is separated from the deeper aquifer by the Maastrichtian–Paleogene aquitard, which is composed of several hundred metres thick marls and argillaceous or chalky limestones with chert intercalations.

The base of the Upper Cretaceous carbonate aquifer is probably formed by marls of Lower Cretaceous (Aptian–Albian) age. Groundwater contained in deeper sedimentary rocks below the Upper Cretaceous can be expected to be more or less stagnant and brackish to saline.

In the eastern parts of the Aleppo plateau, the hydrogeologic conditions of the upper aquifer system are relatively uniform: Eocene chalks and marly limestones

Table 3.1 Scheme of main aquifers in the eastern part of the northern Arabian platform

		Aleppo plateau	Jezire	Palmyrean fold zone	Southern Syrian steppe and Hamad	East Jordanian limestone plateau
Quaternary		Aquiferous deposits in morphologic depressions	Rad aquifer: unconsolidated deposits, aquiferous in part of the plain areas	Aquifers in morphologic depressions		
Neogene		Miocene limestone, locally part of upper aquifer system				Qirma sandstone: local aquifer in Wadi Sirhan
Paleogene		Chalk, limestone, chert	Ras el Ain/Tel Abiad aquifer	Chalk, chert, limestone: brackish water aquifer at shallow to intermediate depth	Chalk, chert, limestone: **upper aquifer system**, mainly brackish	Shalala (B5): local aquifer Rijam (B4): fresh water aquifer in Jafr area
		Main upper aquifer system				
Upper Cretaceous	Maastrichtian	marl **major aquitard**		marl **discontinuous aquitard**		Muwaqqar marl
	Campanian to Cenomanian	limestone, dolomite, chert, chalk **main deeper aquifer, brackish water**				
Lower Cretaceous						Kurnub sandstone, deep brackish water aquifer
Paleozoic						Disi sandstone, deep brackish water aquifer

constitute an extensive aquifer, which is underlain by the 100–400 m thick Upper Cretaceous–Paleogene marl aquitard. The productivity of the chalk aquifer is highly varying: its permeability depends, to a large extent, on fracturing of the rock, and productive zones are restricted mainly to areas where tectonic movements have created a relatively high number of fractures and fissures. Such zones are found, in particular, along larger wadis, while aquifer productivity on hilltops and along surface water divides is generally very low. In the morphologic depressions of El Matah and Al Jaboul, the upper aquifer system extends into Pliocene–Quaternary basin sediments overlying the chalk aquifer. In the Jebel al Hass area, basalts constitute locally an upper part of the aquifer system. Leakage through the Upper Cretaceous–Paleocene aquitard to the deeper aquifer system may occur, in particular, along major fracture zones.

The groundwater in the upper aquifer system is generally unconfined, depth to groundwater ranges from a few metres to around 100 m below land surface.

The plateau area in the southeast of the northern Syrian steppe, between the Palmyrean fold zone (Jebel Bishri) and the Euphrates river, is covered mainly by Miocene limestones, sandstones and evaporites, which constitute a shallow brackish water aquifer.

In the western parts of the plateau – the area between Hama, the eastern rim of Jebel ez Zaouiye and the Idleb plateau – the hydrogeologic conditions of the upper aquifer system are complex.

Aquiferous rocks comprise Eocene chalks and nummulitic limestones, and limestones of Miocene age; permeability is relatively high in karstified limestones. The marl aquitard underlying the upper aquifer system is wedging out toward the eastern margin of the rift zone. According to these conditions, the area comprises various discontinuous groundwater occurrences and perched water levels are found in topographically higher areas. The Upper Cretaceous–Paleocene chalky marl and chert formation, which forms part of the main aquitard further east, acts locally as aquifer with low productivity. To a considerable extent, groundwater from the upper aquifer system leaks into the deeper Upper Cretaceous carbonate aquifer. Fractured and karstified Miocene limestones are an important component of the upper aquifer system in the area north of Aleppo. Several perennial springs discharge from the Miocene limestones, such as the springs of Hailan, which provided the main source of water supply for Aleppo until the beginning of the twentieth century.

3.3.1.3 Jezire

In the Mesopotamian–Euphrates plain of the Jezire, main aquifers are found in:

- Quaternary deposits
- Miocene carbonate rocks and sandstones
- Paleogene carbonate rocks

Aquifers of pre-Paleogene age (Permian–Upper Cretaceous) are situated at depths of 200–3,500 m below the plains and contain brackish to saline water.

The most important aquifers of the Jezire have been denominated, according to their main geographic distribution: Ras el Ain, Tel Abiad and Radd aquifers.

The highly productive Ras el Ain aquifer is composed of karstified nummulitic limestone of middle to upper Eocene and Oligocene age. The base of the aquifer is formed by a marl aquiclude of Upper Cretaceous–Lower Eocene age; the aquifer is generally confined by clay, marl, clayey limestone and gypsum of lower to middle Miocene age. In some areas, the overlying Miocene aquiclude is missing and the aquifer is unconfined. In the upper Syrian Jezire, the top of the confined Ras el Ain aquifer is situated at shallow depth of several metres below surface.

The catchment of the Ras el Ain aquifer reaches in the north far into Turkish territory. The aquifer thickness varies between 200 and 300 m in Turkey and increases to around 1,000 m at Qamishly on the northeastern border of Syria. In the south, the aquifer extends until Tell Tamer on the Khabour river. Groundwater discharges from the aquifer in the large springs of Ras el Ain on the Syrian–Turkish border, which is one of the largest karst springs of the world.

The Tel Abiad aquifer is also a karst aquifer in Paleogene limestones with similar hydrogeologic characteristics as the Ras el Ain aquifer. The main discharge of the Tel Abiad aquifer is concentrated in springs on the Syrian–Turkish border: Ain el Arous on the Balikh river and Ain el Arab.

The Rad aquifer constitutes a generally shallow aquifer in unconsolidated to semi-consolidated deposits of Upper Miocene to Quaternary age and extends over parts of the Mesopotamian plains in the Syrian Jezire between Qamishly, Karatchok and the Radd marshes near Hasake. Permeable zones with considerable thickness and moderate to high permeability are developed in gravel, conglomerate and sand layers of the Miocene–Quaternary formations.

Apart from the main aquifers, the Jezire comprises several aquifers in Paleogene–Quaternary sediments, which are of minor importance because of their limited extent and/or relatively low transmissivities.

Eocene marly limestones, exposed along the eastern margin of the geologic Aleppo plateau, are drained along the Euphrates valley and provide village water supplies through shallow wells and springs in the Jerablus area.

Minor aquifers in the Jezire of Syria and Iraq are:

- Limestones and sands of the Oligocene–middle Miocene Lower Fars formation, which yield limited quantities of brackish groundwater
- Clayey limestones and gypsum of the Upper Fars formation
- Pliocene conglomerates, sandstones and marly limestones

Along the anticlinal zone of Jebel Abd el Aziz – Jebel Sinjar, Paleogene–Lower Miocene limestones provide fissure type aquifers with local importance for water supply and irrigation.

Quaternary sediments – sands, sandstones, loam with gravels, gypsiferous conglomerates – form shallow aquifers in the valleys of the Euphrates, Khabour and Balikh rivers and their tributaries.

3.3.1.4 Palmyrean Fold Belt

The Palmyrean fold zone comprises a major sub-regional aquifer system in Upper Cretaceous limestones and dolomites. In the Ad Daw and Sabkhet el Mouh plains, the Upper Cretaceous aquifer system is overlain by aquifers in Paleogene chalks and limestones and in Pliocene–Quaternary sediments.

The Upper Cretaceous carbonate rocks provide a fissure type aquifer. Karstification appears to be much less intensively developed than in the limestone and dolomite aquifers of the northwestern mountain and rift zone. The aquiferous zones of the Upper Cretaceous in the Palmyrean fold zone are formed, in particular, by Cenomanian–Turonian limestones and dolomites, but include also stratigraphically younger members of the Upper Cretaceous, such as layers of chert, limestone and silicified limestone in the Campanian and Maastrichtian. Outcrops of the aquiferous Upper Cretaceous are restricted to the anticlinal cores of the southern and northern Palmyrean mountains and the mountain chains east of Nebek (Jebel Sharq en Nebek). These outcrop areas are assumed to be the main recharge zones of the Upper Cretaceous aquifer. Deep confined sections of the Upper Cretaceous aquifer system are found in the Ad Daw and Sabkhet el Mouh depressions, the confining layers being formed by the Maastrichtian–Paleogene marl aquitard.

Fresh groundwater has been tapped in the Upper Cretaceous aquifer through shallow wells and boreholes in particular in wadis within the southern Palmyrean mountains and the mountains east of Nebek at Nasriye, Qaryatein, Al Barde and around Sawane. The Paleogene sequence of chalk, limestone, chert and marl provides an aquifer with low to moderate productivity at shallow to intermediate depth in several areas of the Palmyrean fold belt: in some parts of the Ad Daw plain and its western surroundings, in the low hills adjoining Sabkhet el Mouh in the north and south.

Pliocene–Pleistocene deposits of the Ad Daw basin are aquiferous in the more permeable layers with water levels at 15–60 m below surface. Aquiferous sections are found, in particular, in coarse detrital layers at the periphery of the plain. Groundwater from deeper aquiferous Campanian siliceous limestones appears to leak, at some points, into the overlying Neogene aquifer.

In the Sabkhet el Mouh plain, sandy layers of the Neogene sequence comprise a brackish water aquifer with salinities of 1,100–6,000 mg/l TDS.

In the eastern prolongation of the Palmyrean fold zone, occurrences of groundwater support water supply and limited irrigation at several locations of the steppe area. The exploited aquifers comprise:

- Eocene chalks at Arak and Hafne.
- Upper Cretaceous, mainly Campanian, limestones and cherts at Soukhne, situated at a depth of 250–340 m below surface.
- Campanian cherts tapped at Al Koum in the Jebel Bishri area at a depth of 250–340 m below surface and Pliocene deposits around Al Koum, which receive groundwater through leakage from the deeper Campanian aquifer.

Groundwater in the aquifers of the eastern outliers of the Palmyrean fold zone is prevailingly brackish (Sect. 3.4.4.1).

3.3.1.5 Southern Syrian Steppe, Hamad and East Jordanian Limestone Plateau

In the southern Syrian steppe and the Hamad, groundwater is found mainly in Paleogene chalks, limestones and cherts, and in fractured and fissured Upper Cretaceous limestones and dolomites. The Upper Cretaceous and Paleogene aquiferous layers are, in some areas, separated by the Maastrichtian–Paleogene marl aquitard (Muwaqar aquitard in Jordan); in structurally uplifted zones, the marls grade into carbonate deposits and the aquitard becomes leaky or is missing.

The Paleogene chalks and limestones form an aquifer at shallow to intermediate depth in wide parts of the plateaus of the southern Syrian steppe and the Hamad, which is, in many parts of the area, connected through leakage with underlying Mesozoic carbonate aquifers or with overlying Neogene–Quaternary sedimentary or volcanic rocks. The main aquiferous sections are found in lower Eocene limestones and cherts and in middle Eocene chalky limestones. In Jordan, these aquiferous members are denominated B4/B5 aquifer or Umm Rijam and Wadi Shalala aquifers. Toward west, the Paleogene plunges under the extensive cover of Neogene–Quaternary basalts of Jebel el Arab.

The stratigraphically lower member of the Eocene aquifer system (lower Eocene chert – limestone aquifer, B4 or Umm Rijam aquifer) extends over wide areas of the southern Syrian steppe and the Hamad and has been tapped by numerous wells in southern Syria, e.g. around Saba Biar, and in northeastern Jordan. The aquifer is used through dug wells of 6–25 m depth in the Wadi el Miyah – Wadi al Murabaa area in Syria, by a group of drilled wells at Humeime (Syria) and by boreholes of 35–100 m depth in the Sawab area (Iraq–Syria) and in northeastern Jordan. The aquifer is, in part of its extent, confined under marly sediments of the middle Eocene. The productivity of the lower Eocene aquifer is generally low.

The stratigraphically higher part of the Eocene contains a rather discontinuous aquifer (middle Eocene chalky limestone aquifer, Wadi Shalala or B5 aquifer), which is locally hydraulically connected with the underlying lower Eocene chert – limestone aquifer. The middle Eocene aquifer has been tapped mainly by dug wells of 50 to nearly 100 m depth in Wadi el Heil and in the Saba Biar–Juwef area in southern Syria, and in northeastern Jordan. Well yields are generally low.

The Paleogene aquifer system becomes unsaturated in the eastern parts of its outcrops near the Rutba uplift: the Paleogene is here situated above the regional groundwater level, the underlying Upper Cretaceous marls are missing or grade into limestone – dolomite facies near the uplift. In the Jordanian part of the Hamad area, the eastern limit of the Rijam aquifer is defined by the limit of saturation in a north–south trending zone around 50–60 km west of the border with Iraq. Toward northeast, the Paleogene aquifer dips under a thick cover of Pliocene sediments of the Euphrates basin.

The aquiferous sections in the Upper Cretaceous of the southern Syrian steppe and the Hamad correspond generally to rock units of Cenomanian–Turonian–Campanian age. On structurally uplifted areas in the east – the Rutba arch and At Tenf and Owered swells – aquiferous layers are found in carbonate rocks of Maastrichtian and possibly Campanian and Jurassic age.

The Upper Cretaceous carbonate aquifer complex has been tapped in the Wadi al Miyah–Wadi Murabaa area in Syria, in the H4–Rishe area in northeastern Jordan, and in southwestern Iraq (Tayarat aquifer).

On most of the western slope of Wadi Sirhan, the outcropping Rijam formation is unsaturated. The chalky and cherty limestones of the Rijam formation constitute a phreatic aquifer in the Jafr and Azraq area and in a 5–10 km wide belt over the western slope of Wadi Sirhan. Confined conditions occur in the Hamza graben and in Wadi Sirhan, where the top of the Rijam formation descends to a depth of 80 m below surface. The saturated thickness of the aquifer is 75–100 m in the water table areas and 100–200 m in the confined sections.

In the central part of the morphologic Jafr depression, the Rijam formation constitutes an aquifer which extends over around 1,250 km^2. The aquiferous layers consist of chalky limestones and cherts with marl and clay layers of the lower part of the B4 (Rijam) formation. The upper part of the B4 formation and the B5 formation are missing. The aquifer reaches a maximum saturated thickness of 30 m. Depth to aquifer is in the range of 15–35 m below surface.

The Shalala limestone member, representing the upper part of the Shalala formation, provides a saturated aquifer in a limited area on the border between Jordan and Saudi Arabia. The aquifer has a saturated thickness of 20–47 m and is situated at a depth of around 60 m below surface. Permeabilities of the Shalala aquifer are generally low.

Moderately high well yields are found in areas, where the Shalala aquifer is overlain by sandstones and sandy limestones of the Miocene Qirma formation. The Shalala and Qirma formations constitute a hydraulically connected unconfined aquifer in the Hamza area and the northern Wadi Sirhan. The aquifer is intensively exploited for irrigation in the Qurayat area in Wadi Sirhan, where groundwater levels are situated at 13–30 m below surface.

On most of the east Jordanian limestone plateau, the Upper Cretaceous aquifer is confined below the Muwaqar aquitard. The limestones and cherts of the Aman formation generally form a connected aquifer with the limestones of the Wadi Sir formation (Aman–Wadi Sir, B4/A7 aquifer). Argillaceous and marly sediments of part of the Ajloun group (A1–A6 formations) probably constitute an aquitard, which separates the Aman–Wadi Sir aquifer from the deeper Kurnub sandstone aquifer.

The Paleozoic–Lower Cretaceous Disi–Kurnub sandstone aquifer complex provides a large groundwater reservoir under the east Jordanian limestone plateau. The hydrogeologic features of the deep sandstone aquifer complex are considered in (Sect. 5.2). Granitic rocks of the basement complex constitute, in general, the impermeable base of the aquifer systems of the Jordanian limestone plateau.

3.3.2 Groundwater Regimes

3.3.2.1 Hydraulic Properties of Main Aquifers

Transmissivities of most aquifers of the eastern part of the northern Arabian platform are low to moderate. Table 3.2 presents some information on transmissivity

Table 3.2 Hydraulic parameter values of aquifers in eastern Jordan

Aquifer	Area	T (m^2/d)	K (m/s)	References
Rijam	El Jafr	40–7,700	10^{-5}–3×10^{-3}	GITEC and HSI (1995)
	Azraq	6–230 (max. 2,250)		Margane et al. (2002)
Aman-W.Sir	El Jafr	40–1,750		Hobler et al. (1991)
Lower Ajlun	El Jafr	320		Hobler et al. (1991)
B4/B5	Hamad		3×10^{-5}	GITEC and HSI (1995)

and hydraulic conductivity values, which have been reported for Upper Cretaceous and Paleogene aquifers of the sub-region. Fresh water aquifers, which occur at shallow depth on the Aleppo plateau, the Jezire, the Jafr area and along some wadi systems, have generally a limited thickness and, accordingly, relatively low transmissivities.

Exceptionally high transmissivities are found in the karstified Paleogene Ras el Ain and Tel Abiad aquifers on the northern boundary of the Jezire, which support high spring discharges.

3.3.2.2 General Groundwater Flow

Groundwater flow on the plateaus and morphologic depressions of the eastern part of the northern platform is directed to:

- Closed basins of the internal drainage zone, which is situated between the Mediterranean Sea, Dead Sea and Euphrates basins: Jaboul, Matah, Sabkhet el Mouh, Damascus and Azraq plains and Wadi Sirhan.
- The rift valleys in the west and the Euphrates river system in the east.

The partly complex flow systems can include different flow directions in upper and deeper aquifers.

3.3.2.3 Aleppo Plateau

Recharge rates in the upper aquifer system of the Aleppo plateau depend on rainfall, rock outcrops and morphology. In the northwestern part of the plateau, outcropping karstified limestones (Eocene nummulitic limestones, Miocene limestones) and relatively high rainfall provide favourable recharge conditions. Recharge rates of 15–20% of annual rainfall may be assumed for the western, more humid zones of the Aleppo plateau. Average recharge rates of 11 mm/a have been estimated for areas covered by Helvetian limestones south of Aleppo, and of 12 mm/a for the Jebel al Hass area covered by Miocene basalts.

In the southeastern dry parts of the plateau, recharge is generally low. Infiltration of rainfall from events with low intensity is not sufficient to exceed the field capacity of the soil and most of the soil moisture is lost by evapotranspiration.

Groundwater recharge may occur along wadi courses, where accumulation of surface runoff can infiltrate, and through percolation in irrigation areas.

Groundwater flow in the upper aquifer system (Paleogene aquifer system) of the Aleppo plateau follows, in general, the topographic–hydrographic slope to closed basins and, in the west and east, toward the Orontes and Euphrates valleys in the west and east, respectively. The groundwater divide enclosing the zone of internal drainage coincides approximately with the surface water divide. The groundwater flow regime in the upper aquifer system is, however, significantly influenced by downward leakage into the deeper Upper Cretaceous aquifer in several zones. Lekage into the deeper aquifer occurs, in particular, in the west of the plateau, where the underlying marl aquiclude is thinning toward the anticlinal structure of the rift zone, and in fracture zones along the lower course of the Queiq river and the western rim of the Matah depression. Groundwater flow toward the closed basins probably reverses its course in some areas after leakage into the deeper aquifer, which drains toward topographically lower river valleys. Main groundwater discharge zones are the salt flats and seasonal lakes of Al Jaboul and Matah, where major volumes of groundwater discharge naturally by evaporation. Seasonal springs issue on the margins of the flats of closed basins and in the Queiq valley upstream and downstream of Aleppo. At present, the groundwater regime of the upper aquifer is significantly affected by groundwater withdrawal for irrigation.

The Upper Cretaceous carbonate rocks underlying the Aleppo plateau constitute a productive brackish water aquifer in an area extending from the border of Syria and Turkey to the northern Palmyrean mountains and, in the west, approximately the Aleppo–Hama highway, an area covering around 20,000 km^2. Well yields of boreholes tapping the Upper Cretaceous aquifer are in a range of 30–140 m^3/h with minor drawdown.

Isotope data indicate that the groundwater stored in the Upper Cretaceous carbonate aquifer of the Aleppo plateau originates prevailingly from recharge in past periods with wetter climate several thousand years ago and may be related to groundwater movement from distant recharge areas. Recharge areas may be presumed at outcrop areas of the Upper Cretaceous limestones and dolomites in the northern Palmyrean mountains or in the eastern Taurus mountains, where present mean annual precipitation is around 400 mm and >600 mm, respectively.

No points of discharge of the deeper groundwater are known on the Aleppo plateau. Upward leakage of deeper groundwater into the upper aquifer system or into sabkhas possibly occurs in the structural and morphologic depressions of Matah–Harayeq. Upward leakage from the Upper Cretaceous aquifer into the overlying aquifers may occur also in the lower ranges of the Euphrates valley in the east of Aleppo, where the Upper Cretaceous is covered by a thick sequence of younger deposits.

Groundwater movement in the Upper Cretaceous of the Aleppo plateau is probably directed, with very low flow velocities, westward to the rift graben, where the old brackish ground water may provide a minor component of spring discharge, and, to some extent, also to the Euphrates valley in the west.

Topographic elevations of the probable main discharge zones are: Jaboul 308 m asl, Matah 249 m, El Rhab 170 m, Er Rouj 218 m, Orontes at the Syrian–Turkish border 100 m, Euphrates 276 m.

3.3.2.4 Jezire

The main recharge areas of the Ras el Ain and Tel Abiad aquifers in the Syrian Jezire extend into the southern ranges of the Taurus mountains, where mean annual precipitation reaches up to 1,000 mm. The recharge areas are covered mainly by Eocene limestones and Pliocene–Quaternary basalts. The catchment area is estimated to extend over 7,500 km^2, and has a mean annual precipitation of 450 mm. The average recharge is estimated at 1.6×10^9 m^3/a.

Groundwater flow is directed toward south to the main spring discharge areas along the Syrian–Turkish border. The total discharge of springs from the Ras el Ain and Tel Abiad aquifers may be around 52 m^3/s. Mean discharge of the spring Ras el Ain is 38.7 m^3/s from an estimated stored groundwater volume of 7.4×10^9 m^3.

In the semi-arid Mesopotamian–Euphrates plain, direct recharge from precipitation is relatively low. Recharge to the shallow aquifers in the plains occurs mainly from surface runoff in the Khabour river and its tributaries. Recharge from precipitation and runoff infiltration to the Upper Miocene–Quaternary Radd aquifer amounts to around 350×10^6 m^3/a. Groundwater flows within the aquifer generally to the extensive Radd marshes in the south, where an estimated volume of 270×10^6 m^3/a discharges through evapotranspiration.

In the eastern Jezire in Iraq, groundwater flow is directed to discharge areas in the Euphrates valley, Wadi Tharthar, the artificial Tharthar reservoir, and to local salt flats.

3.3.2.5 Palmyrean Fold Belt

Present day groundwater recharge in the Palmyrean zone is restricted mainly to the outcrops of the aquiferous Upper Cretaceous and Paleogene formations in the anticlinal mountain chains and to infiltration of sporadic surface runoff. Recharge rates under the present climate conditions with mean annual rainfall of 100–200 mm are certainly low. Most of the groundwater in the Upper Cretaceous and Paleogene aquifers is fossil, originating from Pleistocene recharge.

Groundwater flow in the main aquifers of the Palmyrean zone is directed toward Sabkhet el Mouh, which is situated at an elevation of around 370 m asl and constitutes a sub-regional groundwater discharge zone. In the east of the Ad Daw plain, groundwater moves into the Sabkhet el Mouh plain under the morphologic rise separating the two plains on the surface. The subsurface catchment of Sabkhet el Mouh extends, south of the southern Palmyrean mountains, into the plateau area of the southern Syrian steppe.

Some groundwater discharge occurs in springs on the margins of the Ad Daw plain, in particular at Qaryatein on the southwestern edge of the plain.

In the Maqsam–El Baida area in the southeast of the Ad Daw plain, groundwater apparently leaks from the Upper Cretaceous aquifer probably through a deep fault zone into the overlying Neogene–Quaternary aquifer.

Evaporation in the Sabkhet el Mouh salt flat constitutes an important component of groundwater discharge. To some extent, deep groundwater flow may move from the Sabkhet el Mouh basin eastward to the Euphrates river.

3.3.2.6 Southern Syrian Steppe, Hamad and East Jordanian Limestone Plateau

The climate in the southern Syrian steppe and Hamad and on the east Jordanian limestone plateau is arid with mean annual precipitation between 120 and 50 mm. Present-day recharge is, accordingly, very limited. Most of the groundwater is fossil.

An impact of recent indirect recharge through infiltration of surface runoff is, however, indicated by isotope data (Sect. 3.5) and by the occurrence of shallow groundwater bodies along some wadi stretches. Shallow groundwater sustained from recharge is e.g. found in Wadi al Miyah, Wadi Murabaa and Wadi Sawab in southeastern Syria and southwestern Iraq and along Wadi Ruweishid in north-eastern Jordan.

Groundwater moves in the southern Syrian steppe and the Hamad in a general east-northeast direction to the Euphrates valley. A belt of the southern Syrian steppe adjoining the Palmyrean zone is included in the hydrogeologic Sabkhet el Mouh catchment.

Separate groundwater regimes exist in some parts of the southern Syrian steppe in the upper Paleogene aquifer and the lower Mesozoic carbonate aquifer. In the east near the Rutba uplift zone, the marls of the Maastrichtian–Paleogene aquitard grade into limestone facies and the Paleogene aquifer is either unsaturated or hydraulically connected with the deeper aquifer.

Subsurface outflow toward the Euphrates valley appears to occur through a multi-aquifer system in Mesozoic to Neogene deposits.

In the Upper Cretaceous and Paleogene aquifers of the east Jordanian limestone plateau, groundwater flows generally toward east-northeast to the morphologic depressions of Wadi Sirhan and Azraq. The Paleogene constitutes only in parts of the plateau a saturated aquifer. Groundwater flow in the Upper Cretaceous aquifer system is, in some areas, controlled by major faults, as indicated by the groundwater salinity distribution (Sect. 3.4.4.3).

In the deep sandstone (Disi–Kurnub) aquifer system, groundwater movement follows a sub-regional flow path from outcrop areas in the Interior Homocline in the south in a wide semi-circle to the Dead Sea basin (Chap. 5).

References. Abu-Ajamiieh (1967), ACSAD (1983), Ahmed and Kraft (1972), Boeckh et al. (1970), Burdon and Safadi (1963), ESCWA (1999b), GITEC and

HSI (1995), GTZ and NRA (1977), Hobler et al. (1991), Kattan (2002), Khouri (1982), Luijendijk and Bruggemann (2008), Margane et al. (2002), Medvedev (1966), Mikhailov (1964), Oufland (1966a, b), Ponikarov et al. (1967b), Sunna (1995), United Nations (1982: 158), Wagner (1997), Wagner et al. (1982), Ward and Smith (1994), Wolfart (1966).

3.4 Groundwater Salinity and Hydrochemistry

3.4.1 Groundwater Salinity Distribution

On the plateau areas in the east of the northern Arabian platform, fresh groundwater occurs, in particular, in the upper aquifer system of the semi-arid zones of the Aleppo plateau and the western fringes of the east Jordanian limestone plateau. Large quantities of fresh groundwater discharge from Paleogene karstified carbonates on the northern boundary of the Syrian Jezire.

In the deeper aquifer system and, in the more arid areas in the east and southeast, also in the upper aquifer system, the groundwater is, in general, brackish.

In the upper aquifer system of the Aleppo plateau, groundwater salinity is generally low to moderate in the recharge areas and increases toward the local discharge areas in the closed basins of Jaboul, Matah and Harayeq. In the sabkha areas the groundwater is generally brackish with total salinity up to 7,000 mg/l TDS.

In the Palmyrean fold zone, the extent of fresh water aquifers is very limited. Groundwater with moderate salinity is found in some of the hill zones on the peripheries of the Ad Daw and Sabkhet el Mouh plains. In most of the Upper Cretaceous, Paleogene and Pleistocene–Quaternary aquifers, the groundwater is brackish.

The Paleogene carbonate rocks act in the Palmyrean fold zone only locally as fresh water aquifers of limited extent, as outcrops are generally restricted to small areas along anticlinal flanks situated above main groundwater levels. The Paleogene aquifers below Pleistocene–Quaternary sediments in Ad Daw and Sabkhet el Mouh plains contain brackish to saline groundwater.

The general pattern of groundwater salinity in the southern Syrian steppe and Hamad can be characterized as follows:

Groundwater salinity is:

- Low to moderate (<1,000 mg/l TDS) in local fresh water occurrences in the Lower Eocene chert aquifer in the Wadi el Miyah, Wadi Sawab and Wadi Ruweishid areas
- Moderate to high (750–1,500 mg/l TDS) in the Eocene limestone – chert aquifer of the steppe area bordering the southern Palmyrean mountains
- Generally high (1,500–2,500 mg/l TDS) in the Paleogene chert aquifer in most of the central Hamad Plateau
- High to very high (1,500 to >3,500 mg/l) in several parts of the Hamad plateau (Sabaa Biar–Juwef–Rishe areas)

Main sources of the high groundwater salinity, which prevails in wide areas of the Hamad, are assumed to be evaporative enrichment during the recharge process and solution of rock material during very long retention periods of 24,000 and 36,000 years in carbonate and chert aquifers. The occurrence of groundwater with relatively low salinity appears related to recent groundwater recharge. Fresh water occurrences in Paleogene aquifers covered by the Jebel el Arab basalts are considered in Chap. 4.

An increase of groundwater salinity together with a change from oxic to anoxic conditions occurs, on the northern Arabian platform, in particular where groundwater from an overlying fresh water aquifer leaks through bituminous marly chalky rocks of the Maastrichtian aquitard into the underlying limestone–dolomite aquifer. These conditions are common in the eastern part of the northern Arabian platform, but is also observed in aquifers of the Judean highlands. "An increase in salinity and change from oxic to anoxic conditions are observed in the Upper subaquifer of the Judea group. . .at the western foothills of the Judea Mountains" "The deterioration in the water quality is explained as a result of seepage of more saline, organic-rich water from above. . . The latter is derived from the bituminous chalky rocks of the Mount Scopus Group, which confine the aquifer". "The incoming organic matter consumes the dissolved oxygen and allows bacterial sulfate reduction. The latter accounts for the H_2S in the aquifer, as indicated by sulfur isotopic analyses" (Gavrieli et al. 2002: 483).

On the east Jordanian limestone plateau, fresh groundwater with salinities of generally less than 600 mg/l TDS occurs in the Rijam (B4) aquifer of the Jafr area. Locally, the water quality is influenced by irrigation return flow leading to an increase of water salinity to 2,000–3,000 mg/l TDS. Electrical conductivity values of groundwater from the Rijam aquifer in the Wadi Sirhan catchment range from approximately 1,200–3,000 μS/cm. Locally elevated salinity (EC 3,600 μS/cm) is attributed to the presence of evaporite minerals in the limestone aquifer. Groundwater salinity in the Shalala (B5) aquifer appears to be, in general, similar to salinity in the Rijam aquifer.

3.4.2 Hydrochemistry of Paleogene Chalk Aquifers

Paleogene chalks and chalky limestones constitute a major component of the upper aquifer system in wide parts of the eastern plateaus of the northern Arabian platform. Aquiferous chalks extend over the Aleppo plateau, the southern Syrian steppe and Hamad, the east Jordanian limestone plateau, and synclinal structures of the Palmyrean zone. In the western mountain and rift zone, Paleogene chalk aquifers are found around Irbid in northern Jordan, in the Jenin sub-basin on the West Bank and in the Bekaa and the southwestern coastal zone of Lebanon.

The hydrochemical conditions of the chalk aquifers are somewhat different from the conditions in typical limestone and dolomite aquifers.

Chalks are generally fine grained, pure low magnesium carbonates with abundant intercalations of clay minerals. The chalk matrix provides a large internal surface area for water–rock contact and reaction. In the outcrop areas, congruent solution reactions predominate and the low Mg/Ca ratios in the rock are reflected in the groundwater hydrochemistry. Downgradient, incongruent solution and precipitation of carbonate, ion exchange, and, in confined systems, oxidation–reduction reactions predominate. Significant solution of carbonate occurs at shallow depth. The predominance of Ca and HCO_3 ions in groundwater of the outcrop areas can be attributed to the solution of calcite. Calcite saturation is usually attained within the unsaturated zone.

Hydrochemical changes within the aquifer comprise, in particular:

- Increase of Cl concentrations from solution of relict marine waters within the chalk matrix
- Conversion of Ca–HCO_3 water to Na–HCO_3 type water through cation exchange

The clay minerals within the chalk matrix function as ion exchange medium. "Clay minerals may exchange their Na^+ ions for Ca^{2+} and Mg^{2+}, causing the impoverishment of these cations in water". "The ion exchange and adsorption processes are summarized by:

$$(1/2)\mathrm{Ca} + \mathrm{Na} \rightarrow \mathrm{Na} + (1/2)\mathrm{Ca}_x$$

where x is the adsorbing clay mineral" (Rosenthal 1987).

Within the chalk aquifer, water moves very slowly downgradient through the matrix, but more rapidly in the fissure system with a continuous exchange of water and solutes between the fissures and the matrix. "Thus, although the bulk of the water in the matrix is moving only very slowly, it is involved in the transport process because it is moving by continuous exchange through diffusion" (Downing et al. 1993: 58).

The chalk aquifers of the upper aquifer system in the west of the Aleppo plateau – the area between Hama and Aleppo – contain prevailingly Ca–HCO_3 type water with low to moderate salinity. The natural hydrochemical groundwater composition appears related prevailingly to:

- Input of dissolved substances from rainfall and enrichment by evaporative processes during recharge
- Dissolution of soil and rock carbonate through interaction with biogenic soil CO_2 and water

Mg/Ca ratios in fresh groundwater of the Aleppo plateau vary from 0.2 to 0.6. These ratios are higher than in groundwaters of the nummulitic limestone aquifers, but on average lower than in the Upper Cretaceous limestone and dolomite aquifers of the western mountain and rift zone.

The chalk aquifers on the plateau areas comprise, in general, an oxidized milieu.

Chalk aquifers covered by Neogene basalts on the Aleppo plateau contain Ca–Na–HCO_3 type water.

In morphologic depressions, in particular in the plains of closed basins, dissolved substances are enriched by evaporation or dissolution of evaporite minerals in sabkhas and in Pliocene lacustrine sediments.

In the Irbid area in northern Jordan, Paleogene chalks mainly of the Rijam (B4) formation contain fresh groundwater of Ca–HCO_3 type. Total salinity ranges from around 540 to 700 mg/l TDS. The anion composition changes from prevailingly HCO_3 predominance in the west around Ramtha with relatively high HCO_3 concentrations to higher Cl and lower HCO_3 concentrations in the more arid areas around Mafraq further east. Spring water generally has low salinities of around 300 mg/l TDS. Elevated salinities of up to 1,000 mg/l TDS found at some locations may be attributed to contamination from the surface in the phreatic aquifer, which is indicated by NO_3 concentrations of up to 264 mg/l.

According to Lloyd (1965), the chalk waters of the Belqa group aquifer in northern Jordan fall into the bicarbonate group "but with lower Ca and higher Na content than the equivalent limestone waters, probably indicating that the chalk is a less pure carbonate rock than the limestones of the area". Lloyd states, that the chalk groundwaters with a mean total salinity of 532 mg/l TDS "show a close grouping with a few analyses indicating the effects of metasomatic change".

In the Jafr area of the east Jordanian limestone plateau, the Rijam chalk (B4) aquifer contains fresh groundwater with a salinity of less than 600 mg/l TDS. The ionic composition is characterized by approximately equal percentages of Ca and Na and of HCO_3 and Cl. The major ion composition of the Na–Ca–Cl–HCO_3 type water indicates calcite dissolution with a significant evaporative Na–Cl concentration from recharge in an arid climate. Locally higher salinities of up to 3,000 mg/l TDS of Na–Cl type water are attributed to irrigation return flow. East of the Jafr area in downstream groundwater flow direction toward Wadi Sirhan, groundwater in the Rijam aquifer is brackish with salinities of 1.5 g/l TDS.

Paleogene chalks provide a relatively extensive aquifer in the Jenin sub-basin on the West Bank within the western mountain and rift zone. Groundwater discharging from the Jenin (Avedat) chalk aquifer in springs shows similar hydrochemical characteristics as the chalk aquifers in the Aleppo plateau in northern Syria. Groundwater salinity is, on average, 390 mg/l TDS; the chalk groundwaters are Ca–HCO_3 type waters. The chalk waters can be distinguished in their hydrochemical composition from groundwater of the Upper Cretaceous limestone and dolomite aquifer by:

- Higher Cl, SO_4 and Na concentrations
- Lower Mg concentrations

The chemical characteristics of the Paleogene chalk aquifer and the differences from the hydrochemical composition from groundwaters of the Judea aquifer can be related to the aquifer lithology: "The Judea Group is a high-transmissivity karstic sequence composed of dolomite and limestone beds, thoroughly flushed by soluble salts and of argillaceous components. Conversely, the Avedat Group is characterized by much lower transmissivities and is composed of limestones alternating with chalk and clay horizons" (Rosenthal 1987). Cation exchange and adsorption processes are important in the chalk aquifer with its high clay content.

Groundwaters in Paleogene chalk aquifers of the Lebanon mountain zone appear similar in their hydrochemical characteristics to chalk groundwaters of the Aleppo plateau and the Jenin area on the West Bank (Figs. 3.5 and 3.6; Table 3.3).

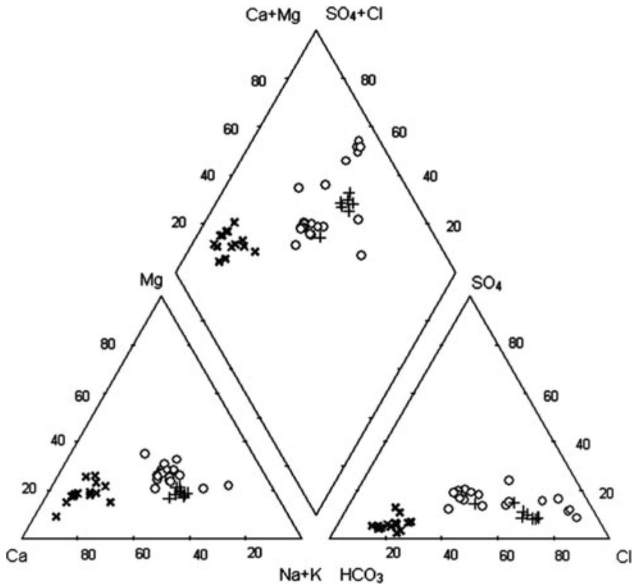

Fig. 3.5 Piper diagram: Groundwater samples from Paleogene chalk aquifers. × Hama-Aleppo area, northern Syria, samples of uncontaminated groundwater, data from Boeckh et al. (1970), ○ Rijam (B4) aquifer, Jafr area, southern Jordan, data from Hobler et al. (1991), + Rijam (B4) aquifer, Ramtha area, northern Jordan, data from Rimawi (1985)

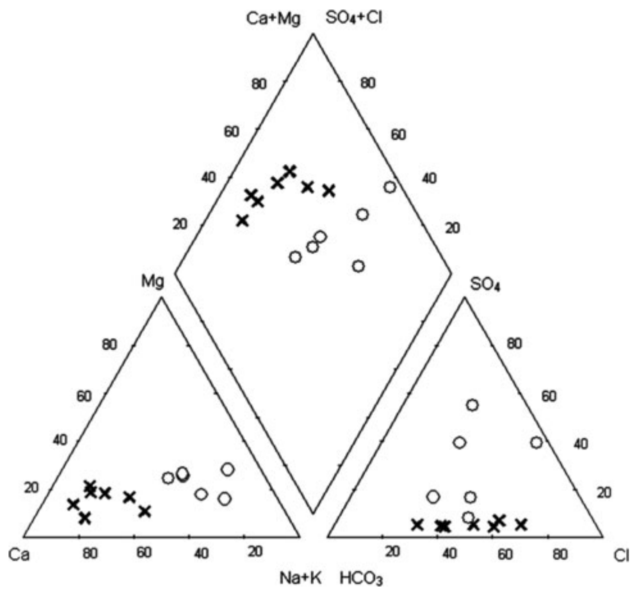

Fig. 3.6 Piper diagram: Groundwater samples from Paleogene chalk aquifers of the Aleppo plateau, northern Syria. Contaminated groundwater and groundwater in salt flat zones, data from Boeckh et al. (1970), × groundwater influenced by contamination from the surface, ○ groundwater in salt flat zones, salinity elevated through evaporation and dissolution of evaporites

Table 3.3 Hydrochemical parameters of chalk groundwaters in different areas of the northern Arabian platform

	TDS (mg/l)	HCO_3 (mg/l)	HCO_3 (meq%)	Mg/Ca
Aleppo plateau, fresh groundwater	400–700	200–250	70	0.15–0.4
Ramtha area	500–700	275–450	>60	0.6–0.9
Jafr	<600	100–280	40–60	0.4–1.0
Jenin	400	212	66	3
Lebanon	500	165–329	70	2

Data from Abumaizer (1996), Boeckh et al. (1970), Hobler et al. (1991), Rosenthal (1987), UNDP (1970)

The fresh water aquifers in Paleogene chalks on the northern Arabian platform are prevailingly phreatic aquifers with water levels at a few tens of metres below surface. These aquifers are, in many areas, endangered by contamination from the surface, in particular domestic waste and irrigation return flow.

3.4.3 Hydrochemical Features of Cretaceous and Neogene - Quaternary Aquifers in Northern Syria

3.4.3.1 Upper Cretaceous Aquifers of the Aleppo Plateau and the Jezire

Groundwater in the deeper Upper Cretaceous aquifer of the Aleppo area and the adjoining northern Syrian steppe is brackish with salinities of 3,000–4,000 mg/l TDS, high SO_4 concentration and elevated H_2S. The groundwater of the Upper Cretaceous carbonate aquifer shows a rather homogeneous hydrochemical composition over an extended area. SO_4, HCO_3 and Ca concentrations appear to be controlled mainly by a hydrochemical equilibrium, where concentrations of these three major constituents are approximately at a saturation level. The elevated H_2S contents reflect a low oxygen and strongly reducing environment in the confined aquifer. Variations of the hydrochemical composition are mainly related to varying Na and Cl concentrations (Fig. 3.7).

The sulfate source may be provided by evaporite layers in the Upper Cretaceous sedimentary sequence, the occurrence of which has been observed in Campanian carbonate rocks east of Hama and is indicated by extensive collapse structures in Jebel Shomariye in the northern Palmyrean mountains.

No significant hydrochemical impact of leakage from the upper aquifer into the Upper Cretaceous aquifer can be seen. Mixtures of groundwater from the brackish Upper Cretaceous aquifer and the overlying Paleogene chalk aquifer are found in some boreholes in the Aleppo–Hama area.

The brackish water tapped in the Upper Cretaceous aquifer on the Aleppo plateau is, at present, extracted from about 80 boreholes with depths between 400 and 775 m is used for irrigation as a substitute for irrigation from the depleting upper aquifer or in newly developed irrigation areas.

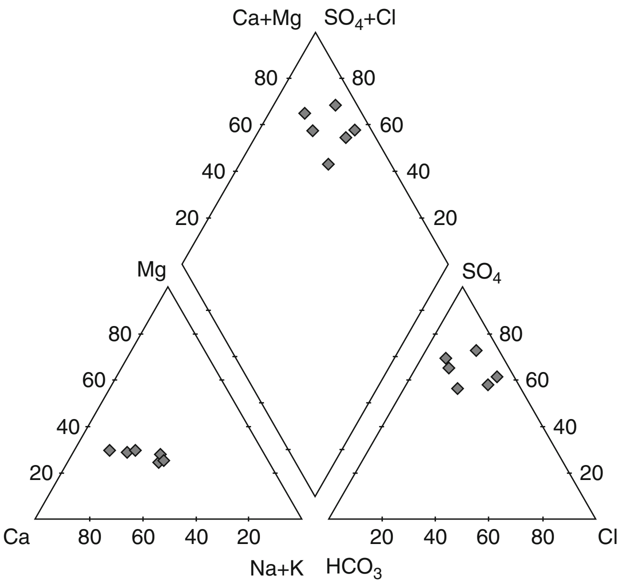

Fig. 3.7 Piper diagram: Groundwater samples from the deeper Upper Cretaceous aquifer of the Aleppo plateau. Data from Boeckh et al. (1970) and files of Ministry of Agriculture and Agrarian Reform, Jebel Al Hoss Agricultural Development Project, Aleppo

In the Khabour area, artesian wells discharge brackish, partly thermal groundwater from an anoxic aquifer with average H_2S concentrations of 7.5 mg/l. Methane is found in the water of some deep wells. The deeper brackish groundwaters are Ca–SO_4 type waters with salinities of 1,580–3,600 mg/l TDS. SO_4 concentrations are generally high with 700–2,000 mg/l, Cl concentrations vary from 350 to 700 mg/l, Mg/Ca ratios are around 0.6–0.7. The brackish groundwaters are similar in their hydrochemical composition to the groundwaters of the Upper Cretaceous aquifer of the Aleppo plateau. Water from some boreholes and springs appears to represent mixtures of fresh shallow groundwater and of the deeper brackish groundwater (Fig. 3.8).

3.4.3.2 Shallow Aquifers of the Aleppo Plateau

Miocene fractured and karstified limestones constitute, in wide areas west to northwest of Aleppo, an upper member of the shallow Paleogene–Neogene aquifer system. Groundwater in the Miocene carbonate rocks is generally Ca–HCO_3 type fresh water with a salinity of around 200–400 mg/l TDS.

Fresh groundwater in Pliocene lacustrine – fluvial deposits occurs in the surroundings of Sabkhet Jaboul. The groundwater is generally Ca–HCO_3 type water with a salinity of 300–500 mg/l TDS. Toward the centre of Sabkhet Jaboul, the groundwater becomes brackish.

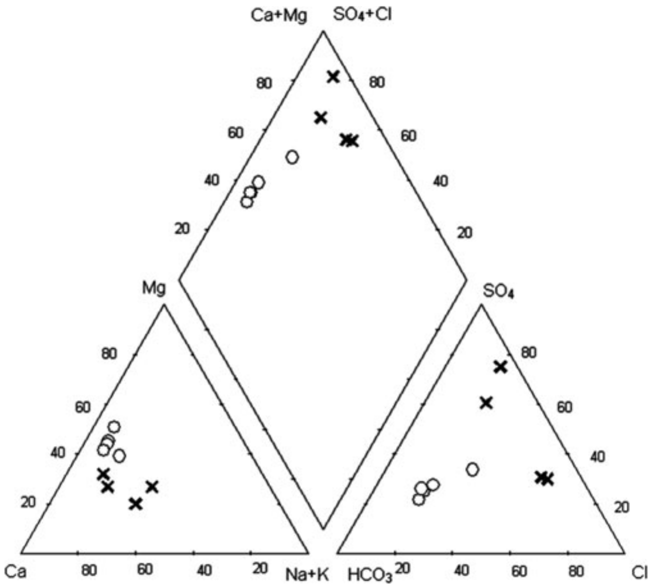

Fig. 3.8 Piper diagram: Groundwater samples from Paleogene aquifers in the Syrian Jezire. Data from Kattan (2002). ○ springs, × boreholes with admixture of deeper brackish groundwater

In the south of the Aleppo plateau (northern Syrian steppe), the upper aquifer system comprises, in addition to the main Paleogene aquifer member, aquiferous layers in Quaternary and locally in Maastrichtian sedimentary rocks. Groundwater in Quaternary aquiferous layers is generally brackish with salinities of 1,800–5,600 mg/l TDS. In the chalk–marl sequence of the Maastrichtian, aquiferous layers are found in cherts and silicified zones at shallow depth in the outcrop area of the Maastrichtian south of Khanaser and has been tapped in some boreholes in the south of the Aleppo plateau near the Palmyrean fold zone. The groundwater is generally brackish Na–Cl or Ca–SO_4 water with salinities of 1,300–5,600 mg/l TDS.

In the northern Syrian steppe around Resafe, shallow groundwater in Miocene gypsiferous deposits is brackish Ca–SO_4 to Na–Cl type water with salinities of 3,000–6,500 mg/l TDS.

3.4.3.3 Shallow Aquifers of the Euphrates–Mesopotamian Plains

In the Euphrates–Mesopotamian plain, fresh water and brackish water aquifers are generally restricted to the Paleogene–Neogene–Quaternary section of the sedimentary sequence. High volumes of discharge of fresh groundwater are sustained by subsurface inflow from the adjoining alpidic geologic units in the north.

Groundwater from the Paleogene Ras el Ain and Tell Abyad aquifers, issuing near the Syrian–Turkish border, is fresh Ca–(Mg)–HCO_3 type water with salinities of generally 400–500 mg/l. Groundwater issuing from the Ras el Ain aquifer around the Khabour river has salinities of 400–440 mg/l TDS; Mg/Ca ratios range from 0.86 to 1.2 (Fig. 3.8).

In most of the Jezire, brackish SO_4 type waters prevail with frequently high H_2S contents. In wide areas of the plains, evaporite layers in the Neogene Fars formation constitute a source of high sulfate concentrations in the groundwater.

3.4.4 Hydrochemical Features of Aquifers in the Palmyrean Zone and the Southeast of the Northern Arabian Plate

3.4.4.1 Palmyrean Fold Zone

Groundwater of the deeper Upper Cretaceous limestone and dolomite aquifer of the Palmyrean fold zone contains relatively high SO_4 concentrations at many places. The sulfate content may be attributed to dissolution of evaporite layers intercalated in the Mesozoic rock sequence, possibly in Campanian carbonate rocks or in older formations. The occurrence of evaporite deposits is indicated by large collapse structures on Jebel Shomariye in the northern Palmyrean mountains.

Brackish groundwater with elevated SO_4 concentration, salinity of 1,200–4,600 mg/l TDS and H_2S smell is found in the Upper Cretaceous in the wider surroundings of Palmyra and in the southern Palmyrean mountains at Basiri and Sawane. Near Palmyra, a brackish spring with 2,200 mg/l TDS and H_2S smell discharges from a cave into a small stream.

On the western surroundings of the Ad Daw plain, water with higher salinity and elevated temperature (Zamlet el Haber, 55°C) or steam (Abou Rabah) rise from the deep confined Upper Cretaceous aquifer.

A few perennial fresh water springs rise from the Upper Cretaceous limestone and dolomite aquifer at the southwestern border of the Ad Daw plain. The groundwater is of Ca–HCO_3 type with a salinity of 100–400 mg/l TDS.

In the Maqsam–Al Baida area, groundwater with a salinity of 900–1,100 mg/l TDS is extracted from wells in the Pliocene–Pleistocene sediments. This groundwater with relatively low salinity appears to leak from the Upper Cretaceous aquifer into the overlying basin deposits.

Groundwater salinity in the Pliocene–Pleistocene aquifer is, on average, considerably higher in a range of 1,000–14,000 mg/l TDS. The elevated salinity originates primarily from dissolution of evaporite layers in the lacustrine sediments. The wide-spread occurrence of evaporite minerals on the surface creates an increased salinity already in the runoff water in some streams, from which the shallow aquifer receives its main recharge.

In the eastern extension of the Palmyrean mountain zone northeast of Palmyra, groundwater occurrences are found in Upper Cretaceous to Paleogene carbonate formations at various locations (Arak, Hafne, Jebel Bishri area). The groundwaters are generally brackish with highly varying salinity and hydrochemical composition:

- Fresh water with a salinity of 800 mg/l TDS and H_2S smell issues in a spring from Eocene chalks and limestones at Arak.
- Brackish water with a salinity of 2,000–3,000 mg/l TDS of prevailingly Ca–SO_4 type has been tapped in Upper Cretaceous (mainly Campanian) limestones and cherts at Soukhne and at depth of 250–340 m below surface at Jebel Bishri.
- Water with 1,500–2,800 mg/l TDS in Pliocene deposits, leaking from the deeper Campanian aquifer, is extracted in shallow wells at Al Koum village.

3.4.4.2 Southern Syrian Steppe and Hamad

In the southern Syrian steppe and the Hamad, the separation between upper and deeper aquifer systems is discontinuous in many areas. In boreholes, water from the Paleogene aquifer and the Upper Cretaceous aquifer can frequently not be distinguished because of natural leakage or of mixing within uncased wells.

The groundwater is generally brackish, except for some fresh water lenses along larger wadi courses.

Fresh HCO_3 type water with no predominant cation occurs in the H4 area in northeastern Jordan. In general, the fresh to brackish groundwaters in the southern Syrian steppe show a slight tendency to Cl predominance, while the cations vary in a range of more or less equal percentages of Na, Ca and Mg. Mg/Ca ratios are mainly between 0.5 and 1.5.

Relatively high Na and Cl percentages occur in Paleogene and Upper Cretaceous aquifers of the Sabaa Biar – Juwef and Wadi al Miyah areas. Both areas constitute structural and paleogeographic depressions with considerable accumulation of marly deposits. Groundwater salinity is partly very high with TDS values up to 8,000 mg/l.

Deep groundwaters in the Upper Cretaceous aquifer are frequently Cl waters with relatively high SO_4 and HCO_3 concentrations and H_2S concentrations indicating anoxic conditions. In several wells in structural highs, SO_4 type waters have been encountered.

Main sources of the high salinity in wide areas of the Hamad region are assumed to be a solution of rock material during very long retention periods in carbonate and chert aquifers and enrichment by evaporation in areas with shallow groundwater occurrence (Figs. 3.9 and 3.10).

The hydrochemical composition of brackish groundwaters in the southern Syrian steppe and the Hamad shows high variations of major ion concentrations and no particular differentiation of specific hydrochemical groups. The diffuse aspect of the hydrochemistry of these groundwaters are probably related to a groundwater regime with slow groundwater movement and long retention periods, in which local conditions of groundwater recharge and flow and of the hydrochemical environment are dominant rather than wide ranging phenomena of groundwater flow and hydrochemical development.

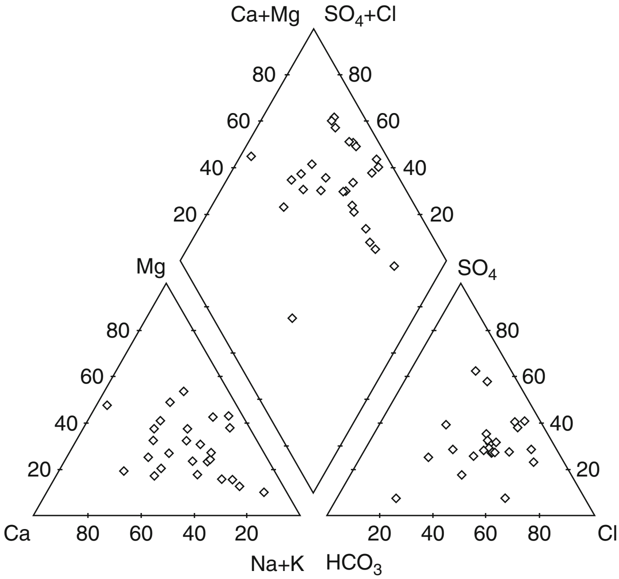

Fig. 3.9 Piper diagram: Groundwater samples from the southern steppe and Hamad in Syria. Data from ACSAD (1983)

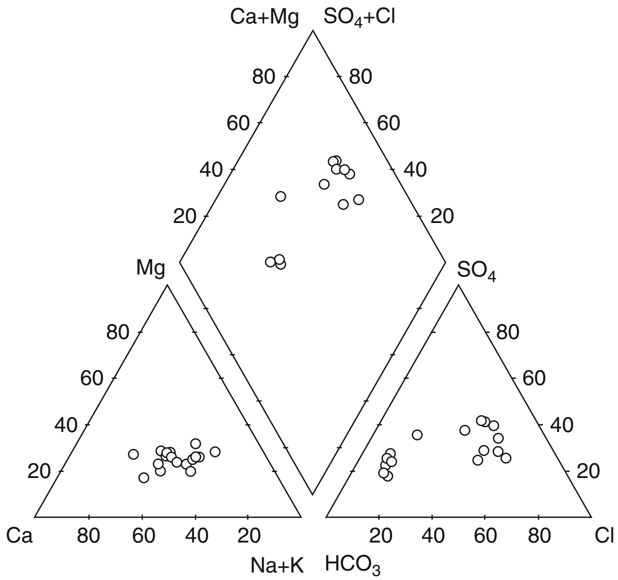

Fig. 3.10 Piper diagram: Groundwater samples from the Hamad in northeastern Jordan. Data from ACSAD (1983)

3.4.4.3 East Jordanian Limestone Plateau

Hydrochemical aspects of the Rijam chalk aquifer have been mentioned in Sect. 3.4.2.

Groundwater salinity in the Upper Cretaceous aquifer (A7/B2 aquifer) of the east Jordanian limestone plateau, increases from less than 600 mg/l TDS in the outcrop areas in the western highlands to 1,000–4,000 mg/l TDS in the Jafr area and to nearly 7,000 mg/l TDS in Wadi Sirhan. In general, the salinity of the groundwater increases along the main flow path toward east. The salinity increase is particularly remarkable in the sections, where the aquifer is confined under the Muwaqar (B3) marl aquitard. The water type changes from Ca–Mg–HCO_3 water in the western highlands to prevailingly Na–Cl water in the area east of Jafr.

The increase in NaCl is probably caused by dissolution in a poorly flushed aquifer and leakage through marls during long retention periods.

References. Abu-Ajamiieh (1967), Abumaizer (1996), ACSAD (1983), Boeckh et al. (1970), Downing et al. (1993), Droubi (1983), ESCWA (1999c), Faradzhev (1966), GITEC and HSI (1995), GTZ and NRA (1977), Hobler et al. (1991), Kattan (2002), Khouri and Agha (1979), Kozlov et al. (1966), Luijendijk and Bruggemann (2008), Medvedev (1966), Mikhailov (1966), Nativ et al. (1995), Oufland (1966a, b), Salameh and Khdier (1985), Ponikarov et al. (1967b), Protasevich and Maksimov (1966), Rosenthal (1987), Shatsky et al. (1969), UNDP (1970), United Nations (1982: 158 ff.), Wagner (1997), Wagner et al. (1982), Wolfart (1966).

3.5 Groundwater Age, Information from Isotope Data

3.5.1 *^{14}C and ^{3}H Data*

The semi-arid plateau areas in the east of the northern Arabian platform receive very limited present-day recharge. The general recharge conditions are reflected in the statistical distribution of ^{3}H and ^{14}C values of random samples of groundwater from the sub-region:

From a sample set of 131 tritium analyses, ^{3}H is:

Below detection level in 114 samples (87%)
1.5 TU in 5 samples (4%)
3–7 TU in 6 samples (4.6%)
Significant with 16 TU to maximum 65 TU in 10 samples (7.6%)

In a set of 111 samples, ^{14}C values are:

Lower than 5 pmc, indicating ages of 24,000–36,000 years BP, in 48 samples (43%)
In a range 5.3–30 pmc, corresponding to ages of 10,000–24,000 years, in 45 samples (40.5%)

31–53 pmc, corresponding to ages of 5,000–10,000 years, in 14 samples (12%)
More than 60 pmc considered recent with retention periods of less than 4,000 years in 5 samples (4.5%)

More than 80% of the samples appear to represent Pleistocene recharge at periods of more than 10,000 years BP.

^{3}H contents in most samples from the deeper as well as from the shallow aquifer of the Aleppo plateau are below detection level. The groundwater in the deeper Upper Cretaceous aquifer may be assumed to be fossil; the shallow aquifer probably contains groundwater from Pleistocene and Holocene recharge.

^{14}C of spring water from the Paleogene Ras el Ain aquifer of the Syrian Jezire (one sample) is 34 pmc corresponding to an age of 9,000 years BP, ^{3}H values of samples from the aquifer are below detection level. ^{14}C values of deeper confined groundwater from the Khabour area in the Jezire range from 5.6 to 6.9 pmc, water ages are calculated, after correction for dilution factors and sulfate reduction, as 6,700–12,000 years BP.

The majority of ^{14}C water ages of samples from the southern Syrian steppe and the Hamad ranges from >20,000 years up to 40,000 years. The water of these samples is free of detectable tritium. Younger groundwater with ^{14}C ages of a few thousand years and ^{3}H values of 14–60 TU was found in wadis where recent indirect recharge takes place. These renewable resources, which generally extend as lenses with moderate salinity of less than 1,000 mg/l TDS along major wadis, have been explored e.g. in Wadi al Miyah and Wadi Murabaa in southern Syria and Wadi Muqat in northeastern Jordan.

For most groundwaters in the Palmyrean fold zone, retention periods of 10,000 to >20,000 years are indicated from ^{14}C data.

For the steppe area covering the Palmyrean fold zone, the southern Syrian steppe and the Hamad, the following general pattern of groundwater salinity in relation to groundwater ages is indicated:

- Old groundwater in most of the plain areas is brackish with a total salinity of 1,100–5,000 mg/l TDS and generally high Cl and SO_4 concentrations.
- Old groundwater with moderate salinity (500–2,000 mg/l TDS) occurs in fissured and karstified Upper Cretaceous (Cenomanian–Turonian) limestones and dolomites in the anticlinal structures of the Palmyrean Mountains, e.g. at Qaryatein, Sawane, Hafne and Arak. Along the southern margin of the Ad Daw basin, groundwater with relatively low salinity and high age (900–1,400 mg/l TDS, 20,000–30,000 years) has been explored in Pleistocene deposits. It is assumed that the fresh water occurrences, which have a limited potential and are quickly depleted during exploitation, originate from subsurface inflow from the southern Palmyrean mountains.
- The salinity of young groundwater varies according to surface and recharge conditions: Fresh water lenses with a salinity of 500–1,000 mg/l TDS are created by indirect recharge with limited evaporative enrichment of Cl and SO_4. Recent recharge with elevated salinity occurs in areas with Pliocene lacustrine sediments, e.g. the Ad Daw basin, where young groundwater with a salinity of up to

4,700 mg/l TDS is found. The relatively high groundwater salinity in these areas is caused mainly by dissolution of evaporites on the surface and within the lacustrine sediments.

In some areas, in particular in the Hamad of southern Syria and northeastern Jordan, ^{14}C values may be significantly lowered by oxidation of fossil organic matter in the aquifer or adjoining aquitards, accompanied by SO_4 reduction. The occurrence of such secondary processes is indicated by high HCO_3 concentrations, smell of H_2S and often relatively low (negative) $\delta^{13}C$ values.

In groundwater samples from the Rijam aquifer of the lower reaches of the east Jordanian limestone plateau, ^3H values are generally below detection level, ^{14}C values are low corresponding to water ages of 20,000 to >40,000 years BP.

3.5.2 *Stable Isotopes of Oxygen and Hydrogen*

3.5.2.1 Precipitation

$\delta^{18}O$ and δ^2H values of precipitation samples from the eastern part of the northern Arabian platform scatter rather closely to the MMWL with mean d values of +16.5 to +19.5‰ (stations Aleppo, Palmyra, Azraq). The general distribution of the data with a wide variation of $\delta^{18}O$ values between −3.65 and −7‰ does not differ significantly from the data distribution of precipitation samples in the western highland zone, indicating a dominant influence of Mediterranean meteoric conditions (Fig. 3.11).

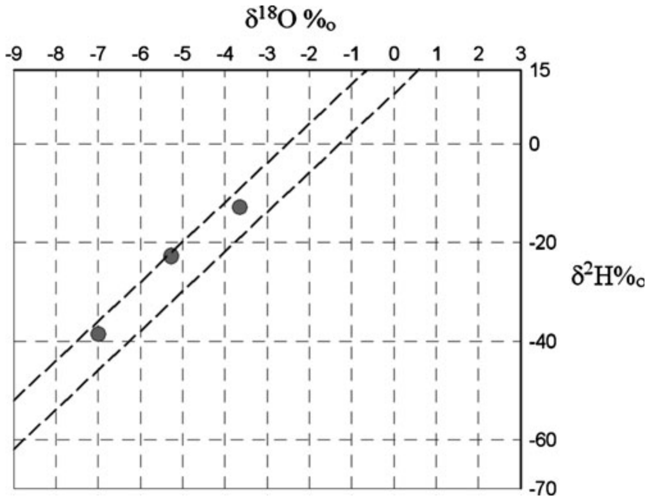

Fig. 3.11 $\delta^{18}O/\delta^2H$ diagram: Rain water samples from stations in the east of Syria and Jordan; stations Aleppo, Palmyra, Azraq. Data from Almomani (1996), Kattan (1996c)

3.5.2.2 Aleppo Plateau

In the Aleppo plateau and adjoining areas, the stable isotope composition shows:

- Significant differences between samples the from the deeper Upper Cretaceous aquifer and samples from the overlying shallow Paleogene aquifer
- Similarities between data of the deeper aquifer in the Aleppo plateau and the Upper Cretaceous aquifer of the Palmyrean mountain zone

$\delta^{18}O$ values of samples from the deeper aquifer of the Aleppo plateau are in a range of −7.5 to −8.5‰, scattering around a MWL with d around +13‰. The samples from the shallow aquifer have $\delta^{18}O$ values of −3.8 to −5.5‰ and d values of +9 to +2‰, showing a significant evaporative trend. Mixtures of the two water types may occur in uncased boreholes and in zones of groundwater leakage between the two aquifers.

The range of $\delta^{18}O$ and $\delta^{2}H$ values of groundwaters from the deeper aquifer of the Aleppo plateau corresponds to data ranges of groundwater samples in the Qalamoun area on the eastern slope of the Antilebanon mountains and from the Palmyrean mountain zone (Qaryatein, Sawane). It may be assumed, that the groundwater in the Upper Cretaceous aquifer on the Aleppo plateau as well as in the Palmyrean zone originates from recharge under a semi-arid climate corresponding to the present conditions on the eastern slope of the Antilebanon mountains. This climate was more humid than the present local climate, but apparently more continental than the present sub-humid climate in the mountains and highlands near the Mediterranean Sea.

The isotope data of groundwater in the upper aquifer system of the Aleppo plateau indicate a groundwater regime with low recharge under the present semi-arid to arid climate with a significant evaporative impact on the infiltrating water and relatively long retention periods (Fig. 3.12).

From the results of isotope hydrologic investigations, it can be concluded that:

- The deep aquifer in the Aleppo area is not recharged significantly through leakage of renewable groundwater in the shallow aquifer.
- The groundwater stored in the deep aquifer originates from distant recharge possibly in the northern Palmyrean mountains.
- The deep groundwater is fossil with an age of more than 10,000 years.

Isotope data from the upper aquifer (Paleogene to Neogene) indicate:

- Groundwater recharge during the Holocene with rising evaporative isotope enrichment with increasing aridity (d values below +10%).
- Limited components of actual recharge in the extracted groundwater (detectable tritium only in one of six samples).

The groundwater movement in the Upper Cretaceous carbonate aquifer of the Aleppo–Hama area is mainly directed toward the Orontes Valley (Al Ghab–Ar Rouj rift graben). The $\delta^{18}O$ values of around −6‰ of groundwater discharging in large springs of the Upper Cretaceous aquifer at the eastern border of Al Ghab

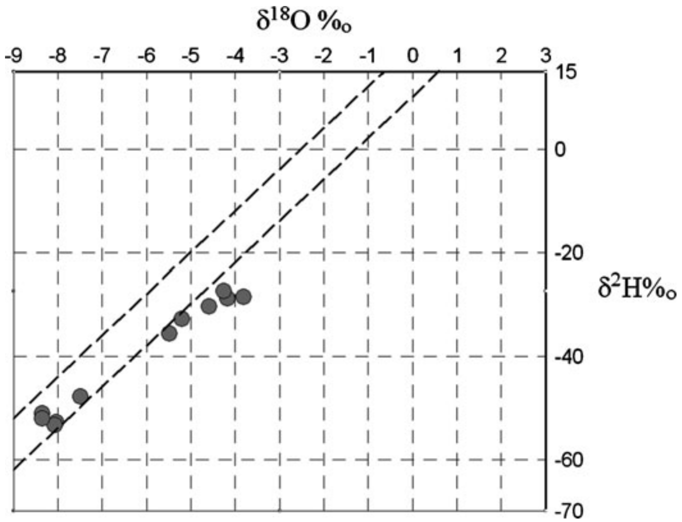

Fig. 3.12 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Aleppo plateau. Data from Wagner (1997), Wagner and Geyh (1999)

indicate, that the main proportion of the spring discharge originates from groundwater circulation sustained by present recharge in nearby aquifer outcrop areas and that the quantity of groundwater from the confined eastern parts of the catchment (^{18}O around −8‰) is comparatively very low.

3.5.2.3 Jezire

$\delta^{18}O$ values of fresh groundwater from the Ras el Ain aquifer on the northern rim of the Syrian Jezire are −6.4 to −6.7‰, d values vary between +14.4 and +15.9‰. $\delta^{18}O$ values of deeper confined groundwater in the Khabour area are significantly more negative, ranging from −7.2 to −8.2‰, corresponding d values lie between +15.5 and +20.3‰. As on the Aleppo plateau, the stable isotope values indicate recent groundwater recharge of the shallow fresh water and a Pleistocene origin for the deeper groundwater. Influences of evaporative isotope enrichment in the shallow groundwater appear less pronounced than on the Aleppo plateau.

The deeper confined groundwaters with $\delta^{18}O/\delta^{2}H$ ratios near the MMWL have corrected ^{14}C ages of more than 10,000 years and seem to be formed by direct infiltration of atmospheric precipitation with no or low evaporation. The groundwaters in the unconfined aquifer seem to originate from a mixture of rain water, snow melt and evaporated recycled water from irrigation in recharge zones between 700 and 950 m asl (Fig. 3.13).

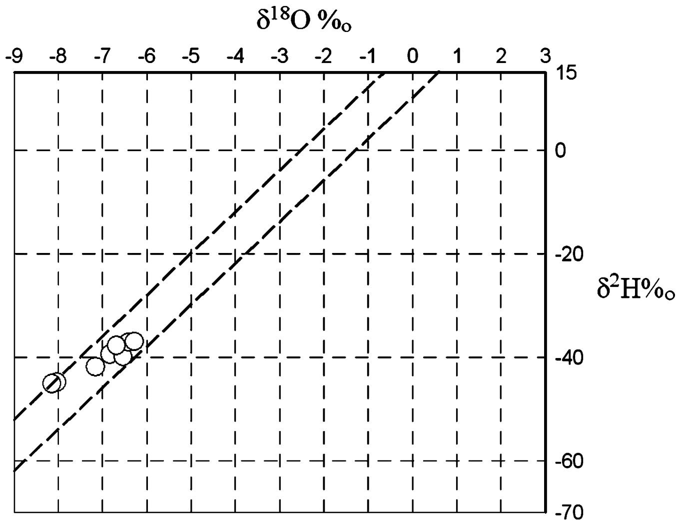

Fig. 3.13 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Syrian Jezire. Data from Kattan (2002)

3.5.2.4 Palmyrean Fold Belt

$\delta^{18}O/\delta^{2}H$ values of most groundwater samples from the Palmyrean fold belt scatter around a MWL with d +15‰ in a range of $\delta^{18}O$ between −6.9 and −8.9‰. The group of groundwaters with relatively uniform $\delta^{18}O/\delta^{2}H$ data comprises samples from the area between the Damascus plain and Qaryatein, from the southern Palmyrean mountains, the Ad Daw plain until Palmyra, and the eastern prolongations of the Palmyrean chains at Jebel Bishri. ^{14}C data of the group of samples vary from 1.1 to 26.9 pmc, indicating a wide range of retention periods from 10,000 to 34,000 years BP. ^{3}H values are, in general, below detection level.

The range of $\delta^{18}O$ and $\delta^{2}H$ values of these samples from the Palmyrean fold belt coincides approximately with average values of the Qalamoun area on the eastern flank of the Antilebanon mountains.

Exceptions from the general trend of $\delta^{18}O/\delta^{2}H$ data are found in a few samples, in which recent recharge is indicated from ^{3}H and ^{14}C data ($\delta^{18}O$ −5.88 to −6.03‰, ^{3}H 23–42 TU in 1980, ^{14}C 28.9–50.9 pmc) and an occurrence of fossil fresh water at Arak northeast of Palmyra ($\delta^{18}O$ −6.46 to −6.96‰, ^{14}C 1.5–4.8 pmc).

The variation of $\delta^{18}O$ values in the Palmyrean fold zone may reflect recharge at different altitude levels over a range of around 1,000 m (Fig. 3.14).

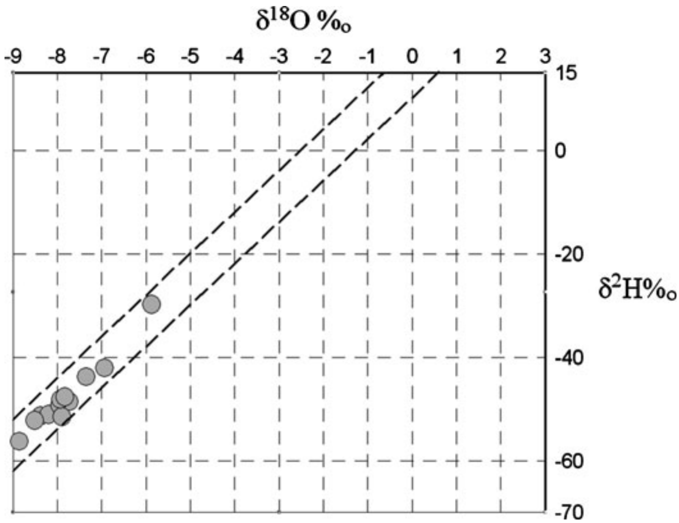

Fig. 3.14 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Palmyrean fold zone, Syria. Data from investigations of ACSAD–BGR (Wagner and Geyh 1999)

3.5.2.5 Badiye and Hamad

The tritium and stable isotope data from different aquifers in the Badiye and Hamad suggest a grouping into two main water types (Fig. 3.15).

- Fossil groundwater related to Pleistocene recharge with:

  ^{3}H: below detection level
  $\delta^{2}H$: −37 to −60‰
  $\delta^{18}O$: −6 to −9‰
  D = +6 to +18‰

- Groundwater with evident impact of recent recharge with:

  ^{3}H: 5.3 to 74 TU
  $\delta^{2}H$: −22 to −33‰
  $\delta^{18}O$: −4.7 to −6‰
  d = +8.8 to +17.3‰

The majority of samples apparently represents groundwater from Pleistocene recharge.

Apart from the mentioned two main water types, the aquifers, which comprise in some areas saturated sections of 100–200 m thickness, may contain groundwater of more complex origin (Figs. 3.16–3.17):

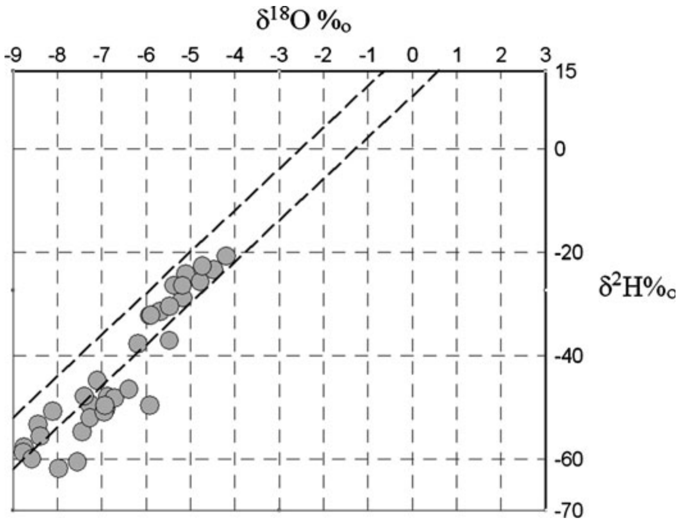

Fig. 3.15 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the southern Syrian steppe and Hamad. Data from investigations of ACSAD–BGR (Wagner and Geyh 1999)

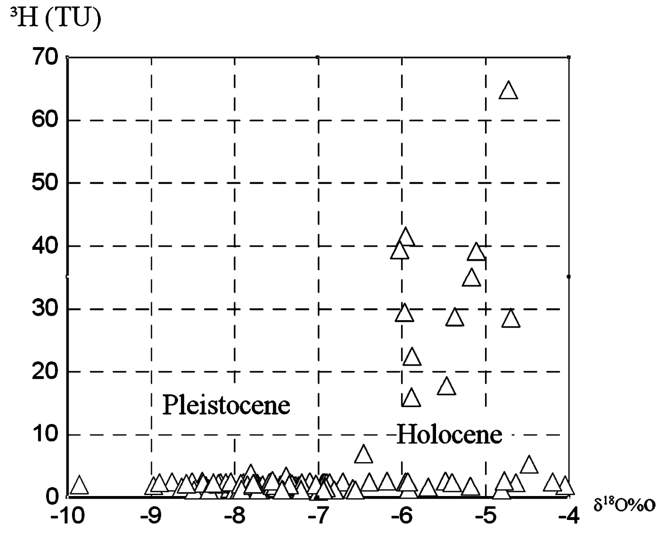

Fig. 3.16 $\delta^{18}O$ and ^{3}H values of groundwater samples from the southern Syrian steppe and Hamad. After Wagner and Geyh (1999)

- Groundwater from Holocene recharge but without or very little recharge during the past decades (^{3}H below detection level, $\delta^{2}H > -33‰$).
- Mixtures of Pleistocene and Holocene recharge with ^{3}H values between 18 and 35 TU and ^{14}C values between 22 and 36 pmc.

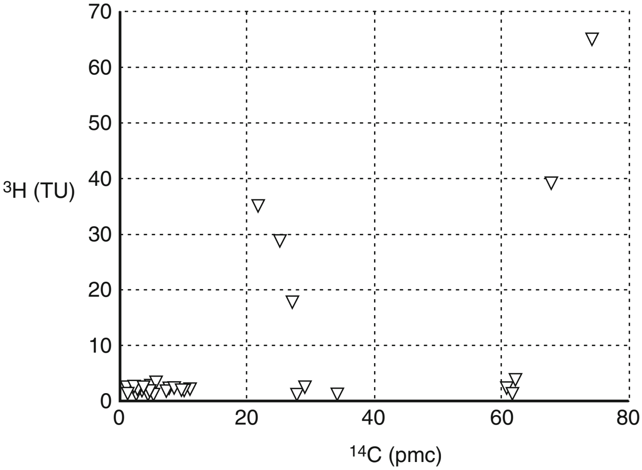

Fig. 3.17 $\delta^{18}O$ and ^{14}C values of groundwater samples from the southern Syrian steppe and Hamad. After Wagner and Geyh (1999)

Table 3.4 Ranges of $\delta^{18}O$ and d values in different areas of the eastern part of the northern Arabian platform

	^{18}O‰ range		d‰ range	
Aleppo plateau				
Upper aquifer	−3.8 to −5.5		+2 to +9	
Deeper aquifer (Upper Cretaceous)		−7.5 to −8.5		around +13
Jezire				
Paleogene aquifer	−6.4 to −6.7		+14.4 to +15.9	
Upper Cretaceous aquifer		−7.2 to −8.2		+15.5 to +20.3
Palmyrean fold belt				
General range		−6.9 to −8.9		around +15
Impact of recent recharge	−5.9 to −6.0		+17.3 to +15.7	
Southern Syrian steppe and Hamad				
General range		−6.9 to −9		+6 to +18
Impact of recent recharge	−4.7 to −6		+8.8 to +17.3	

3.5.2.6 East Jordanian Limestone Plateau

On the east Jordanian limestone plateau and on the northern edge of Wadi Sirhan, $\delta^{18}O$ values of the Paleogene–Neogene aquifer are in a range of generally −6.4 to −5.2‰ with d values between −1.6 and +15‰. With few exceptions, ^{3}H is below detection level, groundwater ages are generally high.

3.5.3 Pleistocene and Holocene Groundwater

The impact of paleo-recharge is particularly evident in the aquifers of the eastern part of the northern Arabian platform with its at present mainly arid climate conditions. The Pleistocene groundwater has more negative ^{18}O and ^{2}H values than the Holocene groundwater, but the range of deuterium excess values of Pleistocene and Holocene water is similar. We may conclude, that Pleistocene recharge took place in a cooler climate but precipitation during the Pleistocene had principally the same source as Holocene precipitation: storms originating over the eastern Mediterranean Sea (Table 3.4).

The Holocene groundwater, restricted mainly to the ranges of extensive wadi systems, comprises partly water recharged during the past few decades, but can also be several hundred or a few thousand years old. Samples collected from existing boreholes often represent water from various recharge events stored in the aquifer.

References. GITEC and HSI (1995), Kattan (1996b, 2002), Wagner (1997), Wagner and Geyh (1999).