Chapter 2
Northwestern Mountain and Rift Zone of the Northern Arabian Platform

2.1 Geographic and Hydrologic Features

The northwestern rim of the Arabian Plate is distinguished from most other parts of the plate by its morphology of elongated mountain chains and deep grabens and by its relatively humid climate, which is dominated by the meteorologic cycles above the adjoining eastern Mediterranean Sea. The mountainous sub-region extending parallel to the Mediterranean Sea coast constitutes, together with vast plateau areas in the east, the northern Arabian platform which occupies the northwestern sector of the Arabian Shelf.

In the west and north, the northern Arabian platform is delimited along boundaries of the Arabian Plate: the Mediterranean Sea coast and the zone of collision of the plate with the Alpidic chains of the Taurus mountains.

2.1.1 Morphology, Climate, Vegetation and Water Supply

2.1.1.1 Morphology

The morphology of the northern Arabian platform is dominated in its western part by chains of mountains and highlands with adjoining intermountain or coastal plains and, in the east, by vast plateau like landscapes. The morphology of the western mountainous part has been formed predominantly by Neogene–Quaternary tectonic events: uplift of the northwestern rim of the Arabian Plate and dissection by graben structures from rift movements. The uplift appears to be related to the northward movement and counter-clockwise rotation of the Arabian Plate. The zone along the northwestern rim of the Arabian Plate, which is characterized by a very pronounced morphological relief, is denominated in the following descriptions as "northwestern mountain and rift zone".

Two main mountain belts run roughly parallel to the Mediterranean Sea in south–north to SSW–NNE direction over the northwestern mountain and rift zone:

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- The coastal mountain chains of the Judean highlands, the Lebanon mountains and the Ansariye mountains
- The eastern mountain belt comprising the highlands of Jordan, the Hermon–Antilebanon mountains and Jebel ez Zaouiye

The two mountain belts are separated by a zone of approximately south–north oriented rift valleys: Wadi Araba as a continuation of the Red Sea graben, the Dead Sea, Jordan valley and Lake Tiberias depressions, the Bekaa valley and El Ghab, ending, in the north, in the Amiq depression and Kara Su valley on Turkish territory (Fig. 2.1).

The rift valleys have their lowest altitude at the Dead Sea shore with 200–460 m below sea level. The valley floor rises to 900 m asl in the Bekaa valley and descends

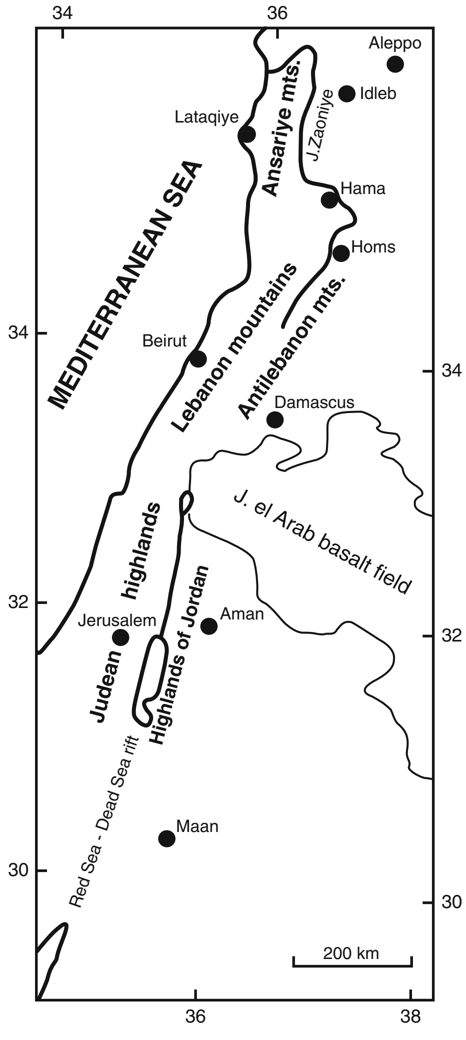

Fig. 2.1 Main orographic–geographic units of the northwestern mountain and rift zone

again to 170 m asl in El Ghab and 80 m in the Amiq depression. The Bekaa plain connects, as an around 10 km wide intermountain valley between Lebanon and Antilebanon mountains, the graben system of the Jordan valley in the south with the Masiaf–El Ghab graben structures in Syria in the north.

The coastal mountain belt is divided by relatively narrow morphologic depressions into four main mountain massifs. The belt comprises, from south to north:

- The Judean highlands, or mountains of Judea and Samaria, which reach their highest elevations in the area around Jerusalem with 800–1,000 m asl
- A zone of valleys between the Jordan river and the sea coast (<300 m asl) and the highlands of Galilea and of southern Lebanon (around 300–500 m asl)
- The Lebanon mountains with a maximum elevation of >3,000 m asl
- The Akar plain including the valley of southern Nahr el Kebir
- The Ansariye mountains rising to >1,500 m asl
- The valley of northern Nahr el Kebir
- The Basit mountains with the 1,700 m high Jebel el Akra

The eastern mountain belt comprises the highlands of Jordan and the Hermon–Antilebanon mountain chain. The mountain belt is adjoined or interrupted by a few superimposed young morphological depressions: the Yarmouk valley and the Damascus, Homs and Acharne plains. In the north, the belt ends in the moderately high Jebel ez Zaouiye and the Idleb plateau.

The *highlands of Jordan and the Judean highlands* rise from the Dead Sea–Jordan valley along steep escarpments with altitude differences of up to more than 1,000 m.

The highlands of Jordan accompany the Dead Sea–Jordan valley to the east in a stretch of 300 km, ranging from the deeply incised Yarmouk valley in the north to the Interior Shelf in southern Jordan. Viewed from the east, the highlands appear rather as a series of hills, to the west the highlands drop in a steep slope over more than 1,000 m down to the Jordan–Dead Sea valley. Topographic elevations of the highland peaks rise from 1,200 m asl in the north to 1,700 m asl at Jebel Mubarak in the south. The highlands are crossed by a number of east–west directed wadis which, as the Yarmouk river on the northern boundary, run in steep incisions and gorges down to the rift valley: wadis Zerqa, Walla, Mujib, al Hasa, which drain different hydrologic tributary basins of the Jordan–Dead Sea valley.

The Judean highlands appear on their eastern face as a reflected image of the highlands of Jordan: a mountain area rising in cliffs and steep slopes from the Jordan–Dead Sea valley at less than 200 m below sea level to altitudes of 800–1,000 m asl near Jerusalem. Toward west, the land surface descends in moderate slopes to the Mediterranean coastal plain. The morphology of the crest zone of the highlands appears as a flat dome, on which partly karstified Upper Cretaceous strata are exposed.

In the north, the highlands are separated from the Lebanon mountain chain by plain and hill areas (hills of Galilea and of southern Lebanon).

The geologic–morphologic structures of the Judean highlands and the highlands of Jordan continue toward north into the *Lebanon and Antilebanon* mountain ranges. Morphologically, the Lebanon and Antilebanon chains are separated from the highlands of Judea and Jordan by a zone of valleys between the Jordan river and the Mediterranean Sea coast and by the Yarmouk valley.

The Lebanon mountains culminate in Qornet as Saouda at 3,088 m asl. The southwest of the Lebanon mountains comprises an area with less pronounced morphologic relief with mountain peaks between around 500 and 983 m asl and a broad zone of hills, which extend toward the Mediterranean Sea in the west. The northwestern boundary of the Lebanon mountains is adjoined by a zone of hill and plain areas, delimited by the Mediterranean Sea coast in the west, the Ansariye mountains in the north, and large faults and flexures in the east, southeast and south. The eastern part of the hill zone is occupied by Neogene basalts of the Tell Kalakh volcanic massif, which extends over the Lebanese–Syrian border area with altitudes between 50 and about 600 m asl. The western part of the hill and plain zone, adjoining the Mediterranean Sea coast, comprises the Akar plain in the north, hills, fluvial and coastal plains around Tripoli, the Koura plateau, and the narrow Chekka coastal plain in the south.

The Antilebanon mountains extend over a length of 165 km from the Houle depression in the south to the Homs plain in the north. Peak altitudes reach 2,814 m asl in the Mount Hermon massif and 2,629 m asl at Talaat Mousa in the northwest of the Antilebanon mountains. The northern prolongation of the Dead Sea–Jordan rift graben structure is formed by the Bekaa valley, which separates the Lebanon and Antilebanon mountain chains. The altitudes of the Bekaa valley floor range from 500 to 1,000 m asl.

The uplift and rift structure of Lebanon mountains–Bekaa valley–Antilebanon mountains continues toward north into the *mountain and rift zone of northwestern Syria* where, however, peak altitudes are more moderate. The mountain and rift zone in northwestern Syria comprises the Ansariye mountains, the Ghab valley and Jebel ez Zaouiye. The Ansariye mountains, the northern section of the coastal mountain belt, extend over 120 km parallel to the coast. The highest peaks of the Ansariye mountains reach altitudes of 1,385 and 1,552 m asl. They are separated from the Lebanon mountains by the valley of Nahr el Kebir el Janoubi and the adjoining coastal plain of Akar. Coastal plains of a few kilometres width extend along the mountain foot in the north and south of the Ansariye mountains.

Topographic elevations range from 120 m asl in the Ghab valley to 500 m on the Homs plain and 870 m and 1,051 m at the peaks of Jebel ez Zaouiye and the Shin plateau, respectively.

2.1.1.2 Climate

The climate of the northwestern mountain and rift zone is dominated by the weather conditions over the eastern Mediterranean Sea. During summer, the position of the Inter-Tropical Convergence Zone over the Arabian and Sahara deserts creates stable hot and dry climate conditions (Sect. 1.4.3.1). During winter, the convergence zone with dry climate and high barometric pressure moves to the south, the Mediterranean area comes under the influence of moist air inflows from the Atlantic, and rain storms enter into the Mediterranean Sea basin from the west to northwest.

Precipitation is concentrated to the winter season between November and April. Even in the relatively humid western parts of the sub-region, a generally continuous dry season extends from May into October.

The morphology of the highland and mountain zone has a dominant influence on the climatic conditions. High precipitation occurs during the rainy winter season on the western slopes and the peak areas of the Lebanon mountains and of Mount Hermon with mean annual precipitation rates of $>1,000$ mm.

The Lebanon mountains are characterized by relatively high precipitation with an annual average of 1,170 mm and more than 1,500 mm in the high mountain area and bear a thick snow cover during the winter season.

Mean annual precipitation ranges

- From 600 to 1,000 mm on the eastern Lebanon mountain slopes
- From 500 to 800 mm on the Ansariye mountains
- From 700 to 1,000 mm on the coastal plains in Syria and Lebanon, decreasing to around 300 mm toward south in the Gaza Strip
- From 500 to 800 mm in the Judean highlands and the western slopes of the Jordanian highlands and of the Antilebanon–Jebel ez Zaouiye chains, reaching $>1,000$ mm on the high ranges of Mount Hermon

Rainfall is very low in some parts of the rift valleys, in particular in the Dead Sea valley and at the northern edge of the Bekaa. In most of the Jordan valley–Dead Sea–Wadi Araba depression, rainfall is low with an average of around 50 mm/a. Mean annual precipitation reaches 400 mm around Lake Tiberias on the northern end of the Jordan valley; in the Wadi Araba catchment mean annual precipitation ranges from 250 mm in the highlands in the northeast of the valley to less than 50 mm at Aqaba.

On the leeward eastern slope of the highlands and mountain zone, precipitation decreases rapidly to semi-arid or even arid conditions. Mean precipitation on the Damascus plain does not exceed 250 mm/a and the eastern city boundaries of Greater Damascus and Aman areas reach into the steppe and desert environment of Al Badiye.

2.1.1.3 Vegetation, Water Supply and Historic Developments

The vegetation of the coastal mountain belt and the coastal plains is mediterranean with evergreen shrubs. Forests with pines, oaks and cedars occur on the higher mountain areas. Rainfall sustains rain fed agriculture in many parts of the sub-region, prevailing crops being wheat, barley, grapes and fruit trees, in particular olive trees. Plantations of olive and fruit trees extend over wide areas of the western cultivated zones, poplars, eucalyptus and reed border stream banks. Supplementary winter irrigation and irrigation during summer is used prevailingly for cultivation of wheat, bareley, cotton and vegetables and, in some areas, of sugar cane and tobacco. Along the coast, also bananas and date palms are grown.

Irrigated areas are found in parts of the rift valley area – Jordan valley, Bekaa plain, El Ghab – and in the areas around Homs and Hama, Al Ghouta around Damascus, and the Zebedani valley in the Antilebanon mountains.

The morphologic relief created by the Neogene to Recent tectonic movements, the sub-humid Mediterranean climate with relatively reliable winter rains as well as the extensive outcrops of karstified carbonate formations make the northwestern mountain and rift zone to the area with the most abundant renewable groundwater resources of the Arabian Plate. The easy perennial access to groundwater in springs and shallow wells is certainly one of the reasons that urban and civilization centres have flourished since several thousand years in this area, which was situated between the Mesopotamian and Egyptian high cultures on the Euphrates–Tigris and Nile rivers.

Availability of water from winter rains and from rivers and springs with perennial flow favoured the agricultural and urban developments throughout the past millenia. Archeological and historical sources tell us that

- Settlements at Jericho date back to around 5000 BC
- The towns of Aleppo and Damascus exist continuously since 5,000 years
- Phenician towns flourished along the Mediterranean Sea coast during the second and first millennium BC
- The Israelites met, during their wanderings in the highlands of Jordan and Syria around 1200 BC, with established local kingdoms of Kanaan, Edom, Moab, Amon and Basan
- Around 1000 BC King David established his capital in the already existing town Jerusalem

The civilizations in the northwestern Arabian highlands were mainly local powers between the Mesopotamian and Egyptian empires and later mainly provincial units of the Hellenistic, Roman, Abassid and Ottoman empires. The Umayad Caliphate ruled the Islamic world from Damascus for 88 years.

The naturally available water resources in the northwestern mountain and rift zone were apparently, in general, adequate for the domestic and agricultural water demand of the population during the past millenia, although occasional drought years may certainly have caused temporary supply problems. The relationships between water sources, climatic cycles and development of civilisations is presented in the fascinating book "Water shall flow from the rock" (Issar 1990).

The water supply situation has changed dramatically during the last decades with the increase of population, urbanization and expansion of intensively irrigated agriculture. Recent water supply problems have been caused by the tremendous growth of the major cities. In Jordan, about 90% of the total present population of four million live in cities, towns and villages of the highlands. In spite of the relatively large water resources of the area, the high population density and a high growth rate create imminent problems of water supply. Damascus and the surrounding oasis Al Ghouta have received over millenia adequate water supply from the Barada and Aouaj rivers, which are fed by perennial karst springs. With a population exceeding four million, additional sources for the urban water supply have to be found.

Application of presently available techniques of well drilling and water pumping have lead to a tremendous increase of groundwater exploitation for irrigated agriculture in parts of the plain areas of the northwestern mountain and rift zone.

2.1.2 Main Hydrologic Basins and River Flow

Surface drainage on the northwestern mountain and rift zone is directed to the Mediterranean Sea and to the Dead Sea. The Aouaj and Barada rivers drain from the eastern slopes of the Antilebanon mountains into the closed basin of the Damascus plain (Figs. 2.2 and 2.3).

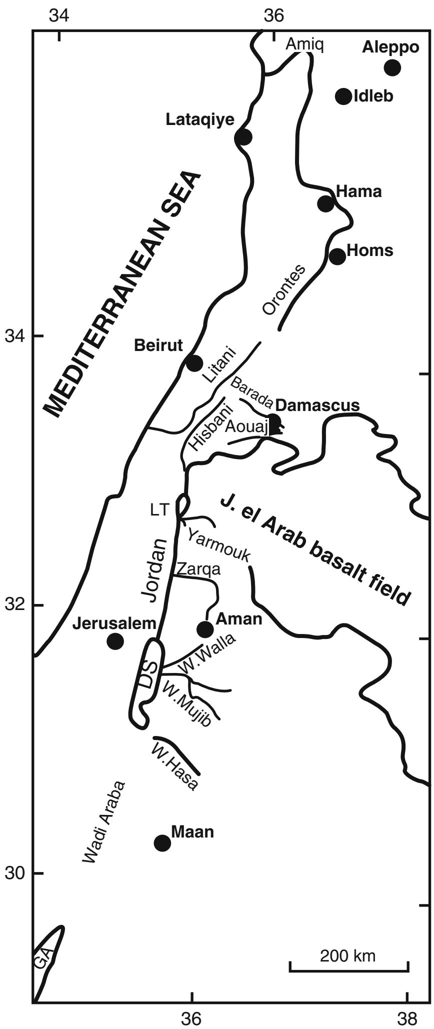

Fig. 2.2 Main rivers and wadis in the northwestern mountain and rift zone. GA Gulf of Aqaba, DS Dead Sea, LT Lake Tiberias

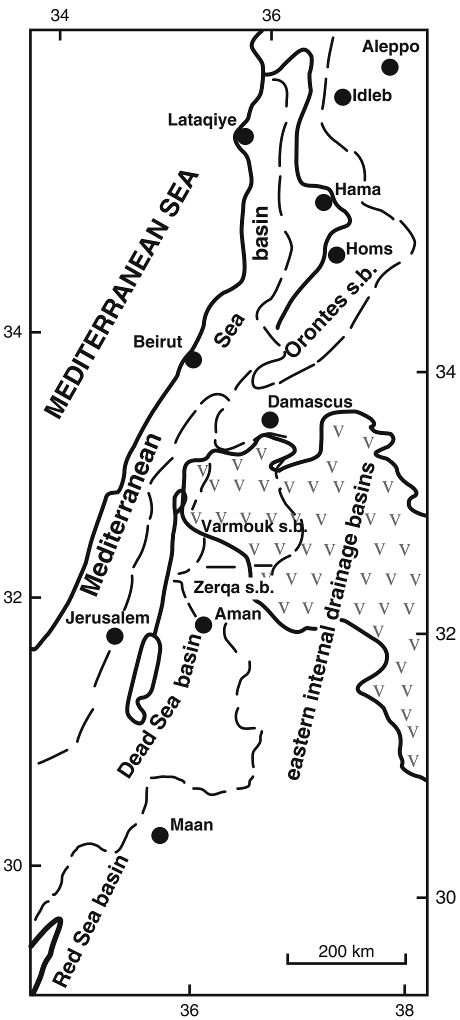

Fig. 2.3 Main hydrologic basins of the northwestern mountain and rift zone. The *Mediterranean* Sea basin with the *Orontes* sub-basin (the Litani sub-basin is not delineated) and the *Dead Sea* basin including the *Zerqa* and *Yarmouk* sub-basins are adjoined in the east by the zone of *interior drainage* of the eastern part of the northern Arabian platform and the *Red Sea* basin within the Interior Shelf

2.1.2.1 Mediterranean Sea basin

The Mediterranean Sea basin includes the sub-basins of the Orontes and Litani rivers and a dense network of coastal rivers and streams on the western slopes of the Lebanon and Ansariye mountains.

The *Orontes river* (Nahr el Aasi) begins in the northern Bekaa plain in Lebanon at Al Labwe spring near Baalbek at an elevation of 400 m asl. With a length of 487 km, the Orontes is the longest perennial river which originates on the Arabian

Plate. Streamflow of the Orontes is fed, to a large extent, by spring discharge on the foot of the mountain ranges adjoining the Orontes valley. A total mean discharge of 23–38 m^3/s from 54 springs is reported (Khouri 1991).

From the Bekaa plain, the Orontes river flows into the Homs plain at around 400 m asl and reaches, after a wide eastward curve between Homs and Hama, the Ghab valley at 120 m asl.

On Syrian territory, the Orontes river is regulated through several reservoirs, such as the reservoirs at Qatine near Homs, and at Rastan and Maharde; the largest reservoir at Rastan between Homs and Hama has a capacity of 228×10^6 m^3. River water is used intensively for irrigation, water supply and industry. Irrigation canals divert water from the Orontes river to extensive agricultural areas in the Homs–Hama area, the Acharne plain downstream of Hama and the Ghab valley.

The about 10 km wide Ghab valley, which extends for 50 km in south–north direction between the Ansariye mountains and Jebel az Zaouiye, has been converted through drainage measures and flood regulation of the Orontes river into a large irrigation area.

Mean stream flow of the Orontes increases from 16.1 m^3/s in the Bekaa valley to 75.5 m^3/s near the river mouth at the Mediterranena Sea.

A major tributary of the Orontes is the Aafrin river, joining the Orontes near the northern boundary of Syria.

The 170 km long *Litani river* runs from its headwaters near Baalbek in the Bekaa plain to the Mediterranean Sea coast in southern Lebanon. Flow is regulated by an irrigation and hydroelectric power dam in the Bekaa plain.

The western slopes of the *Lebanon mountains* are dissected by 11 perennial streams and additionally by about 18 wadi systems with seasonal flow. The streams and wadis are generally characterized by steep slopes and relatively short length of the stream courses. The length of the perennial streams ranges from 23 to 50 km, the size of the catchment areas from 90 to 390 km^2, mean annual stream flow from 0.6 to 15 m^3/s. Most of the stream flow during summer originates from groundwater discharge from Mesozoic carbonate aquifers.

The zone of hills and plains between the northwestern margin of the Lebanon mountains and the southern tip of the Ansariye mountains is crossed by a few larger streams: Nahr el Abrache with its headwaters in the Ansariye mountains, Nahr el Kebir el Janoubi, the catchment of which extends over the southern part of the Ansariye mountains and Jebel Akroum in the northern Lebanon mountains, Nahr Oustouene, Nahr Arka, Nahr Abou Mousa–el Bared and Nahr Abou Ali, which originate in the northern Lebanon mountains.

The rivers running toward the Mediterranean Sea on the western slopes of the *Ansariye mountains* are generally characterized by short stream length, steep slopes and deep canyons. Flow on most of these coastal rivers is restricted to the rainy season. Streamflow in Nahr el Kebir ash Shimali and Nahr el Kebir al Janoubi, which have relatively extensive catchments in the north and south of the Anasriye mountains, continues throughout the year.

2.1.2.2 Jordan–Dead Sea basin

The Dead Sea received, prior to installation of intensive irrigation schemes in the Jordan–Dead Sea valley, fresh water from the Jordan river and its tributary stream systems. The headwaters of the Jordan river are formed by the Dan, Banias and Hasbani rivers on the western slopes of Mount Hermon and the Golan heights. Downstream of the confluence of the headwater tributaries, situated at 90 m asl, the Jordan river crosses Lake Houle and Lake Tiberias. The lake and marsh area of Houle has, to a large extent, been drained through a canal system completed in 1958. South of the Houle area, the Jordan river reaches, after crossing a 12 km long gorge, an alluvial plain around Lake Tiberias, which is situated at 212 m below sea level and occupies about 165 km^2.

Quantity and quality of discharge from Lake Tiberias, which receives water from a number of saline springs, is controlled artificially by pumping and diversion of water into canal systems. The water released presently into the Jordan river from Lake Tiberias is brackish.

The Jordan river runs, after leaving Lake Tiberias, in meandering course through the lowlands of El Ghor to the northern end of the Dead Sea 105 km further south at 392 m below sea level.

The from a few kilometres to 20 km wide Jordan valley floor comprises El Ghor, gently sloping fans and terraces east and west of the Jordan river, and El Zor, the narrow flat stream bed of the meandering Jordan river.

Major tributaries of the Jordan river from the east are the Yarmouk river, which rises in the Syrian–Jordanian basalt plateau, and Zerqa river with its headwaters in the Aman area.

The Yarmouk river drains a large catchment area between Mount Hermon and Jebel el Arab in Syria and Jordan. The mean discharge of the Yarmouk into the Jordan river decreased from previously around 500×10^6 m^3/a to presently around 360×10^6 m^3/a, mainly because of increasing groundwater extraction in the catchment area.

The Zerqa river originates from the confluence at Soukhne of Wadi Dhuleil from the east and Sail ez Zerqa from south. The average annual discharge of the Zerqa river into the Jordan river was around 65×10^6 m^3/a and is now regulated through the King Talal dam.

The highlands of Jordan are crossed in general east–west direction by Wadi Mujib and Wadi Walla, which form deep gorges in part of their courses and reach the eastern boundary of the Dead Sea–Jordan valley.

The eastern slopes of the northern part of the Judean highlands are dissected by wadis, incised along tectonic structures, with courses toward the Jordan–Dead Sea valley. The wadis have relatively small catchments and generally steep slopes. In the Nablus–Jenin area, various shallow depressions, related to the Neogene tectonics, constitute closed basins with relatively small dimensions of up to 20 km^2.

The total discharge of the Jordan river into the Dead Sea declined from previous $1{,}370 \times 10^6$ to $250–300 \times 10^6$ m^3/a at present, after diversion of stream flow into large canal systems. The water level of the 85 km long and about 16 km wide Dead Sea is situated, at present, at around 400 m below the Mediteranean Sea level, the deepest point at the bottom of the Dead Sea is 730 m below sea level.

In the eleventh to sixteenth centuries, the water level of the Dead Sea was situated at 375 m below Mediterranean Sea level, and, at the beginning of the twentieth century, at 390 m below sea level.

The depth of the water reaches in the northern part of the Dead Sea more than 300 m. In the south, the Lisan peninsula narrows the width of the Dead Sea to 4 km, separating a southern sector of the sea with merely 5–10 m water depth from the northern Dead Sea basin. The water in the Dead Sea is a brine with a salt content of 340 g/kg.

Diversion of water from Lake Tiberias and the Jordan river has resulted in a drop of the sea water level of 0.5–0.8 m/a. The decrease of the sea water level is expected to continue until a new equilibrium in the water level is reached in about 400 years at 100–150 m below the present level.

Since the Neogene, the rift valley was occupied by a series of lakes with varying degrees of water salinity. The Lisan lake, the ultimate predecessor of the Dead Sea, attained a level of 180 m below sea level around 15,000 years B.P. The salinity of the Lisan lake was probably lower than the salinity of the present the Dead Sea.

South of the Dead Sea, the rift graben extends through the 174 km long Wadi Araba until the Gulf of Aqaba, the northern end of the Red Sea. The valley floor of the 8–25 km wide Wadi Araba rises from 400 m below sea level at the southern shore of the Dead Sea to about 250 m asl at the watershed about 100 km further south and then descends gradually to the Red Sea level.

The highland peaks east of Wadi Araba reach altitudes of around 1,500 m above the valley floor (1,200 m asl) near the south end of the Dead Sea and 1,592 m asl in Jebel Baqir in the south. Elevations of the highlands west of Wadi Araba are lower with altitudes of up to 900 m asl.

Several wadis with relatively small catchment areas between 160 and 500 km^2 enter Wadi Araba from the adjoining highlands in the east, such as Wadi al Hasa, Wadi Feifa, Wadi Fifan, Wadi Musa (Figs. 2.4 and 2.5).

References. Salameh (1996), Sunna (1995), Wolfart (1966), Yechieli et al. (2001).

2.2 Geology

2.2.1 Stratigraphic Sequence in the Mountain Areas

The sequence of sedimentary rocks of the northwestern mountain and rift zone comprises the following major stratigraphic complexes:

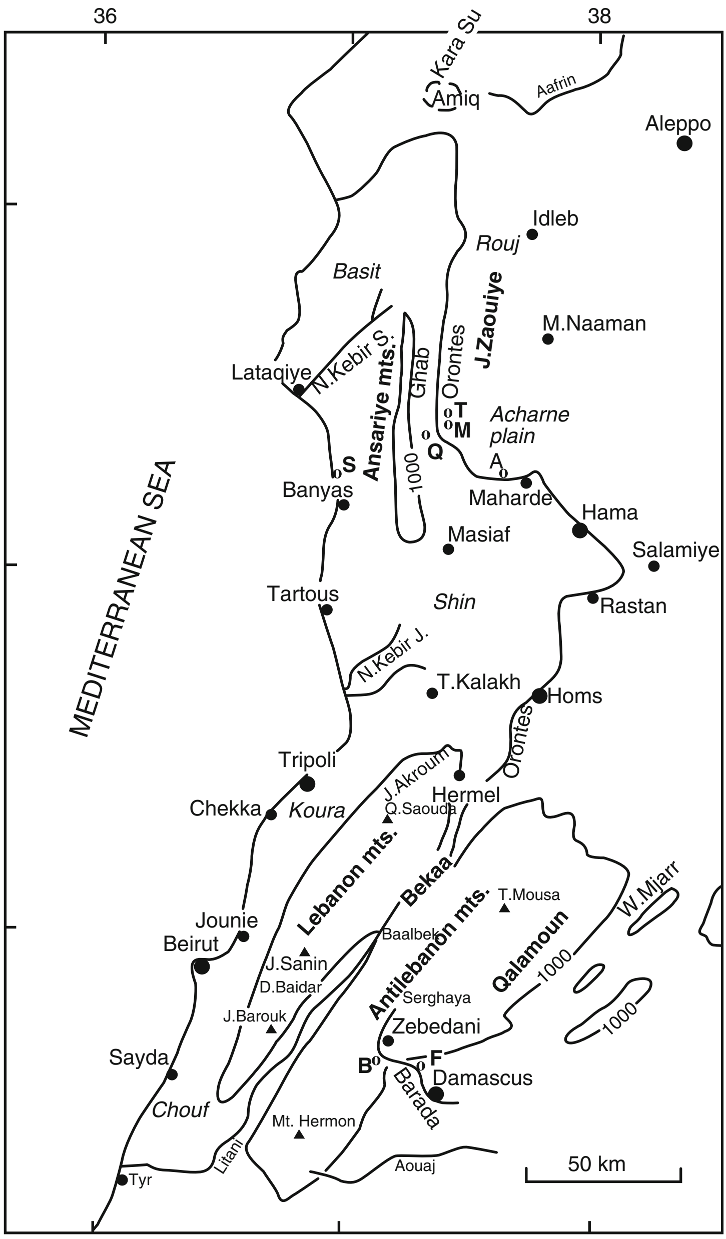

Fig. 2.4 Northwestern mountain and rift zone, location map, northern part. ___1000____ isoline 1,000 m altitude asl; o spring; A Tell Ayoun; F Ain el Fije; M Ain el Moudiq; S As Sinn; T Ain Taqa; Q Abou Qbeis

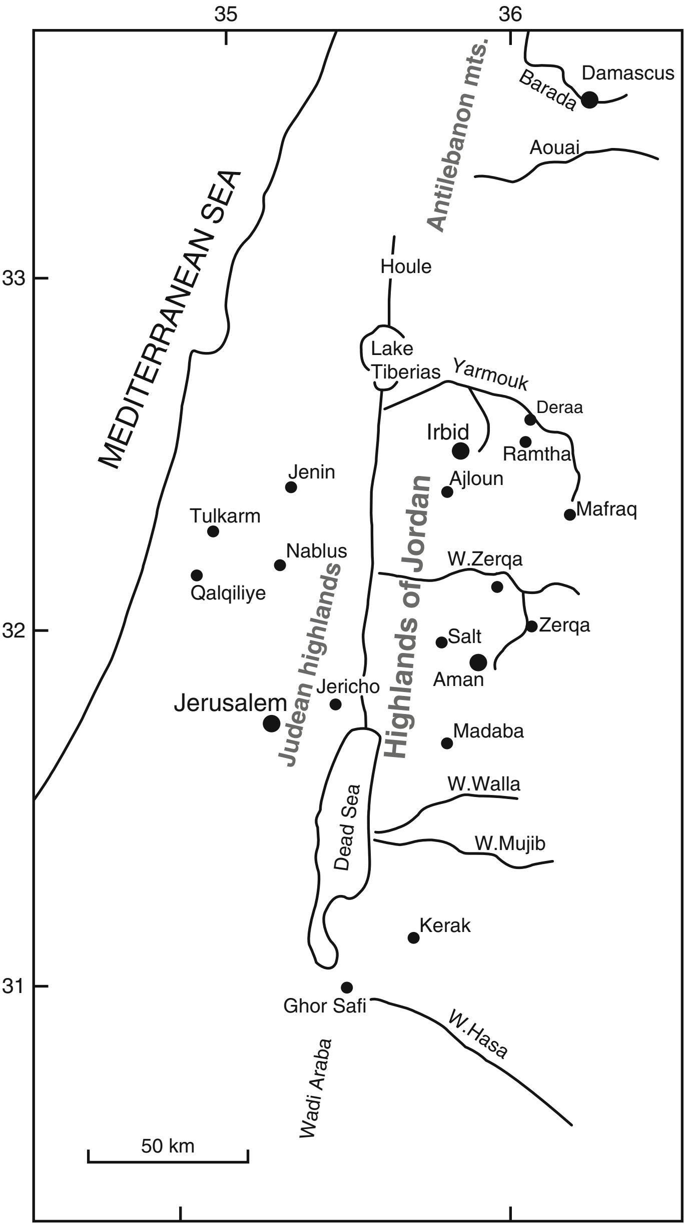

Fig. 2.5 Northwestern mountain and rift zone, location map, southern part

- Cambrian to Lower Cretaceous sandstone formations with shale intercalations
- Jurassic to Upper Cretaceous limestones and dolomites with intercalations of marls
- An Upper Cretaceous–Paleogene bituminous marl formation
- Paleogene limestones and chalks with marl and chert intercalations
- Neogene–Quaternary prevailingly terrestrial sediments in tectonic–morphologic depressions

2.2.1.1 Highlands of Jordan and Judea

The highlands of Jordan and Judea are covered prevailingly by Upper Cretaceous carbonate formations. Rock units of older stratigraphic age are exposed on the Interior Shelf in southern Jordan and in small areas in anticlinal structures and on the escarpments toward the Dead Sea. Paleozoic sandstones (Disi or Rum group) extend in the subsurface of the highlands of Jordan from the outcrop area in the south until the northern edge of the Dead Sea. In southern Jordan, terrestrial to coastal marine sandstone sedimentation continued from the Paleozoic up to the Lower Cretaceous. In the northern part of the highlands of Jordan and in the Judean highlands, Jurassic carbonate formations (Zerqa group in Jordan, Malih formation of the West Bank) indicate a marine ingression.

The Lower Cretaceous Kurnub group in Jordan and the Ramali formation on the West Bank comprise mainly terrestrial sandstones alternating with shale layers. In Palestine, marine marls and limestones related to an Aptian–Albian marine ingression are intercalated, toward west, in the upper part of the sandstone sequence. The Lower Cretaceous sandstones are followed by a thick carbonate complex of mainly Upper Cretaceous (Albian–Campanian) age. The complex, comprising the Ajloun group and the lower part of the Belqa group in Jordan and the Judea group on the West Bank, is built-up by limestones and dolomites with intercalations of marl, chalk and chert. The complex is sub-divided into a number of formations (Table 2.1), which are discussed according to their hydrogeologic properties in Sect. 2.3.3. The Maastrichtian to lower Paleogene is represented by marls, marly limestones and cherts with layers of oil shale (Muwaqar formation in Jordan, Mount Scopus formation of the West Bank). The Paleogene comprises chalk, limestones and marls of the Rijam and Shalala formations in Jordan and the Jenin or Avedat formation on the West Bank. The Maastrichtian–Paleogene deposits overlie the Upper Cretaceous carbonate complex mainly in synclinal structures around Irbid in northern Jordan and in the Nablus–Jenin area in Palestine.

2.2.1.2 Lebanon and Antilebanon Mountains

The stratigraphic sequence of formations outcropping in the Lebanon and Antilebanon mountains contains prevailingly rocks of Mesozoic age. The Upper Cretaceous in the Lebanon and Antilebanon mountains resembles the limestone–dolomite sequence in the highlands of Jordan and Judea. The Jurassic and Lower Cretaceous

Table 2.1 Stratigraphic sequence in the Judean highlands and the highlands of Jordan

		Judean highlands			Highlands of Jordan	
Quaternary						
Neogene						
Paleogene		Jenin (Avedat)		Chalk, limestone	Rijam (B4)	Chalky limestone
Upper Cretaceous	Maastrichtian	Abu Dis (Mt. Scopus)		Chalk, marl	Muwaqar (B3)	Chalky marl
	Campanian				Aman (B2)	Limestone, chert
	Santonian				Umm Ghudran (B1)	Marly limestone
	Coniacian				Wadi Sir (A7)	Limestone, dolomite
	Turonian	Judea group	Jerusalem	Limestone, dolomite	Shuayb (A5/6)	Marl, limestone
	Cenomanian		Bethlehem	Chalky limestone	Humar (A4)	Limestone, dolomite
			Hebron	Limestone	Fuheis (A3)	Marl, limestone
			Yatta	Marl, chalk	Naour (A1/2)	Limestone, dolomite
			Beit Kahil	Limestone, marl		
Lower Cretaceous		Ramali (Kurnub)		Sandstone	Kurnub	Sandstone, shale
Jurassic		Malih		Limestone, marl	Zarqa	Siltstone, sandstone
Triassic						
Paleozoic					Khreim	Siltstone, Sandstone, Mudstone
					Disi (Ram)	Sandstone

Simplified scheme after Haddad et al. (1996), Margane et al. (2002), Sunna (1995), Weinberger et al. (1994)

Table 2.2 Stratigraphic sequence of the Lebanon mountains. Simplified scheme after Khair et al. (1992), UNDP (1970)

Neogene			Marl, conglomerate, limestone
Paleogene			Chalky limestone
Upper Cretaceous	"Senonian"	Chekka marl	Chalky marl, chert
	Turonian	Maameltein limestone	Limestone, marl
	Cenomanian	Sanin limestone	Karstified limestone
Lower Cretaceous	Albian	Hamama marl	Marl, limestone
	Aptian	Mdarej limestone	Limestone, sandstone, volcanics
		Abeih	Argillaceous sandstone
	Neocomian–Barremian	Chouf sandstone	Sandstone
Jurassic	Portlandian	Salima limestone	Marl, limestone, shale
		Bikfaya limestone	Karstified limestone
	Kimmeridgian	Bhannes volcanic complex	Basalt, volcanic tuff, limestone
	Bajocian	Kesrouan limestone	Karstified dolomite, limestone

are represented mainly by thick marine carbonate complexes with intercalations of volcanic rocks in the Upper Jurassic and of detrital deposits in the Lower Cretaceous. The Lower to Middle Jurassic comprises limestones with dolomite beds with a thickness of 1,400 m in Mount Hermon and of around 700 m in the Lebanon mountains (Kesrouan limestone). The Upper Jurassic of the Lebanon mountains includes carbonate, detritic and volcanic formations. In the Antilebanon mountains, the Upper Jurassic consists of a several hundred metres thick succesion of prevailingly limestones and dolomitic limestones with marl intercalations.

Detritic deposits with limestone intercalations of the Lower Cretaceous are followed by a 400–1,000 m thick series of limestones and dolomites of Upper Cretaceous, mainly Cenomanian–Turonian age (Sanin limestone and Maameltein limestone in Lebanon). The top of the Cretaceous consists of a 400–600 m thick series of chalky marl and marly limestone with chert (Chekka marl in Lebanon) of "Senonian" (Maastrichtian–Paleocene) age, which corresponds to the Muwaqar and Mount Scopus formations in Jordan and Palestine. Paleogene chalks or nummulitic limestones occur in synclinal depressions in the Lebanon–Antilebanon zone (Table 2.2).

2.2.1.3 Northwestern Syria

The geologic formations of the Ansariye mountains comprise mainly Mesozoic carbonate formations:

- Jurassic limestones and dolomites with a thickness exceeding 800 m
- Lower Cretaceous (Aptian–Albian) marls and marly limestones, 150 m
- Upper Cretaceous (Cenomanian–Turonian) limestones and dolomites, 350 m
- Maastrichtian marls

Eocene nummulitic limestones occur in some areas on the slopes of the Ansariye mountains.

In the northwest and in the coastal area, the Jurassic to Turonian sequence is covered by formations of Maastrichtian to Quaternary age:

- Maastrichtian marls
- Eocene nummulitic limestone, up to 150 m
- Miocene–Pliocene marly limestones and basalt
- Quaternary limestones and conglomerates

Outcrops in Jebel ez Zaouiye include Cenomanian–Turonian limestones and dolomites, marls of late Cretaceous age in very reduced thickness, and Eocene nummulitic limestones.

2.2.1.4 Neogene–Quaternary Deposits

Neogene–Quaternary deposits extend over tectonic–morphologic depressions within or adjoining the Antilebanon mountains: the Damascus plain and the Qalamoun area on the eastern margin of the Antilebanon mountains, and intermountain basins, e.g. the Zebedani valley.

2.2.2 Geologic Structure of the Mountain Massifs

The mountain massifs of the northwestern mountain and rift zone are formed generally by asymetric horst–anticlinal structures with steep fractured flanks toward the rift valleys and more gentle slopes toward the Mediterranean Sea coast and to the eastern part of the northern Arabian platform (Fig. 2.6).

2.2.2.1 Highlands of Judea and Jordan

The mountain area of the Judean highlands shows, as a main structural element, a NNE trending anticlinal dome, the Judean anticlinorium, which was uplifted during the Pliocene. The uplift structure is from 40 to 50 km wide and about 130 km long, and is separated from the Dead Sea depression by the Dead Sea graben fault. North–south to northeast–southwest running faults and flexures accompany the eastern slope of the anticline in a multi-step vertical displacement of, in total, several kilometres. The general anticlinal structure of the Judean highlands is differentiated into tectonic units of local extent by SSW–NNE trending elements – flexures, anticlines, synclines – and, in particular in the northern part of the highlands, by southeast–northwest trending faults.

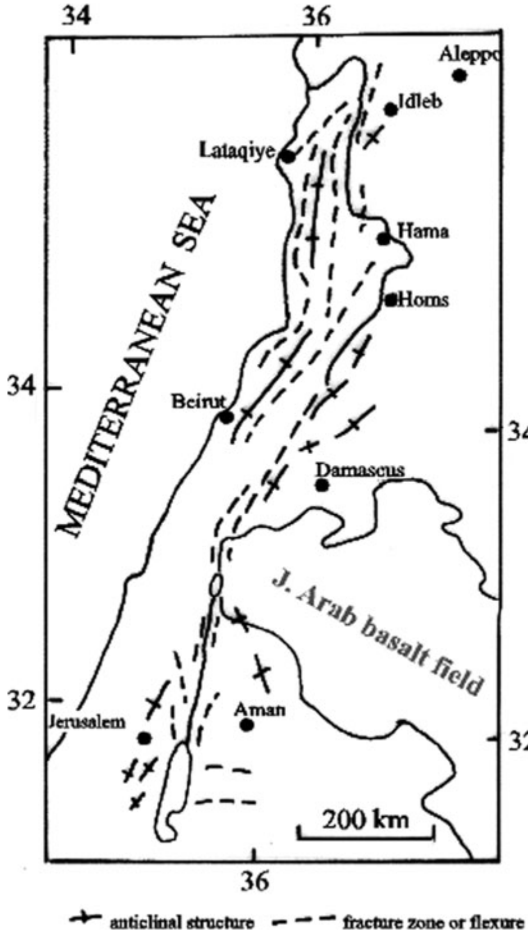

Fig. 2.6 Main geologic structures of the northwestern mountain and rift zone. After Wolfart (1966), Ponikarov et al. (1967a), Lenz (1969), Wiesemann (1969)

Major structural units are:

- A southern SSW–NNE trending anticline, the Hebron anticline, extending over the highland uplift west of the Dead Sea depression
- The Ramalla anticline, which comprises the central part of the highlands and is separated from the Hebron anticline by an east–west shift in the Jerusalem area
- The Fara and Anaba anticlines in the north, surrounding the Nablus syncline on the northwestern slope of the highlands

Main tectonic activities, which formed the structure of the highlands, occurred during the Tertiary until the Pleistocene (Lenz 1969).

The geologic structure of the highlands of Jordan is dominated by the appproximately north–south trending rift fault zone and anticlinal uplifts accompanying the rift zone in the east. The crest of the anticlines runs near the western escarpment of the highlands more or less parallel to the rift graben. Along the anticlinal structures, the limestones and dolomites of the Upper Cretaceous Humar and Aman–Wadi Sir formations are exposed in extensive outcrops. Major uplift structures (Ajloun dome north of the Zerqa river, structural highs at Baqa, Salt and Naour) form the highland crests from northwest to southwest of Aman (Margane et al. 2002: 8). The dip of the strata is generally directed from the centres of the anticlines toward the Dead Sea–Jordan valley in the west, the Yarmouk river in the north and the Jordanian limestone plateau in the east.

The highlands are crossed by several latitudinal, northeast to southeast trending fault systems (Wadi Kerak–Wadi Fayla fracture, the Wadi Zerqa Main–Siwaqa fault, Aman flexure, Wiesemann 1969).

2.2.2.2 Lebanon Mountains

The Lebanon mountains constitute a large anticlinal uplift running in SSW–NNE direction approximately parallel to the Mediterranean Sea coast and comprise, in their central and northern parts, the most intensively uplifted sections of the eastern Mediterranean coastal mountain ranges. Extensive outcrops of Jurassic–Cretaceous carbonate formations occupy the anticlinal crest of the range.

In the west, the mountain slopes rise directly from the Mediterranean Sea coast or from relatively narrow coastal plains. In the east, the anticlinal structure of the Lebanon range is cut off by the sub-regional Yamoune fault system, which extends from Lake Tiberias through Lebanon into northwestern Syria.

The general structure of the Lebanon mountains is sub-divided into three major tectonic–morphologic zones:

- The central and northern mountain area north of Dahr el Beidar with a broad anticlinal zone of high mountains.
- The southern high mountain area of Jabal Barouk centered around a relatively narrow anticlinal uplift, adjoined in the west by the Chouf area with hills and low mountains.
- The hill area of southwestern Lebanon.

The central and northern parts of the Lebanon mountains – north of Beirut and of the main mountain pass Dahr el Baidar – comprise large generally SSW–NNE trending structures with extensive outcrops of Upper Cretaceous and Jurassic carbonate rocks.

In the anticlinal zone of the northern high Lebanon mountain area, Jurassic and Upper Cretaceous karstified carbonate formations are exposed over around 700 km^2. That northern mountain zone includes the highest peaks of the Lebanon chains (Qornet as Saouda, 3,083 m asl).

The central Lebanon mountains are formed by a large about 36 km long SSW–NNE trending anticlinal structure, which is covered by Jurassic and Upper Cretaceous limestone and dolomite formations. The crest zone near the main

Lebanon water divide includes several mountain peaks at around 2,000 m asl and culminates in Jebel Sanin east of Beirut at 2,548 m asl.

The high mountain area of the southern part of the Lebanon mountains south of Dahr el Baidar comprises a 50 km long NNE–SSW trending anticlinal structure with a narrow, 3–6 km wide outcrop belt of Jurassic limestones and dolomites at the anticlinal crest. Altitudes of mountain peaks descend from >1,800 m asl in the north (Jabal Barouk 1,950 m) to 1,200 m asl further south.

An 8–16 km wide outcrop belt of Upper Cretaceous carbonate rocks extends over the eastern slope of the central and northern Lebanon mountains between the mountain peak region and the Bekaa valley boundary. A major structural feature on the eastern mountain slope is the SSW–NNE Yamoune fault, which separates a steep narrow strip of high mountain area from mountain slopes with less pronounced relief east of the fault. The eastern slope of the southern Lebanon mountains consists prevailingly of a narrow, 2–4 km wide strip of outcropping Jurassic carbonate rocks, which is delimited by the Yamoune fault from the Bekaa valley.

In the southern Lebanon mountain zone, two faults branch out from the Yamoune fault system in northwest and northeast direction, respectively: the Ram fault crossing the Lebanon mountains toward the Mediterranean Sea coast and the Hasbaya fault extending from the Bekaa plain into the Hermon–Antilebanon massif.

2.2.2.3 Antilebanon Mountains

The structure of the Antilebanon mountains is dominated by major SSW–NNE directed anticlines with outcrops of Mesozoic formations, the flanks of which dip under Paleogene–Neogene depressions: the Bekaa graben in the west, the Damascus plain and Qalamoun depression in the east. The anticlinal Mount Hermon–Antilebanon chain constitutes the northern prolongation of the uplift structure of the highlands of Jordan on the eastern rift boundary.

The Antilebanon mountains are crossed by major S–N to SSW–NNE directed faults in continuation of the Dead Sea–Jordan fault system (faults of Rachaya, Hasbaya and Serghaya). Along these fault systems, several intermountain basins subsided between the mountain chains, such as the Zebedani basin and the Bekaa plain. The Hasbaya fault delimits the Bekaa valley on the western foot of Mount Hermon, the NNE directed Rachaya fault crosses the western slope of Mount Hermon. The Serghaya fault runs from the eastern slope of Mount Hermon obliquely through the Antilebanon mountains and borders the intermountain basins of Zebedani and Serghaya.

The Barada valley separates the mountain chain into the Mount Hermon or Jebel esh Sheikh massif in the south and the Antilebanon mountains proper in the north. Mount Hermon is formed by a NNE trending anticlinal dome structure with wide outcrops of Jurassic deposits. Cretaceous–Paleogene formations cover the western and eastern foothills of the massif. In the northeast of Mount Hermon, the Jurassic outcrops are adjoined by Neogene conglomerates along a fault with a throw of around 3,000 m.

The Antilebanon mountains north of the Barada valley comprise mainly SSW–NNE directed anticlinal structures with prevailing outcrops of Upper Cretaceous formations. The Jurassic outcrops of the Mount Hermon dome continue into a narrow belt of horst structures near Zebedani–Serghaya.

The Antilebanon mountains are bounded, in the west, by the Bekaa valley, in the east by the volcanic plateaus of Golan and Hauran and by the Damascus plain. In the northeast, the Antilebanon mountains are separated from the SW–NE to WSW–ENE trending Palmyrean chains by the synclinal structure of Qalamoun.

2.2.2.4 Northwestern Syria

The Ansariye mountains constitute an asymetric horst–anticline with the core of the uplift running near the eastern rim of the mountain chain. Jurassic and Cretaceous formations are exposed in the core of the anticline, while Paleogene and Neogene deposits cover most of the western part of the mountains, which descends in a gentle slope toward the Mediterranean Sea coast. To the east, the mountains are bordered by steep cliffs along the rift graben border.

The meridional "Syrian–Lebanon fault" (Ponikarov et al. 1967a), which represents the northern prolongation of the Yamoune fault, marks the eastern boundary of the Ansariye mountains. The fault separates the southern section of the Ansariye mountain area from the Masiaf plateau along a rectilinear scarp with a vertical displacement of more than 500 m. Toward north, the fault splits into two branches, which accompany the Ghab rift graben in the west and east. The vertical displacement reaches around 1,200 m along the western branch of the fault, and 600 m along the eastern branch.

In the north, the Ansariye mountains dip under the narrow Nahr el Kebir plain, which is covered by Paleogene–Miocene formations and separates the Ansariye mountains from the allochthonous ophiolite massif of Al Basit.

East of the Ghab valley, the anticlinal uplift of Jebel az Zaouiye reaches moderate altitudes of up to 870 m asl. Near the northern boundary of Syria, the rift graben diverges into the Orontes valley and, east of the valley, into the depression of the Rouj lake. Further north, the faults disappear under Pliocene sediments in the Amiq lake depression. The western rim of Jebel ez Zaouiye forms a steep cliff, which is cut by a system of faults and flexures, while its eastern slope dips from the anticlinal crest, situated close to the rift boundary, gently to the east.

At the northern tip of Jebel Ansariye, the coastal belt of anticlinal uplifts of Mesozoic formations ends at the highly disturbed margin of the northern Arabian platform. The boundary is marked morphologically by the Nahr el Kabir esh Shimali and Aafrine valleys, which delimit the platform area covered by Mesozoic–Tertiary sedimentary formations from the allochthonous ophiolite massif of Al Basit.

East of the rift graben, a southwest–northeast trending fault system (Aafrine–Kilis fault) separates the Arabian Platform from a zone, which has been intensively disturbed during the Mesozoic–Tertiary by tectonic movements on the margin of the alpidic mountain chains and is covered by allochthonous blocks and molasse sediments in the foreland of the Taurus mountains. Movement along the fault during the Neogene–Quaternary was accompanied by volcanic flows.

2.2.3 Geologic Set-Up of the Rift Valleys

2.2.3.1 Jordan–Dead Sea–Wadi Araba Rift Valley

The Jordan–Dead Sea–Wadi Araba graben cuts in approximately north–south direction as a deep morphologic–tectonic depression through the northern Arabian platform and adjoining areas of the Interior Shelf, separating the highlands of Jordan from the Judean highlands.

During the Mesozoic and until the Eocene, the geologic development of the present Jordan–Dead Sea–Wadi Araba zone corresponded to the events on the adjoining shelf areas of the Arabian Plate. Taphrogenic movements began along an old geosuture in the Oligocene. The movements resulted in the uplift of areas adjoining the graben and in sedimentation of great masses of clastic deposits in the graben zone. Marine influence and fresh water lakes alternate in the graben furrow during the Oligocene to Miocene. A marine connection between the Gulf of Aqaba and the Mediterranean Sea may have existed during the late Miocene–early Pliocene. The subsidence of the graben continued until the Holocene, accompanied by basaltic volcanism in particular during the Peistocene.

The Jordan valley contains a cover of Miocene–Quaternary detrital and lacustrine sediments, the Jordan valley group, above Mesozoic formations.

The sediments of the Jordan valley group comprise:

- Conglomerates of the Al Beida formation (Miocene–Pliocene)
- Clayey deposits of the Lisan formation (Pleistocene–Quaternary)
- Alluvial fans and stream deposits: mainly poorly sorted sandy gravels with silt, clay and boulder intercalations (Pleistocene–Quaternary)

The total thickness of the Jordan valley group sediments reaches 300–400 m near the Dead Sea.

The sediments of the Al Beida formation, the lower part of the Jordan valley group, are composed mainly of coarse detrital, generally cemented deposits. The formation is overlain by a sequence of alternating clays, marls, sand and gravel: the lacustrine Lisan formation and detrital fan deposits.

The mainly Pleistocene Lisan formation, the marl facies of the upper Jordan valley group, is composed of thinly laminated marl, clay, gypsum beds and nodules of sulfur. The formation represents lacustrine deposits of the Lisan lake which occupied, as an ancestor of the Dead Sea, wide parts of the Jordan–Dead Sea valley during the upper Miocene–Pleistocene.

Pleistocene–Quaternary fluviatile deposits form gravel fans, which spread out from the mouths of tributary wadis into the valley floor, where the fan deposits are interfingering with the lacustrine Lisan marls.

Gravel fans of larger extent adjoin the entrances of Wadi Qilt and Wadi Muhallish on the western boundary of the Jordan valley and are found, on the eastern flank, at the confluence of the Yarmouk and Zerqa rivers and of Wadi al Arab with the Jordan valley.

Mesozoic formations occur, within the valley, below the Jordan valley group sediments, in outcrops on the mountain escarpments of the Jordan valley, and insome areas of the valley. The Mesozoic of the Jordan valley corresponds to the sequences of the Upper Cretaceous Ajloun–Belqa groups and Kurnub and Zerqa groups of Lower Cretaceous and Jurassic age in the adjoining highlands (Table 2.1).

The eastern shores and part of the western shores of the Dead Sea are flanked by narrow plains, which, on their outer margins, are bounded by the escarpments of the highlands of Jordan and Judea and geologically by major flexures and fault zones.

The plains are covered mainly by alluvial deposits, which overlie a tectonically disturbed sequence of Precambrian–Lower Cretaceous sandstones, Upper Cretaceous carbonate rocks and Tertiary deposits. Gravel fans of Pleistocene–Quaternary age mark the entrance of the larger tributary wadis from the Jordanian highlands into the Dead Sea valley, e.g. Wadi Walla and Wadi Mujib.

The 174 km long Wadi Araba between the Dead Sea and the Gulf of Aqaba is bordered in the east by a narrow spur of Precambrian rocks of the Arabian Shield and of Paleozoic–Cretaceous sandstone formations of the Interior Shelf. The margins of the NNE trending Wadi Araba graben are demarcated by a complex pattern of NW to NNE trending margin faults.

The highlands east of Wadi Araba and the graben zone itself comprise a sequence of Precambrian to Quaternary formations:

- Precambrian crystalline rocks
- Precambrian–Cambrian quartz porphyry, porphyrite and ignimbrite
- Cambrian, Ordovician and Lower Cretaceous prevailingly sandy sedimentary rocks with minor marine dolomite–limestone–shale intercalations
- Upper Cretaceous–Paleogene carbonate rocks
- Oligocene–Miocene predominantly clastic deposits
- Quaternary terrestrial and lacustrine sediments in the graben
- Pleistocene basalts

The tectonic Wadi Araba depression is filled with marine, lacustrine and fluviatile Neogene of about 2,000 m thickness. Lacustrine sediments of the Lisan lake – Lisan formation – extend over the northern part of Wadi Araba until about 80 km south of the present Dead Sea shore with a thickness of up to 800 m. The Lisan formation is composed of shale, marl with gypsum and sulfur inclusions. Coarse clastics and sands are intercalated on the graben margins. Quaternary wadi sediments, comprising sand, marl and clay, are found in the gorges and valleys in the highlands east of Wadi Araba and in extensive alluvial fans at the mouth of wadis on the margins of the valley. Mud flat deposits and aeolian sand dunes cover part of the central rift valley. The total thickness of Holocene sediments reaches up to 150 m.

2.2.3.2 Bekaa and Midle Orontes Area

The boundary of the SSW–NNE trending Bekaa depression is, along some stretches, demarcated by major faults: the Yamoune fault on the southern part of the western flank of the valley, the Rachaya and Serghaya faults along the eastern mountain foothills. Outcrops in the Bekaa valley comprise:

- Upper Cretaceous (mainly Cenomanian) limestones and dolomites
- Neogene lacustrine deposits and conglomerates
- Alluvial deposits

The southern part of the Bekaa graben comprises along its axis a synclinal structure, which is filled by continental Neogene to Quaternary deposits of several hundred metres thickness. On the southern flank of the syncline, Upper Cretaceous and Paleogene deposits appear on the surface of the Bekaa valley. The flat valley floor changes into a landscape with more accentuated relief, into which the Litani river is incised in gorges until it changes its course toward west and crosses the southern tip of the Lebanon mountain massif in direction to the Mediterranean Sea coast. The graben structure of the Bekaa valley merges in the north into the Homs plain and in the south into the morphologic depression of Houle.

In the middle Orontes area, the Lebanon–Syrian fault system separates the Antilebanon mountains in northwestern Syria from a mosaic of different geologic–morphologic structures:

- Shin basalt plateau
- Homs and Selemiye plains
- Masiaf and Hama plateaus
- Acharne plain and Ghab valley
- Jebel ez Zaouiye
- Idleb plateau

These units constitute, together with the eastern slope of the Ansariye mountains, the middle section of the Orontes river catchment.

The eastern border of the rift graben is accompanied in the middle Orontes basin by moderate tectonic uplifts, the "monoclinal horst anticlines" (Ponikarov et al. 1967a: 190) of the Masiaf hills and Jebel ez Zaouiye. Toward east, the uplifted zones descend to the plateaus of the eastern part of the northern Arabian platform. On the Masiaf hills, the strata dip toward east grading into the nearly horizontal structure of the Hama plateau.

Tectonic depressions of the rift graben system, the Acharne plain and the Ghab valley, separate Jebel ez Zaouiye from the Masiaf plateau and from the Ansariye mountains. The Shin basalt plateau hides the transition from the Lebanon mountains to the Masiaf plateau.

The Homs plain constitutes a shallow depression at the northern margin of the Bekaa plain.

The Idleb plateau north of Jebel ez Zaouiye forms a zone of low hills between the Rouj branch of the rift graben and the Aleppo plateau in the east. The present Idleb plateau constituted, during the Paleogene to Miocene the southern rim of the Aafrin depression, a foredeep of the alpidic Taurus mountains.

The following *stratigraphic units* are exposed in the various tectonic depression zones of the middle Orontes basin:

- Cenomanian–Turonian limestones and dolomites
- Campanian chalks, limestones and marls
- Maastrichtian marls with chert and limestone layers
- Pliocene–Quaternary lacustrine and alluvial deposits in the rift depressions of the Ghab valley and the Acharne plain

Paleogene and Miocene carbonate rocks extend over the Idleb plateau.

References. Al Ejel and Abderahim (1974), Batayneh (2006), Bender (1974a, 1982), Dubertret (1955), Haddad et al. (1996), Khair et al. (1992), Lenz (1969), Margane et al. (2002), Ponikarov et al. (1967a), Salameh and Shaqur (1981), Salameh and Udluft (1985), Shahab (1997), Sunna (1995), UNDP (1970), Weinberger et al. (1994), Wiesemann (1969), Wolfart (1966).

2.3 Main Aquifers

2.3.1 Stratigraphic Distribution of Main Aquifers

The most important aquifers of the northwestern mountain and rift zone are constituted by Jurassic and Upper Cretaceous limestone and dolomite formations. These Mesozoic carbonate aquifers are exposed over wide parts of the mountain chains and have been intensively karstified. Relatively high precipitation on the mountains makes the carbonate formations to highly productive karst aquifers with major national importance for domestic supply and irrigation.

The high degree of karstification is shown in numerous caves and in the occurrence of several large karst springs discharging high water volumes from extensive catchment areas. Some of the caves extend over considerable stretches and show phantastic stalactite formations, such as the caves of Jeita, a major tourist attraction in Lebanon.

The Mesozoic carbonate formations comprise the following aquifers of national importance for the countries of the sub-region (Fig. 2.7):

- Upper Cretaceous Aman–Wadi Sir (B2/A7) aquifer in Jordan
- “Mountain aquifer” (Cenomanian–Turonian) in the West Bank

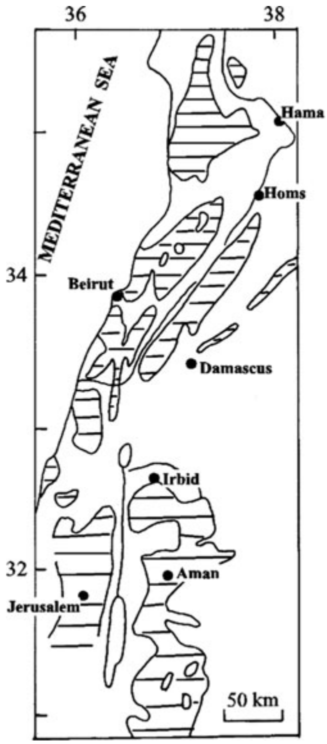

Fig. 2.7 Outcrops of Mesozoic carbonate formations in the northwestern mountain and rift zone generalized, after Dubertret (1966), ESCWA (1999a), Khair and Haddad (1993), Salameh (1996) hatched fields Outcrop of Jurassic and Cretaceous limestone and dolomite formations

- Jurassic and Cretaceous "Water Towers" of Lebanon (Kesrouan and Sanin aquifers)
- Jurassic and Cenomanian–Turonian limestones and dolomites on the Hermon, Antilebanon and Ansariye mountains in Syria

In addition to the Mesozoic karst aquifers, the northwestern mountain and rift zone comprises:

- Paleogene limestone and chalk aquifers in synclinal structures within the mountain and highland areas
- Pleistocene–Quaternary sand and gravel aquifers in basins and coastal areas
- Perched aquifers along the eastern and western shoulders of the rift graben
- Miocene reef limestones in the coastal area of Lebanon

Karstified Jurassic limestones provide important aquifers where they are uplifted in anticlinal structures to levels of present groundwater circulation: in the Lebanon mountains, Mount Hermon, the crests of the Antilebanon and Ansariye mountains. Lower Cretaceous sedimentary rocks contain aquiferous horizons which are generally connected hydraulically to the main Upper Cretaceous limestone and dolomite aquifer. On the flanks of anticlines in the Antilebanon mountains and in the Lebanon mountains, Lower Cretaceous sandstones and limestones form separate aquifers in areas of limited extent.

2.3.2 *Highlands of Judea and Jordan*

In the highlands of Judea and Jordan, the main aquifer system is formed by fractured and karstified Upper Cretaceous limestones and dolomites, the "mountain aquifer" or Judea group aquifer on the West bank and Aman–Wadi Sir and Humar aquifers in Jordan.

2.3.2.1 West Bank

Aquiferous sections of the mountain aquifer of the West Bank are found in the Hebron and Jerusalem formations (Table 2.3). The base of the mountain aquifer, the Lower Cretaceous Qatan formation, is composed of shale, chalk and marl (upper part of the Kurnub group). In synclinal structures the mountain aquifer is confined below the Mount Scopus chalk–marl formation.

The mountain aquifer complex is divided, in part of its extent, into sub-units by argillaceous aquitards:

- Marls of the Bethlehem formation between the aquiferous Jerusalem and Hebron formations
- Marl sequences in the Yatta formation, separating the Hebron aquifer from aquiferous layers in the upper Beit Kahil aquifer
- Argillaceous layers between the upper and lower Beit Kahil formations

The Hebron and Jerusalem formations form the most productive aquifer section of the mountain aquifer complex. Transmissivity in the Beit Kahil formation is generally low.

The total thickness of the mountain aquifer is 600–700 m.

Limestones of the Paleogene Jenin formation constitute an important aquifer in the Nablus synclinal structure around Nablus–Jenin.

2.3.2.2 Highlands of Jordan

In the highlands of Jordan, the about 700 m thick Upper Cretaceous aquifer complex consists of a sequence of limestones and dolomites with marl, chalk and chert intercalations. Considerable volumes of the precipitation, which reaches mean annual rates of >500 mm in the Ajloun–West Aman areas and around 350 mm at Kerak, infiltrate on the karst outcrops and make the crest of the highlands to the main recharge area of the Upper Cretaceous aquifers.

The fractured and karstified Upper Cretaceous limestones and dolomites constitute, in a sub-regional view, a coherent aquifer. In detail, the sequence of Upper Cretaceous carbonate formations of the highlands of Jordan is sub-divided, from bottom to top, into:

Table 2.3 Scheme of main aquifers in the northwestern mountain and rift zone

		Judean highlands	Highl. of Jordan	Lebanon mountains	Antilebanon mts.	Northwestern Syria
Quaternary Neogene				Aquifers in morphologic depressions		
Paleogene		Jenin aquifer in Nablus-Jenin area	Rijam (B4) aquifer in Irbid area		Nummulitic limestone, local aquifer	
Upper Cretaceous	Maastrichtian	Major Aquitard Mount Scopus form	Muwaqqar marl	Chekka marl	marl	marl
	Campanian Santonian Coniacian		Aman (B2) Wadi Sir (A7) **major karst aquifer**			
	Turonian Cenomanian	Judea group "mountain aquifer"	Humar (A4)	Sanin limestone	limestone and dolomite	
Lower Cretaceous			Kurnub sandstone, deep brackish water aquifer			
Jurassic				Kesrouan limestone **major karst aquifer**	limestone	limestone
Triassic Paleozoic			Disi sandstone, deep brackish water aquifer			

- The lower Ajloun group (A1–A6, Cenomanian), which is composed prevailingly of marls, shales and marly limestones and includes dolomitic limestone of the Humar formation (A4)
- Limestones and dolomites of the Wadi Sir formation (A7, Turonian)
- Marls of the Wadi Ghudran formation (B1, Santonian)
- Limestones, cherts and chalky limestones of the Aman formation (B2, Campanian)

The Upper Cretaceous aquifer system is underlain by a sandstone aquifer complex of Cambrian to Lower Cretaceous formations (Disi and Kurnub aquifers). The top of the Upper Cretaceous aquifer system is followed by the Maastrichtian Muwaqar marl aquitard, which overlies the Aman formation.

The Aman–Wadi Sir (B2/A7) and the Humar formations provide the major aquifers of the Upper Cretaceous sequence. The *Aman–Wadi Sir aquifer*, consisting of limestones, cherts and sandy, marly and phosphatic limestones, is exposed in extensive outcrops in the highlands of Jordan and on the southern parts of the escarpment toward the Jordan valley. The total thickness of the Aman–Wadi Sir aquifer is 90–350 m. In some areas, in particular in the northern highlands of Jordan, the marly and chalky Wadi Ghudran formation constitutes an aquitard between the aquiferous Aman and Wadi Sir formations.

In the highlands of the Yarmouk basin in northwestern Jordan, the Upper Cretaceous carbonate sequence comprises:

- A highly productive upper aquifer (B2, Campanian)
- A deeper aquifer with lower well yields (A7, Turonian)

The Aman–Wadi Sir aquifer is here generally situated at depths of less than 200 m below surface.

The geologic structure with dips toward the Yarmouk and Jordan valleys creates, along the main mountain slopes and in the Jordan valley, confining conditions in the Aman aquifer and the Wadi Sir aquifer. Piezometric heads in the aquifers, confined below overlying marl aquicludes, reach tens of metres above ground surface.

On the southern part of the Jordan valley escarpment, the Upper Cretaceous carbonate aquifer is, according to the geological structure and morphology, cut into several blocks, which extend for a few kilometres in length and width and are separated by faults or other unconformities.

The *Humar formation* (A4) constitutes a significant aquifer mainly in the Aman–Zerqa and Salt areas and is exposed in a rather narrow outcrop in the Aman area. The aquifer is underlain by the Fuheis marl aquitard (A1/A3) and is, east and west of the outcrop area, confined below the Shueib marl aquitard (A5). In the Sukhne area, the aquifer is situated near the surface below gravels of Wadi Zerqa. The saturated thickness of the Humar aquifer is 40–45 m.

In the Yarmouk basin in northwestern Jordan, the Humar formation occurs at greater depth and has a relatively low permeability, as the carbonate rocks of the formation grade into marl and siltstone beds. South of Aman, the thickness of the Humar formation decreases to about 10 m in Wadi Mujib and grades into marl and siltstone beds.

Around Naour southwest of Aman, the Ajloun group comprises near its base an aquiferous limestone and dolomite sequence with marl, sandstone and siltstone intercalations and a total thickness of 220 m, the *Naour aquifer* (A1/A2, Cenomanian). The Naour aquifer is separated from the overlying Humar aquifer by the Fuheis marl aquitard (A3).

In part of the northwestern highlands of Jordan, the Upper Cretaceous aquifer complex is underlain by a thick sandstone sequence, the Lower Cretaceous *Kurnub sandstone* and, at greater depth, the *Disi sandstone*. The Kurnub group consists prevailingly of sandstones interbedded with siltstone and clay, with a mainly silty upper part and an arenaceous lower part. Together with the Zerqa group, a Triassic–Jurassic sequence of limestones and dolomites with interbedded shale and sandstone, the Kurnub group constitutes a generally deep aquifer system in the highlands. The Kurnub sandstones are exposed at some locations west and northwest of Aman, on the southern part of the Jordan valley escarpment and in deeply incised tributary valleys of the Dead Sea and the Jordan river. The thickness of the sandstones varies, in general, from 185 to 300 m. The Zerqa group disappears toward south. In boreholes in the northern part of the Jordan valley, the Zerqa group has been tapped in a thickness of up to 1,700 m.

The deep Disi sandstone aquifer is reviewed in Chap. 5.

In the sub-regional groundwater regime, various hydraulic connections exist between the Upper Cretaceous aquifer and the underlying Kurnub sandstone aquifer:

- On the eastern slopes of the highland anticline, groundwater leaks generally from the Upper Cretaceous aquifer into the lower sandstone aquifer
- In some parts of the highlands, piezometric levels in the Kurnub sandstone are higher than in the overlying carbonate aquifer, producing some upward leakage of the sandstone water

In the area south of Aman, the Kurnub sandstone aquifer contains confined groundwater with salinities of up to a few thousand mg/l TDS, with artesian conditions in deep boreholes. In the Baqaa valley north of Aman, several springs discharge from the outcropping Kurnub aquifer.

In the Irbid area in northern Jordan, chalks and limestones of Paleogene age form a *shallow aquifer* (Umm Rijam or B4 aquifer) above the Muwaqar aquitard. The Umm Rijam formation, composed of limestones, chalks and chert intercalations, is exposed in a 4–15 km wide strip in the northwestern border area of Jordan between Ramtha and the Yarmouk river. In the north and northeast, the formation disappears under the cover of Neogene–Quaternary basalts. Groundwater flow in the shallow Rijam aquifer follows a differentiated pattern with flow directions toward the Yarmouk river and its tributaries with numerous emergences of springs (Margane et al. 2002: 22).

An alluvial aquifer is formed by gravels of Wadi Zerqa at Sukhne. The shallow Sukhne gravel aquifer with a saturated thickness of 20 m is hydraulically connected with the underlying Humar aquifer.

2.3.3 Jordan–Dead Sea–Wadi Araba Rift Valley

Main fresh water resources in the Jordan valley are found in the Pleistocene–Quaternary gravel fans and, in limited areas, in Upper Cretaceous carbonate formations. The thickness of the aquiferous gravel fan deposits ranges between a few metres to around 50 m.

Zones with higher aquifer productivity are restricted to the near surface gravel fans of larger wadis, which receive recharge from seasonal surface runoff. The groundwater in the gravel fans is generally unconfined; confined conditions can occur at the escarpment boundary and on the fringes of the fans, where the Lisan marls intercalate with the gravel deposits. Fresh water occurrences are generally limited to the gravel fan aquifers, where groundwater with low to moderate salinity extends in lenses above brackish to saline deeper water. Along the Zor area in the graben center, thin layers of shallow fresh water overlie saline groundwater or brines.

The Upper Cretaceous B2/A7 and the A4 formations provide deeper aquifers within the valley with, in many areas, elevated groundwater salinity. At various locations in the northern Jordan valley, wells were drilled into the B2/A7 composite aquifer are artesian and produce thermal water with temperatures of 28–56°C.

Groundwater in the deep Kurnub sandstone aquifer is saline.

Neogene conglomerates provide a fresh water aquifer in limited areas in the north of the Jordan valley. The productivity of the about 100 m thick conglomerate aquifer is generally low.

The extent of the Paleogene Jenin (B4) aquifer in the Jordan valley is restricted to the areas around Jericho and some locations in the northern part of the valley. Groundwater salinity in the Paleogene aquifer is generally high with 5,000–7,000 mg/l TDS. In the Jericho area, water with moderate salinity has been tapped in some boreholes drilled into the about 300 m thick Paleogene chalky limestones. The productivity of the aquifer is generally low and the groundwater in the deeper parts of the aquifer is brackish.

Southeast of the Dead Sea, a 1 km to >5 km wide plain extends between the graben fault structure and the sea shore. The plain is covered mainly by Quaternary sediments with alluvial fans, which consist of sands and gravels with thin marl intercalations (fans of Wadi Kerak and Wadi Isal), and interfinger with lacustrine sediments (clay, gypsum, aragonite) of the Pleistocene Lisan formation.

The sedimentary sequence under the plain contains a complex aquifer system with:

- The Paleozoic–Lower Cretaceous Disi and Kurnub sandstone aquifers
- Aquiferous limestones and dolomites of the Upper Cretaceous Ajloun–Belqa group
- The alluvial Quaternary aquifer

Main freshwater resources are contained in the alluvial fan deposits, which are replenished from flood flow infiltration and lateral flow from the Ajloun and Belqa aquifer across the eastern margin of the Dead Sea valley.

2.3.4 Lebanon and Antilebanon Mountains and Bekaa

2.3.4.1 Lebanon Mountains

The Lebanon mountains certainly contain the most productive aquifer system of the Arabian Plate. According to Khair et al. (1992), the mean volume of annually replenished groundwater circulation in the Lebanon mountains and its foreland on the coast and the Beqaa Valley is more than 2×10^9 m^3, corresponding to about 20% of the total annual precipitation in Lebanon. The high groundwater potential is created by:

- Abundant precipitation in the winter season with a mean of 930 mm/a in Lebanon in general and 1,400–1,500 mm on the upper slopes of the Lebanon mountains.
- High infiltration rates on widely exposed karst surfaces characterized by numerous sinkholes.
- The occurrence of thick karstified sections in Jurassic and Upper Cretaceous limestone and dolomite formations.

In particular the Kesrouan limestone of Jurassic (Bathonian–Kimmeridgian) age and the Sanin limestone of Upper Cretaceous (Albian–Cenomanian–Turonian, mainly Cenomanian) age provide highly productive aquifers and have been denominated the first and second “water towers of Lebanon”.

The limestones and dolomitic limestones of the Kesrouan and the Sanin formations compose highly karstified carbonate complexes. The high degree of karstification has been favoured by the wide extent of outcrops of the carbonate rocks, intensive fracturing, high percentage of dolomite and dolomitic limestone which are particularly susceptible to karstification, and the relatively high precipitation rates in the mountain areas. Large interconnected cavern systems penetrate the thick Jurassic and Upper Cretaceous carbonate complexes. The mature stage of karstification in Jurassic and Upper Cretaceous carbonate rocks has significantly increased their porosity (more than 24%) and infiltration rate (40–44% of precipitation).

The Kesrouan aquifer is overlain by the Bhannes volcanic complex, which acts as an aquitard, separating the Kesrouan aquifer from the overlying Bikfaya aquifer. The Jurassic outcrop belt is delimited in the west by outcrops of Lower Cretaceous sandstones and marls, the Chouf sandstone and Aptian–Albian marl aquitards and, in the east, by the Yamoune fault.

The Sanin aquifer is composed of limestones and dolomitic limestones with thin marl intervals and is connected, in some areas, with aquiferous sections in the overlying Maameltein limestone. The 800–1,000 m thick Sanin limestone aquifer extends in the Lebanon mountains over a surface of 4,290 km^2.

The Mastrichtian Chekka marls constitute an aquiclude or aquitard where they extend over the Upper Cretaceous aquifer complex on mountain slopes, foothills and in coastal plain areas. The Neocomian–middle Albian sequence comprises, together with the late Jurassic, prevailingly aquitards and aquicludes with some aquiferous horizons in sandstone and limestone units.

2.3.4.2 Coastal Area of Lebanon

On long stretches of the Lebanon coast, outcrops of the Upper Cretaceous reach directly to the sea shore.

On the northern coast of Lebanon, a zone of plains and hill areas extends in front of the mountain range: the Akar plain in the Lebanon–Syrian border area adjoined to the east by basalt massifs, a coastal plain and foothills of the Lebanon mountains near Tripolis, a narrow coastal plain at Chekka, and the Koura plateau between the coastal plains and the Lebanon mountain chain.

The Akar plain extends over 720 km^2 in the Lebanese–Syrian border area along the Mediterranean Sea coast. The plain is crossed by Nahr Abrache, Nahr el Kebir el Janoubi and Nahr Oustouene. Mean annual rainfall is around 800 mm.

The plain is underlain by a multi-aquifer system comprising as main aquifers:

- Upper Cretaceous limestones and dolomites which are exposed in wide parts of the mountainous catchment area in the Ansariye and Lebanon mountains
- Neogene basalts
- Neogene–Quaternary sediments: sandstones, sand, limestones, conglomerates, alternating with clays, silt and marls

Productivity of the shallow basalt and sedimentary aquifers is generally low to moderate, higher well yields are found in the Upper Cretaceous aquifer, the top of which is situated in the plain area at depths of a few metres to more than 200 m below surface.

In the fractured Pliocene basalts of the Tell Kalakh massif east of the Akar plain, groundwater issues in generally seasonal springs with low discharge and has been tapped by shallow wells and a few deeper wells with low to moderate yield.

The hill and plain area along the coast of Tripoli comprises shallow aquifers in Miocene reef limestones and fluviatile to coastal sediments. South of Tripoli, the Abou Ali river drains, in northwest direction, a local basin with sedimentary aquifers of Miocene–Quaternary age. Deeper groundwater flow in the Upper Cretaceous aquifer is obviously directed westward below the Koura plateau toward the coast at Chekka, independent from the surface drainage.

The coastal plain at Chekka extends for 1–2 km from the shore and is bordered to the east by the Koura plateau, a hill area with topographic altitudes of 300–450 m asl. The Cenomanian–Turonian aquifer is overlain in the Koura plateau by Senonian marls. Part of the Koura plateau is covered by Miocene to Quaternary sediments: Miocene limestones, Miocene–Pliocene marls and clays, alluvial deposits, which contain a shallow aquifer system in the limestones and alluvial deposits.

At Chekka, submarine springs discharge from the confined Upper Cretaceous Sanin aquifer, which is covered by “Senonian” Chekka marls. The submarine springs of Chekka constitute one of the largest known submarine discharges of groundwater into the Mediterranean Sea. The simultaneous occurrence of perennial and seasonal springs at almost the same locations indicates the existence of various karst channels with independent groundwater circulation.

The thickness of the confining layer is about 115 m in the coastal area of Chekka. The springs are supposed to rise at locations, where the thickness of the marls is reduced, or on local anticlinal structures, where the marls are cut by fissures. The springs represent the lowest discharge area of the Upper Cretaceous carbonate aquifer of the northern Lebanon mountains. The Upper Cretaceous aquifer is underlain by low permeability marls of Lower Cretaceous age.

The total thickness of the Upper Cretaceous Sanin limestone formation in the Chekka catchment reaches up to 900 m.

In west central Lebanon, outcrops of the Upper Cretaceous limestone and dolomite formations reach over large strips until the sea coast. A narrow belt of Miocene limestones and Quaternary deposits adjoins the sea coast between Beirut and Jounie.

Main aquifers in the southwestern Lebanon mountains and foothills are Upper Cretaceous limestones and dolomites (Sanin aquifer) and Paleogene limestones. A coastal plain of about 1–2 km width extends over a long stretch of the coast between Saida and Tyr (Sur). Unconsolidated deposits of the coastal plain contain aquiferous layers which are, to some extent, connected with the underlying Paleogene or Upper Cretaceous aquifers. South of Tyr, the perennial springs Rachichiye and Ras el Ain discharge from the carbonate aquifer through the overlying coastal sediments.

2.3.4.3 Antilebanon Mountains

As in the Lebanon mountains, the main aquifers of the Antilebanon are formed by karstic Mesozoic carbonate formations: Jurassic limestones and Upper Cretaceous (Cenomanian–Turonian) limestones and dolomites. Groundwater from the Mesozoic karst aquifers issues in a considerable number of perennial spings, some of them with high discharge volumes.

Chalky limestones and fractured cherts of Eocene age provide aquifers of local importance on synclinal structures within the Antilebanon mountains west of Damascus and in the Qalamoun area between the Antilebanon and Palmyrean mountains north of Damascus. Groundwater on the periphery of the synclines issues in springs with low to moderate discharge (1–10 l/s) and is extracted through shallow wells. In the central parts of the synclines, confined groundwater is extracted from Eocene limestones and cherts.

2.3.4.4 Bekaa Valley

Major aquifers in the Bekaa valley are:

- More than 800 m thick Upper Cretaceous limestones and dolomites
- Eocene karstic limestones extending in particular over the southern end of the valley and the adjoining hill and mountain area of Jebel el Aarbi

- Neogene–Quaternary deposits in the valley plain, composed of conglomerates and alluvial and fluvial sediments

The Upper Cretaceous limestones and dolomites are exposed on the mountain flanks west and east of the valley and in the southern part of the valley and are situated at a depth of several hundred metres to more than 1,000 m below the northern and central valley floor.

The groundwater regime in the Bekaa valley is interrelated with the aquifer systems of the adjoining Lebanon and Antilebanon mountains through:

- Surface inflow of spring discharge on the boundaries of the valley
- Subsurface inflow into the valley mainly in the Upper Cretaceous aquifer

Major fault systems, in particular the Yamoune fault on the eastern slope of the Lebanon mountains, act along some stretches as barriers to groundwater flow, causing groundwater discharge in large perennial springs. Subsurface groundwater inflow from the Upper Cretaceous aquifer of the Lebanon mountains into the Neogene–Quaternary aquifer of the plain occurs in the northern part of the Bekaa, feeding the spring Ras el Aasi.

On the southern section of the Bekaa graben, karstified reef limestones of Eocene age constitute a productive aquifer, which feeds the springs Ain Hasbani, one of the sources of the Jordan river, and Ain et Tine. At its southern tip, the basin branches into the Litani river drainage in the west and the Hasbani river drainage in the east.

Groundwater with moderate salinity of 500–1,000 mg/l TDS is found in alluvial deposits, in particular in gravel fans of the larger wadi systems. The shallow aquifer system in the alluvial deposits is replenished from infiltration of surface runoff and base flow from the tributary wadis and by lateral inflow of groundwater from the Upper Cretaceous carbonate aquifer complex.

Groundwater from the shallow Neogene–Quaternary aquifer is exploited in particular in the central part of the Bekaa valley in the area around Baalbek. The Eocene limestone aquifer is intensively exploited in its outcrop area in the southern Bekaa.

2.3.5 Ansariye Mountains and Middle Orontes Area

In the Ansariye mountains, fractured and karstified Jurassic and Cenomanian–Turonian limestones and dolomites act as major aquifers. The two aquifers are generally separated by a 150 m thick aquitard of Aptian–Albian marls, but faults and main fracture zones create hydraulic interconnections. Claystones interbedded in the middle Jurassic probably act as aquitards and as base of the main groundwater circulation system.

In parts of the high mountain area, the Jurassic and Cenomanian–Turonian aquifers are unsaturated or contain locally perched groundwater bodies. On the lower mountain slopes and in the coastal area, groundwater in the Jurassic and Cenomanian–Turonian aquifers is confined below overlying formations with low permeability: Lower Cretaceous marls above the Jurassic aquifer, Maastrichtian or Pliocene aquitards above the Cenomanian–Turonian.

Several submarine springs with significant flow discharge at the Mediterranean Sea coast in the area of Banias–Tartous–Amrit. Most of the submarine springs issue from the confined Upper Cretaceous limestone and dolomite aquifer.

Several shallow – partly perched – aquifers are developed above the main Mesozoic aquifer system:

- In Mesozoic carbonate rocks, where the Mesozoic formations are uplifted in the mountain areas above the zone of saturation of the main aquifer system
- In Albian limestones, which are separated from the Jurassic aquifer by Aptian clay layers, and from which small springs rise in the crest area of the mountains with discharges of 0.3–2.5 l/s
- In Eocene nummulitic limestones, which feed small springs with discharges of about 3 l/s on the northwestern flank of the Ansariye mountains
- In marine or terrestrial Quaternary deposits in coastal areas south of Tartous and between Nahr el Sinn and Lataquie, and in fluviatile sediments of Nahr el Kebir ash Shimali near Lataquiye and of Nahr el Kish
- In Helvetian–Quaternary limestones in the coastal plain of Lataquiye, in chalky and calcareous marls of the lower Tertiary northwest of Nahr el Kebir esh Shimali

In the Jebel Basit area, shallow groundwater is found in the ophiolite rocks and in Triassic and Upper Cretaceous sedimentary rocks, tectonically intercalated into the ophiolites. Groundwater occurrences have a limited extent and discharge in numerous intermittent springs.

Cenomanian–Turonian limestones and dolomites constitute a main aquifer system on the Masiaf and Hama plateaus, the Acharne plain and Jebel ez Zaouiye. The Upper Cretaceous carbonate aquifer is unconfined in an around 35 km wide zone east of the rift graben, which comprises the main outcrop areas. Further east, the aquifer is confined below Upper Cretaceous aquitards: Campanian chalks and marls, Maastrichtian–Paleogene marls.

A particular characteristic of the areas adjoining the rift zone is the occurrence of discontinuous aquifers and of perched aquifers. Groundwater, which accumulates from local recharge in aquifers underlain by aquitards at levels above the main groundwater system, leaks into the deeper aquifer along fault systems or in zones where the aquitard is thinning or disappearing. Aquifers with water levels above the hydraulic head of the Cenomanian–Turonian aquifer system are found in several areas adjoining El Ghab in the east:

- Pliocene sediments in the Acharne plain
- Eocene nummulitic limestones on Jebel ez Zaouiye
- Paleogene–Neogene carbonate rocks on the Idleb plateau

The aquitards below these aquifers are marl and clay layers in the Pliocene of the Acharne plain and Maastrichtian marls in Jebel ez Zaouiye and the Idleb plateau.

The Maastrichtian marls disappear toward the anticlinal structures adjoining the rift graben.

In the Homs plain and the Shin volcanic plateau, aquifers of prevailingly discontinuous nature are found. In the Homs plain, lacustrine Pliocene sediments contain aquiferous lenses of conglomerates and sandstones between marls with low permeability. Groundwater from the non-persistent aquifer lenses is extracted through 10–80 m deep wells.

In the Shin plateau west of Homs, groundwater has been tapped in fractured basalts through 100–300 m deep boreholes. Well yields are generally low.

Toward east, the Homs plain and the Hama plateau grade into the Selemiye plain, where Paleogene chalks provide a more extensive shallow aquifer. Sporadic surface runoff and groundwater flow in the Selemiye plain are directed toward the Orontes river in the west. The groundwater in the shallow aquifer is intensively exploited by wells and leaks probably, to some extent, into the deeper Upper Cretaceous aquifer.

References. Agrocomplect (1984–85), Al Charideh (2007), Boeckh et al. (1970), Davidson and Hirzallah (1966), GTZ and NRA (1977), Hirzalla (1973), Hobler et al. (1991), Kareh (1967, 1968), Kozlov et al. (1966), Kroitorou et al. (1985), Margane et al. (2002), Mijatovic and Bakic (1966), Nations Unies (1967), Ponikarov et al. (1967b), Salameh (1996, 2004), Salameh and Shaqur (1981), Shahab (1997), Sunna (1995), UNDP (1970), Wagner (1996b), Wolfart (1966).

2.4 Groundwater Regimes

2.4.1 Hydraulic Parameters

Transmissivities are relatively high in many parts of the karstified Mesozoic limestone and dolomite aquifers of the northwestern mountain and rift zone. In the Lebanon mountains, considerable hydraulic conductivities and high aquifer thickness in the order of 1,000 m yield transmissivities of generally between 1,000 and 90,000 m^2/d in the Jurassic as well as in the Upper Cretaceous aquifer complexes. High transmissivities of around 100,000 m^2/d are found in karstified zones, while transmissivities in poorly fissured limestones may be as low as 10 m^2/d. Karstification is assumed to be restricted, in general, to shallow depth, e.g. 18–33 m below land surface in the Rachin area in the northern Lebanon mountains, but may reach several hundred metres in localized zones.

Transmissivities in the confined parts of the Upper Cretaceous Judea group aquifer of the West Bank (mountain aquifer) are in the order of 10,000–100,000 m^2/d; for the phreatic part of the aquifer, transmissivities of several hundred m^2/d are reported. In the western highlands of Jordan, transmissivities of the Upper Cretaceous carbonate aquifers may range from 10 to 3,000 m^2/d.

Very high transmissivities of the Upper Cretaceous karst aquifers are found at some locations: in the Mukheibe well field in the Jordan valley, one well yielded an artesian flow of 1.6 m^3/s.

Values of hydraulic conductivity of Mesozoic karst aquifers in the Lebanon mountains as well as in the highlands of Jordan and of Judea are generally in the order of 10^{-5} to 10^{-3} m/s, effective porosities are in the order of 1–5%.

2.4.2 Groundwater Recharge

In the eastern basin of the Judean mountains, average annual precipitation decreases from 800–1,000 mm on the peak areas to 600–150 mm on the mountain slopes situated in the rain shadow and about 100 mm in the Jordan valley. Balance estimates indicate groundwater recharge rates of 25–30% of precipitation and runoff rates of 5% of the precipitation. Corresponding to the spatial distribution of precipitation, recharge rates are relatively high in the north and west of the Judean highlands and decrease toward east and southeast. An average recharge rate of 144 mm/a has been computed for the mountain aquifer of the West Bank.

Estimates of annual groundwater recharge for various areas of the West Bank are listed in Table 2.4.

Recharge to the Aman–Wadi Sir aquifer in the highlands of Jordan varies generally from 14 to 30% of mean annual precipitation “depending on rainfall distribution, topographic situation, soil cover, karstification, etc.” (Margane et al. 2002).

For the Aman–Zerqa basin with an area of 4,586 km^2, a groundwater recharge of 88×10^6 m^3/a has been estimated, corresponding to an average recharge rate of 19 mm/a. The main volume of recharge (42×10^6 m^3/a) is received in the Upper Cretaceous limestone aquifers, while a minor part of replenishment is contributed through inflow from the semi-arid basalt area in the east.

Groundwater recharge rates in the Upper Cretaceous aquifers of the Aman–Zerqa basin are the highest rates in Jordan and sustain 30% of the national renewable groundwater resources.

Table 2.4 Estimates of annual groundwater recharge for various catchment areas of the West Bank after Gvirtzman (1994), Kroitorou et al. (1985, 1992), Sunna (1995)

Catchment area		Estimated groundwater recharge	
	km^2	10^6 m^3/a	mm/a
Highlands north of Jerusalem (eastern catchment)	135	49	363
West of Hebron (northern catchment)	696	77.3	111
Dead Sea	1,045	60.4	58
Jordan valley	805	153	190
Tulkarm–Qalqiliye (western catchment)	1,005	246	245
Jenin–Nablus (northern catchment)	1,050	124	118

In Lebanon with its relatively favourable climatic and infiltration conditions, the average total recharge to all outcropping aquifers is estimated at around 2.5×10^9 m^3/a. That recharge volume corresponds to approximately 25% of the mean annual precipitation of 930 mm over Lebanon's total area of 10,452 km^2.

Estimates of groundwater recharge in individual sub-basins in Lebanon, which extend over catchment areas of 40–851 km^2, indicate the following recharge rates:

- On outcrops of Jurassic and Upper Cretaceous karst aquifers: 37–43% recharge of mean annual rainfall of 550–1,450 mm or 200–600 mm/a
- On outcrops of Eocene limestones and chalks: 27% recharge of mean annual rainfall of 750–900 mm or around 240 mm/a
- On coastal plains covered with Quaternary sediments or basalts: 15% recharge of mean annual rainfall of around 1,000 mm or 150 mm/a

The areas receiving significant recharge comprise 50–90% of the catchments in most sub-basins and 20–35% in some coastal plain catchments.

For the main groundwater basins of Lebanon, the following ranges of mean annual recharge rates have been calculated:

- High Lebanon mountains 350 mm
- Southern Lebanon mountains, southern Bekaa, Antilebanon mountains 210 mm
- Northern Bekaa basin 180 mm

A general groundwater balance of the Upper Cretaceous Sanin aquifer of the northern Lebanon mountains assumes a mean recharge of 585 mm/a or 42% of precipitation, sustaining a total mean annual discharge of 13 m^3/s at springs in the mountain area and, near Chekka, on the coastal plain and under the Mediterranean Sea. Submarine discharge, estimated at $120–350 \times 10^6$ m^3/a, may account for about 40–50% of the total net discharge. The submarine discharge at Chekka comprises 17 springs, 7 of which are perennial. Total spring discharge is reported as:

- 4 m^3/s fresh water base flow
- 60 m^3/s fresh water discharge in winter

The submarine springs show high seasonal discharge fluctuations, some springs cease in summer or show even reverse circulation of salt water into the outlet points.

An evaluation of satellite images and aerial photographs covering the Lebanon mountain area and its foreland, showed that 57% of the area have a high to very high recharge potential with recharge rates of 30–50% of mean annual precipitation. The areas with high to very high recharge potential correspond to the outcrops of fractured and karstified Jurassic and Cenomanian limestones and dolomites on the elevated parts of the Lebanon mountains. Over the total area, around 24% of the precipitation contributes to groundwater recharge.

High recharge rates of around 350 mm/a are indicated for outcrop areas of the Upper Cretaceous limestone and dolomite aquifer of the Ansariye mountains, corresponding to around 30% of the mean annual precipitation of 1,050 mm. A significant part of the recharged groundwater discharges in submarine springs.

2.4.3 Groundwater Flow Systems and Flow Volumes

Sub-regional groundwater flow systems in the extensive Mesozoic carbonate aquifers of the northwestern mountain and rift zone are directed toward discharge zones on the Mediterranean Sea coast and along the rift graben. Within the mountain and highland areas, groundwater discharge zones of various hydrogeologic catchments, some of them with large dimensions, are found on aquifer outcrop boundaries at particular structural and/or topographic situations.

Each of the six mountain and highland chains of the northwestern mountain and rift zone comprises several groundwater flow systems with local to sub-regional extent.

2.4.3.1 Judean Highlands

The main aquifer complex in the Judean highlands is recharged mainly by precipitation on the outcrops of the Upper Cretaceous limestones and dolomites at altitudes above 500 m asl. The higher mountain ranges contain phreatic zones of the aquifer complex, the main volumes of groundwater storage are found in confined zones of the aquifer at intermediate to lower ranges of the highlands.

The Judean highlands comprise three main groundwater flow systems with recharge areas on top of the highlands and discharge areas in the adjoining lowlands:

- The eastern basin extending between a water divide, which runs approximately over the crest of the Judean highlands, and the Jordan–Dead Sea valley
- The western basin between the water divide on the highlands and the Mediterranean Sea coast
- The northern basin or Nablus basin, which covers a large synclinal structure in the northern part of the highlands

The groundwater divides separating the basins coincide, in general, approximately with anticlinal structures (Hebron, Ramalla, Anabta, Fara anticlines).

The *eastern basin* extends over an area of around 4,200 km^2 on the eastern flank of the Judean highlands and comprises several separate groundwater catchments with general eastward groundwater flow from the mountain zone to the Jordan valley and Dead Sea lowlands. The eastern boundary of the Upper Cretaceous limestones and dolomites of the mountain aquifer, which constitute the main aquifer complex of the eastern basin, is formed by a large fault system along the rift graben. Groundwater levels in the mountain aquifer system descend from around 450 m asl on the highlands to 400 m below sea level on the Dead Sea shore.

Annual groundwater recharge volumes of 70–172 $\times$ 10^6 m^3 have been estimated for the eastern catchment of the Judean highlands, which covers an area of 2,200 km^2, with an average of around 100 $\times$ 10^6 m^3.

Natural groundwater discharge occurs in several springs and groups of springs on the eastern slope of the highlands and in the Jordan–Dead Sea valley. Springs on the mountain slopes appear to be fed by two major systems of karst conduits:

- An older system related to a former higher level of the Lisan lake, the predecessor of the Dead Sea, around 180 m below sea level
- A younger system which developed after recession of the Lisan lake

The upper system carries relatively fast flowing recent groundwater e.g. to the Elisha springs. The deeper systems contains older groundwater which is mixing through interconnections with the upper karst system. The deeper karstified sections are extensively exploited by well fields. The location of springs on the highland slopes is mainly controlled by the structural–morphological features of the escarpment. Major springs issuing from the Upper Cretaceous mountain aquifer on the mountain slopes of the eastern basin are Ain Auja west of Jericho and several springs in Wadi Qilt: Ein Fara, Ein Fawar, Ein el Qilt situated at 325, 80 and 10 m altitude asl, respectively. Ain Auja has a high seasonal discharge in years with heavy rainfall (e.g. $>70\ m^3/s$ in 1991–1992) and runs dry frequently in summer.

In the Jordan valley, numerous springs issue along the rift fault zone: Ain Elisha, Ain Sultan and the springs Duyuk, Sosha and Noeima. The salinity of these springs is relatively low with Cl concentrations around 30 mg/l and around 400 mg/l TDS.

Ain Elisha, located at the rim of the rift valley, is fed from water recharged in the Judean mountains and has a relatively constant discharge of 180 l/s. The total annual fresh water discharge in springs in the eastern basin is in the order of $40 \times 10^6\ m^3$.

The brackish Feshkha springs on the northwestern tip of the Dead Sea coast constitute a major discharge zone for most of the deeper sections of the aquifer complex. The springs with a discharge of some thousand m^3/h irrigate the largest oasis in the Dead Sea basin. Over twenty springs, streamlets, ponds and drainage canals are spread along a 4 km long strip of the western Dead Sea shore which is here only around 600 m wide (Table 2.5 and Fig. 2.8).

The *northern catchment* (Nablus–Gilboa basin) extends over a large synclinal structure in the north of the highlands of Judea and Samaria and is covered, to a large extent, by Maastrichtian–Paleogene sedimentary rocks: the Mount Scopus marl formation and the Jenin (Avedat) chalk formation. The Jenin formation provides a shallow aquifer, separated from the deeper Upper Cretaceous mountain aquifer by the Mount Scopus aquitard.

Table 2.5 Mean annual discharge of springs on the eastern slope of the Judean highlands after Kroitorou et al. (1985, 1992), Sunna (1995)

Spring	Mean discharge $\times 10^6\ m^3/a$
Auja	10
Feshkha	40
Wadi Qilt	5
Ein Qilt + Sultan	9
Jericho springs	13
Ain Fawar	11–36
Ain Fara	1.4

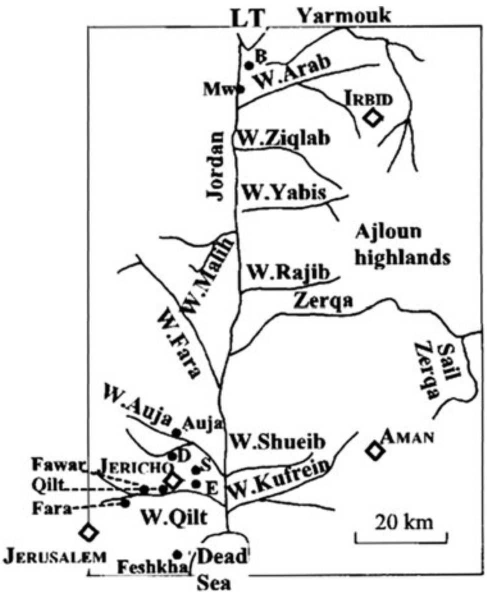

Fig. 2.8 Wadis and springs in the Jordan river catchment.; B Al Himme springs (Balsam and Maqla); D springs Duyuk, Sosha, Noeima; E Ein Elisha; S Ain Sultan; LT Lake Tiberias; Mw Mukheibe well field

Groundwater movement is directed mainly toward north. Groups of springs with small to moderate flow issue from the Jenin aquifer in particular in the Beisan area, where total spring discharge was nearly 100×10^6 m^3/a in 1952–1960. The main volume of groundwater flow emerges from springs or is extracted from wells in the Harod and Beit Shean valleys west of the northern Jordan valley.

The *western catchment* (Yarqon–Taninim basin) occupies the western slope of the Judean highlands between the crest area and the Mediterranean Sea coast. Groundwater moves in the main Judea group aquifer generally toward west. In the pre-development stage, a large percentage of the groundwater flow discharged in springs in the foothills and the coastal plain. In the areas of Tulkarm and Qalqiliye, groundwater is extracted through wells from the Upper Cretaceous aquifer and the Paleogene Jenin aquifer.

Groundwater balance estimates indicate a flow volume of 140×10^6 m^3/a for the northern catchment and of 360×10^6 m^3/a for the western catchment. These estimates do not differentiate between Plaestinian and Israeli territories.

2.4.3.2 Highlands of Jordan

The groundwater flow regime in the Upper Cretaceous carbonate aquifer complex of the highlands of Jordan is differentiated by major groundwater divides into flow systems of four main hydrogeologic sub-basins of Wadi Mujib, the Zerqa river, Yarmouk river and Azraq.

Regional groundwater movement in northwestern Jordan is directed to the Jordan–Dead Sea valley either immediately through the Upper Cretaceous carbonate aquifers or through leakage into the Kurnub sandstones. The general westward oriented groundwater flow system is, however, overlain in wide areas by a system of eastward groundwater flow in the A7–B2 aquifer (Margane et al. 2002: Fig. 2.8). The "configuration of the groundwater table indicates that the groundwater in the Upper Cretaceous aquifer system flows to the east and partly infiltrates to the sandstone aquifer system. In this aquifer it takes a westerly course and is discharged along the western slopes bordering the Dead Sea" (Salameh and Udluft 1985: 46).

In the *Wadi Mujib* sub-basin, groundwater flow is generally directed to the Dead Sea valley. In the *Aman–Zerqa* sub-basin, groundwater moves from recharge mounds around Aman to the Jordan valley in the west and the to Zerqa valley in the east and northeast. Along the south–north course of Wadi Zerqa, groundwater flow direction changes along a barrier of uplifted Muwaqar marls toward north and discharges partly in springs. The groundwater regime in the Aman–Zerqa area is now highly disturbed by pumping.

In the *Yarmouk* sub-basin, groundwater flow is, in general, directed to the Yarmouk and Jordan valleys.

Main groundwater discharge occurs in springs and seepages along the Jordan valley and in tributary wadis on the western escarpment, such as Wadi Arab and Wadi Ziglab, or through lateral outflow into the deposits of the Jordan valley floor.

In the *Azraq* sub-basin, groundwater flows eastward from the highlands into the east Jordanian limestone plateau with significant leakage into the underlying sandstone aquifer complex, in which groundwater movement is oriented to the Dead Sea–Jordan valley in the west.

2.4.3.3 Jordan–Dead Sea Valley

The Jordan–Dead Sea valley receives groundwater from various aquifers of the adjoining highland escarpments. Groundwater reaches the valley:

- As surface base flow from spring discharge in tributary wadis
- As spring discharge on barriers formed by the rift fracture and flexure system
- As subsurface flow through conduits within the rift faults

Direct recharge from precipitation within the valley, with mean annual rainfall of around 100 mm, is negligible, but the catchment areas of the main Mesozoic aquifers extend over wide areas of the adjoining escarpments and highlands, which receive significantly higher precipitation. The aquifers within the valley – mainly the Upper Cretaceous carbonate aquifers and Pleistocene–Quaternary gravel aquifers – are replenished prevailingly by percolation of runoff in tributary wadis, irrigation water return flow, canal losses, infiltration of occasional flood flow and subsurface inflow.

Spring discharge zones are located in several areas on the western tectonic boundary of the Jordan–Dead Sea valley and along the foothills on the northern end of the Jordan valley. A zone of thermal springs extends over the eastern escarpment between the southern end of the Dead Sea and Lake Tiberias. The thermal springs issue from Lower Cretaceous sandstones in the south and, in the north, from Upper Cretaceous carbonate aquifers. Topographic elevation of discharge points of the thermal springs range from 570 m asl in the south to around 100 m below sea level at the sites of the springs Balsam and Maqla in the northern Jordan valley.

Spring discharge in the eastern Jordan valley–Dead Sea catchment amounts to 160×10^6 m^3/a. Main discharge volumes issue from the Upper Cretaceous Humar (A4) and Aman–Wadi Sir (A7/B2) aquifers and from alluvial aquifers in the wadis of the northern highlands and the Dead Sea area. Around 24×10^6 m^3/a are contributed from spring discharge of the deeper sandstone aquifer system, mainly the Lower Cretaceous Kurnub aquifer (data of 1983–1993, Margane et al. 2002). The groundwater discharge supports a baseflow in wadis of the Jordan–Yarmouk and Dead Sea catchments of presently 155×10^6 m^3/a. Total discharge from the sandstone aquifer complex east of the Dead Sea is around 90×10^6 m^3/a.

Artificial groundwater extraction from wells in the Yarmouk–Jordan river–Dead Sea catchment in Jordan reached, between 1993 and 1998, an average of 416×10^6 m^3/a, creating a high deficit of the groundwater balance between recharge/inflow and natural + artificial discharge.

Groundwater movement in the Pleistocene–Quaternary aquifer of the Jordan valley is generally directed from the escarpment to the central Zor area, groundwater streamlines running from the eastern and western escarpment toward the central part of the valley with a slight bend to the south. Depth to groundwater ranges from about 100 m in Mesozoic aquifers at the foothills of the escarpment to around 5 m in the central part of the Zor area. Natural groundwater discharge occurs through evaporation in the Zor area and small seepages into the Jordan river. At present, groundwater discharge is primarily controlled by artificial extraction in wells mainly from the Upper Cretaceous aquifers (B2/A7, A4, A1/A2, Judea group aquifers).

Groundwater extraction in the eastern part of the Jordan valley–Dead Sea area is estimated at 140×10^6 m^3/a. In the *north of the Jordan valley*, wells at the confluence of Wadi el Arab and the Yarmouk valley at Mukheibe discharge artesian water from the B2/A7 aquifer, which is overlain by the Muwaqar marl aquitard. The exploited aquifer is recharged in the highlands and receives some inflow through upward leakage from the deeper A4 and Kurnub aquifers.

Groundwater recharge to the Upper Cretaceous aquifers in the northeastern Jordan valley and tributary catchments (Yarmouk, Wadi el Arab, Wadi Jarim, Wadi Yabis) is estimated at 127×10^6 m^3/a, of which 100×10^6 m^3/a discharge in spring flow and base flow in the tributary wadis. Groundwater extraction through wells of 73×10^6 m^3/a is considered to produce heavy overexploitation of the groundwater resources.

In the *southeastern Jordan valley* catchment, fresh water in the Upper Cretaceous carbonate aquifer system and brackish water in the deeper Lower Cretaceous

Kurnub sandstone aquifer flows from the highlands and the escarpment toward the Jordan–Dead Sea valley. Main discharge zones are found in wadi sediments in the lower reaches of the tributary wadis. The groundwater of the Upper Cretaceous carbonate aquifer system is recharged in the highlands of Aman – As Salt and around Wadi Mujib. The deeper sandstone aquifer complex receives groundwater mainly from inflow from sandstone aquifers of the Interior Shelf, supplemented by leakage from the overlying carbonate aquifers and very limited recharge on outcrops on the escarpment.

Renewable groundwater in the southeastern Jordan catchment is estimated at 10×10^6 m^3/a.

2.4.3.4 Wadi Araba

Wadi Araba may be divided into a northern segment which drains to the Dead Sea, and a southern segment south of the water divide at Jebel er Risha (about 250 m above sea level in the central Wadi Araba) draining to the Gulf of Aqaba. Permanent surface run-off exists neither in the northern nor in the southern regime. In northeastern Wadi Araba, the groundwater flows in a westerly direction with a component toward north to the Dead Sea. In the southeastern part of Wadi Araba, groundwater flow is directed toward the Red Sea in the south.

Recharge in Wadi Araba comes mainly from precipitation on the adjoining highlands in the east and lateral inflow into the fluviatile and alluvial deposits on the wadi floor. A part of the recharge takes place along the wadi courses of the tributary wadis and Wadi Araba itself. The considerable intermittent surface runoff and partly permanent baseflow from the mountains east of the Wadi Araba rift valley, which receive more than 300 mm of precipitation annually, infiltrates completely into the unconsolidated Quaternary sediments within the depression. Baseflow in wadis on the southern escarpment of the highlands of Jordan, the catchment of Ghor Safi–Wadi Araba, is around 76×10^6 m^3/a.

2.4.3.5 Lebanon Mountains

The Lebanon mountains comprise, according to geomorphologic features and geologic structure, several extensive groundwater flow systems in karst aquifers with catchments of several hundreds of km^2. A large number of groundwater flow systems with smaller dimensions are superimposed above the main karst flow systems or extend over catchments limited by outcrops of low permeability formations.

The karstified Jurassic and Upper Cretaceous carbonate formations constitute important aquifers with numerous groundwater flow systems of local extent and a few major flow systems with sub-regional extent. Groundwater discharges in the mountain area from several perennial springs and from many seasonal springs.

Spring discharge from the Mesozoic karst aquifers in the northern Lebanon mountains feeds the headwaters of Nahr Oustouene and Nahr Arka, which run into the Akar plain, and sustain base flow in the river systems of Nahr Abou Mousa–el Bared and Nahr Abou Ali. To some extent, spring discharge from the Jurassic aquifer reinfiltrates into outcrops of the Upper Cretaceous Sanin limestones.

Hydrologic–hydrogeologic regimes in the Lebanon mountains are, in general, rather complex with various interconnections between surface and subsurface flow:

- Streamflow sustained by groundwater discharging at high elevations may recharge aquifers at lower mountain slopes
- Interconnections between different aquifers and between adjoining sub-basins are created by major faults with high throw and locally by abundant minor faults

Khair et al. (1992) defined hydrogeologic units on the territory of Lebanon according to relief, river channels, water divides, faults, anticlinal axes, dip direction of rocks, direction of groundwater flow, synclinal structure, river catchments. The Lebanon mountain area includes around 35 of these hydrogeologic sub-basins.

The main groundwater divide between the catchments of the Mediterranean Sea and the Bekaa valley coincides approximately with the surface water divide connecting the main peaks of the Lebanon mountains and is situated generally at distances of 26–36 km from the Mediterranean Sea coast and 4–16 km from the Bekaa valley.

Groundwater movement in the *northern Lebanon mountain range* is largely controlled by structural and morphologic features. Groundwater discharges in several large perennial springs from the Jurassic and Upper Cretaceous karst aquifers at altitudes between 750 and 1,700 m asl. The northern Lebanon mountain groundwater sub-basin extends in the east to the main water divide on the mountain crest and to the Yamoune fault, which cuts off the Jabal Akroum massif. In the west and northwest, the sub-basin is delimited by a large flexure from the Tell Kalakh volcanic massif, the Akar plain and the Koura plateau. In the south, an approximately west–east directed fault system separates the northern Lebanon mountains from the central Lebanon massif.

Groundwater flow in the mountain area is generally directed toward SW to SSW with numerous springs issuing in particular at the outcrop boundary of the Upper Cretaceous or Lower Cretaceous aquitards.

In the Upper Cretaceous Sanin aquifer, a sub-regional groundwater flow system is directed toward large perennial springs at Rachin, which are situated on the boundary of the Upper Cretaceous aquifer and the overlying Chekka marl aquitard at around 300 m asl. A significant percentage of circulating groundwater of the northern Lebanon basin mountains reaches, however, the Mediterranean Sea coast at Chekka through a confined section of the Sanin aquifer.

A general groundwater balance of the Upper Cretaceous Sanin aquifer of the northern Lebanon mountains assumes a mean recharge of 585 mm/a or 42% of precipitation, sustaining a total mean annual discharge of 13 m^3/s in springs within the mountain area, under the Mediterranean Sea and on the coastal plain near Chekka. Submarine discharge may account for about 40–50% of the total net discharge.

Table 2.6 Mean discharge of major springs at the west slope of the Lebanon mountains after Khair et al. (1992), Shatilah, UNDP (1970)

Spring	River catchment	Altitude (m asl)	Discharge m^3/s	Aquifer
Dalle	Nahr Jaouz	635	1.93	Jurassic
Afka	Nahr Ibrahim	1,150	4.62	Upper Cretaceous
Ar Rueis	Nahr Ibrahim	1,260	3.2	Upper Cretaceous
Al Asal	Nahr el Kelb	1,350–1,660	0.8	Upper Cretaceous
Laban, As Saqia, Sanin	Nahr el Kelb		2.7	Upper Cretaceous
Jeita	Nahr el Kelb		4.48	Jurassic
Antelias			0.56	
Ain ed Delbe	Nahr Beirut		2.2	Jurassic
Safa	Nahr Damour	1,100	1.43	Jurassic
Barouk	Nahr Awali	1,240	1.03	Jurassic

Several large perennial springs sustain the base flow in major rivers, which descend on the western mountain slope to the Mediterranean Sea: Nahr Jaouz, Nahr Ibrahim, Nahr el Kelb, Nahr Beirut (Table 2.6 and Fig. 2.9).

Large springs are located

- At >1,000 m asl along the lower boundary of the outcrop belt of the Upper Cretaceous aquifer of the high mountain area in the catchment of:
  - Nahr Ibrahim: springs Afka and Rueis
  - Nahr el Kelb: springs Al Asal, Laban, As Saqie, Sanin
- Along the lower boundary of the outcrop belt of the Jurassic aquifer, occupying the western part of the central Lebanon mountains, at elevations between 200 and 635 m asl in the catchments of:
- Nahr Jaouz: spring Ad Dalle
- Nahr el Kelb: Jeita
- Nahr Beirut: Ain ed Delbe

Jebel Akroum – on the northeastern tip of the Lebanon mountains with a maximum peak altitude of 1,089 m asl – comprises a separate groundwater flow system between the Yamoune fault in the west and the main Lebanon water divide in the east. Springs of intermediate size discharge in the Jebel Akroum area from the Upper Cretaceous aquifer into the Nahr el Kebir el Janoubi stream system.

Groundwater flow in the *Akar plain* is generally directed toward the sea coast, in the southern part of the plain toward Nahr el Kebir el Janoubi. The shallow aquifers and the deeper Upper Cretaceous aquifer are probably hydraulically connected.

Estimates of groundwater recharge in the catchment area of the Akar plain, extending over around 1,050 km^2, indicate a total volume of groundwater flow of 170×10^6 m^3/a, part of which is extracted by irrigation schemes. It has been assumed that a substantial percentage of the groundwater flow volume discharges into the Mediterranean Sea.

On the western flank of the anticline forming the core of the *southern high Lebanon mountains*, large springs rise at the lower outcrop boundaries between the Jurassic and Upper Cretaceous aquifers and the Lower Cretaceous aquitard. The springs feed the base flow in Nahr Damour and Nahr Awali.

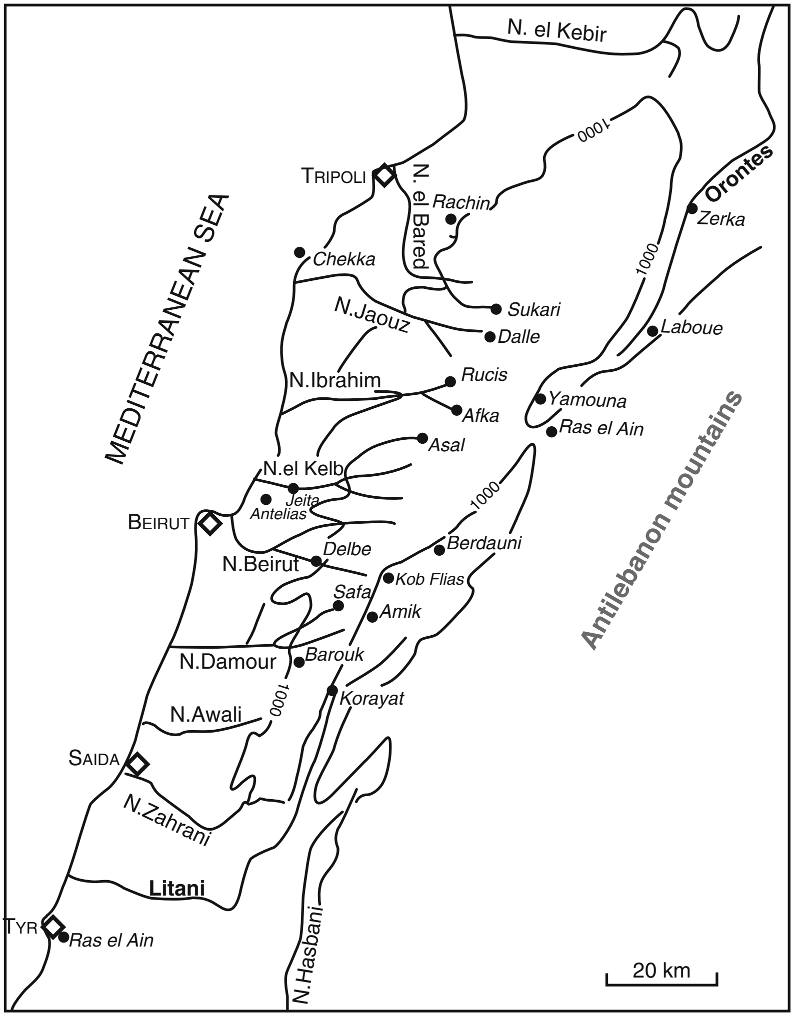

Fig. 2.9 Main wadis and springs in the Lebanon mountain area and the Bekaa. After Khair et al. (1992), Nations Unies (1967). • spring (ain); N. nahr (stream); ___1000___ topographic contour line 1,000 m asl

On the lower western slopes of the *southern Lebanon mountains*, extensive outcrops of the Lower Cretaceous marl aquitard and of the Chouf sandstones divide the karst aquifer system, comprising here prevailingly the Upper Cretaceous Sanin aquifer, into numerous catchments with generally limited extent.

A number of SW–NE to WSW–ENE directed faults and the large SSE–NNW oriented Rum fault dissect the *southwestern hill zone of the Lebanon range* into a complex pattern of tectonic units. Groundwater flow toward the Mediterranean

Sea in the west and to the Houle graben in the east appears to be, to a considerable extent, influenced by the tectonic structure.

The karstic Upper Cretaceous and Jurassic aquifers of the *eastern slope of the Lebanon mountains* are separated into a number of groundwater flow compartments. On the narrow steep slope sections west of the Yamoune fault, groundwater flows generally in an eastward direction. The Yamoune fault acts as barrier at least along part of its extent, causing groundwater discharge from the Upper Cretaceous aquifer section in several springs, in particular Ain Yamoune in the Orontes river catchment with an average discharge of 2.8 m^3/s.

Further important springs issuing along the Yamoune fault are the spring Berdauni from the Upper Cretaceous aquifer in the northern part, springs Kob Elias, Amik, Korayzat from the Jurassic aquifer in the southern part. To some extent, subsurface flow from the eastern mountain slopes reaches the Bekaa plain. On the northeastern mountain sector east of the Yamoune fault, groundwater systems with northeast and south direction feed large springs within the Bekaa valley.

2.4.3.6 Antilebanon Mountains

Groundwater flow in the karst aquifers of the Hermon–Antilebanon mountains is mainly directed to spring discharge areas located on tectonic or stratigraphic boundaries. Springs with high perennial discharge are:

- On the western slope of Mount Hermon: springs Hasbani (Upper Cretaceous aquifer), Chebaa, Sreid and Wazzani (Jurassic)
- On the eastern slope of Mount Hermon: Aouaj spring (Jurassic)
- On the western slope of the northern Antilebanon mountains: springs Ras el Ain at Baalbek, Laboue (Upper Cretaceous)
- On the eastern slope of the northern Antilebanon mountains: Ain Barada (Jurassic) in the Zebedani intermountain basin, Ain el Fije (Upper Cretaceous) in the Barada valley

To some extent, groundwater of the Upper Cretaceous aquifer moves from the mountain area into the adjoining Bekaa valley and Damascus plain.

Ain el Fije, the largest spring in the Antilebanon mountains, issues on the left bank of the Barada river at an altitude of 860 m asl. The spring drains a large catchment of fissured and karstified limestones and dolomites of Cenomanian–Turonian age. Mean discharge is 7.7 m^3/s. Base flow from the spring during the dry season is around 2.5 m^3/s sustained from groundwater storage of about 3.9×10^9 m^3. Ain Fije is the major source of water supply of Damascus City.

Ain Barada issues in the Zebedani valley at 1,100 m asl from Jurassic limestones, with a mean discharge of 3.3 m^3/s. Apart from Ain Fije and Ain Barada, the Barada river receives various minor tributaries, which are fed from springs at altitudes of 1,200–1,750 m asl. The 82 km long Barada river drains a catchment of 1,450 km^2 and has a mean annual discharge of 350×10^6 m^3.

The headwaters of the Aouaj river rise on the eastern flank of Mount Hermon at altitudes of 1,300–1,400 m asl. The Aouaj river has a length of 91 km; mean annual flow is 100×10^6 m^3.

Barada and Aouaj feed the Ghouta oasis in the Damascus plain.

Many small springs issue from shallow aquifers on the mountain slopes and in intermountain basins (Ponikarov et al. 1967b):

- From Bajocian limestones at Arne on the foot of Mount Hermon
- From Aptian and Albian sandstones and limestones of Mount Hermon
- From Lower Cretaceous limestones (Aptian) and sandstones (Albian) in the Zebedani intermountain basin
- From Jurassic (Oxfordian) limestones on the southeast slope of Mount Hermon
- From terrigenous formations (loam, sandy loam, pebbles, lacustrine marls and limestones) at several structural–morphologic depressions between the Antilebanon mountain chains and in the Qalamoun area

Groundwater flow in aquifers of the Damascus plain is directed mainly from the western and northwestern margins toward discharge zones around Lake Ateibe and Lake Hijane in the east. Some subsurface outflow appears to leave the Damascus plain toward east (southern Syrian steppe) and south (Yarmouk groundwater basin).

On the Qalamoun high plain, groundwater flow probably follows mainly the NNE direction of Wadi Mjarr.

2.4.3.7 Bekaa Valley

Groundwater movement within the Bekaa valley generally follows the topographic slope from the foothills toward the axis of the valley and, along the valley axis, toward NNE and SSW, respectively. The groundwater divide between northward flow in the Orontes sub-basin and southward flow in the Litani sub-basin is located approximately on the topographic vertex of the valley near Baalbek with a culmination of the groundwater surface at around 1,010 m asl. The groundwater surface descends to around 700 m asl near Hermel at the northern end of the valley and to 800 m asl at Qaraoun in the south. In the north, the valley grades into the Homs depression.

East of the Yamoune fault and north of the Bekaa water divide between Orontes and Litani river catchments, groundwater flow in the Upper Cretaceous aquifer is directed toward northeast to spring discharge areas in the Bekaa plain.

2.4.3.8 Ansariye Mountains

The main volume of groundwater recharged on the karstic surfaces of the Ansariye mountains circulates in the Mesozoic carbonate aquifers with general flow direction toward the Mediterranean Sea coast.

The groundwater divide between the Mediterranean Sea and the Orontes sub-basins is located along the anticlinal crest at a distance of 2–5 km from the Ghab valley and of around 30 km from the sea coast.

Cenomanian–Turonian limestones and dolomites form an extensive main aquifer on the western slope of the Ansariye mountains. Groundwater flow in the Cenomanian–Turonian aquifer of the northern part of the mountains is directed toward south–southwest to the large springs Banias and Nahr el Sinn, with mean discharges of around 1.5 and 10.5 m^3/s, respectively. Groundwater storage in the catchment of Nahr el Sinn is about 700×10^6 m^3.

In the southern part of the mountains, groundwater in the Jurassic and Cenomanian–Turonian aquifers moves prevailingly toward west and southwest to the coastal area around Tartous. Significant volumes of groundwater may discharge from the Cenomanian–Turonian aquifer system directly into the Mediterranean Sea.

At the foot of the steep slope of the Ansariye mountains on the boundary of the Ghab valley, various springs with discharge in the order of 100 l/s drain catchments of generally limited extent in the Jurassic carbonate aquifer. At the southwestern edge of the Ghab valley, the spring of Abou Qbeis drains a relatively large catchment with a mean discharge of 0.7 m^3/s.

2.4.3.9 Eastern Catchment of the Middle Orontes Area

Groundwater movement in the Cenomanian–Turonian aquifer in the eastern catchment of the middle Orontes sub-basin is directed to discharge points in large springs located at altitudes of 172–180 m asl within the Orontes valley and along the border of the Ghab graben. Major discharge points are the springs at Tell Ayoun near Sheizar, where a mean volume of 5.8 m^3/s flows directly into the Orontes river, and Ain et Taqa and Ain el Moudiq on the edge of the Acharne plain, Jebel ez Zaouiye and Ghab valley, with mean discharges of 3.8–5.7 and 1.3–1.8 m^3/s, respectively.

The subsurface catchment of the Cenomanian–Turonian aquifer system draining into the Orontes–El Ghab depression probably extends far to the east until the northern Palmyrean mountains. Main recharge to the Cenomanian–Turonian aquifer certainly occurs on the fissured and partly karstified outcrops of the limestones and dolomites between Masiaf, Hama and Jebel ez Zaouiye. Additionally, some subsurface inflow comes from the vast area of extent of the aquifer east of the outcrop areas.

Groundwater flow in shallow aquifers is partly directed to the closed basins further east on the Aleppo plateau and, to some part, to local discharge areas, e.g. small seasonal springs on Jebel ez Zaouiye or to areas like Maaret en Naamane where groundwater is extracted from shallow wells. A large amount of the seasonally recharged groundwater leaks, however, into the main Upper Cretaceous aquifer system discharging along the rift valley.

Various springs with low to medium discharge volumes issue along the boundary of the rift valley with Jebel ez Zaouiye and with the Idleb plateau. These springs are alimented mainly from Paleogene nummulitic limestone and chalk aquifers.

In the Acharne plain, Pliocene deposits composed of marls and sandstones provide a shallow aquifer, which is exploited by wells of a few tens of metres depth with generally low yields. The Pliocene aquifer feeds several small springs with mean discharges of 10–19 l/s.

References. Agrocomplect (1984–85), Al Charideh (2007), Bajjali (2006), Chebaane et al. (2004), ESCWA (1999a: 108 ff.), Gat and Dansgaard (1972), GTZ and NRA (1977), Gvirtzman (1994), Hobler et al. (1991), Hughes et al. (2008), Issar (1990), Kareh (1967, 1968), Kattan (1996a), Kozlov (1966), Kroitorou et al. (1985, 1992), Margane et al. (2002), Mijatovic and Bakic (1966), Ponikarov et al. (1967b), Salameh (1996, 2004), Salameh and Udluft (1985), Scarpa (1994), Shaban et al. (2006), Sunna (1995), Wagner (1996a).

2.5 Groundwater Salinity and Hydrochemistry

2.5.1 Mesozoic Karst Aquifers

2.5.1.1 General Hydrochemical Features

The mountain and highland ranges in the northwest of the Arabian Plate – the highlands of Jordan and Judea, the Lebanon, Antilebanon and Ansariye mountains and Jebel ez Zaouiye – comprise karstic Mesozoic limestone and dolomite aquifers, which receive significant recharge. These aquifers contain, in the unconfined zones, a group of waters with rather uniform hydrochemical composition characterized by predominant Ca, Mg and HCO_3 ions and relatively low salinity, a composition which is dominated by limestone and dolomite dissolution, typical for karst environments. Representative for the karst waters of the northwestern mountains and highlands is e.g. groundwater issuing in the large spring Ain el Fije in the Barada Valley upstream of Damascus. Hydrochemical parameter values of Ain el Fije are:

Salinity 230 mg/l TDS
HCO_3 170 mg/l, SO_4 5 mg/l, Cl 6 mg/l
Mg/Ca ratio 0.6

Ain el Fije drains a catchment area of several hundred km^2 in the Antilebanon mountains with a mean annual precipitation of 800 mm. The mean residence time of the spring water in the aquifer is 20–50 years.

HCO_3 and Ca concentrations of Ain el Fije are slightly higher than in very young groundwater recharge (Table 1.6), reflecting a stronger impact of carbonate dissolution during a somewhat longer retention period in the Ain el Fije spring water.

Groundwaters with a hydrochemical composition similar to the Antilebanon karst groundwater occur in wide areas of the northwestern mountain and highland sub-region in:

- The highlands of Jordan: Humar (A4) and Aman–Wadi Sir aquifers
- The Upper Cretaceous mountain aquifer in the Jerusalem–Jericho area of the West Bank
- Jurassic and Cenomanian aquifers in the Lebanon mountains
- Cenomanian–Turonian aquifers in the Ansariye mountains

Mean hydrochemical parameter values of these waters are in the following ranges:

- Salinity 180–710 mg/l TDS
- HCO_3 200–300 mg/l
- Cl 15–45 mg/l
- SO_4 9–45 mg/l
- Mg/Ca ratio generally 0.4–0.7

The hydrochemical composition is controlled primarily by dissolution of limestone and dolomite, which can be represented schematically as

$$CaMg(CO_3)_2 + 2CO_2 + 2H_2O \rightarrow Ca + Mg + 4HCO_3.$$

2.5.1.2 West Bank: The Judean Highlands

The main aquifer of the West Bank is constituted by karstified limestones and dolomites of Upper Cretaceous age (Hebron and Jerusalem formations, Cenomanian–Turonian, "mountain aquifer"). Groundwater with the typical hydrochemical composition of the karst water group of the northwestern highlands are found in the main recharge zone of the Judea aquifer – the outcrop areas along the anticlinal mountain crest. The groundwater in the phreatic part of the Judea aquifer is Ca–Mg–HCO_3 type water with low salinity of around 150–500 mg/l TDS, Cl concentrations in the range of 30–48 mg/l and Mg/Ca ratios of generally 0.7–0.9. These groundwaters, characterized by recent recharge and limestone–dolomite dissolution, discharge in springs, which are fed by phreatic or perched groundwater that flows in the upper part of the Judea group sequence through dolomites and limestones. Groundwater with similar hydrochemical composition is found in wells situated close to the recharge areas (Fig. 2.10).

Downstream of the recharge area, the Judea aquifer is mostly confined under the Mount Scopus aquiclude. Springs with the typical karst groundwater are situated on the northern mountain slope in the Jericho area at elevations between 300 m asl and 200 m below sea level at distances of up to 22 km from the recharge area: the springs Qilt, Fara and Fawar along Wadi Qilt, springs Duyuk, Nueima and Shosa, the spring group of Ain Sultan, and Ain Elisha near Jericho. The springs form outlets of an old karst system developed in the upper part of the Judea group aquifer.

Wells situated in the Jericho area extract groundwater with salinities of around 1,000 mg/l TDS and somewhat elevated Mg, Na and Cl concentrations. "These trends can be explained by intermixing of ground water originating from the Rift

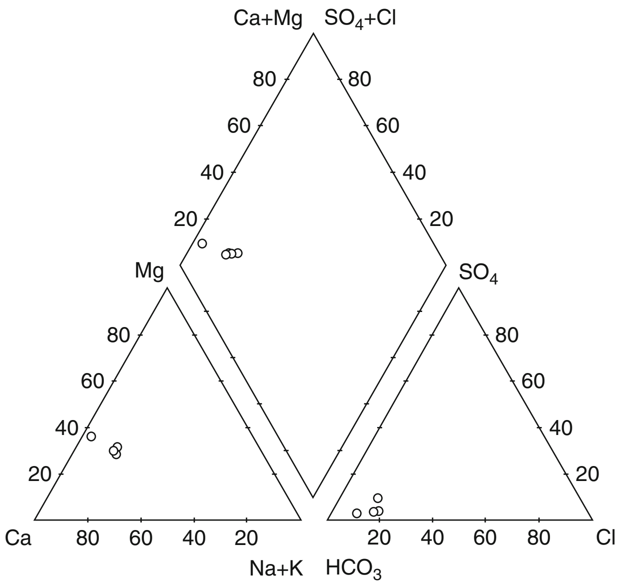

Fig. 2.10 Piper diagram: Spring water samples from the Judea aquifer of the West Bank. Springs Fara, Fawar, Qilt and Elisha, mean values, data from Kroitorou et al. (1985)

Valley Fill, and interaction with the aquifer rocks, which change in composition from limestone in the west to dolomite in the east" (Kroitorou et al. 1992).

The main springs discharge water from an upper fast-flow karstic system, where an impact of water–rock interaction after the recharge process is rather limited. The springs constitute one hydrochemically homogeneous group. The wells tap deeper confined parts of the aquifer with longer retention periods and increasing groundwater salinity in direction of groundwater flow.

A major discharge zone of the Judea aquifer of the West Bank is situated at the Dead Sea shore at Ain Feshka with brackish water of around 3,000 mg/l TDS. In the Jordan valley, groundwater from the Judea aquifer mixes with brackish water in the overlying Quaternary aquifer.

Groundwater salinity in the Upper Cretaceous Judea group aquifer of the Tulkarm–Qalqiliya area on the western foreland of the Judean mountains is generally moderate with electrical conductivity values between 500 and 1,200 μS/cm and Ca and HCO_3 as predominant ions. The major ion composition varies in a relatively wide range. Mean concentrations of 80 samples are 87 mg/l for Cl, 23 mg/l for SO_4 and 320 mg/l for HCO_3. The Mg/Ca ratio is, on average, 0.8 (data from Shahab 1997).

Deviation of ion ratios from the typical groundwater of the Judea limestone–dolomite aquifer observed in many samples may be related to mixture with water from the overlying Avedat chalk aquifer; contamination from the surface may also have a locally significant impact.

2.5.1.3 Highlands of Jordan

Outcrops of Upper Cretaceous limestone and dolomite aquifers provide the main recharge zones of the highlands of Jordan in the Irbid, Ajloun, Wadi Sir areas and the northern Mujib sub-basin. The Upper Cretaceous karst aquifers of these areas contain prevailingly Ca–HCO_3 type groundwater with moderate salinity, typical for the karst groundwater group of the northwestern highlands. The characteristic composition of karst carbonate water of Ca–HCO_3 type with a total salinity around 400–700 mg/l TDS is found in springs, base flow and in wells in the aquifer outcrop area (Fig. 2.11).

Water of base flow fed by groundwater discharge from Upper Cretaceous aquifers in the Yarmouk river and in wadis on the northern part of the western escarpment of the highlands of Jordan is Ca–HCO_3 to Ca–Na–HCO_3 type water with salinities between 320 and 550 mg/l TDS.

Lloyd (1965) characterizes the limestone waters of the highlands of Jordan: "These waters belong almost completely to the Bicarbonate Group of waters and as would be expected contain a predominant amount of the Ca ion. The movement of water in limestones is essentially along joint and fracture plains with the result that the amount of rock surface in contact with the water is small compared to the volume of water transmitted. ... the inability of the water to penetrate the crystalline limestones such as those in A4 and A7 formations allows little

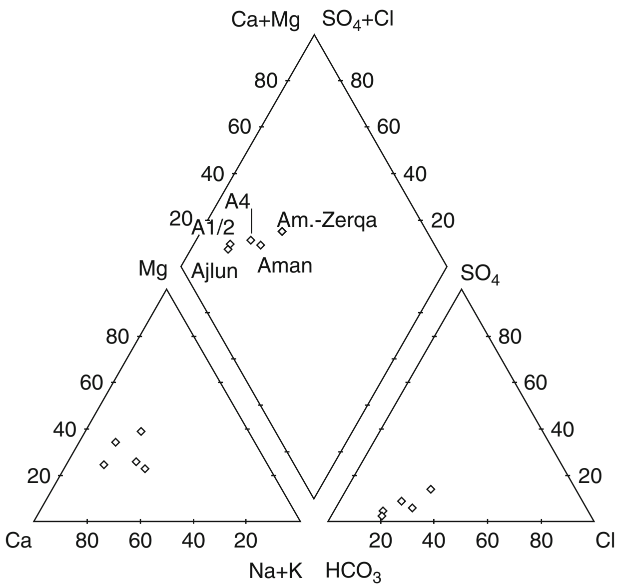

Fig. 2.11 Piper diagram: Groundwater samples from Upper Cretaceous carbonate aquifers of the highlands of Jordan. Mean values of analyses from the A1/2 (Naour) and A4 (Humar) aquifers, from the A7 (Wadi Sir) aquifer in the Ajlun–Irbid and Aman–Zerqa areas, and from the B2 (Aman) aquifer in the Aman–Zerqa area, data from Rimawi (1985)

opportunity for the extraction of the soluble chlorides and sulphates. This results in relatively pure waters".

Variations in the hydrochemical composition of groundwater in the outcrop areas of the Upper Cretaceous aquifer complex appear related mainly to the aquifer lithology. Cl and SO_4 concentrations are particularly low in karstic limestones of the Humar (A4) aquifer in the Irbid, Ajloun, Aman areas and somewhat higher in chalky limestones and dolomites of the Aman–Wadi Sir (B2/A7) aquifer. HCO_3 concentrations in the outcrop areas are generally in a range of 250–300 mg/l. Mg/Ca ratios vary in wide ranges between 0.2 and 1.1 with an average of 0.6.

Groundwater salinity increases, in general, along the path of groundwater flow from the recharge areas in the highlands to the areas with natural groundwater discharge or groundwater extraction downstream. Low salinities are characteristic for the outcrop area of the aquifer, in which tritium values of 4.5–10 T.U. indicate the occurrence of present-day recharge. Salinity in samples from the Upper Cretaceous Aman–Wadi Sir (B2/A7) aquifer ranges from less than 400 to 1,660 mg/l TDS.

The increase of salinity is accompanied by various hydrochemical processes resulting in changes of the hydrochemical composition of the groundwater in the Upper Cretaceous aquifer complex. Groundwaters from the outcrop area of the Aman–Wadi Sir (B2/A7) aquifer system have a geochemical facies typical of karst environments indicating limestone and dolomite dissolution during infiltration. Carbonate material of the aquifer is dissolved until the soil CO_2 introduced during recharge is consumed and a saturation equilibrium is reached at concentrations of around 400 mg/l HCO_3. In the confined parts of the aquifer, dissolution of sulfate and chloride from rock material leads to an increase in Cl and SO_4 concentrations; sulfate reduction and additional carbonate dissolution leads to an increase of HCO_3 concentrations. The redox processes are assumed to involve oxidation of organic carbon mainly in the confining aquitard of the Belqa formation (B3), reduction of SO_4 to HS, and reaction of the resulting CO_2 with aquifer carbonate to increase the HCO_3 concentration up to around 430 mg/l.

In the Ajlun highlands at altitudes between 620 and 1,000 m asl, groundwater in the outcropping Wadi Sir (A7) aquifer has a salinity of 340–435 mg/l TDS with very uniform hydrochemical composition of the water from different wells. The water infiltrating into the karstic formation attains a rather stable chemical composition with HCO_3 concentrations of 240–290 mg/l and Mg/Ca ratios of 0.5–0.6. Cl and SO_4 concentrations are relatively low with 32–43 mg/l Cl and $<$1–41 mg/l SO_4. Sources of Cl and SO_4 are probably atmospheric precipitation, small amounts of dissolution of salts and evaporite minerals from the marine carbonate aquifer and anthropogenic sources, such as wastes and fertilizers.

In the northern Wadi Mujib sub-basin, groundwater in the Aman–Wadi Sir (A7/B2) aquifer is prevailingly Ca–HCO_3 type water with salinities of around 350–600 mg/l. Groundwater with higher salinity of up to 1,600 mg/l TDS and Cl or SO_4 predominance is found at some locations.

In the Aman City area, the unconfined highly fractured Aman–Wadi Sir (A7/B2) dolomitic limestone aquifer is recharged from precipitation in the winter months and through leakage from the drinking water system and the waste water drainage system. Leakage from cesspools also contributes to the recharge. The groundwater is generally Ca–HCO_3 type water with electrical conductivity values between 450 and 1,350 μS/cm. Anthropogenic impacts are indicated by Cl concentrations of up to 125 mg/l and NO_3 concentrations exceeding 100 mg/l. Nitrate concentrations are particularly high in street runoff with 158–250 mg/l NO_3 in the city centre. A significant correlation between Ca and NO_3 concentrations indicates that dissolution of carbonate rocks is enhanced by the slightly acidic conditions created by the reaction of NO_3 with rain water.

Groundwater in the Upper Cretaceous aquifer in the Aman–Zerqa sub-basin downstream of Aman City is prevailingly Ca–HCO_3 type water with low to moderate salinity (electrical conductivity 295–1,170 μS/cm). NO_3 concentrations between 37 and 112 mg/l indicate wide-spread anthropogenic contamination. Groundwater tapped in deeper parts of the Upper Cretaceous aquifer complex appears to be characterized by Mg/Ca ratios close to 1, indicating an equilibrium with a dolomitic aquifer lithology. Cl and NO_3 concentrations are relatively low in these deeper groundwaters, which appear not to be affected heavily by contamination from the surface.

In deep confined parts of the aquifer complex, brackish groundwater with an electrical conductivity of 1,450 μS/cm is found under reducing conditions.

Ca–HCO_3 type groundwater with moderate salinity reaches within the Upper Cretaceous aquifer into the Jordan valley, where it discharges in thermal springs and is tapped in boreholes.

2.5.1.4 Lebanon Mountains

Groundwaters in the Jurassic and Upper Cretaceous aquifers of the Lebanon mountains are generally typical representatives of the hydrochemical group of karst waters of the northwestern mountains and highlands. Ion ratios are very similar to ratios of the Ain el Fije spring water. The groundwater is Ca–HCO_3 type water with salinities between 215 and 520 mg/l TDS, percentages of HCO_3 are generally in a range of 82–96 meq%, of Ca in a range of 54–82 meq%. HCO_3 concentrations are 230–570 mg/l in the Cenomanian–Turonian aquifer, 215–510 mg/l in the Jurassic aquifer. Mg/Ca ratios range between 0.3 and 0.4 in the Cenomanian–Turonian aquifer and vary from 0.1 to around 1 in the Jurassic aquifer.

Along the Mediterranean Sea coast, Ca–Cl type water is found in the Cenomanian–Turonian aquifer with a salinity of around 750 mg/l TDS, Cl concentration around 250 mg/l and a Mg/Ca ratio of 0.7.

2.5.1.5 Antilebanon Mountains

The characteristics of karst groundwater from the Upper Cretaceous aquifer of the Antilebanon mountains, as represented by spring water of Ain el Fije, have been mentioned in Sect. 2.5.1.1. Variations in the hydrochemical composition of groundwater in the Cenomanian–Turonian aquifer of the Antilebanon mountains in Syria involve mainly variations in HCO_3 concentration, ranging from 110 to 220 mg/l, and of Mg/Ca ratios between 0.14 and 0.66 (Fig. 2.11).

Seasonal variations of the Mg/Ca ratio in the Ain el Fije spring water from 0.76 in the dry season to 0.6 in winter appear to be related to higher Ca dissolution in fresh recharge and a somewhat higher percentage of Mg in the groundwater storage in the dolomitic aquifer.

SO_4 concentrations in the typical groundwaters of the Cenomanian–Turonian aquifer are less than 20 mg/l. Higher SO_4 concentrations in some springs (30–130 mg/l) indicate a contribution from the Jurassic aquifer, which contains layers of gypsum and anhydrite.

Springs issuing from the Jurassic aquifer on the slopes of Mount Hermon have low salinities of 125–300 mg/l TDS. Mg/Ca ratios of 0.17–0.30 and low HCO_3 concentrations of 92–200 mg/l of these Ca–HCO_3 type waters may be related to very short retention periods, during which a hydrochemical equilibrium with the aquifer rocks has not yet been attained (Fig. 2.12).

Reported values of ion concentrations of groundwater from Jurassic and Upper Cretaceous aquifers of the western slope of the Antilebanon mountains show a homogeneous hydrochemical composition of Ca–HCO_3 type water with salinities of about 315 mg/l TDS and HCO_3 concentrations around 200 mg/l. Cl and

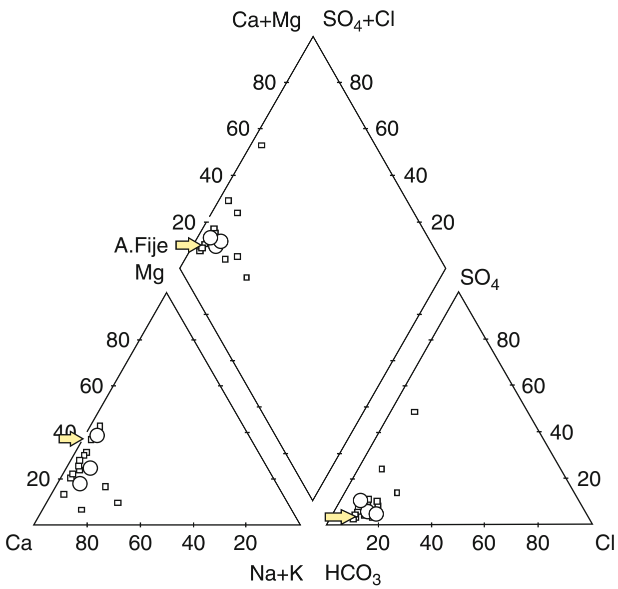

Fig. 2.12 Piper diagram: Spring water from Mesozoic aquifers of the Antilebanon mountains. □ Data from Syria: Ponikarov et al. (1967a), Kattan (1996a); ○ data from Lebanon: UNDP (1970)

SO_4 concentrations are generally low, Mg/Ca ratios range from 0.24 to 0.52. The hydrochemical composition corresponds closely to the composition of most groundwaters on the eastern slope of the Antilebanon mountains.

2.5.1.6 Northwestern Syria

Groundwaters of the Upper Cretaceous and Jurassic aquifers of the Ansariye mountains show, in general, the typical hydrochemical composition of the karst groundwaters of the northwestern mountains and highlands. They are represented by Ca–HCO_3 type waters with salinities of 330–460 mg/l TDS and HCO_3 concentrations of 180–340 mg/l. Mg/Ca ratios of most samples are in a range between 0.15 and 0.9. Cl and SO_4 concentrations are generally low. Slightly elevated Cl concentrations, up to 28 mg/l Cl, in the Upper Cretaceous aquifer of the southwestern part of the Ansariye mountains may be attributed to an impact of marly intercalations within the aquifer.

Water in several springs issuing on the eastern border of the Ansariye mountains has elevated Ca and SO_4 concentrations, up to 250 mg/l Ca and 570 mg/l SO_4. These elevated concentrations probably originate from gypsiferous layers in the Jurassic aquifer, which is tectonically uplifted in the core of the Ansariye anticline. The SO_4 concentrations show seasonal variations with lower values during the rainy season, attributed to an dilution effect from fresh recharge. Seasonal variations are also observed in Mg and HCO_3 concentrations in some spring waters with an increase of concentrations during the dry season. Probably the groundwater stored in the Jurassic aquifer over longer periods is characterized by somewhat higher Mg, HCO_3 and SO_4 concentrations in comparison to the groundwater recharge during the rainy season.

On Jebel ez Zaouiye and in the plateau and plain areas of the middle Orontes catchment (Masiaf plateau, Hama plateau, Acharne plain), waters of the hydrochemical group of karst waters of the northwestern highlands have been tapped in the Cenomanian–Turonian aquifer through several boreholes. These waters extracted from wells are Ca–HCO_3 type waters with a salinity of 375 to around 550 mg/l TDS, HCO_3 concentrations of 218–310 mg/l and Mg/Ca ratios between 0.5 and 0.9.

In the outcrop area of the Cenomanian–Turonian aquifer on the Masiaf plateau, alterations of the hydrochemical groundwater composition through anthropogenic contamination are indicated by NO_3 concentrations of 48–75 mg/l and elevated HCO_3 concentrations of up to 550 mg/l.

Groundwater with moderate salinity and low SO_4 concentration is found in Cenomanian–Turonian aquifer of the middle Orontes catchment only in areas, where the surface of the aquifer is exposed or situated under a cover of Pliocene–Quaternary terrestrial deposits. In the area east of the Hama–Acharne, where the aquifer is overlain by Campanian chalks and marls, the groundwater of this aquifer has elevated SO_4 concentrations of up to 530 mg/l, accompanied by relatively high Ca concentrations (up to 109 mg/l) and Cl concentrations (up to 140 mg/l).

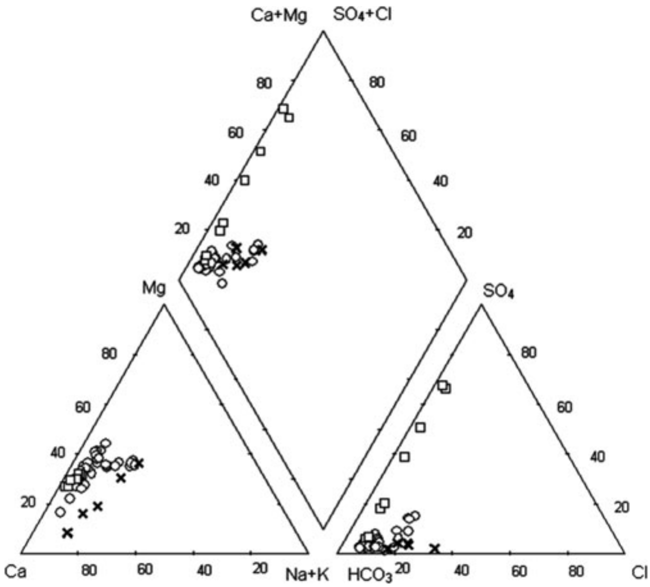

Fig. 2.13 Piper diagram: Groundwater samples from Mesozoic carbonate aquifers of northwestern Syria. ○ Cenomanian–Turonian, Jurassic, Ansariye mountains and Masiaf–Hama–Jebel ez Zaouiye area; □ Jurassic, eastern border of Ansariye mountains; **x** southwestern Ansariye mountains. Data from Boeckh et al. (1970)

The composition of that group of Ca–HCO_3 to Ca–SO_4 type waters may be interpreted as a mixture of local low salinity groundwater recharge with brackish sulfate rich groundwater, which prevails in the Upper Cretaceous aquifer in the area east of the Hama–Aleppo (Chap. 3). In the water discharging from the Upper Cretaceous aquifer in large springs on the Orontes river and on the boundary of the Ghab depression (springs Tel Ayoun, Ain et Taqa, Ain el Moudiq), relatively high SO_4 concentrations of 68–180 mg/l indicate components of the sulfate rich water in the sub-regional groundwater discharge (Fig. 2.13).

2.5.2 Nummulitic Limestone Aquifers

Eocene nummulitic limestone aquifers occur, in not very extensive areas, in Jebel Ansariye, Jebel ez Zaouiye and the southern Bekaa in Lebanon. Nummulitic limestones are composed chiefly of calcite from shells of foraminifera (nummulites) with low Mg content.

Waters from nummulitic limestone aquifers are typically Ca–HCO_3 type waters, characterized by high percentages of Ca and HCO_3 and low concentrations of Mg, Na, Cl and SO_4. Salinity of the waters from nummulitic limestone aquifers in Syria and Lebanon varies between around 250 and 400 mg/l TDS. HCO_3 percentages of

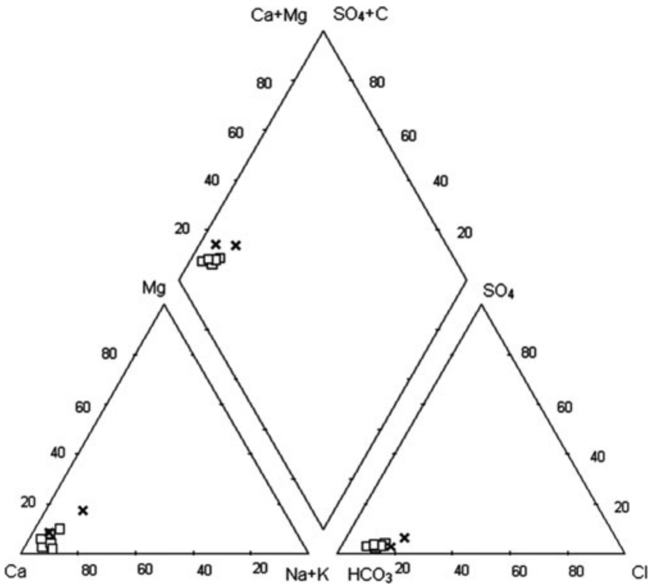

Fig. 2.14 Piper diagram: Groundwater samples from nummulitic limestone aquifers. □ northwestern Syria, data from Boeckh et al. (1970); • Bekaa plain, Lebanon, data from UNDP (1970)

the water samples from wells in Syria range from 80 to 88 meq%. Typical Mg/Ca ratios are 0.03–0.1 (Fig. 2.14).

2.5.3 Aquifers in Intermountain and Foreland Depressions

The rift valleys and plains on the foot of the northwestern mountains are main recipients and mixing zones of groundwater and surface water inflow from the adjoining mountain slopes. Salinity and hydrochemical composition of groundwater is influenced by subsurface inflow from the mountains, local mainly indirect recharge, salt water bodies in the centres of some plains and, in many areas, also by intensive agriculture.

2.5.3.1 Jordan–Dead Sea valley

Natural water occurrences in the Jordan–Dead Sea valley range from fresh water, issuing in springs on the fringes of the valley plain, to brines of the Dead Sea with a salinity of 300 g/kg TDS. The waters in that wide salinity range include a variety of hydrochemical types. The general salinity distribution in the shallow sand and gravel aquifer (Quaternary Jordan valley group) shows fresh water belts on the western and eastern fringes of the valley and a zone of saline water along the valley floor, the Zor, and around the Dead Sea. The fresh groundwater overlies the saline groundwater in a thin body and is restricted to the sand and gravel deposits on the valley margins and in fans protruding toward the valley floor. The groundwater with low salinity approaches, as lateral flow from the western and eastern margins of the valley, the central valley floor, which is occupied by the salt water body. The position of the interface between fresh water and salt water depends on the quantity of fresh water inflow and the lithologic composition of the Jordan valley deposits and is influenced by seasonal climatic variations and rates of artificial groundwater extraction.

Relatively stable interface conditions are maintained in the central Zor area of the valley, which is covered by the Lisan marls. Horizontal groundwater flow is very low within the marls and evaporation and solution of salts provide permanent sources of groundwater salinization. In some areas, the fresh groundwater extends in shallow lenses relatively far toward the valley centre, but a fresh water layer does not exist in the Zor area and in areas, where the Lisan marl formation replaces the sandy facies of the Quaternary Jordan valley deposits.

Some 15,000 years ago, most of the Jordan–Dead Sea valley was covered by the Lisan salt water lake with a lake water level at 180 m below sea level. The entire alluvial aquifer was then saturated with brine. Since the drying up of the Lisan lake, which left as remnant the present Dead Sea, the fresh water–salt water interface has been pushed from the fringes of the Jordan valley toward its central part by fresh water inflow. The aquifer was continuously flushed by lateral groundwater inflow and local fresh water recharge. "The flushing process of the brine from the aquifer following the base (lake) level drop is relatively rapid. In most cases, a few decades are sufficient for a complete flushing and only locally are brine relicts detected at higher levels" (Yechieli et al. 2001).

On the western side of the Jordan valley in the area around Jericho, fresh groundwater issues from the Upper Cretaceous aquifer in springs while water extracted from boreholes is generally brackish. The spring water represents discharges of the Ca–HCO_3 type water of the karst water group of the northwestern highlands. The well water shows a trend of increasing salinity and increase of major ion concentrations in direction of groundwater from west to east toward the valley floor. The hydrochemical data of the waters indicate a trend between two distinctive end members: Ca–(Mg)–HCO_3 type fresh water of the springs in the west to brackish Na–(Mg)–Cl water in the east. Mg percentages remain rather constant around 35–40 meq%, SO_4 percentages are generally below 20 meq%. The source of the elevated salinity in wells in the east downstream of Jericho, reaching up to 3,660 mg/l TDS and Cl concentrations of 1,860 mg/l, may be a deeper brine and/or leachate of the Lisan marls. In some wells, the groundwater quality appears to be influenced by contamination from agricultural activities.

Aquifers below the shallow Jordan valley aquifer are found in Upper Cretaceous limestones and dolomites (Aman–Wadi Sir aquifer, Judea aquifer) and, in some areas, in Paleogene chalks (Jenin aquifer).

The Upper Cretaceous aquifer system in the northern Jordan valley contains various types of fresh to brackish groundwater:

- Water with hydrochemical composition similar to groundwater in the recharge areas in the highlands with slightly to significantly higher salinity:
  - Ca–HCO_3 type groundwater with a salinity of around 500 mg/l TDS from the B2 (Aman) aquifer in the Mukheibe well field in the northern Jordan valley
  - Ca–Mg–HCO_3 type groundwater with salinities of 700–1,000 mg/l extracted from the A7 (Wadi Sir) aquifer in several boreholes in the northern Jordan valley
- Na–Cl type groundwater with salinities of 900–1,370 mg/l TDS discharging in springs and extracted from boreholes

The groundwaters are partly thermal with temperatures between 39°C and 54°C. The thermal groundwaters have a similar hydrochemical facies as modern groundwater from the outcrop areas, although Mg/Ca ratios and SO_4 concentrations are higher, indicating that dolomite and gypsum dissolution is continuing downstream of the recharge area. The carbonate equilibrium is maintained along the flow path by calcite precipitation.

Variations of Mg/Ca ratios between 0.4 and 0.9 may be related to different degrees of dissolution processes of dolomitic carbonates and mixing processes. Elevated Na and Cl concentrations (up to 300 mg/l Cl) found in some waters may originate from saline water in deeper sections of the Upper Cretaceous aquifer. Significant HS^- concentrations indicate an impact of sulfate reduction in the thermal groundwaters.

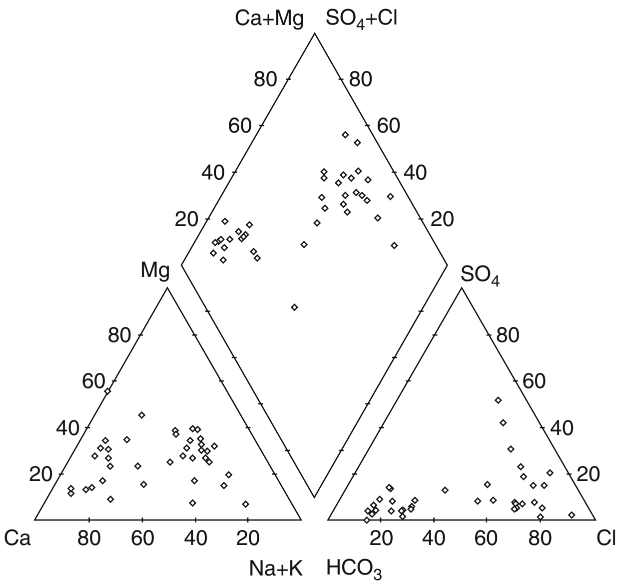

Fig. 2.15 Piper diagram: Groundwater samples from various aquifers of the Jordan valley. Data from Hirzalla (1973)

Thermal brackish water discharges in springs at various points on the eastern rim of the Jordan valley from sandstone aquifers of the Zerqa or Kurnub formations. The water of the thermal springs is mainly Na–Cl type water with salinities between 1,100 and 2,800 mg/l TDS.

Brackish Na–Cl type waters discharging from the Judea aquifer in the Feshkha springs on the eastern shore of the Dead Sea are assumed to constitute a mixture of trapped Mediterranean Sea water and inflowing ground water with no remarkable contribution of Dead Sea brines. The spring water has a salinity of 3,000 mg/l TDS and Cl concentrations of 1,660 mg/l. "...the Mediterranean Sea advanced into the Rift Valley, via the Escherlon Valley, in the geologically recent past, infiltrated into the tectonically shattered terrain and mixed with various amounts of the then prevailing groundwaters. Isolated pockets of these mixed waters became trapped and stayed there although the sea as a whole retreates" (Mazor and Mero 1969). The hydrochemical composition of the trapped sea water has been modified by reactions with the aquiferous rocks. Groundwater with similar hydrochemical characteristics occurs in springs and wells at various locations of the Jordan–Dead Sea valley from Lake Tiberias in the north to the southwestern end of the Dead Sea ("Tiberias–Noit water association" Mazor and Mero 1969). The age of the Mediterranean Sea intrusion into the rift valley is estimated to at least 18,000 years B.P.

In some springs on the eastern Dead Sea shore, saline springs with a Cl concentration of 24,000–40,000 mg/l TDS apparently represent diluted Dead Sea water.

Several springs with fresh to saline water issue in the Lake Tiberias (Buhaira Tabiriye) area at around 200 m below sea level on the northern end of the Jordan valley. In boreholes, fresh to brackish groundwater has been tapped in the area on the eastern shore of Lake Tiberias.

A chain of thermal springs rises along fault zones; the largest spring discharge is concentrated in the Al Himme (Hammat Gader) springs near the right bank of the Yarmouk river. Spring temperatures vary from 26° to 49°C, salinity from 600 to 1,400 mg/l TDS. The spring water is Ca–HCO_3 type water with nearly equal percentages of Ca, Na, HCO_3 and Cl in the higher mineralized waters. Springs on the western shore of Lake Tiberias are mainly brackish Na–Cl waters with salinities between 2,700 and 7,500 mg/l TDS and temperatures of 26–29°C. Salinity reaches 30,000 mg/l TDS in a thermal spring with a temperature of 64°C.

The brackish to saline waters on the western Lake Tiberias shore may be mixtures of three end members: fresh water, remnants of Mediterranean Sea water and rift valley brines. The waters on the eastern shore of Lake Tiberias "could have been formed through dissolution of slightly altered marine waters entrapped in the Judea Group aquifer mixed with diluted Rift Valley brines" (Arad 1988).

In northern Wadi Araba, tongues of brackish or fresh groundwater extend from the edges of the valley to the central zone with highly saline groundwater or overlie the saline groundwater. In the pre-development stage, the Quaternary aquifer contained fresh water with salinities rarely exceeding 800 mg/l TDS. Salinity levels of groundwater in production wells increased to $>$5,000 mg/l TDS. New wells tapped brackish water with TDS of 4,000–5,500 mg/l. Near the Dead Sea residual brines and salt deposits occur within the Quaternary sediments.

2.5.3.2 Bekaa and Middle Orontes Valley

Some plain zones of the Bekaa and the middle Orontes catchment are covered by young basin sediments, while in hill and plateau zones Mesozoic to Tertiary carbonate formations are exposed.

Main aquifers in the Bekaa plain are Quaternary terrestrial deposits and the underlying Cenomanian–Turonian carbonate aquifer. Groundwater in the Quaternary aquifer is generally Ca–HCO_3 type water with salinities of 500–1,000 mg/l TDS. In the southern part of the plain, pockets of brackish Ca–Cl water are found, probably related to impacts of intensive agricultural irrigation.

The Homs plain is covered widely by lacustrine Pliocene deposits, which provide a shallow fresh water aquifer containing Ca–HCO_3 type water with salinities of 300–600 mg/l TDS. Shallow fresh water also occurs in Pliocene–Quaternary terrestrial deposits of the Acharne plain. The Ghab valley, which is covered by Pliocene clayey marls and calcareous clays, contains no productive aquifer. Groundwater from the Mesozoic karst aquifers discharges along the boundaries of the valley.

2.5.3.3 Depressions of the Eastern Forelands of the Antilebanon Mountains

The Antilebanon mountains are adjoined in the east by the tectonic Damascus depression and the synclinal Qalamoun high plateau.

The Damascus plain comprises an important shallow aquifer composed of Quaternary fluviatile–terrestrial deposits above a complex tectonic basin structure with aquiferous Upper Cretaceous to Paleogene carbonate rocks and Pleistocene–Quaternary volcanics. Groundwater in the Quaternary aquifer of the western – upstream – part of the Damascus plain is generally fresh water of Ca–HCO_3 type with salinities between 300 and 550 mg/l TDS. Groundwater salinity increases in the middle and eastern parts of the plain to levels of generally 1,000–4,000 mg/l TDS with an increase of Cl and SO_4 concentrations. The highest groundwater salinities of around 5,000 mg/l TDS with prevailing Na–Cl waters are found in a wide belt in the east of the plain. The main zone of elevated groundwater salinization encloses the area of an ancient lake without outlet, the remnants of which were the now dried up lakes Ateibe and Hijane.

The main source of the increase of groundwater salinity in the downstream parts of the Damascus plain can be seen in evaporative enrichment in a closed basin environment. At present, the groundwater and hydrochemical regime in the Damascus plain is significantly influenced by urban and agricultural activities: water import from the Antilebanon mountains, deviation of surface water in channels, waste water irrigation return flow, groundwater extraction from wells.

The Qalamoun high plateau comprises a complex system of Upper Cretaceous and Paleogene carbonate aquifers covered by aquiferous terrestrial deposits of Neogene age. Groundwater in the shallow Neogene is generally fresh with EC values of 200 to 700 μS/cm. Elevated SO_4 concentrations are found in some wells tapping the deeper Upper Cretaceous aquifer, in particular the upper sections of the aquifer (Campanian–Maastrichtian), where SO_4 concentrations of up to 650 mg/l have been observed. High HCO_3 concentrations of up to 650 mg/l, occurring at some locations in the shallow aquifer, may indicate an impact of agricultural contamination.

Water extracted through shallow wells or qanats (falaj systems, Sect. 8.3) from Paleogene and Quaternary aquifers in the Qalamoun plain is prevailingly Ca–HCO_3 type fresh water.

References. Abumaizer (1996), Al Charideh (2007), Almasamir and Sarcis (1992), Arad (1988), Bajjali (2006, 2008), Bajjali et al. (1997), Batayneh (2006), Boeckh et al. (1970), Clark et al. (1995), GTZ and NRA (1977), Hirzalla (1973), Hobler et al. (1991), Kattan (1996a, b), Khayat et al. (2006), Kroitorou et al. (1992), Lloyd (1965), Mazor et al. (1973), Mazor and Mero (1969), Mazor and Molcho (1972), Nations Unies (1967), Parker (1970), Ponikarov et al. (1967b), Rosenthal (1987, 1988), Salameh and Rimawi (1984, 1987b), Salameh and Khdier (1985), Salameh et al. (2002), Salameh and Shaqur (1981), Shahab (1997), Shatsky et al. (1966), Sunna (1995), UNDP (1970), Wilson and Wozab (1954), Wolfart (1966), Yechieli et al. (2001).

2.6 Isotopic Composition of the Groundwater

2.6.1 Groundwater Age

^{14}C values of most groundwater samples from the higher reaches of the northwestern highlands vary between 55 and 62 pmc, reflecting a modern age of the actively circulating groundwater in the karst aquifers. In some springs, higher ^{14}C values were analysed (91 pmc in Elisha springs on the West Bank, 103 pmc in spring Al Faouar in the Ansariye mountains) indicating very recent (post-bomb) recharge after 1955.

^{3}H values of groundwater from the karst aquifers in the highland areas are reported in the following ranges:

Antilebanon 18–29 TU (data of 1979/80), 9–24 TU (data of 1989/90)
Ajlun–Nuaime area in the highlands of Jordan 4–10.5 TU (data of 1987–1995)
Springs in the Jericho area of the West Bank 7–22 TU (data of 1980s)

^{3}H values of 10–33 TU and a ^{14}C value of 58 pmc reflect recent groundwater recharge in groundwater of the Ansariye mountains.

All these karst groundwaters obviously contain significant components of recent recharge. For spring water of Ain el Fije with a ^{14}C value of 62 pmc, a mean retention period of the groundwater of around 50 years has been calculated. Spring discharge from the large reservoir of the Ain el Fije aquifer comprises a mixture of fast flowing recent groundwater and base flow of older groundwater. For the spring As Sinn – on the foot of the Ansariye mountains at the Mediterranean Sea coast – with a ^{14}C value of 58 pmc, a mean retention period of 60 years is estimated. For the karst groundwaters with ^{14}C values between 55 and 64 pmc, retention periods of some decades to a few thousand years can be assumed. The comparison of corresponding ^{14}C and ^{3}H values of aquifers on the Qalamoun high plain yields an initial ^{14}C value of 68 pmc, corresponding to an adjustment of the ^{14}C water ages by 3,000 years.

In the wadis running from the highlands of Jordan toward the Jordan valley, ^{3}H values range from below detection level to 10 TU. ^{14}C values of 42–64 pmc have been found at some locations in Wadi Ziglab and Wadi Yabis and in water of a spring on the rim of the Jordan valley.

In the carbonate aquifer of the highlands in Jordan south of Aman, detectable tritium levels occur predominantly in valleys and indicate the importance of indirect recharge. In many groundwater samples from recharge areas, ^{3}H is below detection level, implying that the large volumes of direct recharge can only move through a thin high permeability upper section of the aquifer over the top of the underlying slower moving older waters. Tritium levels decline with increasing well yield.

In the area around Lake Tiberias and the lower Yarmouk valley and in the lower reaches of Wadi el Arab, ^{14}C values in springs and boreholes vary from 3 to 18 pmc. Groundwater samples from these confined parts of the aquifers is generally free of detectable tritium. ^{14}C values appear to have been influenced by secondary hydrochemical processes in the aquifer: SO_4 reduction through oxidation of fossil organic matter and subsequent $CaCO_3$ dissolution. Corrections considering these hydrochemical processes lead to water ages of about 4,200–7,000 years at Mukheibe well field, corresponding to flow velocities of 10–15 m/a between the recharge area and the well field. Retention periods in the deeper less permeable aquifers are calculated as 7,000–15,000 years.

Groundwater ages in the carbonate aquifers of that area range up to 32,000 years, many groundwater samples have ^{14}C activities of less than 10 pmc and old groundwater is present even in the recharge mound areas.

Groundwater in some recharge areas on the top of the highlands is modern with ages of less than 4,000 years. High groundwater ages of up to 26,000 years are found in the southeast of the highlands north of Maan.

In the springs on the slope of the Judean highlands in the Jericho area, an unexpected trend of increasing ^{14}C values with distance from the recharge zone is observed. That trend can be explained by a mixing of recent fast flowing groundwater in an upper karst system with older deeper groundwater. For the relatively older groundwater, which has been tapped by boreholes, retention periods of 1,800–4,000 years were calculated. Springs on the mountain slope appear to contain admixtures of 20–70% of older groundwater. In the spring Ain Elisha downstream of Jericho at 200 m below sea level, only groundwater from the upper flow system is discharging. The end members of the mixed groundwater are represented by Elisha spring with a ^{14}C value of 90 pmc and by older water from boreholes with about 40 pmc.

2.6.2 Stable Isotopes of Oxygen and Hydrogen

2.6.2.1 Isotopic Composition of Precipitation

The precipitation throughout the eastern Mediterranean Sea area is characterized by a relatively large deuterium excess

$$d = \delta^2H - 8 \times \delta^{18}O > +15‰.$$

The scatter in the isotope content of precipitation with a high deuterium excess is inherited from processes over the sea. The Mediterranean Meteoric Water Line (MMWL), typical for rain in the eastern Mediterranean area, has been defines as

$$d = \delta^2H - 8 \times \ \delta^{18}O + 22‰.$$

Rain in observation stations at lower topographic altitudes is more enriched in heavy isotopes and the d value is lower than at mountain stations (Gat and Carmi 1970; Gat and Dansgaard 1972).

Mean stable isotope values of precipitation at stations in the highlands of Jordan, the Antilebanon and Ansariye mountains and adjoining plain areas and on the Mediterranean Sea coast are listed in Table 2.7 and Fig. 2.16.

Table 2.7 Mean $\delta^{18}O$ and δ^2H values of precipitation in different areas of the northwestern mountain and rift zone (data from Abumaizer 1996; Al Charideh 2007; Bajjali 2006; Kattan 1996c; Salameh 2004)

Area	$\delta^{18}O$ ‰	δ^2H ‰	d ‰	Altitude m asl
Highlands of Jordan	−6.63 to −7.25	−29.7 to −33.3	+23.3 to +26.1	555–1,475
Antilebanon mountains (Bloudan)	−8.55	−48.8	+19.6	1,540
Plains and valleys within the highlands of Jordan	−5.42 to −6.06	−23.2 to −26.5	+17.5 to +24.2	350–715
Homs plain	−6.42	−32.2	+19.2	490
Ansariye mountains	−7.3			1,000
Mediterranean Sea coast				
Tartous	−4.96	−22.9	+16.8	5
Bet Dagan	−5.29	−22.8	+19.5	
Jordan valley (Deir Alla)	−3.52	−13.2	+14.9	−224

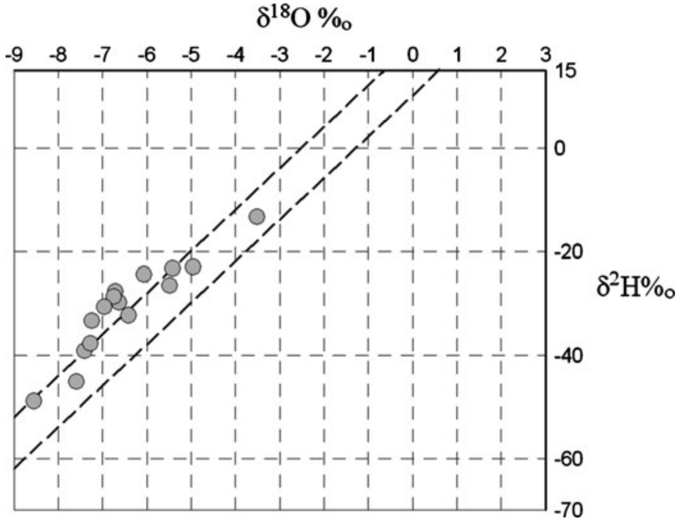

Fig. 2.16 $\delta^{18}O/\delta^{2}H$ diagram: Rain water samples of stations in the northwestern mountain and rift zone. Data from Almomani (1996), Kattan (1996c)

The following trends can be deduced for values of stable isotopes of oxygen and hydrogen in rain water samples:

- In the highlands of Jordan, $\delta^{18}O$ values are between −6.6 and −7.3‰ and d values > +23‰
- On the highest parts of the Antilebanon mountains, $\delta^{18}O$ is −8.55‰ and d +19.6‰
- Generally less negative $\delta^{18}O$ and lower d values are observed on the plain areas adjoining the highlands and, in particular, on the Mediterranean Sea coast and in the Jordan valley

In general, $\delta^{18}O$ values reflect the topographic altitude of the rainfall station. Altitude gradients of $\delta^{18}O$ values in different areas of the northwestern mountain and rift zone range between −0.2‰/100 m and −0.29‰/100 m.

2.6.2.2 Karst Aquifers of the Northwestern Mountain and Rift Zone

Most groundwater samples from the Jurassic–Upper Cretaceous karst aquifers of the northwestern highland zone scatter around the Mediterranean Meteoric Water Line

$$d = \delta^{2}H - 8 \times \delta^{18}O + 22‰.$$

with d values varying between around +19 and +24‰.

Ranges of $\delta^{18}O$ values in different areas of the highlands are

−5.7 to −6.7‰ in the highlands of Judea
−6.0 to −6.5‰ in the recharge areas of the highlands of Jordan
−7.0 to −8.2‰ on Mount Hermon
−7.7 to −9.0‰ in the Antilebanon mountains north of the Barada river
−5.0 to −6.8‰ in the Ansariye mountains

The differing ranges of $\delta^{18}O$ values in different areas of the northwestern highlands apparently reflect the altitudes of the recharge areas with most negative values in the up to more than 2,000 m high Antilebanon–Mount Hermon range. According to unpublished data, $\delta^{18}O$ values may also be more negative than −8‰ in aquifers of the Lebanon mountains, but no published data are available to the author.

d values of < +15‰ and deviations from general trends to less negative $\delta^{18}O$ values are observed in some wells in recharge areas, in aquifers influenced by local recharge at lower altitudes and in plain areas adjoining the mountain ranges, such as the Damascus plain, the Qalamoun high plateau and the Jordan valley.

2.6.2.3 Judean Highlands

$\delta^{18}O$ and $\delta^{2}H$ values of water from boreholes and springs on the eastern slopes of the Judean highlands are in the same range as those in the recharge area of the Upper Cretaceous aquifer on the mountain crest. There is no trace of paleowater recharged under a different climatic regime.

$\delta^{18}O$ and $\delta^{2}H$ values in the recharge area around Jerusalem as well as in the main springs in the Jericho area and in springs on the western shore of the Dead Sea are −5.6 to −6.7‰ and −21.1 to −25‰, respectively, with d between +20.5 and +28.6‰.

2.6.2.4 Highlands of Jordan

In the recharge areas of the Upper Cretaceous aquifer complex in the highlands of Jordan around Irbid–Ajlun, $\delta^{18}O$ values are generally between −5.9 and −7.0‰ and d values between +15.7 and +20.8‰.

In some wells tapping the outcropping A7 (Wadi Sir) aquifer in irrigation areas, significant seasonal variations of the isotope values are observed with less negative $\delta^{18}O$ and $\delta^{2}H$ values during the dry season. Seasonal variations of $\delta^{18}O$ values reach 1‰ and of $\delta^{2}H$ values 4.5‰. The range of d values of groundwater samples collected in the dry season extends to relatively low values of +10.7‰.

The variations reflect recharge of the groundwater from two sources. The main source of recharge is infiltration from precipitation on the outcropping karst aquifer, indicated by low groundwater salinity and remarkable ^{3}H contents in the groundwater. A second source of recharge is irrigation return flow. The irrigation water is enriched in heavier stable isotopes through evaporation and affects the isotopic composition of the groundwater in particular in the dry summer months.

From $\delta^{18}O/\delta^{2}H$ values of groundwaters on the slope of the highlands of Jordan to the Jordan valley, altitudes of recharge areas and interconnections between sub-aquifers can be deduced:

$\delta^{18}O$ and $\delta^{2}H$ values of groundwater in the recharge area of the Upper Cretaceous karst aquifer of the Yarmouk catchment in the highlands of Jordan range from −6 to −6.5‰ and −29 to −34‰, respectively, with d values around +18‰.

On the northeastern slope of the highlands, $\delta^{18}O$ values are generally in a range between −6.9 and −5.7‰ with d values varying mainly from +16 to +17.5‰. The values indicate an origin from recharge areas above 1,000 m altitude.

In the intermediate area between the highlands and the Jordan valley at altitudes of 100–400 m asl, wells produce locally recharged water from the B2 aquifer, which is slightly enriched in heavier isotopes ($\delta^{18}O$ −4.5 to −5.7‰, $\delta^{2}H$ −20 to −27‰). In the Jordan valley, where the head in the A7 (Wadi Sir) aquifer is higher than in the overlying B2 (Amman) aquifer and groundwater leakes upward into the B2 aquifer, the isotopic composition resembles that of the recharge area in the highlands ($\delta^{18}O$ −5 to −6‰, $\delta^{2}H$ −5 to −29‰).

Parts of the water from the confined A7 aquifer enters laterally into the Jordan valley deposits. The mixed water shows isotopic compositions, which lie between those of the A7 aquifer and the Jordan valley deposits of local recharge.

The isotopic composition of water from the fault springs Balsam and Maqla on the foothills resembles that of groundwater in the recharge areas with $\delta^{18}O$ values of around −6‰ and d values around +19‰. The isotope data of these springs, which are situated at 200 m below sea level, indicate recharge in the high mountain areas.

Boreholes tapping the A7 aquifer along the foothills of the Jordan valley, e.g. in the Mukheibe well field, generally produce a mixture of water with a major amount of groundwater flowing from the high mountain area and small proportions of water from the B4 aquifer recharged at lower altitudes. $\delta^{18}O$ values of these mixed waters range from −5 to −6‰, d around +20‰. The values fluctuate depending on pumping rates and well interferences.

Brackish groundwater recharged locally within the Jordan valley has $\delta^{18}O$ values from −3.2 to −4‰, ^{3}H values of 2.5–10.7 TU and EC values of 2,600–13,800 μS/cm. Mixtures of lateral groundwater inflow from the B2/A7 aquifer and of locally recharged groundwater in the Adasiye area in the Jordan valley foothills are characterized by low ^{3}H values and $\delta^{18}O$ values of −4.85 to 5.58‰ (Fig. 2.17).

Groundwater from wells tapping the Paleogene chalk and limestone (Rijam) aquifer around and east of Irbid have generally $\delta^{18}O$ values of −4.1 to −5.2‰, and d values around +12‰. ^{3}H values of 1.0–2.9 TU in most samples from these wells indicate a regime with some recent recharge in the shallow aquifer.

2.6.2.5 Antilebanon Mountains and Eastern Foreland

The $\delta^{18}O$ and $\delta^{2}H$ values of groundwater in the Antilebanon mountains and Mount Hermon reflect present-day recharge from Mediterranean precipitation

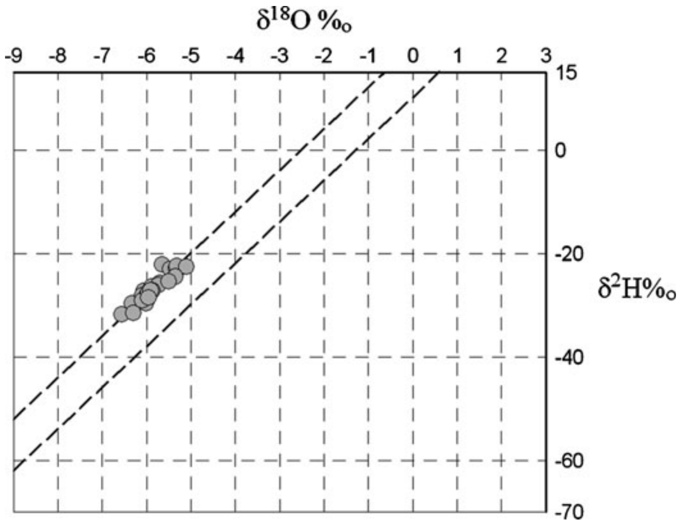

Fig. 2.17 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from Mesozoic aquifers in northwestern Jordan between the highlands of Irbid – Ajlun and the Jordan valley. Data from Abumaizer (1996)

with a deuterium excess of > +20‰. The $\delta^{18}O$ and $\delta^{2}H$ values are related to the mean altitude of the catchment area: $\delta^{18}O$ values of Ain el Fije, issuing at 860 m asl from a high mountain catchment of the Cenomanian–Turonian aquifer, are around −8.5 to −9‰, $\delta^{18}O$ values of Barada spring, situated at 1,100 m asl and draining a more locally restricted catchment in Jurassic limestones, are around −8.0‰. From the $\delta^{18}O$/altitude relationship the mean recharge altitudes of the groundwater discharged from the springs at Ain el Fije and at Barada are estimated to be 2,100–2,600 m asl and 1,700 m asl, respectively.

Relatively enriched $\delta^{18}O$ values in some wells in the Zebedani plain may indicate an impact of irrigation return flow ($\delta^{18}O$ −6.6‰, d +13.3‰).

$\delta^{18}O$ values in many spring waters of the Antilebanon mountains and probably in the Lebanon mountains are more negativ than −8‰, the most negative values of recent groundwater of the Arabian Plate (Fig. 2.18).

The $\delta^{18}O$ and $\delta^{2}H$ values of samples from springs and wells on the *Qalamoun* high plateau vary from a composition characteristic for present-day rainfall of Mediterranean origin (d values of +17.4 to +22.5‰) to a more enriched stable isotope signature (d values of +12.3 to +14.4‰). The less negative isotope signature in many groundwater samples from wells is attributed to the pronounced change of the local climate along the leeward slope of the Antilebanon mountains with an increasing evaporative isotope enrichment in a more continental climate.

Isotopic compositions are rather homogeneous over the different aquifer units of the Qalamoun groundwater system: the Mesozoic (Jurassic–Upper Cretaceous) carbonate aquifer, the Paleogene chalk and nummulitic limestone aquifer, and the shallow aquifer composed of Paleogene–Neogene detrital deposits.

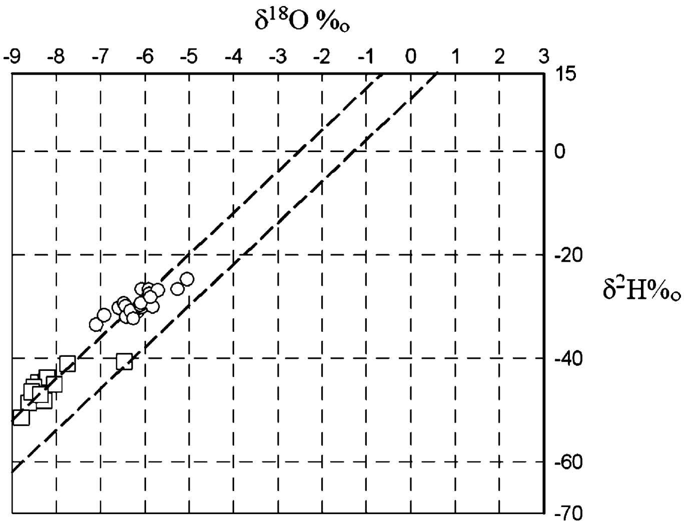

Fig. 2.18 $\delta^{18}O/\delta^{2}H$ diagram: Water samples from springs and wells in the Antilebanon and Ansariye mountains in Syria. □ Antilebanon mountains; ○ Ansariye mountains. After Kattan (1996a, c), Wagner and Geyh (1999)

The wide range of the altitude of the recharge areas between 800 m asl on the Qalamoun plateau and >2,000 m asl on the top of the Antilebanon Mountains is reflected in the wide scatter of the delta values along the Mediterranean Meteoric Water Line. A mean altitude gradient of −0.25‰ $\delta^{18}O$/100 m was estimated corresponding to the altitudes of the sampling points and of the hydrogeologically derived catchment areas as well as the corresponding $\delta^{18}O$ values (Fig. 2.19).

The sand and gravel aquifer of the *Damascus plain* in the foreland of the Antilebanon mountains is replenished from inflowing surface water through infiltration in streambeds, canals, and on irrigated fields, and, to some extent, through subsurface inflow and recharge from local precipitation. The recharge conditions in the plain are reflected in the pattern of $\delta^{18}O$ and ^{3}H values of the shallow groundwater (Table 2.8).

The wide distribution of $\delta^{18}O$ values of less than −7.5‰ in the Damascus plain shows the dominant influence of water originating in the higher Antilebanon mountain range on the groundwater regime of the plain. The water from the mountains reaches the plain through streamflow in the Barada and Aouaj rivers, the water supply network from Ain el Fije, and subsurface inflow in the Upper Cretaceous aquifer. d values in wide parts of the plain are around +20‰.

Groundwater from deeper boreholes in the Damascus plain has prevailingly $\delta^{18}O$ values of −8 to −9‰, d values around +20‰ and, in many cases, detectable tritium. The deep groundwater is probably recharged by relatively fast subsurface inflow from the Antilebanon mountains. The distribution of d, tritium and ^{14}C values indicates differing flow conditions in different parts of the plain: relatively

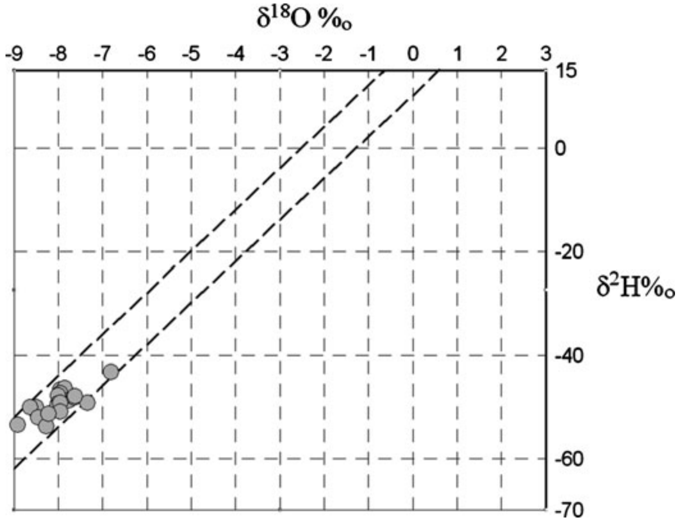

Fig. 2.19 $\delta^{18}O/\delta^{2}H$ diagram: Groundwater samples from the Qalamoun area, Syria. After Wagner and Geyh (1999)

Table 2.8 $\delta^{18}O$ and ^{3}H values in different parts of the Damascus plain (after Selkhozpromexport 1986; Kattan 1996c)

	^{18}O ‰	^{3}H TU
Infiltration of stream water along Barada river	−7.3 to −8.1	17–24
Infiltration within Damascus City of river water and of domestic waste water, originating prevailingly from Ain el Fije	−8.3	>17
Plain north of Damascus City (subsurface inflow of groundwater recharged in the Antilebanon–Qalamoun Mountains)	–8.2	>17
Areas with only local recharge	Less negative than −7	
Area around salt lake	–5.5 to –1.3	

fast groundwater movement from the west, inflow of older groundwater from the north or northwest.

2.6.2.6 Northwestern Syria

The stable isotope values of the water from springs in the *Ansariye mountains* prove its present Mediterranean origin with d values of around +20‰ (+18.4 to +23.8‰, Fig. 2.18). $\delta^{18}O$ values are less negative than those in the Antilebanon mountains according to the lower altitude of the mountain chain with peak elevations of 1,300–1,560 m asl.

$\delta^{18}O$ values reflect an altitude effect and allow an estimate of recharge areas of springs and boreholes situated in the coastal zone. Estimated altitudes of recharge areas of the groundwater in the coastal area range from 400–700 m asl on the northern mountain slopes ($\delta^{18}O$ −6.24‰) to 100–300 m asl for the southwestern mountain slopes ($\delta^{18}O$ −5.56‰).

Groundwater with d values of +15 to +18‰ and no detectable tritium is found in springs issuing from the Cenomanian–Turonian karst aquifer at the eastern border of *El Ghab*. The catchment of these springs extends into the more arid zone of the Syrian steppe.

References. Abumaizer (1996), Al Charideh (2007), Almomani (1996), Bajjali (2006, 2008), Bajjali et al. (1997), Clark et al. (1995), Gat and Carmi (1970), Gat and Dansgaard (1972), Gat et al. (1969), Kattan (1996a, b, c), Kroitorou et al. (1992), Lloyd (1981), Mazor and Molcho (1972), Prizgognow et al. (1988), Salameh (2004), Selkhozpromexport (1986), Wagner and Geyh (1999).