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Hydrogeologie, Ingenieurgeologie

ARMIN MARGANE, MANFRED HOBLER,
MOHAMMAD ALMOMANI & ALI SUBAH

Contributions to the Hydrogeology of Northern and Central Jordan

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With 18 figures and 11 tables

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Contributions to the Hydrogeology of Northern and Central Jordan

ARMIN MARGANE, MANFRED HOBLER, MOHAMMAD ALMOMANI & ALI SUBAH

Hydrogeology, aquifer, groundwater, groundwater recharge, spring discharge, water balance, monitoring, observation wells, hydraulic conductivity, hydrochemistry, groundwater model, water management

Jordan

Abstract: Within the framework of a technical cooperation project between the Water Authority of Jordan (WAJ) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany, a hydrogeological assessment of the groundwater resources of Jordan has been carried out in recent years. This investigation showed that the deficit in the groundwater balance has increased considerably over the past twenty years. In many areas water levels are rapidly declining and spring and base flow has ceased. Since the available water resources are limited, the only possible solution will be to decrease water spending in the agricultural sector and make additional resources available from careful exploitation of fossil groundwater resources, reuse of treated waste water, rainwater-harvesting, artificial recharge and modernizing the supply network. In addition to that, the increasing water quality problems have to be addressed.

[Beiträge zur Hydrogeologie im nördlichen und mittleren Jordanien]

Kurzfassung: Im Rahmen eines Projektes der Technischen Zusammenarbeit zwischen der Water Authority of Jordan (WAJ) und der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Deutschland, wurde in der jüngsten Vergangenheit eine hydrogeologische Gesamtanalyse der Grundwasservorkommen Jordaniens durchgeführt. Diese Untersuchung zeigte, daß das Defizit in der Grundwasserbilanz in den vergangenen zwanzig Jahren stark zugenommen hat. Indiz hierfür ist, daß in vielen Gebieten die Grundwasserspiegel rapide absinken und der Quell- und Basisabfluß z. T. auf Null reduziert ist. Da die verfügbaren Wasserressourcen begrenzt sind, wird die einzig mögliche Lösung darin bestehen, die Wassernutzung im landwirtschaftlichen Bereich zu verringern und zusätzliche Ressourcen zu erschließen, z. B. durch vorsichtige Erschließung von fossilen Grundwasservorkommen, Wiederverwendung von Abwässern, rainwater-harvesting, künstliche Grundwasserneubildung, und eine Modernisierung des Leitungsnetzes. Darüber hinaus nehmen die Probleme in Hinsicht auf die Wasserqualität zu und sollten vordringlich in Angriff genommen werden.

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Contents

1 Introduction

A comprehensive evaluation of the groundwater resources of the Hashemite Kingdom of Jordan was carried out in the late 1970s by the BGR (National Water Master Plan; GTZ & NRA 1977). Only about 400 water wells and a few deep oil exploration wells had been drilled at that time. Today there are approximately 5000 boreholes in Jordan and the information on the geological structure and the hydrodynamic pattern has increased considerably.

Within the framework of a technical cooperation project between the Water Authority of Jordan (WAJ)/Ministry of Water and Irrigation (MWI) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany, hydrogeological assessments of the groundwater resources of Jordan have been carried out in recent years. The results have been documented in a set of technical reports on the groundwater resources of southern (HOBLER et al. 1991) and northern Jordan (BGR-WAJ reports in the references). These reports represent an updated hydrogeological evaluation of the groundwater resources of the entire country.

This paper refers to the results achieved in the northern and central part of Jordan, north of km 70 PGN (Palestine Grid North; comp. Fig. 1). Valuable information was obtained from:

- lithological descriptions of about 3,700 registered wells (water wells and 85 deep exploratory wells for hydrocarbons),
- reports prepared by the Natural Resources Authority (NRA) on the most important lithostratigraphic units (POWELL 1989 a and b),
- project reports of drilling programs (PARKER 1969, GITEC & HSI 1992–1994, CES & ARABTECH 1994) and
- geological maps 1 : 25,000 and 1 : 50,000 and explanatory notes (Mapping Program of the NRA).

Data related to water well drilling, groundwater monitoring, groundwater withdrawal, spring discharge, etc. was collected in the field or obtained from previous reports or the data bank of the Ministry of Water and Irrigation. A considerable part of these data was checked, revised and evaluated by the project team.

Drilling activities increased with the agricultural development of the country, especially from the mid 1960s to the early 1970s and during the early 1980s. Since most of the wells were drilled by the private sector (76 % of all wells), the drilling records are often rather incomplete. Only about 41 % of the wells have any lithological descriptions. About 50 % of the water wells are deeper than 200 m.

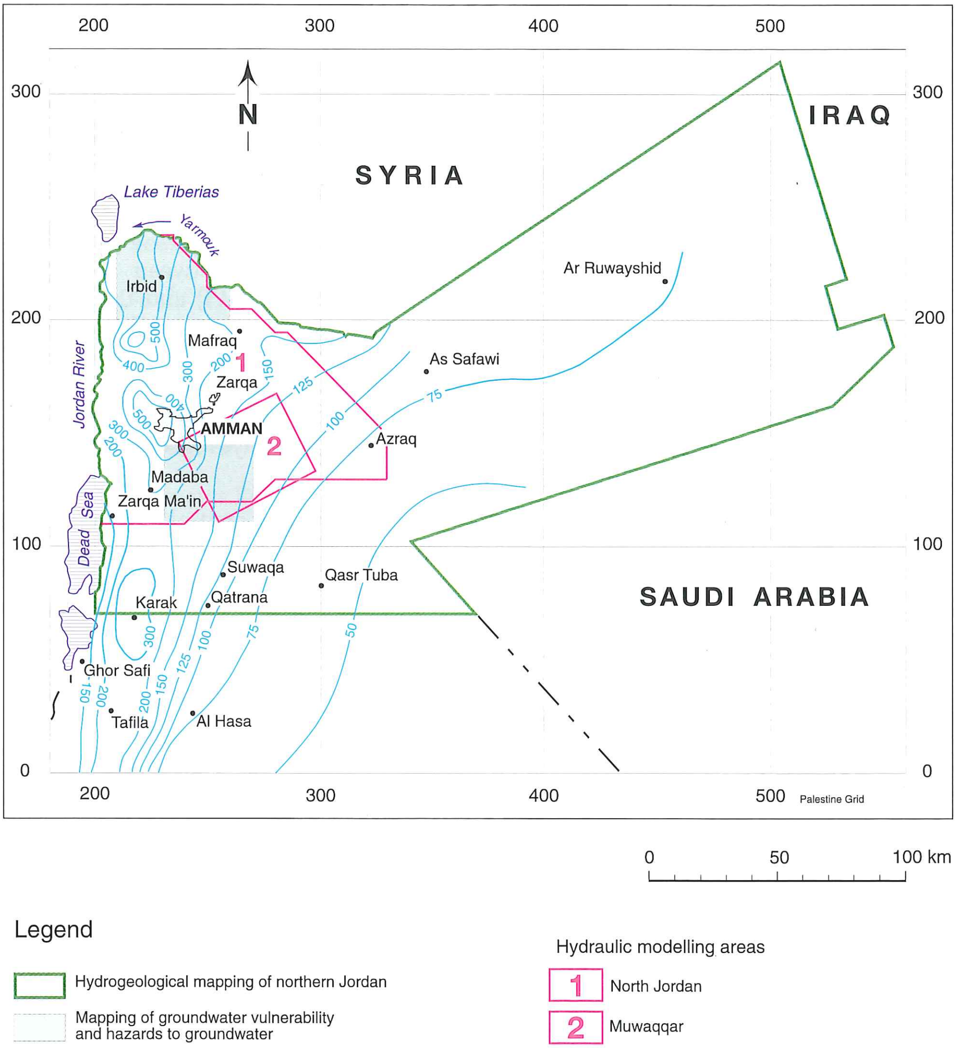


Fig. 1: Location map of the study area and rainfall distribution (modified after MARGANE & AL ZUHDY 1995).

2 Physiographical and Hydrological Situation

In respect to its physiography the northern and central part of Jordan can be subdivided into three parts:

- The Jordan Rift Valley in the west and the accompanying steep escarpment towards the Jordanian highland. In the valley elevations range from around 210 m below sea level (bsl) in the Lake Tiberias area to less than 400 m bsl at the shore of the Dead Sea.
- The north–south trending highland east of the Jordan Rift Valley which reaches a width of about 30 to 50 km. Topographical elevations of around 1000 m above sea level (asl) have been recorded in parts of this uplifted mountainous area (surroundings of Ajlun).
- The desertic, mostly flat to hilly area east of the highland. In the Azraq depression the topographical elevations are just above 500 m asl. Towards Jebel al Arab in the north, elevations gradually increase and reach more than 1000 m asl near the Syrian border.

Accordingly, rainfall is highest in the mountainous area where a Mediterranean type climate prevails (Fig. 1). In Ajlun and Salt in the north, the average rainfall reaches a maximum of 626 respectively 608 mm/yr (averages 1972/73 – 1992/93). To the south, rainfall trends to decrease. In Kerak for example, an average value of only 365 mm/yr has been observed. East of the Jordanian highland a semi-desertic climate prevails and rainfall decreases quickly (Mafraq: 154 mm/yr, Azraq: 66 mm/yr). In the Jordan Rift Valley the average annual rainfall ranges between 150 and 250 mm. Rainfall occurs mainly in the time period from November to March.

Deeply incised wadies discharge towards the Jordan River and the Dead Sea in the western and northern part of the country. Perennial flow occurs in the Yarmouk and the Zarqa River and in the lower reaches of Wadi el Arab, Wadi Taiyiba, Wadi Ziglab, Wadi Jirim, Wadi Kafrein, Wadi Mujib and Wadi Kerak. These rivers and wadies are fed by baseflow and numerous springs.

3 Structural and Geological Set-up

3.1 The structural set-up

The structural setting of the study area (comp. Figs. 2, 3, 4 and 5) is dominated by the Dead Sea Rift Valley where thousands of meters of Tertiary and Quaternary sediments have accumulated. This rift valley extends from Wadi Araba and the Dead Sea in NNE direction to the Jordan Valley and Lake Tiberias. QUENNELL (1959) postulated a left lateral movement of 107 km along this transform system. The formation of the rift commenced in the (?) Upper Eocene–Oligocene (BENDER 1974). Vertical displacement at faults accompanying the eastern flanks of the rift system is high and exceeds thousand meters. The Zemah-1 well, located south of lake Tiberias, revealed a post-Miocene filling of more than 4249 m (MARCUS & SLAGER 1985).

Uplifting, faulting and folding has extensively effected the sedimentary sequence in the highland east of the Rift Valley. One of the most prominent structural features is the Ajlun Dome, north of the Zarqa River, with its eastward extension. In addition, several smaller structural highs have been described such as the one in the area north of Salt, the Baqa uplift northwest of Amman and an uplift south of the Amman Flexure near Naur.

The most important fault systems in the east are the Sirhan Fault-zone (BEICIP 1976), which runs from Wadi Sirhan in Saudi Arabia in northwesterly direction towards Ramtha, and the Hamza Graben, southeast of Azraq. The Hamza Graben is a structural depression that was progressively down-faulted during Turonian to Maastrichtian times. Upper Cretaceous sediments (hydrogeological unit A7/B2) reach a thickness of more than 3000 m in the central part of the Hamza Graben. The NW–SE striking Fuluq Fault forms the eastern boundary of the Hamza Graben. The vertical displacement along this fault reaches more than 3000 m. East of the Fuluq Fault the thickness of the A7/B2 unit is normal. Smaller structural lows exist in the Zarqa area and in the lower Zarqa Main Valley.

A right lateral displacement is inferred for most of the W–E striking fault zones, like the Siwaqa, the Zarqa Main and the Zarqa Faults (BEICIP 1976).

In general, the strata dip from the highland towards the Dead Sea–Jordan Rift Valley in the west, the Yarmouk River in the northeast and the Azraq–Sirhan Depression in the east (Fig. 4).

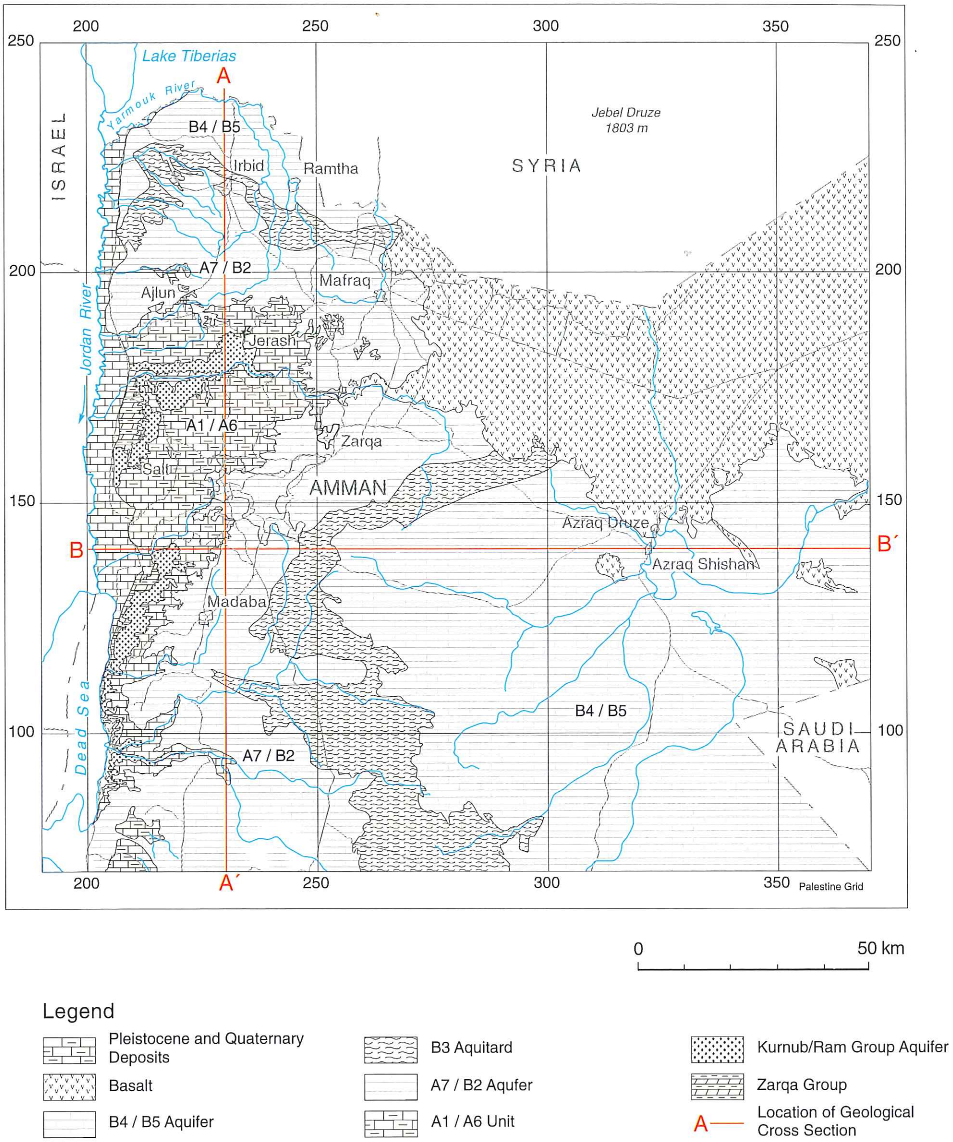


Fig. 2: Map of the hydrogeological units of Northern and Central Jordan (modified after HOBLER et al. 1994)

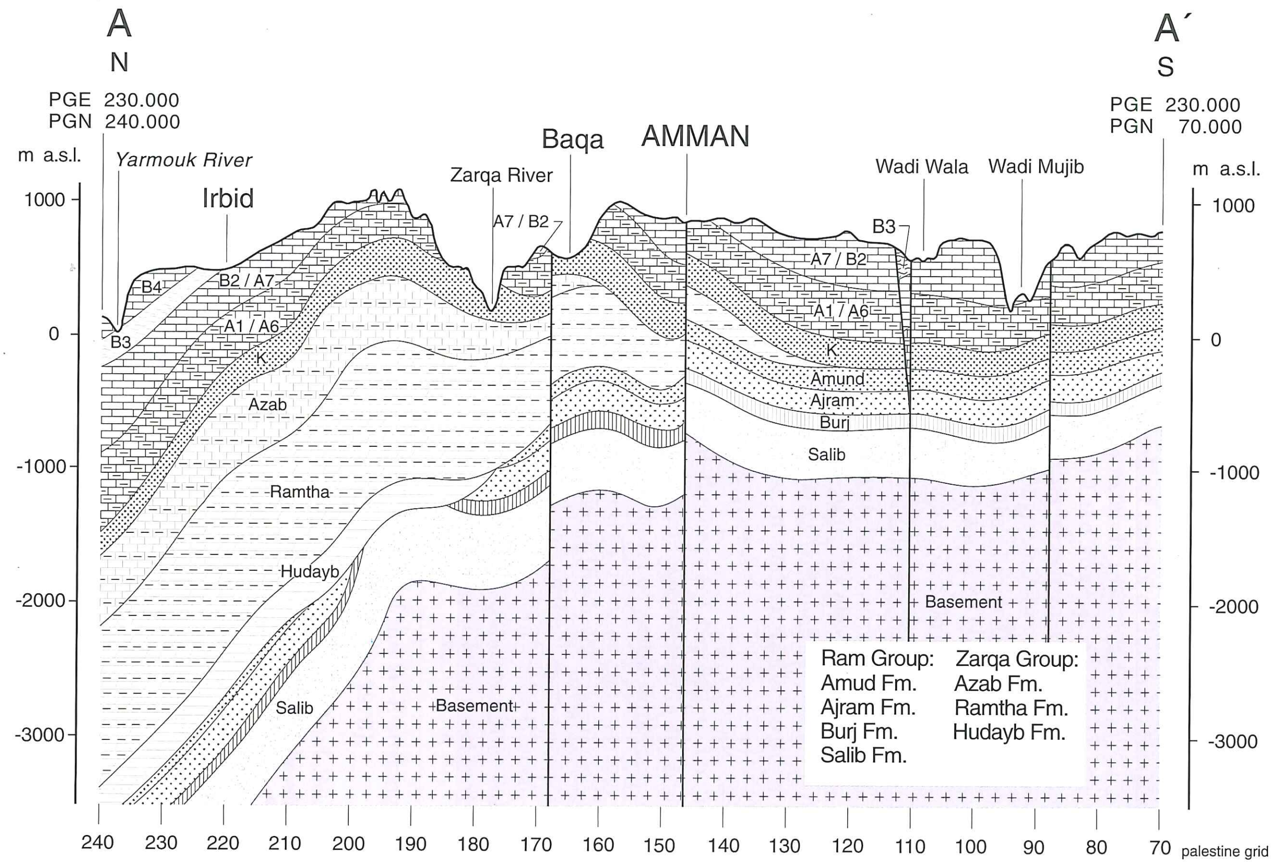


Fig. 3: Geological cross section A–A’, Yarmouk River–Al Lajjun (modified after HOBLER et al. 1994).

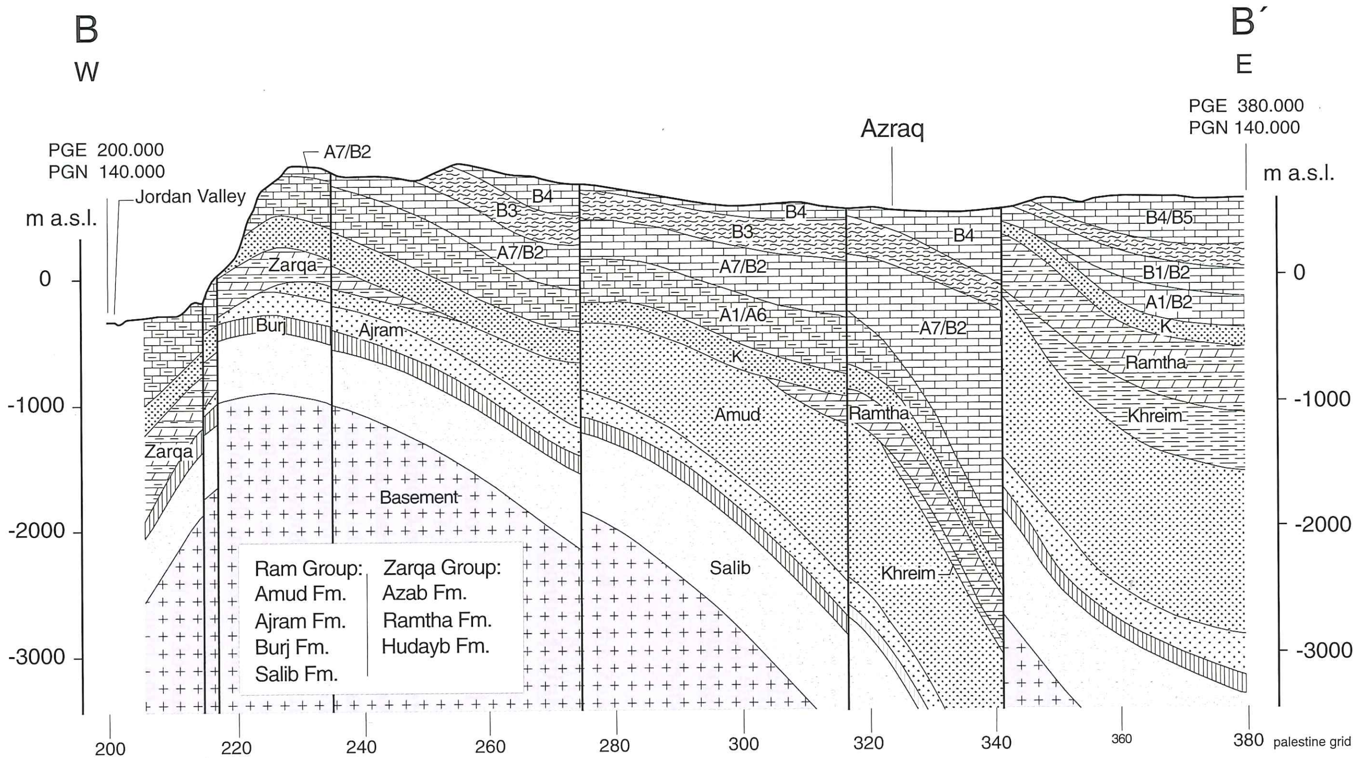


Fig. 4: Geological cross section B–B', Jordan Valley–Wadi El Qattafi (modified after HOBLER et al. 1994).

3.2 The geological set-up

Within the framework of the 'National Geological Mapping Project' the stratigraphic nomenclature of Jordan has been partly revised by the Natural Resources Authority of Jordan (ANDREWS et al. 1991, ANDREWS 1992a, 1992b, POWELL et al. 1989a, 1989b). The results of exploration drilling programs for the discovery of hydrocarbons played an important role in this revision of the stratigraphy. With the increasing number of deep boreholes, the knowledge of the geometry of the entire aquifer system of Northern and Central Jordan has considerably improved in the past 10 years.

Within the framework of the cooperation project, maps of the distribution and thickness of the main hydrogeological units and the depth to top and base of all relevant aquifers have been prepared at a scale of 1 : 250 000 (comp. HOBLER et al. 1994). Table 1 shows the lithostratigraphic and hydrogeological units, and Figure 2 the geological map with the outcrop areas of the hydrogeological units. Figures 3 and 4 show a N–S and a W–E geological cross section.

Table 1 shows that during the time period from the Cambrian to the Lower Cretaceous mainly sandstone, siltstone and mudstone was deposited in a predominantly continental environment. Only the Ram Group and the Zarqa Group contain limestones of minor thicknesses, indicating marine ingressions. The depositional environment changed completely in the Upper Cretaceous. The rock units deposited until the Eocene (Ajlun and Belqa Groups) consist mainly of limestone, dolomite and marl indicating a predominantly marine environment.

4 The Main Hydrogeological Units of Northern and Central Jordan

4.1 The Ram Group (Disi) / Kurnub aquifer (D/K)

The formations of the Ram Group form the deepest aquifer complex in Jordan. The Ram Group is composed of the Amud, Ajram, Burj and Salib formations. It consists mainly of sandstone with few intercalations of siltstone, mudstone and limestone/dolomite and is widely exposed in the southern desert, the main recharge area. It also crops out at the lower slopes of the escarpment east of the Dead Sea, the discharge area for this aquifer. The Ram Group reaches a maximum of thickness of probably more than 2500 m in the northeast (Risha) and thins towards the southwest. A thickness of more than 2000 m has also been observed in the central Jafr basin. In general, the base of the Ram Group dips in northerly to easterly directions. In structural highs in the highland, the base of the Ram Group appears to be comparatively close to the land surface (around –1000 m asl). To the north it drops to values of less than –2000 m asl and could be as deep as –4000 m asl in the Yarmouk River area, in the northwestern corner of the country. The term 'Disi Aquifer' ('Saq Aquifer' in Saudi Arabia) is well established among hydrogeologists in Jordan and is equivalent to the Ram Group.

The aquitards of the Khreim Group (mainly consisting of siltstone, mudstone and sandstone) are restricted to the eastern and those of the Zarqa Group (mainly consisting of siltstone, fine grained sandstone and limestone) to the northern part of the country, so that the Ram Group is directly overlain by the Kurnub aquifer in the central and southwestern parts of Jordan. The Ram Group and Kurnub aquifers are therefore regarded as one aquifer complex (Kurnub/Ram Group aquifer complex).

The Kurnub Group consists mainly of white, multi-colored and gray sandstone, mostly medium- to coarse-grained, with thin beds of gray and brownish siltstone. In northern Jordan, very fine- to coarse-grained, partly carbonaceous sandstones with intercalations of sandy dolomite, dolomitic limestone, siltstone and shale are common.

The Kurnub Group crops out along the slopes of the rift escarpment from the Zarqa River to the south. Additional outcrops occur in eroded anticlinal and domal structures, such as the Baqa'a Valley north of Suweileh, Mahis west of Wadi Shuayb, the area east of Shunat Nimrin, and the Wadi Sir–Wadi Naur area. In general, the thickness of the Kurnub decreases gradually from the northwestern to the southeastern part of the country. The Kurnub Group thins rapidly towards east (Azraq: 100–200 m, Hamad: 40–100 m) and the southern part of Wadi Sirhan. It is absent in the extreme southeastern part of Jordan.

Due to its mostly deep position and probably high mineralization, the Ram Group aquifer is practically not exploited in northern Jordan. There are, however, some areas, especially in the deeply incised wadies discharging to the Dead Sea (Wadi Mujib, Wadi Zarqa Ma'in, Wadi Kafrein), where drilling in recent years showed that exploitation is promising (comp. MARGANE et al. 1995).

Most of the water wells in the Kurnub aquifer are located in the Zarqa Valley and the Baqa'a Valley, where a number of springs emerge from this aquifer. Wells often penetrate not only the Kurnub, but also aquiferous layers in the Zarqa unit. In most other areas exploitation so far was unsuccessful, due to increased salinity of the groundwater or low productivity of the aquifer.

The top of the Ram Group / Kurnub aquifer (D/K) is shown in Figure 5. The groundwater flow pattern of the groundwater in the Ram Group / Kurnub aquifer is presented in Figure 6. It shows a recharge mound in the Ajlun mountains and in the area northwest of Amman. Another mound is expected to exist below the Jebel al Arab area, towards Syria.

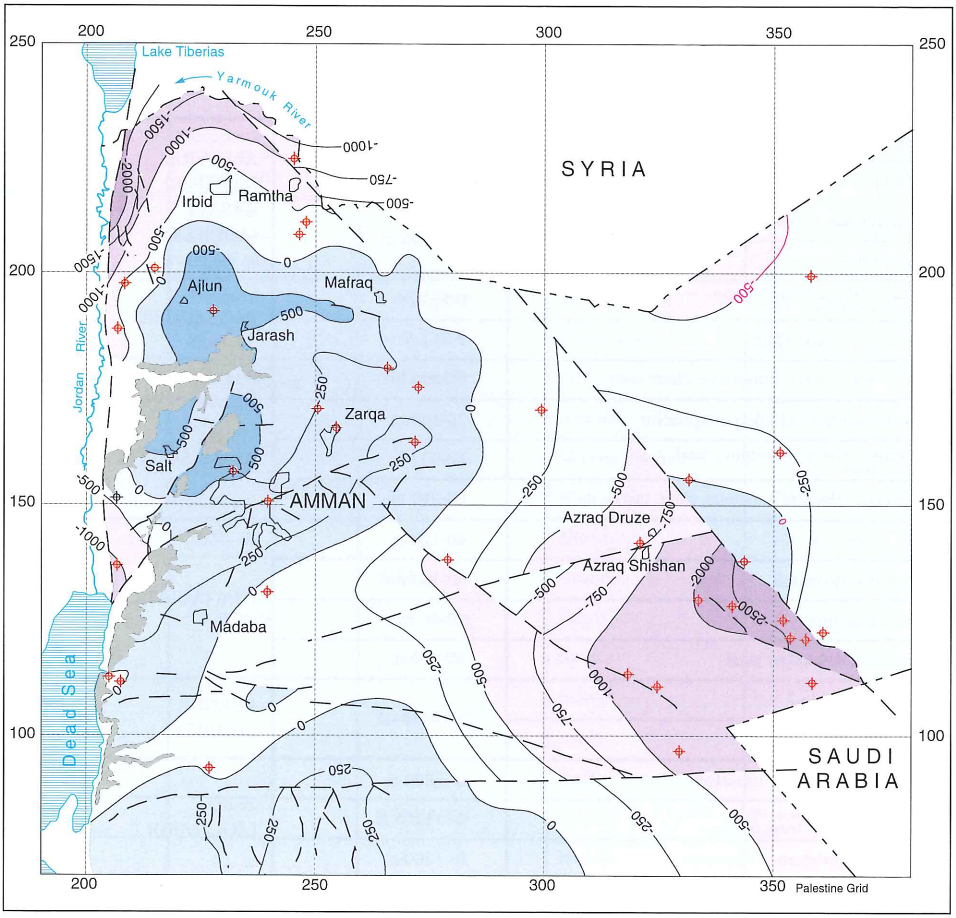
Table 1: Geologic classification of rock units in Northern and Central Jordan

SYSTEM	EPOCH	GROUP	FORMATION	SYMBOL
QUATERNARY	Holocene	JORDAN VALLEY (JV)	Alluvium	Qal
	Pleistocene		Lisan	JV3
TERTIARY	Pliocene Miocene Oligocene		Samra	basalt JV1-2
			Neogene	
	Eocene	BELQA (B)	Wadi Shallala	B5
	Paleocene		Umm Rijam	B4
UPPER CRETACEOUS	Maastrichtian		Muwaqqar	B3
	Campanian		Amman-Al Hisa	B2
	Santonian		W. Umm Ghudran*	B1
	Coniacian	AJLUN (A)	Wadi as Sir	A7
	Turonian		Shuayb	A5/6
	Cenomanian		Hummar	A4
			Fuheis	A3
			Naur	A1/2
LOWER CRETACEOUS		KURNUB (K)	Subeihi	K2
			Aarda	K1
JURASSIC		ZARQA (Z)	Azab	
TRIASSIC			Ramtha	
PERMIAN			Hudayb	
SILURIAN		KHREIM (KH)	Alna	
			Batra	
			Trebeel	
			Umm Tarifa	
ORDOVICIAN			Sahl as Suwwan	
		RAM (D)	Amud	
CAMBRIAN			Ajram	
			Burj	
			Salib	
PRECAMBRIAN			Unassigned clastic unit	
			Saramuj	
			Crystalline Basement	

(*) in Hamza graben equivalent to Rajil Fm., Hamza Fm and Hazim Fm., total theckness up to 2000 m

LITHOLOGY	THICKNESS	AQUIFER UNIT
clastics		ALLUVIUM (AQUIFER) BASALT (AQUIFER)
marl, clay, evaporites	>300 m	
conglomerate with silicious cement,	100-350 m	
sand, gravel		
chalky and marly limestone with glauconite	0-555 m	B4/5 (AQUIFER)
limestone, chalk, chert	0-311 m	
chalky marl, marl, limestone, chert	80-320 m	B3 (AQUITARD)
limestone, chert, chalk, phosphorite	20-140 m	A7/B2 (AQUIFER)
dolomitic marly limestone, marl, chert, chalk	20-90 (*)	
limestone, dolomitic limestone, chert, marl	60-340 m	
marl, limestone	40-120 m	A1/6 (AQUITARD)
limestone, dolomite	30-100 m	
marl, limestone	30-90 m	
limestone, dolomite, marl	90-220 m	
sandstone, shale	120-350 m	KURNUB (AQUIFER)
sandstone, shale		
siltstone, sandstone, limestone	0- >600 m	ZERQA (AQUITARD)
siltstone, sandstone, shale, limestone, anhydrite, halite	0- >1250 m	
siltstone, sandstone, limestone	0- >300 m	
siltstone, sandstone, shale	0- >1000 m	KHREIM (AQUITARD)
mudstone, siltstone	0- >1600 m	
sandstone	0- 130 m	
sandstone, siltstone, shale	0- >1200 m	
mudstone, siltstone, sandstone	0-200 m	
sandstone	0->1500 m	RAM SANDSTONE (DISI) (AQUIFER)
sandstone	0-ca. 500 m	
siltstone, dolomite, limestone, sandstone	ca. 120 m	
arkosic sandstone, conglomerate	0- >750 m	
sandstone, argillaceous, siltstone, claystone	0- 1000 m	BASEMENT COMPLEX
conglomerate, sandstone	up to 420 m	

(*) in Hamza graben equivalent to Rajil Fm., Hamza Fm and Hazim Fm., total theckness up to 2000 m



Legend

Top of Kurnub Formation [m a.s.l.]

- above 500 m
- 500 m to 0 m
- 0 m to -500 m
- -500 m to -1000 m
- -1000 m to -2000 m
- below -2000 m
- outcrop area of Kurnub / Ram Group
- oil exploration well
- 250 contour line of top Kurnub / Ram Group
- fault

Fig. 5: Structure contour map of top of Kurnub / Ram Group aquifer (modified after HOBLER et al 1994).

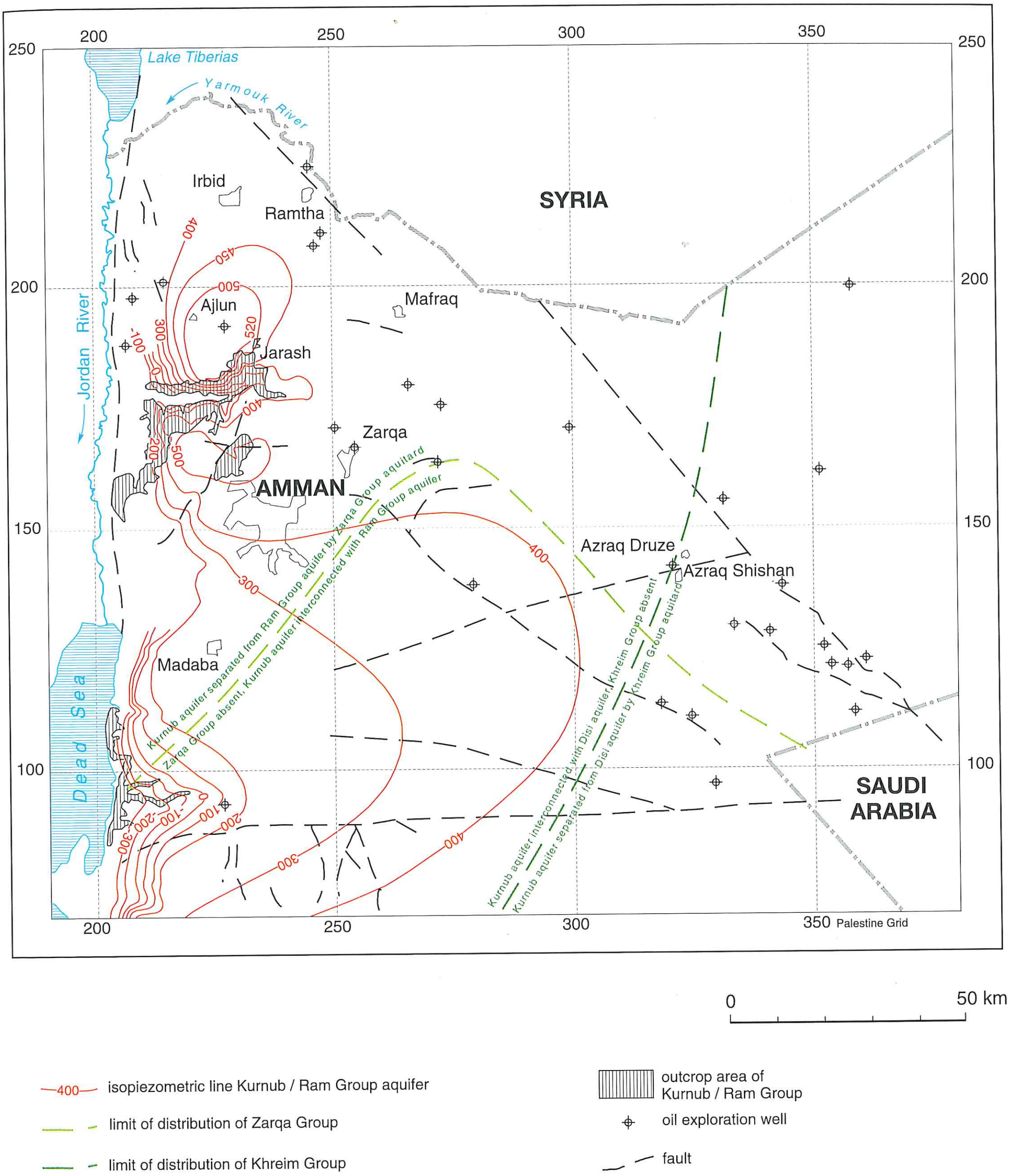


Fig. 6: Groundwater flow pattern of the Kurnub / Ram Group aquifer (modified after HOBLER et al. 2001).

4.2 The aquifers of the Lower Ajlun Group (A1/6)

The Lower Ajlun Group overlies disconformably the Kurnub Group and comprises a Late Cretaceous sequence dominated by marl, limestone, dolomite, and shale. It is subdivided into the Naur (A1/2), Fuheis (A3), Hummar (A4) and Shuayb (A5/6) formations. In the Yarmouk area, the entire Lower Ajlun Group consists mainly of limestone, marly and dolomitic limestone, dolomite and marl. The A1/6 aquifer therefore seems to be hydraulically interconnected with the overlying A7/B2 aquifer in this area. In the Hamad area too, the whole Ajlun Group (A1/7) is mainly composed of dolomite, chert and chalky limestone and thus not separated from the A7/B2 aquifer complex.

The A1/6 reaches its widest surface distribution on the slopes of the Zarqa River valley. From there to the south, A1/6 outcrops are common on the slopes of the rift escarpment and the side wadies.

In general, the thickness of the Lower Ajlun Group increases from SW to NE and ranges between approx. 30 m (Hamad) and > 638 m (Mukheiba). Considerable regional variations in thickness have been recorded according to lithological descriptions from water well drillings. Relatively low thicknesses occur in the Ajlun area, the Dhuleil area and the southern part of the Jordan Valley. High thicknesses of > 500 m have been reported from the Qastal area, Azraq, the Irbid area and the lower Yarmouk Valley. In the easternmost part of Jordan and the southern part of Wadi Sirhan the thickness of the Lower Ajlun Group thins to < 100 m.

The A1/2 and A4 form aquifers of significant local importance where they are near the land surface, i.e. in part of the northern highlands, and in areas, where the A7/B2 aquifer has already been exhausted.

4.3 The Amman/Wadi Sir aquifer (A7/B2)

The uppermost unit of the Ajlun Group and the lower part of the Belqa Group (from the Upper Turonian to the Campanian–Maastrichtian) are considered as one hydrogeological unit. It consists of the Wadi as Sir Limestone Formation (A7), the Wadi Umm Ghudran Formation (B1; respectively equivalent formations in the area of the Hamza Graben) and the Amman Silicified Limestone and Al Hisa Phosphorite formations (B2).

It comprises massive limestone, dolomitic limestone and dolomite with intercalated beds of sandy limestone, chalk, marl, gypsum, chert and phosphorite.

The thickness distribution of the A7/B2 unit reflects the high tectonic activity during the time of the deposition of these formations. The thickness is enormously high in a down-faulted tectonic block delineated by the W–E striking Siwaqa Fault, the WSW–ENE striking Zarqa Main–Azraq Fault, and the NW–SE striking Fuluq Fault. In the Hamza Graben the thickness reaches a maximum of more than 3000 m, close to the Fuluq Fault, and thins progressively from there to the west. South of the Siwaqa Fault the thickness of the A7/B2 unit decreases from more than 300 m close to the fault in southerly and southeasterly directions. In the Hamad area, east of the Fuluq Fault, the thickness decreases from NW to SE and reaches a minimum of around 40 m in the Risha area. In the northwestern part of the study area the A7/B2 thickness trends to increase towards north and towards the Rift Valley.

The structure contour map of the base of the A7/B2 unit is presented in Figure 7. The base of the A7/B2 unit reaches its highest elevations of roughly 1000 m in the area of the Ajlun Dome. From there the base of the A7/B2 drops to the Jordan Valley in the west and the Yarmouk River in the north. In the lower reaches of the Yarmouk River, the base of the A7/B2 appears to be at a depth of approx. –1000 m to –1400 m asl.

The A7/B2 Unit forms the most important aquifer in Jordan because of its vast extent and its relatively high permeability. The groundwater flow pattern is presented in Figure 8. In the eastern part of the country, where the aquifer is confined, exploitation is limited due to the often high salinity of the groundwater (reduced water).

The exploitation of the A7/B2 aquifer has increased enormously over the past decade, so that water levels are declining rapidly. In many areas annual water level decline rates reach about 2 m/yr (Fig. 14).

4.4 The aquifer of the Umm Rijam and Wadi Shallallah formations (B4/B5)

The Muwaqqar Formation (B3) of Maastrichtian to Paleocene age consists mainly of marl and separates the A7/B2 from the B4/B5 aquifer. The Umm Rijam Formation consists of (partly phosphoritic) limestone, chalky limestone, chalk and beds and nodules of brown to black chert. It is exposed in the northwesternmost part of the country, north of Irbid, in the Azraq and Sirhan Depressions and the Hamad–Risha area. Due to erosion, the thickness of the B4/B5 unit is reduced in most of the area. The highest thickness of up to more than 300 m has been recorded from the Hamza Graben, close to the Fuluq Fault and Wadi Sirhan.

The appearance of marls and the decrease of chert in the overlying Wadi Shallala Formation define the top of the Umm Rijam Formation. The latter consists of chalk and chalky marl with thin beds of marly limestone. The marls are locally bituminous. Chert is reported from the Risha and Azraq areas. The section is erosional in most areas and the thickest sequence is again found in the Azraq Depression, adjacent to the Fuluq Fault (> 400 m), and the Sirhan Depression (> 550 m). In the area of the type section in Wadi Shallala the formation is overlain by some 40 m of Oligocene glauconitic marl and limestone of the Tayyiba Formation. However, no other equivalent Oligocene rocks have been found elsewhere in Jordan so far.

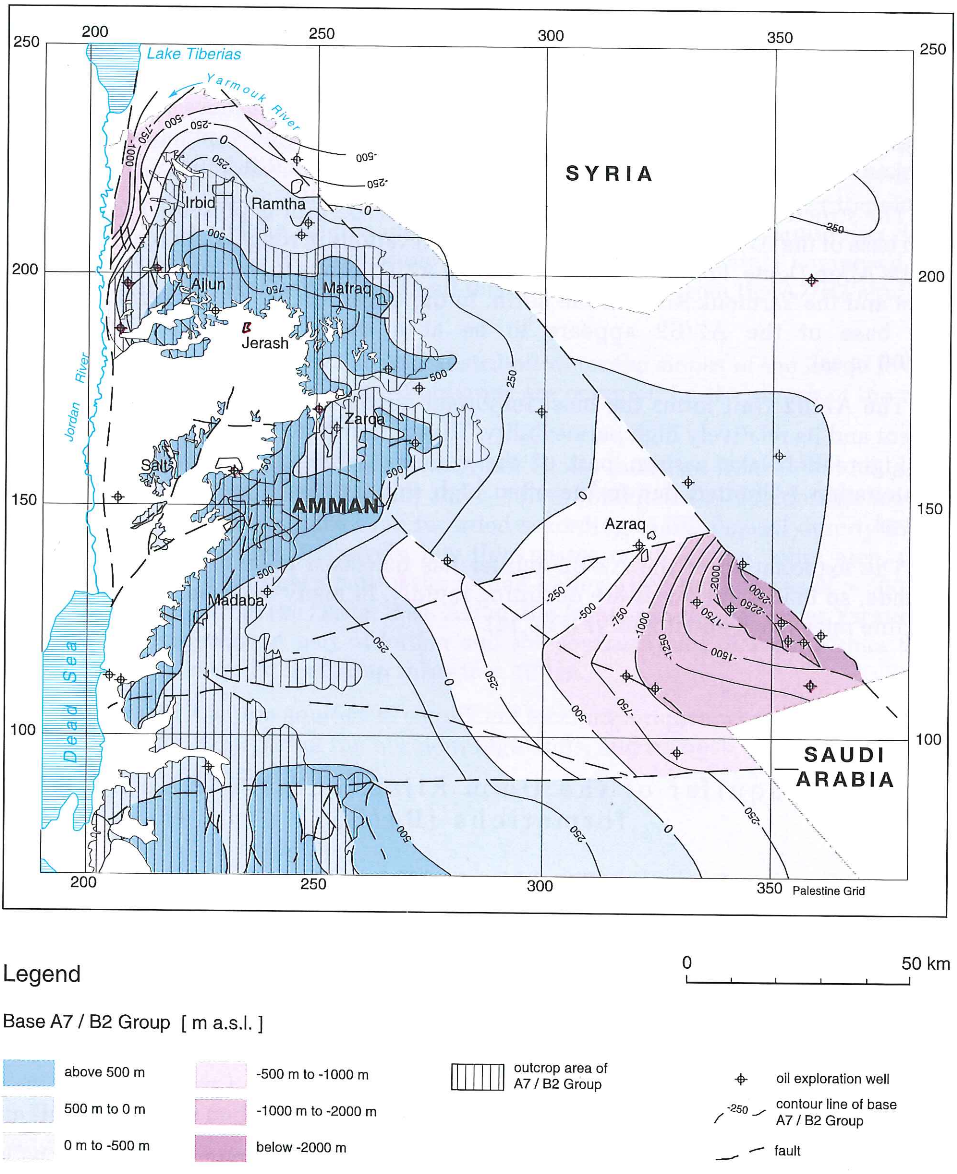
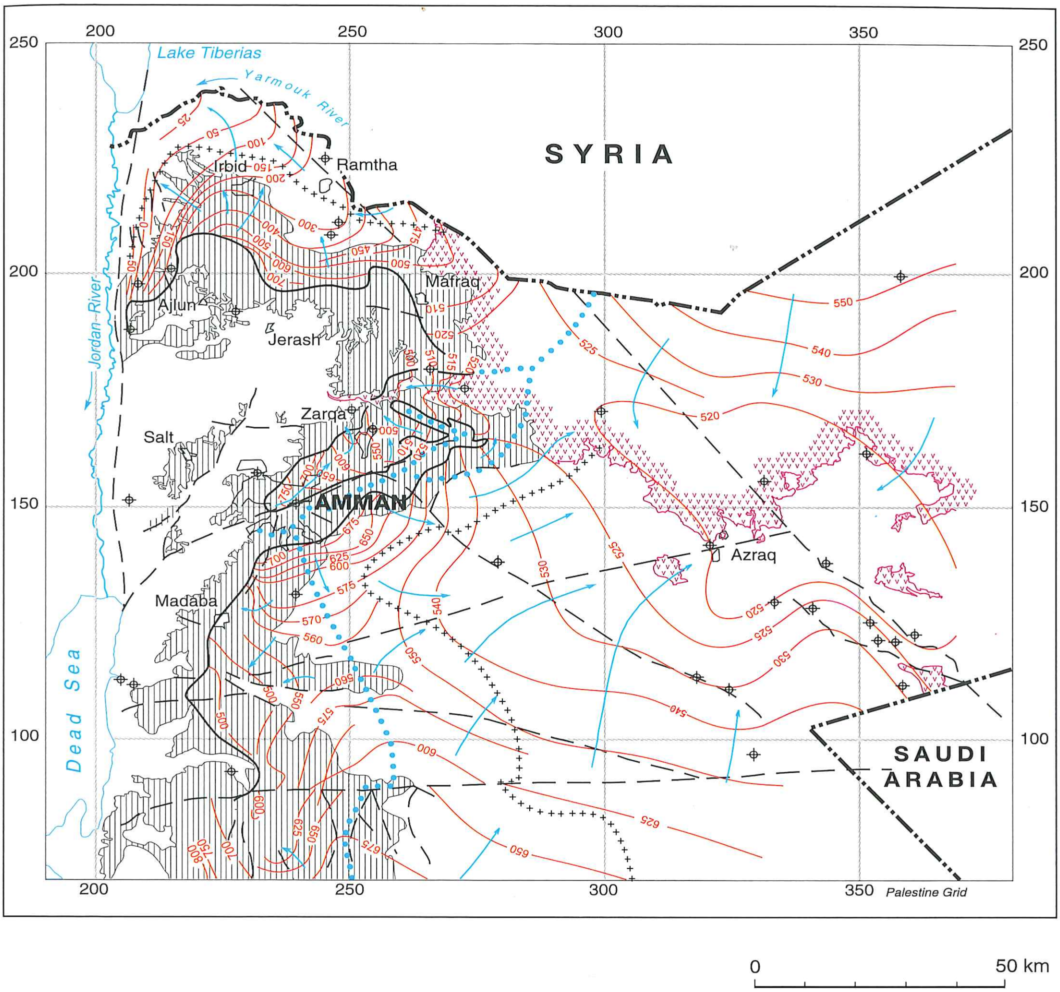


Fig. 7: Structure contour map of base of A7 / B2 aquifer (modified after HOBLER et al. 1994).



outcrop area of A7 / B2 Group

boundary of basalt distribution
A7 / B2 aquifer in hydraulic contact with the basalt aquifer in part of this area

fault

isopiezometric line A7 / B2 aquifer

groundwater divide

direction of groundwater flow

limit of area with confined groundwater

boundary of saturation of A7 / B2 aquifer

oil exploration well

Fig. 8: Groundwater flow pattern of the A7 / B2 aquifer (modified after HOBLER et al. 2001).

The B4/B5 aquifer plays an important role especially in the area north of Irbid, the Azraq area and the Hammad area. The groundwater flow pattern is presented in Figures 9 and 10. In northwest Jordan numerous springs emerge from the B4 aquifer. Exploitation of the aquifer for domestic purposes, however, is negligible, as the groundwater quality often does not meet the groundwater standards (pollution due to high groundwater vulnerability). In the Azraq area, the B4 aquifer is extensively exploited for domestic purposes (water supply of Amman). Due to that, water levels have significantly depleted over the past decade and the Azraq oasis has almost dried up. In the Hammad area exploitation of the aquifer is low due to the low demand. In Wadi Sirhan B5 and B4 formations form separate aquifers of local importance (GITEC & HSI 1992–1994).

4.5 The basalt aquifer

Basalts are found in various parts of Jordan, especially along the eastern margin of the Dead Sea (Wadi Zarqa Ma'in, Wadi Heidan, north of Wadi Mukheiris, Wadi Dardur and the plateau area north and south of Wadi Mujib), at the rims of and on the plateaus facing the Yarmouk Valley and in the lower Wadi el Arab, in the subsurface of the Jordan Valley and in the vast Harrat-Ash Shaam basaltic province north and east of Azraq. All those basalts are associated with the formation of the Red Sea–Dead Sea–Jordan Rift and the relative northward movement of the eastern (Jordanian) plate that governed the area from (? Upper Eocene) Oligocene to recent times.

A new classification of the basalt in the Harrat–Ash Shaam area has recently been introduced by NRA (IBRAHIM 1993). He distinguishes five basalt groups (10.5–9.4 MY, 9.3–8.5 MY, 3.4 to 2.0 MY, 2.9 to 2.0 MY and less than 2.0 MY). Most of the extrusives are extensive flows of olivine basalt with a thickness of up to around 10 m. To a minor degree intercalations of tuff, scoria and clay beds occur.

The basalt extrusions on the eastern margin of the Red Sea–Dead Sea–Jordan Rift are possibly all of Pleistocene age (BENDER 1974), the youngest being approx. 60,000 years old (basalts associated to the Yarmouk Valley).

Maximum observed thickness of basalt drilled in the Harrat-Ash Shaam area of Jordan is 479 m. The thickness increases towards Jebel Druze (Syria) where it may reach approx. 1500 m (WOLFART 1966).

In the western part of the Harrat Ash Shaam area, west of the Fuluq Fault, the basalt appears to be mostly underlain by the Amman–Wadi Sir Formation (A7/B2) as proven by paleontological analyses for some of the recently drilled wells in the Azraq basin (CES & ARABTECH 1993). Near the Fuluq Fault, prograding towards SE, the basalt is underlain by the Muwaqqar (B3) and further on by the Um Rijam Formation (B4). East of the Fuluq Fault basalt overlies successively younger strata towards east and northeast.

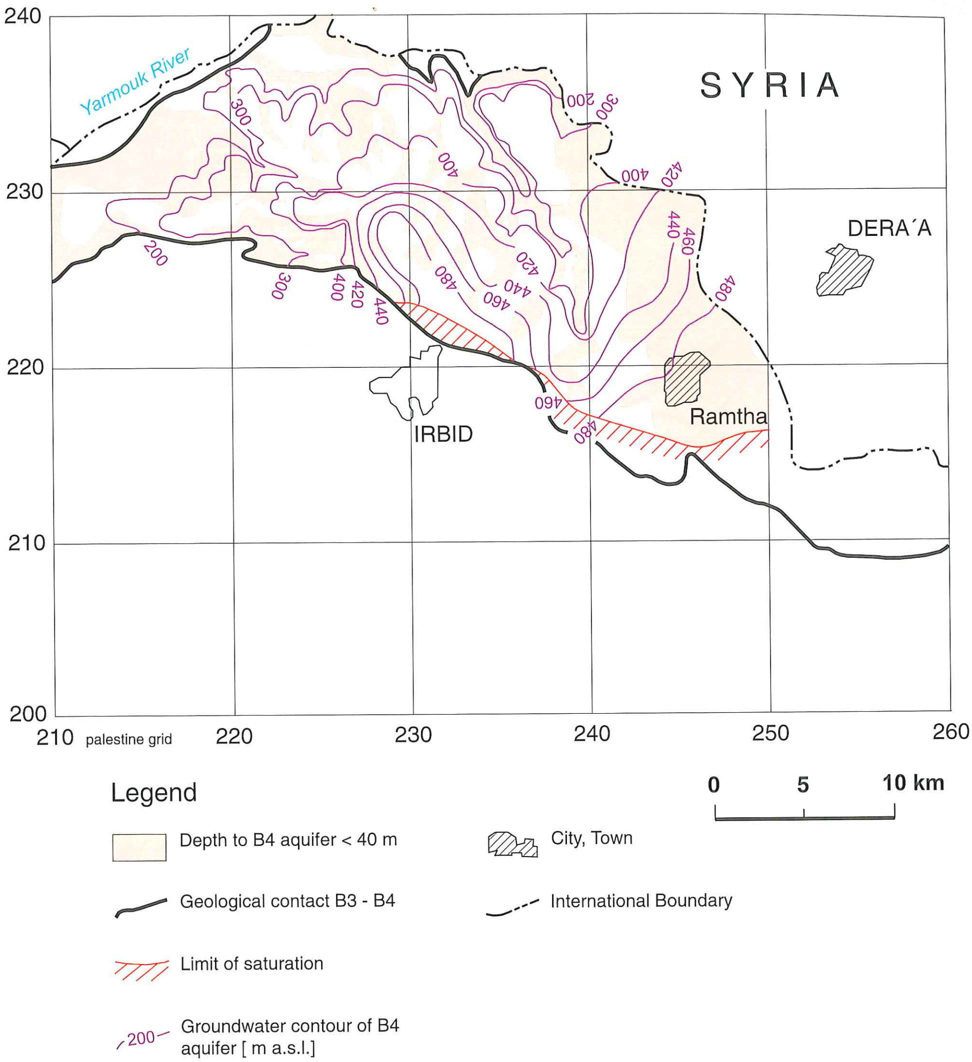


Fig. 9: B4 aquifer – depth to saturated aquifer and groundwater flow pattern (modified after HOBLER et al. 2001).

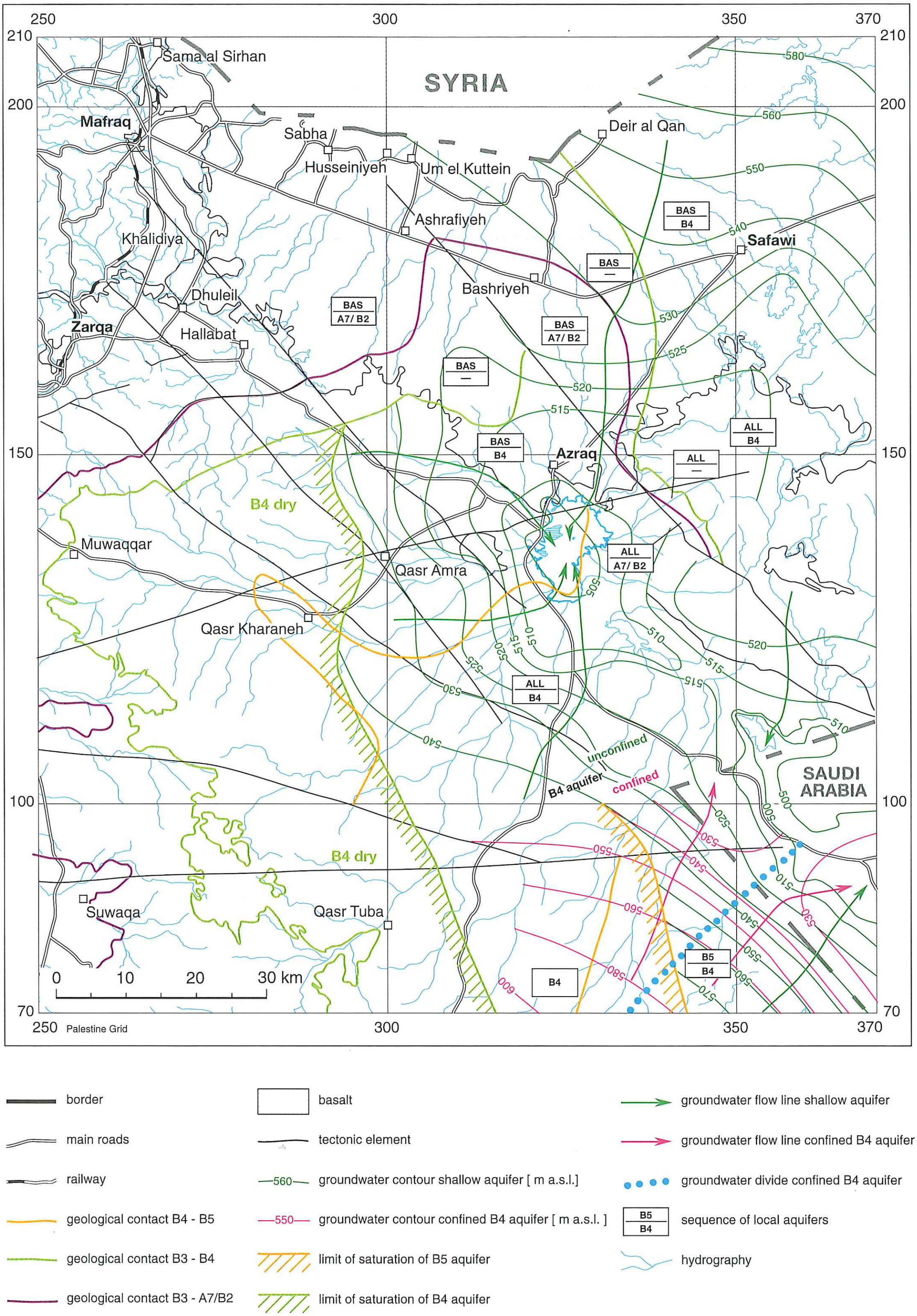


Fig. 10: Groundwater flow pattern of the shallow aquifer system (alluvium, basalt, B4 / B5) in the Azraq area (modified after HOBLER et al. 2001).

In the western part of the Harrat-Ash Shaam, in the area along the 'km-road', the basalt aquifer is heavily exploited, since it is very productive and of good groundwater quality. To the north, however, the depth to groundwater head level is quite high (> 300 m) so that exploitation becomes uneconomic. In the area northwest of Azraq the basalt aquifer forms one aquifer with the underlying B4 aquifer (comp. Fig. 10) whereas to the northwest of Azraq it is underlain by the A7/B2 aquifer.

5 Groundwater Resources

5.1 Groundwater recharge

A variety of approaches exist that can be applied to approximate groundwater recharge (comp. IAH 1990):

- direct measurement (by lysimeters)
- water balances (soil moisture budget, river channel water balance, water budget, water table rise, spring flow, flownet analysis)
- Darcian approach (flow of water in the unsaturated zone)
- tracer techniques (chloride balance, D-^{18}O relationship)

From the above, mainly water balance methods have been applied until now in Jordan. It is impossible to establish a precise regional distribution of the recharge rates, since data are mostly scarce or incomplete. Nevertheless, considering these limitations, the regional recharge in certain areas has been attempted to be calculated by (1) water table rise, (2) spring flow and (3) flownet analysis.

Only few reports actually include data on groundwater recharge in Jordan. The long term average rainfall volume over Jordan amounts to approximately 8450 MCM/yr (comp. MARGANE & AL ZUHDY 1995). However, the area with rainfall less than 75 mm/yr constitutes around 50 % of the total area. In this area rainfall is around 1200 MCM/yr, but recharge is believed to be negligible.

GTZ & NRA (1977) estimated the total recharge at around 482 MCM/yr. Taking the rainfall distribution into consideration the overall recharge rate for the area with rainfall exceeding 75 mm/yr would in this case be approximately 6.6 %. This estimation was based on the assumption of a general long-term groundwater balance (inflow equals outflow), supposing a naturally stationary balance of base flow and groundwater recharge. In fact present-day total groundwater outflow is higher than groundwater recharge, due to the fact that during the glacial and the interstadial periods groundwater recharge in the Middle East was significantly higher than today (historic gradient). The consequences of this phenomenon for the groundwater balance of Jordan were first described by BENDER et al. (1989).

However, WAJ (comp. BILBEISI 1992) estimates the total renewable groundwater resources at only 275 MCM/yr (approx. 4 % of the rainfall exceeding 75 mm/yr). For planning purposes the MWI calculates presently with an annual safe yield of 277 MCM.

For calculation of the groundwater recharge in the 'North Jordan Groundwater Flow Model' (comp. chapter 5.8), the most realistic estimates from the single regions (comp. chapters 5.1.1 and 5.1.2) have been entered as maximum possible recharge rate for each cell of the model grid. Based on the assumption that recharge could only occur in areas where the properties of the outcropping rocks allow percolation, a groundwater recharge of 198 MCM/yr in the groundwater flow model area was calculated. Considering that groundwater recharge in the areas further south of the modeled area (south of Wadi Mujib) are much lower, a total present-day groundwater recharge of around 280 MCM seems most realistic.

Pre-development baseflow in Jordan is estimated at approximately 380 MCM/yr (comp. chapter 5.4). However, it has to be remembered that much of this baseflow originates from recharge during time periods with higher rainfall and thus is not representing the present-day recharge. E.g. part of the baseflow of the Wadi Mujib comes from the Ram Group aquifer, which today receives almost no recharge.

5.1.1 Recharge to the B4/B5 and basalt aquifer

The B4/B5 and basalt aquifers are of importance in four different regions:

- the area north and east of Irbid
- the Azraq depression
- the Sirhan depression and
- the Hammad area

In the Hammad and Sirhan areas recharge is believed to be negligible (GITEC & HSI 1992–1994). WAGNER & GEYH (1996) believe, that much of the groundwater discharged in the Azraq depression is of fossil origin. Based on spring flow calculations recharge in the area North and East of Irbid might reach 8–10 %. Two other estimations of groundwater recharge for this area are based on the assumption that climatic conditions remained constant over time, which, as mentioned before, is not the case. SEILER & ALMOMANI (1994) calculated the recharge to be 3.3 %, based on the relation between chloride content in groundwater and rainfall. Based on a flownet analysis of a strip in the western part of the Azraq area groundwater recharge is approximately 3 % of the rainfall.

5.1.2 Recharge to the A7/B2 aquifer

The A7/B2 unit crops out in all the mountainous ranges of Jordan. Recharge is especially high in the areas where rainfall is elevated, as in the northern highlands around Ajlun (rainfall 300 to > 600 mm/yr), the central highlands around Salt and Amman (rainfall 300 to > 500 mm/yr) and the area around Kerak (rainfall 200 to > 350 mm/yr). PARKER (1969) differentiates five recharge mounds in the aquifer: the Ajlun mound, the Amman mound, the Mazar mound (between Kerak and Wadi Hasa), the Tafila mound and the Shaubaq–Ras en Naqb mound.

The groundwater recharge rates, which have been calculated for this aquifer are shown in Table 2.

Table 2: Groundwater recharge rates of the A7/B2 aquifer

Area	Method	Recharge [%]	Reference
Northern riftside catchment area	climatic balance	14.4	WAJ (1989)
Northern riftside catchment area	spring flow	25–30	HOBLER et al. (2001)
Amman–Zarqa basin	storm-by-storm analysis (US Soil Conservation Service)	14	WAJ (1989)
Salt (springs AM-1, AM-2)	spring flow	18.4	HOBLER et al. (2001)
Wadi Juheira (springs Cd-5)	spring flow	6–8	HOBLER et al. (2001)
Udruh	water level fluctuations	up to 30	HOBLER et al. (2001)

From the above it can be concluded that recharge of the A7/B2 aquifer widely varies from less than 10 to more than 30 % depending on rainfall distribution, topographical situation, soil cover, karstification, etc.

5.2 Groundwater abstraction

Data on groundwater abstraction have been incomplete and unreliable until the recent past as it was known only for most of the governmental wells. It is only since 1993 that WAJ has started installing flow meters in private wells and collecting field data on groundwater abstraction. Based on these figures a distribution map of the groundwater abstractions in northern Jordan was prepared (Fig. 11). According to this assessment the total groundwater abstraction north of km 70 PGN and west of PGE 370 was 464.1 MCM in 1993. Of the total amount 39.9 % (185.2 MCM) was pumped from 282 governmental wells and 60.1 % (278.9 MCM) from 1309 private wells. Since the total groundwater abstraction in the whole country was 532.7 MCM around 87 % are abstracted in the northern and central part of the country. The following Table 3 reveals that most of the water is pumped from the A7/B2 aquifer:

Table 3: Groundwater abstraction in Northern and Central Jordan in 1993

Aquifer	Abstraction [MCM]	Percentage
Alluvium	43.6	9.4
Basalt	67.7	14.6
B4/B5	45.7	9.8
A7/B2	272.3	58.7
A1/6	23.1	5.0
Kurnub	11.7	2.5
Total	464.1	100.0

The main well fields or abstraction areas (comp. Fig. 11) are:

Table 4: Well fields and groundwater abstraction in North Jordan in 1993

Well field or abstraction area	Groundwater abstraction in 1993 [MCM]	Comments
Mukheiba-Wadi el Arab	39.9	mainly domestic water supply for Irbid
NE-Desert	142.0	domestic water supply (23 %) for Irbid and Amman, mainly private irrigation wells
Baqa'a	11.0	domestic water supply and private irrigation wells
Amman	50.0	mainly domestic water supply
Dhuleil	41.6	mainly for irrigation (67 %)
Azraq	44.0	domestic water supply for Amman (42 %) and private irrigation wells
South Shooneh	37.3	mainly private irrigation wells
S-Amman	36.8	mainly for irrigation (96 %)
Wadi Heidan-Wadi Wala	7.5	domestic water supply for Amman
Siwaqa-Qatrana	15.8	mainly domestic water supply for Amman (89 %)

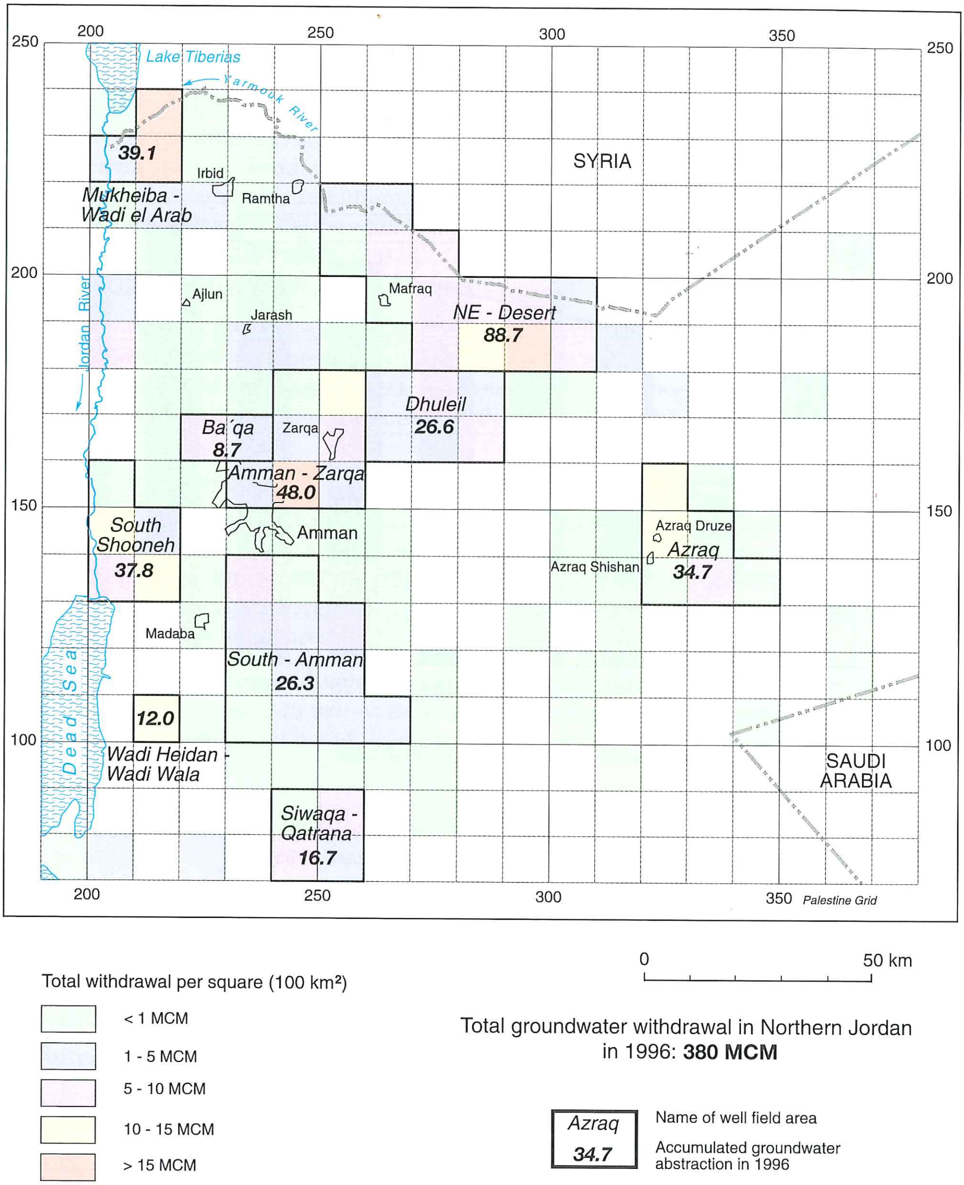


Fig. 11: Groundwater abstraction and location of well fields in Northern and Central Jordan (modified after HOBLER et al. 2001).

WAJ data from the time between 1985 and 1993 indicated an overall annual increment in the total water consumption of around 7 % (Fig. 12).

On the other hand, groundwater abstraction in Jordan seems to be more or less stable in recent years at around 500 MCM/yr (WAJ data).

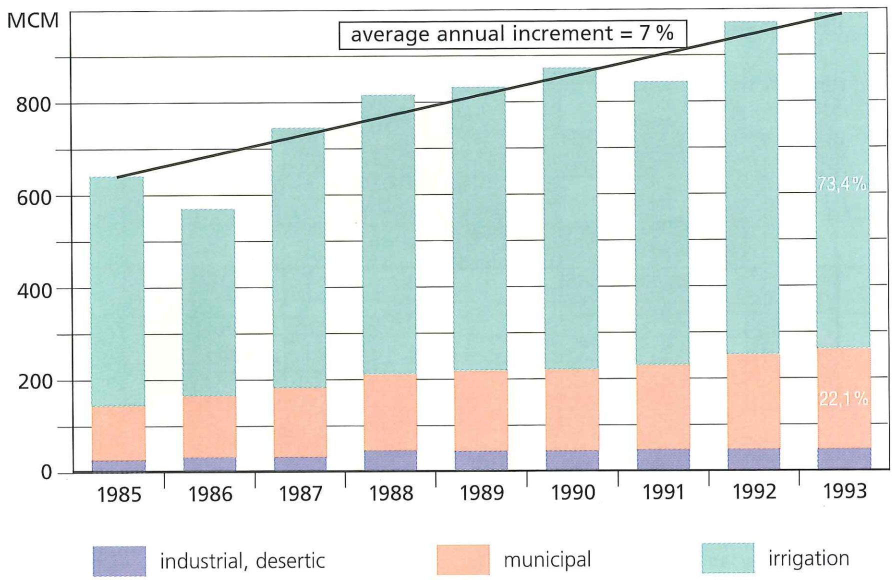


Fig. 12: Water consumption and allocation to the different sectors between 1985 and 1993 (after MARGANE & ALMOMANI 1995).

Table 5: Groundwater abstraction in Jordan between 1993 and 1998
(according to WAJ files)

Catchment area	Area code	1993	1994	1996	1997	1998	AVERAGE
Yarmouk + Wadi al Arab	AD + AE	61.9	57.4	61.0	56.2	55.6	58.4
Jordan river side wadies	AF-AK	3.0	2.8	4.2	5.1	5.5	4.1
Jordan valley	AB	38.0	41.7	39.7	39.1	41.5	40.0
Amman-Zarqa	AL	190.2	164.2	157.8	144.1	145.7	160.4
Azraq	F	50.6	48.8	53.1	53.9	55.7	52.4
Dead Sea	C + AM-AP	93.6	102.9	102.3	102.5	100.8	100.4
Northern Wadi Araba	D	1.2	0.9	5.3	4.6	3.8	3.1
S.Wadi Araba + Disi/Mudawara	E + K	72.0	67.3	77.8	78.0	70.0	73.0
Jafr	G	20.4	16.2	21.3	20.2	21.8	20.0
Sirhan	J	0.9	0.5	2.5	1.5	1.5	1.4
Hammad	H	1.2	0.7	1.0	1.3	1.3	1.1
TOTAL abstraction		532.7	503.2	525.9	506.4	503.1	514.3
Abstraction in Northern Jordan	A, C, F	437.2	417.7	418.0	400.9	404.7	415.7

5.3 Spring discharge

Around 800 springs are presently monitored in Jordan. Of these 233 are measured monthly (class A), 64 every 3 months (class B) and 504 only irregularly (class C), as access to them is difficult. However, the data availability for class A springs is around 40 % on average only. From these data a map of spring discharge for groups of springs emerging in the same catchment area was prepared for a 10 years time interval (average of the water years 1983/84–1992/93). Springs are grouped according to aquifers. As field surveys revealed many springs are unregistered. This unmonitored discharge may be in the order of 10 % of the total monitored discharge.

Table 6 shows the spring discharge in Northern and Central Jordan (north of Palestine Grid North 0). The area is divided into the catchment areas of the 'northern highlands' (north of the Zarqa river), the Amman–Zarqa area and the Dead Sea area (from the northern to the southern end of the Dead Sea with the exception of Wadi Hasa).

Due to the limited data availability the exact development of changes in spring discharge over the past 50 to 60 years cannot correctly be traced. However, discharge has decreased and in many areas even ceased due to the local or regional heavy over-exploitation of the aquifers in the past 10 years. This is for instance the case at Azraq, in Wadi el Arab and in the Amman–Zarqa groundwater basin, where abstraction areas are close to the discharge areas.

The amount of groundwater abstracted from springs in 1993 was around 27.86 MCM and dropped to values around 20 MCM in 1999. However spring abstraction seems to be underestimated, as abstraction from only a few big springs is measured appropriately.

Table 6: Spring discharge in Northern and Central Jordan (1983/84–1992/93)

Aquifer	Northern Highlands	Amman-Zarqa area	Dead Sea area	Total discharge
Alluvium	13.27	1.33	11.76	26.36
B4/B5	3.27	–	–	3.27
A7/B2	34.77	20.39	35.08	90.24
A4	16.37	14.28	0.88	31.53
A1/A2	9.60	4.30	3.40	17.30
Kurnub	1.54	1.09	18.28	20.91
Zarqa	–	0.02	2.01	2.03
Ram Group	–	–	1.09	1.09
Total	78.82	41.41	72.50	192.73

5.4 Baseflow

Measurements of natural baseflow are in most cases available only for a limited number of years and not for all wadies. Therefore, it is fairly difficult to estimate the pre-development and present-day baseflow. Additionally, baseflow is measured in many wadies only randomly (sometimes only every 3 months). Since the calculated baseflow varies considerably from year to year, the margin of error may be as high as 20 %. This high fluctuation in the amount of baseflow is partly due to the significant variation of groundwater recharge from year to year, but also indicates that in many cases direct runoff and baseflow has not been separated properly. All this has to be born in mind when assessing the baseflow in Jordan.

The data in the following Table 7 were compiled considering spring discharge data in the same areas (comp. MARGANE & AI ZUHDY 1996), assuming that present-day baseflow must generally be higher than present-day spring flow. However, spring discharge was calculated as the average for the time period 1983/84–1992/93, which makes an exact comparison difficult. Furthermore abstractions from springs and inflows from sewage water have to be taken into account. Thus, in many cases the present day baseflow can only be estimated.

Concerning the long-term trends in the baseflow, it can be noticed that in many wadies baseflow decreased during the 1980s and 1990s. In Wadi al Arab baseflow ceased completely due to the high groundwater abstraction in the nearby wells.

According to Table 7 it can be stated that present-day baseflow in Jordan is in the order of 280 MCM/yr whereas pre-development (approx. 1965) baseflow is estimated to have been around 380 MCM/yr. Baseflow in northern Jordan amounts to around 160 MCM/yr.

Figure 13 shows the spatial distribution of measuring points for baseflow in Jordan and the average amount of baseflow at each station.

Table 7: Baseflow in Jordan

Area	Name	Period	Recorded Baseflow	Unrecorded Baseflow	Total Baseflow	Total Baseflow	Spring Discharge
					pre-development	today (estimated)	average 1983/84–1992/93
AB	Jordan Valley	1982–89	0.5	35	35.5	25.0	27.4
AD	Yarmouk (from Jordan only)	1963–81	40.0		40.0	35.0	17.0
AE	Wadi al Arab	1973–88	25.0		25.0	0.0	9.2
AF	Wadi Ziqlab	1963–80	8.3		8.3	6.0	0.1
AG	Wadi Jirim (included in AB)	–		0.0	0.0	–	
AH	Wadi al Yabis	1981–92	1.7	3.8	5.5	1.5	5.5
AJ	Waki Kufrinja	1970–88	5.9	1.7	7.6	5.0	7.6
AK	Wadi Rajeeb	1981–93	3.5		3.5	3.5	1.0
AL	Seil Zarqa [4]	1985–93	45.3		27.2	15.0	27.2
AM	Wadi Shuayb	1981–93	5.4	5.9	11.3	8.0	11.3
AN	Wadi Kafrein	1985–93	7.9	3.8	11.7	8.0	11.7
AP	Wadi Hisban	1982-93	3.7	1.0	4.7	3.5	4.7
CA	Dead Sea Side Catchments [1]	1978–93	8.6	39.7	48.3	40.0	48.3
CD	Wadi Mujib	1964–78	37.0	20	57.0	50.0	16.8
CE	Wadi al Kerak	1978–93	6.4	1.4	7.8	6.0	7.8
CF	Wadi al Hasa	1963–81	25.5		25.5	20.0	3.7
DA	Wadi Umruq	1978–93	0.4	2.5	2.9	2.0	2.9
DB	Wadi Feifa	1978–93	4.3	2.4	6.7	5.0	6.7
DC	Khneizira	1978–93	1.5		1.5	1.5	2.2
DE	Wadi Fidan	1978–93	1.6		1.6	1.5	0.2
EA	Wadi Tlah			0.8	0.8	0.8	0.8
G	Wadi Jurdhna	1963–82	46.3		46.3	40.0	
N-Jordan [2] [3]			165.7	86.4	232.9	155.5	163.3
Total A+C			224.7	112.3	318.9	226.5	199.2
Total Jordan			278.8	118.0	378.7	277.3	212.0

1) recorded baseflow measured only south of W.Mujib
2) for W. Mujib: approx. 50 % of baseflow and 15.5 MCM of spring discharge
3) for Dead Sea Side Catchments all unmeasured baseflow and 24.7 MCM of spring discharge
4) recorded baseflow contains outflow from sewage treatment plant Kirbit-as-Samra

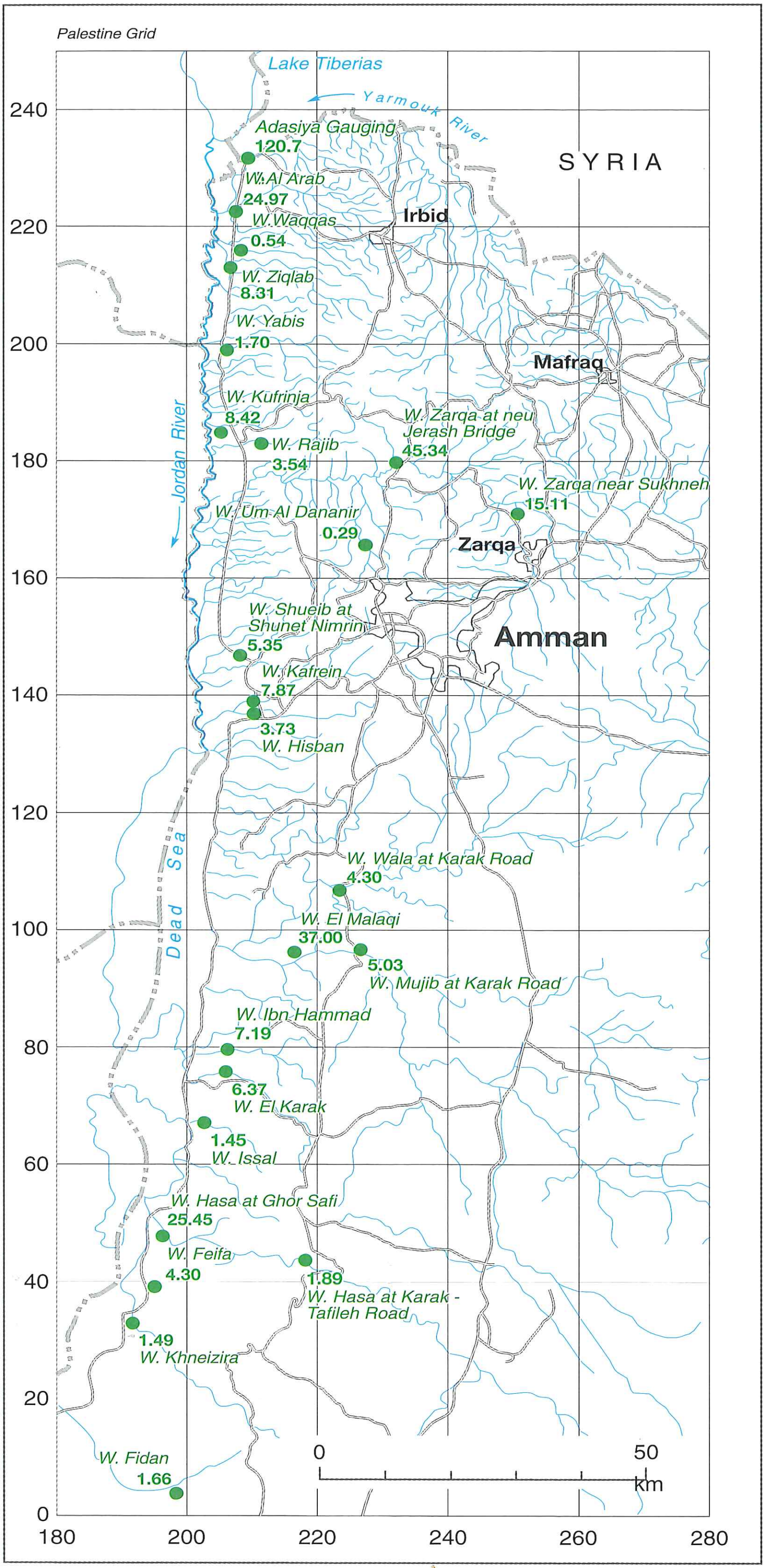


Fig. 13: Baseflow in Northern and Central Jordan (modified after HOBLER et al. 2001).

5.5 Groundwater monitoring

A complete evaluation of the groundwater monitoring network in Jordan is documented in MARGANE (1995). According to that, the network of observation wells for water level monitoring consisted in 1995 of 92 wells throughout the whole country. Seven of those wells were equipped with data loggers and 58 with automatic recorders. At 27 well sites manual measurements were taken at irregular time intervals. Almost half of the wells (44) monitored the water level in the A7/B2 aquifer. Concerning the spatial distribution of monitoring wells, the greatest number of wells was located in the central and northern part of the country.

Altogether in all of the country only less than 20 wells have monitoring records of sufficient quality covering a period of more than 10 years. This fact is crucial for the interpretation, since it can be observed in many monitoring wells that the water levels started to decline already in the early 1970s (e.g. Wadi Dhuleil, Somaya, Tell Burma) to the early 1980s, when the agricultural development began.

From the long-term trend in the monitoring graphs the present-day annual water level decline rates were evaluated (Fig. 14). This evaluation shows that in most areas water level decline is around 2 m/yr. As a consequence of this, groundwater wells have to be deepened or well fields have to be shifted (where the base of the aquifer is inclined) from time to time, especially in areas, which are heavily exploited already since a long time. In the northeastern desert boreholes are more and more shifted towards northeast, with depths to groundwater reaching more than 400 m.

It has been tried to use the annual fluctuation of the water levels in the monitoring wells for a quantification of the amount of groundwater recharge. However, it was noted that this would lead to unreasonably high recharge rates, since in most cases the water level fluctuation is strongly influenced by the pattern of groundwater abstraction in nearby wells, with abstraction rates being high in the summer and low in the winter.

5.6 Hydraulic characteristics of the aquifers

To around 150 pumping tests transmissivity values have been evaluated. Table 8 shows the hydraulic conductivities of all hydrogeological units.

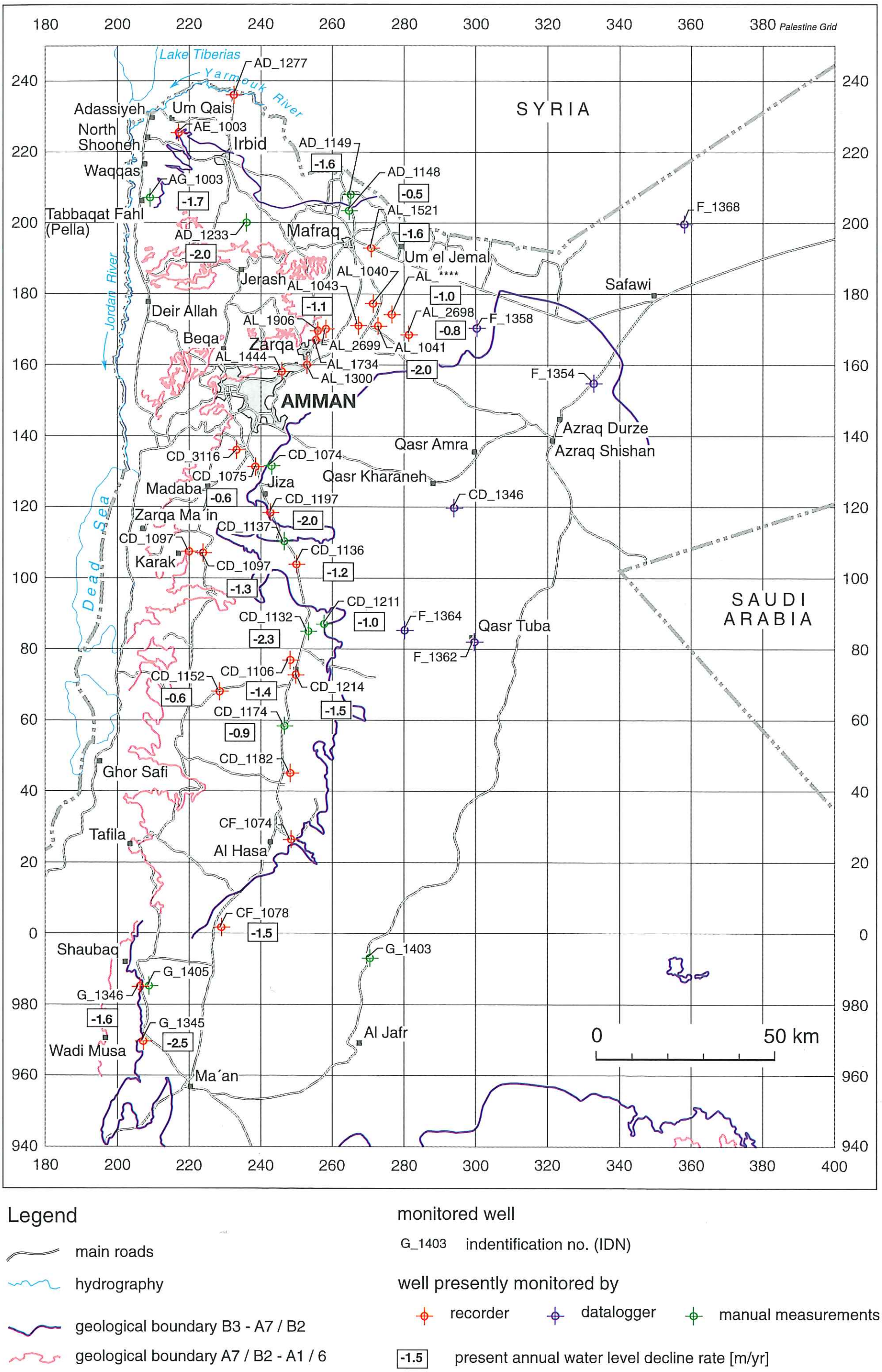


Fig. 14: Tentative annual water level decline rates in the A7/B2 aquifer (modified after MARGANE 1995).

Table 8: Hydraulic conductivities of the main aquifers in Northern and Central Jordan

Geological formation	Aquifer characteristic	Hydraulic conductivity [m/s]	Lithology (thickness)
Basalt (BS)	Aquifer	4.0 E-04 *	basalt
Shallala Fm. (B5) and	Aquifer	5.0 E-05 *	marl, limestone
Um Rijam Fm. (B4)			limestone
Muwaqqar Fm. (B3)	Aquitard	1.0 E-09 **	marl
Amman Fm. (B2)			limestone
Wadi Ghudran Fm. (B1)	Aquifer	2.0 E-05 *	marl, limestone
Wadi as Sir Fm. (A7)			limestone
Shuayb Fm. (A 5/6)	Aquitard	1.0 E-09 **	marl (~100 m)
Hummar Fm. (A4)	Aquifer	2.0 E-05 *	limestone (~70 m)
Fuheis Fm. (A3)	Aquitard	1.0 E-09 **	marl (~80 m)
Naur Fm. (A 1/2)	Aquifer	1.0 E-05 **	marl, limestone (~150 m)
[average]		[7.0 E-06 **]	[total ~ 400 m]
Kurnub	Aquifer	3.0 E-05 *	sandstone
ZARQA GROUP	upper part	1.0 E-05 **	silt-, sand-, limestone
Azab Fm.	aquiferous,	1.0 E-07 **	
	Aquitard		
	Aquitard	1.0 E-07 **	silt-, sandstone, shale,
Ramtha Fm.			limestone, anhydrite, halite
	Aquitard	1.0 E-07 **	silt-, sandstone, shale,
Hudayb Fm.			limestone
KHREIM GROUP			siltstone, sandstone, shale
Alna Fm.			mudstone, siltstone
Batra Fm.	Aquitard	1.0 E-07**	sandstone
Trebeel Fm.			sandstone, siltstone, shale
Umm Tarifa Fm.			
Sahl as Suwwan Fm.			
RAM GROUP	Aquifer	1.0 E-05*	sandstone
Amud Fm.			
Ajram Fm.			
Burj Fm.	Aquifer	1.0 E-05**	silt-, sandstone, dolomite
Salib Fm.			sandstone
Basement Complex	Aquiclude		clastics, volcanics, granite

* statistical evaluation of pumptest data
** estimation

The storage coefficients (s_y) of the hydrogeological units could not be obtained from pumping tests, because pumping tests are in most cases conducted as single well test. The hydraulic conductivities and storage coefficients used for hydraulic modeling are described in chapter 5.8.1.

5.7 Chemical composition of the groundwaters

Water quality problems are increasing either due to salinization or pollution (comp. SALAMEH & BANNAYAN 1993, FRIEDRICH EBERT STIFTUNG et al. 1991).

Groundwater mineralization: only in the area close to the recharge area groundwater resources of low mineralization are found. In the rest of the country, especially in the eastern part, groundwaters are mostly highly mineralized and can only be used to a limited extent.

In the eastern part of the highlands south of Amman the strata are mostly dipping in an easterly direction (HOBLER et al. 1994). A decline of the water level therefore results in a shifting of the limit of saturation to the east. This means that not only boreholes will have to be drilled deeper and deeper in the future (depth to groundwater in many areas already exceeds 200 m bgl; in the NE desert up to more than 400 m !) but that well fields (e.g. in the Siwaqa-Qatrana area) will in the near future reach into the area of higher mineralization. Thus, mining of the fresh groundwater resources will reach a critical point in many well field areas in the coming decade. In addition to that, salinity is increasing in many areas due to irrigation return flow (e.g. in the Dhuleil, Azraq and NE-Desert areas).

The use of brackish waters by applying desalinization techniques has often been considered in the past few years (JICA 1995). However, under the given conditions, this will be not be economically feasible in the near future.

Groundwater pollution: groundwater pollution has increased in recent years and many springs can no longer be used for public water supply (Salt area, Tabaqat Fahl).

The main pollution sources are:

- sewage water (many sewage treatment plants have a low efficiency, effluents from septic tanks and from leaking sewer networks),
- excessive use of fertilizers, pesticides and fungicides (1989: 64 kg of fertilizers and 3.3 kg of pesticides were applied per ha and year),
- leachates from waste disposal sites and
- local pollution (e.g. from small to medium scale factories and industries).

In consequence, unpolluted freshwater resources are becoming increasingly scarce.

Altogether 790 water analyses from water wells and 569 analyses from springs (with less than 5 % difference in total anions to total cations and representing only a single aquifer) were available. Most of these analyses are from the A7/B2 aquifer. The distribution of some critical parameters from water wells is depicted in Table 9.

Table 9: Chemical composition of water samples from water wells
(selected parameters, all from a single aquifer with error < 5%)

EC [μS/cm]		**Na** [mg/l] count		**Cl** [mg/l] count		$\mathbf{SO_4}$ [mg/l] count		$\mathbf{NO_3}$ [mg/l] count	
0–250	1.2%	0–50	30.1%	0–50	14.2%	0–50	43.4%	0–25	63.4%
251–500	1.9%	–100	31.1%	–100	24.1%	–100	27.2%	–50	21.9%
501–750	28.4%	–250	29.0%	–250	34.8%	–250	20.6%	–75	10.3%
751–1000	26.5%	–500	8.1%	–500	15.2%	–500	6.9%	–100	4.5%
1001–1500	22.7%	>500	1.6%	>500	11.8%	>500	1.9%	>100	0%
1501–2000	10.9%								
2001–5000	8.0%								
5001–8800	0.5%								

Alluvial waters often show predominance in chloride or sulfate combined with medium calcium and sodium percentages. The basalt aquifers frequently have high chloride percentages, mostly combined with sodium or calcium and magnesium. Most water samples of the B4/B5 aquifer are from the Azraq area having high chloride and sodium percentages. Water samples of the A7/B2 (Fig. 15) aquifer show a wide range concerning their major components (Na+K: 10–65 %, Ca: 10–60 %, Mg: 15–40 %, HCO_3: 5–80 %, Cl+NO_3: 10–80 %, SO_4: mostly < 20 %), depending on their position in the aquifer system. Waters under highly confined conditions are generally reduced and highly mineralized. Waters from the A1/6 aquifer have a similar distribution as the water from the A7/B2 aquifer. The Kurnub waters mostly are of Ca-HCO_3-type.

In general the salinity of the aquifers increases with the decrease of recharge to it, i.e. highly confined aquifers and aquifers in desertic areas are in most cases highly mineralized. Figure 16 shows the distribution of electric conductivities in the A7/B2 aquifer.

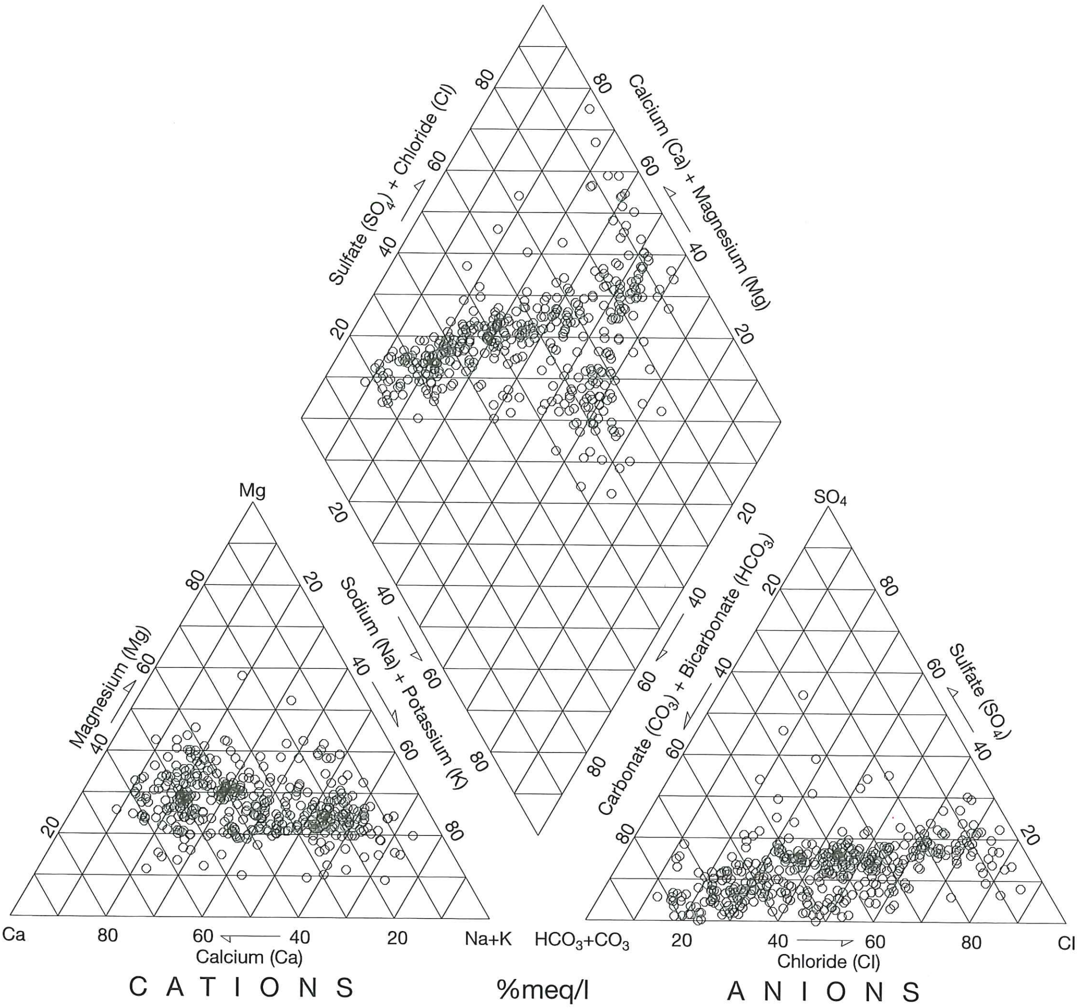


Fig. 15: Hydrochemical compositions of water samples from wells in Northern and Central Jordan – Piper diagram (A7/B2 aquifer – all samples).

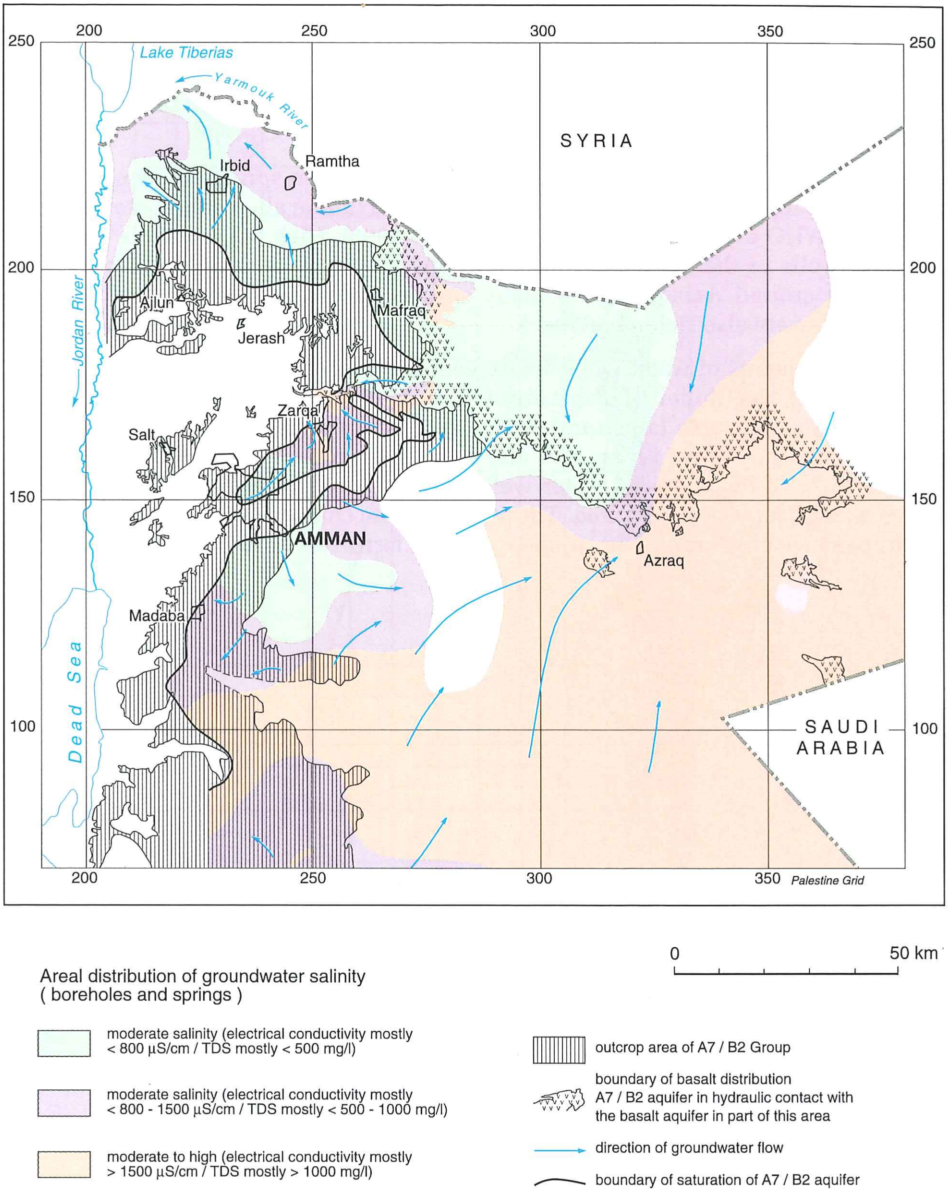


Fig. 16: Groundwater salinity in the A7/B2 aquifer
(modified after HOBLER et al. 2001).

The sodium content of water is of special importance for agricultural uses. Sodium contents above 250 mg/l and waters with a medium to high sodium hazard (Fig. 17) are frequent in the Dhuleil/Hallabat area (A7/B2), the area east of Mafraq (basalt), in the Azraq area (B4/B5) and the Jordan Valley around South Shooneh (alluvium). Due to cation exchange, waters in these areas are often of Na-HCO_3-type.

Around 9 % of the analyses from water wells and from springs show contents in SO_4 of > 250 mg/l, which is the lower limit of the maximum allowable content according to the WHO drinking water standards (WHO 1993). High SO_4 contents are found in water wells in the Dhuleil/Hallabat area (A7/B2), the South Shooneh area (alluvium) and around Azraq (B4/B5). Many springs occurring in the alluvium of the Jordan Valley are also rich in sulfate.

Nitrate contents of water wells are exceeding 50 mg/l in the Amman-Zarqa basin (A1/6, A7/B2), the Dhuleil/Hallabat area (A1/6, A7/B2), the Baqa'a Valley (A1/6), and the South Shooneh area (alluvium). Many springs in the densely populated areas of the highlands northwest of Amman also show high nitrate contents. Altogether in around 15 % of the analyzed water wells and 22 % of the springs nitrate contents above 50 mg/l have been detected. These high nitrate contents are in most cases related to intensive cultivation with abundant use of fertilizers or to dense population.

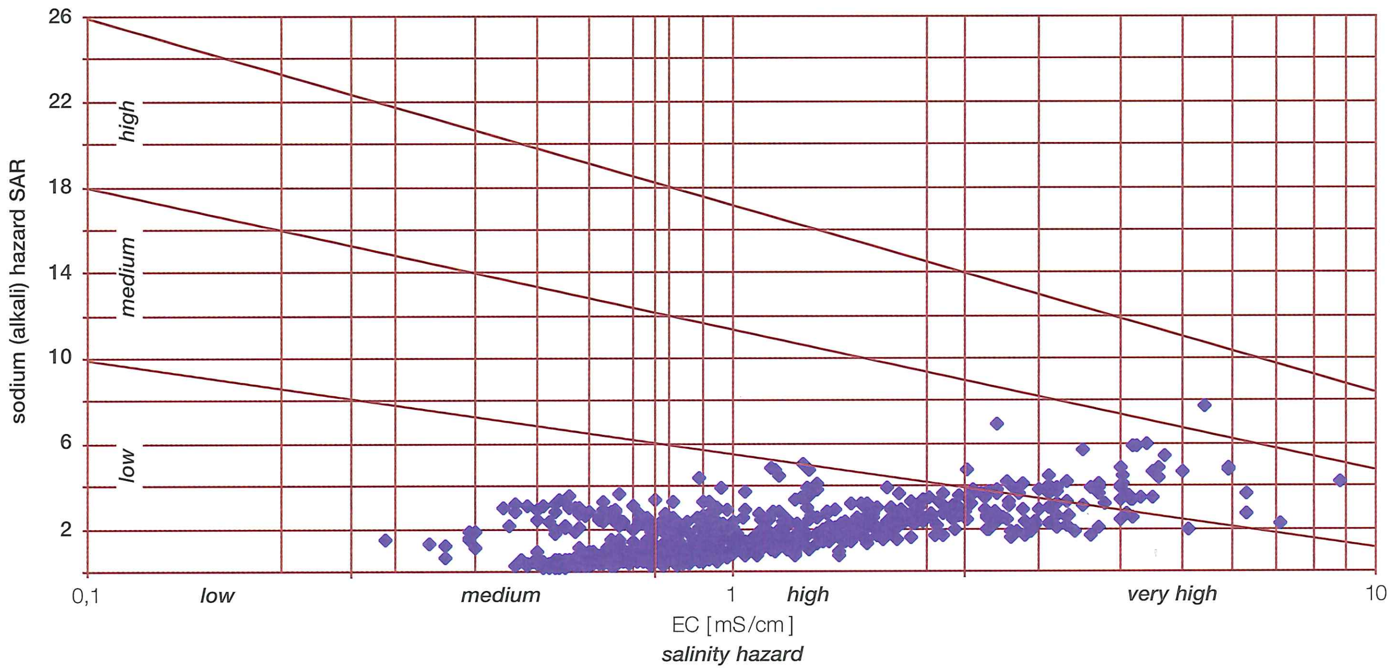


Fig. 17: Hydrochemical compositions of water samples from wells and springs in the A7/B2 aquifer from Northern and Central Jordan – Wilcox diagram (modified after HOBLER et al. 2001).

5.8 Groundwater balance

5.8.1 Results from groundwater modeling

An integrated finite-differences groundwater flow model has been established for the northwestern part of the country (10,500 km≈; BRUNKE 1997). The model boundaries have been defined as follows (Fig. 18):

West: Jordan Valley: a vertical flow to the ground surface is assumed; dynamic constant head boundary: no flow in all model layers except in the upper layer.

North: Lower Yarmouk River: same as Jordan Valley.
Upper Yarmouk Valley: constant head conditions in the first model layer for the Yarmouk River; a constant head of 400 m asl in the deep aquifers (Kurnub and Ram Group) to account for the hydraulic influence of the Jebel al Arab.

East: Between Wadi Shallala and the Azraq oasis the model boundary follows a streamline in the shallow aquifer (A7/B2 and basalt aquifer in the area northeast of Mafraq and Wadi Dhuleil, B4 and Basalt aquifer in the area north of Azraq), i.e. constant head boundary. In the deep aquifer an inflow from the east was defined.

South: The southern boundary follows a streamline in the deep aquifer from Azraq to the Dead Sea (no flow boundary). In the A7/B2 aquifer groundwater flow is in the eastern part directed to the east (Azraq) and in the western part to the west (Wadi Wala). Therefore constant head conditions have been defined here.

Nine hydrogeological units were distinguished:

- the basalt aquifer in the northeastern part of the model area,
- the B4/B5 aquifer,
- the B3 aquitard,
- the A7/B2 aquifer,
- the A1/6 aquifer complex,
- the Kurnub aquifer,
- the Zarqa aquitard,
- the Upper Ram Group aquifer (Amud and Ajram Fms.) and
- the Lower Ram Group aquifer (Burj and Salib Fms.).

During model calibration the following hydraulic parameters have been obtained (Table 10):

Table 10: Hydraulic parameters of the North Jordan groundwater flow model

Hydrogeo-logical unit	horizontal hydraulic conductivity K_h [m/s]	vertical hydraulic conductivity K_v [m/s]	specific storage coefficient	specific yield
Basalt	2.0E-4	2.0E-5	1.0E-5	0.01
B4/B5	3.5E-6 – 1.0E-4	3.5E-7 – 1.0E-5	1.0E-5	0.05
B3	4.2E-10 – 4.2E-7	2.0E-11 – 2.0E-9	1.0E-5	0.01
A7/B2	1.3E-4 – 7.0E-3	2.0E-6 – 1.0E-4	1.0E-5	0.05
A1/6	5.0E-8	5.0E-11	1.0E-5	0.01
Kurnub	3.0E-8	2.5E-8 – 1.3E-6	1.0E-5	0.025
Zarqa	1.4E-7	1.4E-10	1.0E-5	0.01
Upper Ram Group	5.0E-7	2.5E-7	1.0E-5	0.05
Lower Ram Group	5.0E-7	2.5E-7	1.0E-5	0.01

The following groundwater balance results were obtained from the calibration :

Groundwater recharge:	197.7 MCM/yr
Constant head inflows:	8.4 MCM/yr
Total inflows:	206.1 MCM/yr
Spring discharge:	175.6 MCM/yr (dynamic constant head boundary)
Constant head outflows:	30.6 MCM/yr
Total outflows:	206.2 MCM/yr

The groundwater model took into account the groundwater evaporation in the Azraq area. However irrigation return flow and return flow from sewage treatment plants and recharge by water loses from domestic supply systems were not considered. These were included in the water balance (Fig. 18).

According to the model results, strong water level declines are to be expected in the NE-desert area and in the extreme northwest of the country.

5.8.2 A comprehensive water balance for the whole country

Based on the results of the groundwater modeling and the available hydrogeological and other data, a comprehensive water balance was established for the whole country. In Jordan part of the groundwater discharge contains components of fossil groundwater (e.g. baseflow from the Ram Group aquifer in the Dead Sea rift side wadies). This implies that even under natural conditions, groundwater recharge is not in balance with the natural outflow and that there is a deficit in the groundwater balance. However, this does not imply that groundwater withdrawal in Jordan is not sustainable. The results of an overall balance should therefore only be seen as an attempt to demonstrate the serve deficit of the water resources.

The tentative water balance is based on average data of the late 1990s. The **outflow** components reach about 812 MCM/a in total. Groundwater abstraction was about 500 MCM/a, and spring abstraction dropped to about 20 MCM/a. Because of the deep base level of the Dead Sea, transboundary outflow to neighboring countries can probably be neglected. Evapotranspiration in the Azraq area is around 12 MCM/a (Barber & Carr 1973).

The **inflow** components include the recharge of around 280 MCM/a and the transboundary inflow from Syria (mainly through the B4/B5, basalt and A7/B2 aquifers) and Saudi Arabia (mainly through the Ram Group aquifer) of 82 respectively 100 MCM/a according to MWI estimates. The inflows from sources like irrigation return flow, sewage treatment plants and water losses from domestic supply systems can only be roughly estimated. The total amount of 120 MCM/a is based on the following considerations. About 280 MCM of water were annually supplied to the domestic and industrial sectors in 1998 (MWI). The water loss from supply systems was on average around 55 % or approximately 154 MCM/a. It is estimated that around 5–10 % of this amount is recharged to the groundwater. Most of the water used in the agricultural sector is consumed by evapotranspiration. However, in some areas, like for instance the Dhuleil-Hallabat or the northern desert areas, losses of irrigation water are likely. The total annual water consumption in the agricultural sector reached around 720 MCM in 1998 (MWI). It is estimated that irrigation losses are in the order of 15 % or approximately 106 MCM/a. Inflow from return flow of sewage treatment plants (STPs) is throught to be of minor importance since STPs are mostly located in areas where a recharge of treated sewage water is likely to occur only along a short flow path. Altogether these inflow components are believed to constitute only around 120 MCM/yr.

Even with these rather favourable assumptions for some of the inflow components, the water balance deficit amounts to more than 200 MCM/a (Table 11) and clearly confirms the extreme water deficit in Jordan. The very high water level declines of around 2 m in the A7/B2 aquifer in most parts of Jordan are a strong indication for the severe overexploitation of the aquifers.

Figure 18 shows the different components of the water cycle for the whole country of Jordan.

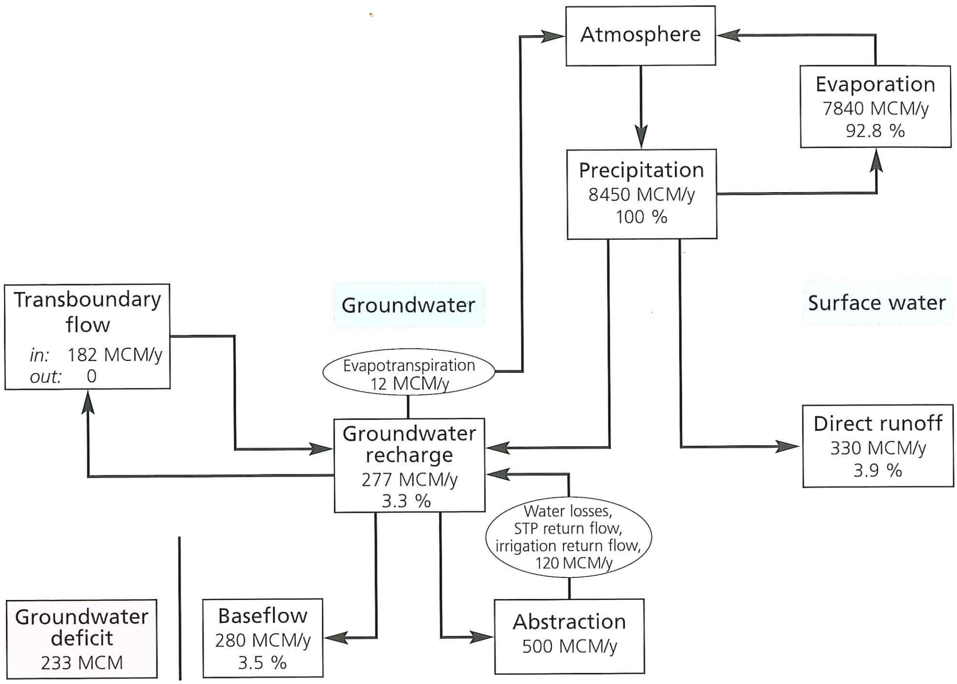


Fig. 18: Groundwater flow model of Northern Jordan.

Table 11: Groundwater balance for the country of Jordan

Balance component	**Amount [MCM]**
Groundwater abstraction	500
Spring abstraction	20
Baseflow	280
Trans-boundary flow (out)	–
Evapotranspiration [mostly Azraq]	12
Total (out)	812
Groundwater recharge	277
Trans-boundary flow (in) [from Syria and Saudi Arabia]	182
Inflow from irrigation return flow, water losses and return flow from STPs	120
Total (in)	579
Balance (deficit)	**–233**

6 Conclusions and Recommendations

Water resources in Jordan are highly overexploited. In the neighboring countries (Syria, Israel/Palestine and Saudi Arabia) the situation is not much different. Therefore, it would be unrealistic to assume that the situation could be resolved by additional water supply from outside (even provided a stable political relation would be given) or the construction of the 'unity dam' (on the Yarmouk River at the border to Syria).

Jordan's population is increasing by around 2.8 % per year (DEPARTMENT OF STATISTICS 2000). Due to this, water demand for domestic purposes is increasing rapidly. An increase in groundwater abstraction for this purpose will, therefore, be unavoidable.

A sustainable management of water resources presently seems almost impossible. However, Jordan's economy is highly dependent on a solution to this problem. Jordan's policies should be based on the following three strategies:

- Reduce the water consumption in the agricultural sector e.g. by:
    - Promoting irrigation techniques that consume less amounts of water,
    - Promoting the growing of crops that consume less amounts of water and
    - Reforming the water rights (e.g. introducing water tariffs for groundwater abstraction from private wells) and
- make additional water resources available, e.g. from:
    - Careful exploitation of fossil groundwater resources: the Ram Group aquifer has proven to be of good quality and exploitable in the area around Disi (HAISTE & SCOTT WILSON KIRKPATRICK 1994). However, conveying water from Disi to Amman is costly. The Ram Group aquifer is naturally flowing out into the Dead Sea. Thus, it would be much easier and more sustainable to exploit this aquifer in the area east of the Dead Sea. A detailed proposal has been made by the project (MARGANE et al. 1995) and first drilling results from the area east of Kerak showed that this would be feasible.
    - Reuse of treated water: if the quality of treated water would be better, water could be reused for irrigation.
    - Rainwater harvesting: almost 90 % of the precipitation is evaporated before forming surface water runoff or reaching the groundwater. However, rainwater-harvesting techniques are presently used only to a very limited extent.
    - Artificial recharge: recent projects, like the Qatrana dam, have yielded little success due to unfavorable conditions. However, there is a wide range of more suitable locations, especially in the upper parts of the catchments in the highlands.
    - Modernizing the supply network.

- Minimize the risk of groundwater pollution and salinization by:
  - Introducing legally binding regulations for groundwater protection (comp. MARGANE et al. 1999),
  - Training the farmers in the proper use of fertilizers, pesticides and fungicides,
  - Increasing the efficiency of sewage treatment plants,
  - Locating and designing sewage treatment plants and waste disposal sites more appropriately,
  - Introducing legally binding regulations for the management of industrial waste and wastewater.

If the water management problems cannot be overcome in the near future, this situation endangers not only the country of Jordan but could cause conflicts with the neighboring countries.

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