

Chapter 10

Saq-Ram Aquifer System (West)



INVENTORY OF
SHARED WATER RESOURCES
IN WESTERN ASIA (ONLINE VERSION)



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Saq-Ram Aquifer System (West)

EXECUTIVE SUMMARY

The Saq-Ram Aquifer System (West) extends on the surface from northern Saudi Arabia into Jordan. At present, it is exploited from the Tabuk Plain in Saudi Arabia to Wadi Rum in Jordan, in an area delineated in this Inventory as the Tabuk-Mudawwara-Disi area.

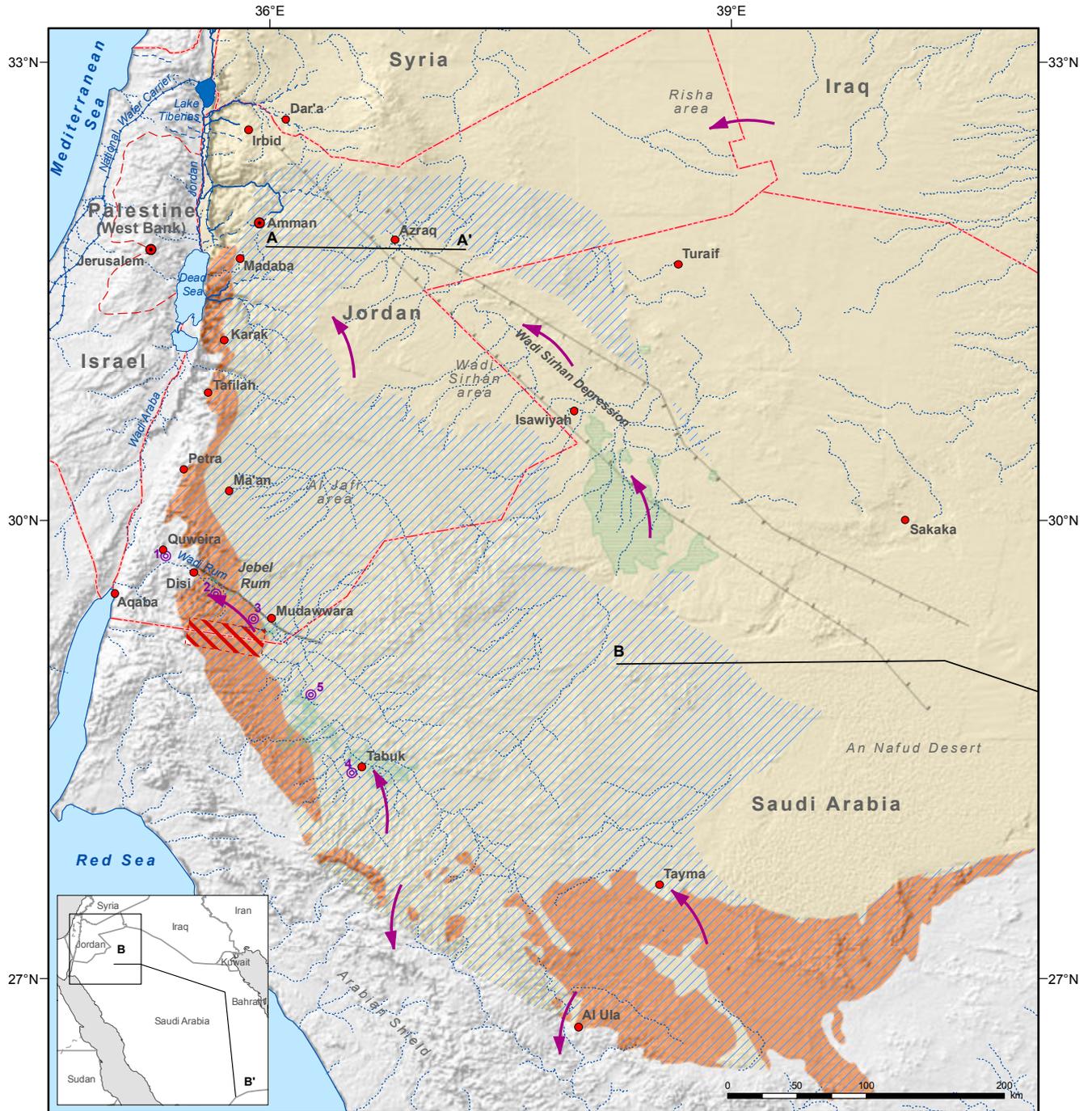
In Jordan, where the aquifer system is known as the Ram Group, it is widely exposed in the southern desert and is present in the subsurface throughout most of the country. Current abstraction in the Mudawwara-Disi area (Jordan) is 60 MCM/yr although higher values of 70-80 MCM/yr were reported in 2008.

In Saudi Arabia south of the Jordanian border (Tabuk area), the Saq lies directly on the Basement and dips gradually towards the north/north-east under less permeable formations. Groundwater abstraction in the Tabuk area has increased drastically from about 29 MCM/yr in 1983 to between 1,050-1,700 MCM/yr in 2004, mostly in the agricultural sector, while recharge remains at 3-10 MCM/yr. The heavy mining of the aquifer system has resulted in water level drops of up to 32 m/yr in the late 1980s in Saudi Arabia. There are indications that the exploitable part of the resource may be exhausted within 30-40 years, unless abstraction can be controlled on both sides of the border.

BASIN FACTS

RIPARIAN COUNTRIES	Jordan, Saudi Arabia
ALTERNATIVE NAMES	Disi, Disi Mudawwara, Ram, Rum, Saq, Saq-Tabuk
RENEWABILITY	Low (2-20 mm/yr)
HYDRAULIC LINKAGE WITH SURFACE WATER	Weak
ROCK TYPE	Porous
AQUIFER TYPE	Unconfined in shallow layers; confined or leaky in deeper layers
EXTENT	308,000 km ²
AGE	Paleozoic (Cambro-Ordovician)
LITHOLOGY	Sandstones
THICKNESS	250-700 m Eastern Jordan: ≥1,000 m Risha Area: 500 m
AVERAGE ANNUAL ABSTRACTION	Jordan: 90 MCM Saudi Arabia: >1,000 MCM
STORAGE	Jordan: 4-10 BCM Saudi Arabia: ~740 BCM
WATER QUALITY	Fresh (mostly <1,000 mg/L TDS)
WATER USE	Mainly agricultural. A rise in municipal and industrial use is expected.
AGREEMENTS	-
SUSTAINABILITY	Overexploitation due to agricultural development. Possible health risk due to high natural radioactivity (Ra).

OVERVIEW MAP



Saq-Ram Aquifer System (West)

- Capital
- Selected city, town
- International boundary
- - - Armistice Demarcation Line
- ~ River
- ~ Intermittent river, wadi
- Canal
- Freshwater lake
- Dike
- A A' Approximate location of geological cross-section
- Graben
- Saq-Ram outcrop
- Approximate subsurface extent of the aquifer formations
- Approximate extent of exploitable area
- Zone of agricultural development (selection)
- No drilling zone
- Direction of groundwater flow
- Water supply well fields
 - 1 Quweira
 - 2 Dubaydib
 - 3 Mudawwara
 - 4 Tabuk
 - 5 Uyanah



Inventory of Shared Water Resources in Western Asia

Disclaimer
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Introduction

LOCATION

The Saq Sandstones in Saudi Arabia are separated by the vast aeolian Nafud Desert and can be divided into the eastern Qassim-Ha'il region¹ with natural groundwater flow towards the north-east, and the western Tabuk-Tayma region where the flow direction is generally northward.²

The lithostratigraphy of the Saq in the Tabuk-Tayma region has many similarities with the Ram³ Sandstones in Jordan.⁴ In this Inventory, the term Saq-Ram Aquifer System refers to the Cambro-Ordovician Sandstones, which extend from the Tabuk-Tayma region to the northern borders of Jordan and Saudi Arabia and beyond.⁵ The aquifer system occurs along the eastern margins of the Arabian Shield where its outcrops can be seen on the surface, extending from central Saudi Arabia to the Dead Sea in western Jordan (see Overview Map).

AREA

The Ram Sandstones are found across the whole of Jordan (both in the subsurface and as outcrops), except in the Wadi Araba area. The Saq Sandstones cover a large part of Saudi Arabia from the Qassim area to the northern borders of the country (see 'Overview and Methodology: Groundwater' chapter, Map 1). The Saq-Ram Sandstones cover a total area of approximately 560,000 km², of which 82,000 km² are situated in Jordan and 478,000 km² in Saudi Arabia.⁶ The shared part of the Saq-Ram Aquifer System (West) as delineated in this Inventory covers an area of approximately 308,000 km².

The Tabuk-Mudawwara-Disi area stretches from the Tabuk Plain in Saudi Arabia to the Wadi Rum Desert in Jordan, between the localities of Disi, Mudawwara and Jafr. This area is surrounded on two sides by aquifer outcrops which form spectacular mountains and high cliffs that rise to an altitude of about 800 m in the south⁷ to 1,750 m near Jebel Rum in Jordan.⁸ The Tabuk Plain is covered by gravel, resting directly on the sandstones, while further north in Wadi Rum the terrain changes to broad sand-covered valley floors.

CLIMATE

The aquifer system stretches across an arid terrain where mean annual temperature ranges between 20°C and 24°C. Mean annual precipitation over the entire area is estimated at 50-100 mm but reaches up to 365 mm around Karak.⁹ The area along the southern border of Jordan commonly receives less than 50 mm/yr. Potential evaporation reaches more than 3,500 mm/yr¹⁰ and actual evaporation is greater than 90% of all precipitation.¹¹

POPULATION

The total population presently living in the Tabuk-Mudawwara area is less than 750,000 of which over 500,000 are in Tabuk Province in Saudi Arabia¹² and about 250,000 in Jordan (133,000 in Aqaba Governorate and about 116,000 in Ma'an Governorate). When the water conveyance system from the Disi-Mudawwara area to Amman (population of more than 2.3 million) is completed, more than 3.5 million people will depend on this aquifer system.¹³

OTHER AQUIFERS IN THE AREA

Other aquifer systems in the area include the Tawil-Sharawra, the Jubah-Jawf (Paleozoic) and the Secondary-Tertiary-Quaternary,¹⁴ which consists of Upper Cretaceous to Quaternary Formations/Sediments and is exploited in Iraq, Jordan and Saudi Arabia.

INFORMATION SOURCES

The riparian countries did not focus on transboundary areas of the aquifer system until the 1980s and studies from the 1980s and 1990s cover the Saq in Saudi Arabia or the Ram (Disi)-Kurnub in Jordan. It is only in recent years that groundwater studies have become more focused on the Tabuk-Mudawwara-Disi area as a potential shared aquifer system. This chapter uses data from these studies and relevant regional data. Delineation of the Overview Map was based on several references from both riparian countries.¹⁵



Table 1. Nomenclature and correlation of the Saq-Ram Aquifer System (West) (aquifer-aquitard) in Jordan and Saudi Arabia

JORDAN			SAUDI ARABIA		
PERIOD	UNITS (GROUP)	SUB-UNITS (FORMATION)	PERIOD	UNITS (GROUP)	SUB-UNITS (FORMATION)
Silurian	Khreim ^a (aquitard)	Sahl as Suwwan, Umm Tarifa, Trebeel, Batra and Alna.	Ordovician	Qassim (aquitard)	Handir, Ra'an-Quwarah, Zarqa-Sara-Hawban.
Cambro-Ordovician	Ram (aquifer)	Amud: sandstone.	Cambro-Ordovician	Saq (aquifer)	Saq: sandstone.
		Ajram: sandstone.			Burj: ^b limestone.
		Burj: siltstone, dolomite, limestone, sandstone.			Siq-Quweira: sandstone.
		Salib: arkosic sandstone, conglomerate.			

Source: Abunayyan Trading Corporation and BRGM, 2008; Barthelemy et al., 2010; Margane et al., 2002; Teimeh et al., 1990.

(a) In western Jordan, the Khreim disappears and the Ram is in contact with the Kurnub Sandstones.

(b) Found only at great depths without any surface exposures [Abunayyan Trading Corporation and BRGM, 2008].

AQUIFER TYPE

In general, the Saq-Ram Aquifer System (West) is unconfined in the outcrop areas and their surroundings and becomes a confined or leaky²⁷ aquifer towards the north and north-east as the sandstones dip below the rocks of the Khreim Group or the Permian to Jurassic Sequence (aquitards)²⁸ in Jordan and the Qusaiba-Hanadir Shales (aquitards)²⁹ in Saudi Arabia (Figure 1).

Transmissivity values vary over a wide range for the entire aquifer system. However, it is clear that the values for the confined/leaky part are higher than those for the unconfined part. Storativity/storage coefficient values show relatively less variation.



The region of Al Ula, Saudi Arabia, 2012. Source: Amru Essam.

AQUIFER PARAMETERS

A large variation in hydraulic parameters is expected between confined and unconfined areas and towards the northern and north-eastern areas where the aquifer base reaches greater depths. This variation is reflected in the results of individual studies on the Saq³⁰ and the Ram.³¹ Table 2 summarizes the results of a number of comprehensive studies that focused on the shared part of the aquifer.

Table 2. Hydraulic parameters of the Saq-Ram Aquifer System (West)

AREA	TRANSMISSIVITY (m ² /s)	STORATIVITY	SOURCE
Tayma-Tabuk	2.2x10 ⁻³ -6.5x10 ⁻³ AVG: ^a 4.5x10 ⁻³ (unconfined) 5.8x10 ⁻³ -4.3x10 ⁻² AVG: 2.6x10 ⁻² (confined)	1.0x10 ⁻² -4.0x10 ⁻² (unconfined) 1.0x10 ⁻⁴ -2.0x10 ⁻³ (confined)	BRGM and CNABRL, 1985.
Tabuk-Mudawwara	1.1x10 ⁻³ -1.7x10 ⁻³ 3.9x10 ⁻³ (Disi Basin) 1.4x10 ⁻² (Jafr Basin)	1.0x10 ⁻³ -5.0x10 ⁻³	Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.
Tabuk-Mudawwara	3.4x10 ⁻³ (unconfined) >1.1x10 ⁻² (confined)	..	Hydrogeological Services International (1990) as cited in Barthelemy et al., 2010.
Jordan	AVG: 8x10 ⁻³	1x10 ⁻² -3x10 ⁻²	Barthelemy et al., 2010.

Source: Compiled by ESCWA-BGR.

(a) AVG refers to average values.



Hydrogeology - Groundwater

RECHARGE

Potential sources of present-day recharge to the Saq-Ram Sandstones include:

- Runoff from the Basement in the south-west directly passing over outcrops of the permeable sandstones.
- Infiltration of runoff through wadi beds.
- Infiltration of rain falling directly on the sandstones, sand dunes or through overlying soils.
- Infiltration of excess irrigation water (locally, mainly in outcrop areas).

The occurrence of recharge to the Saq and Ram Sandstones in southern Jordan and north-western Saudi Arabia during previous pluvial periods is inferred from isotopic data, which suggests the recharge took place 10,000-30,000 years ago.³² Combining isotopic data with field observations in wells along a regional flow line from the Quweira area to the Saudi border near Mudawwara indicated that the oldest waters are now emerging from deep wells in the Jordan Valley.³³ A field survey from 2002 also concluded that modern recharge is negligible (0.03 mm/yr) in areas with no outcrops and where rainfall is less than 75 mm/yr. However, present-day recharge to the sandstones occurs as evidenced by recharge mounds north/north-west of Amman³⁴ and the Wadi Araba Escarpment.³⁵ In such areas, recharge has been shown to increase with elevation from 3 to 11 mm/yr.³⁶ For the Saq, an average annual recharge of 2.5 mm was estimated for the Saq outcrops.³⁷

FLOW REGIME

Until the 1980s, groundwater flow was directed northwards, starting from the Tayma-Tabuk area in Saudi Arabia, crossing the southern desert in Jordan, passing the Jafr Basin and converging across the Azraq Basin to the natural discharge zone, the low-lying Dead Sea.³⁸ There is no discharge to the north-east as the formation is too deep there, but one model showed flow from the Tabuk-Tayma area towards Wadi Sirhan³⁹ while other models simulated a flow from Wadi Sirhan westwards to the Dead Sea.⁴⁰ Modelled groundwater table contours of the Ram Sandstone Aquifer also indicate an inflow across the southern and eastern border from



Wadi Rum, Jordan, 2008. Source: Eileen Maternowski.

Saudi Arabia into Jordan.⁴¹ Net flow calculations for the aquifer system indicated that downward leakage from overlying aquifers might take place⁴² and might have increased due to the formation of cones of depression.⁴³ Depth to the water table varies from around 150 m near the outcrops and in Wadi Sirhan to over 400 m in central Jordan.⁴⁴ Increased abstraction since the 1980s has changed the general pattern of groundwater flow, with a significant effect in the Tabuk area, where substantial volumes of water are abstracted for agriculture purposes (see below). This has produced a very large and deep cone of depression, locally diverting the natural north-easterly groundwater flow direction,⁴⁵ reducing the assumed natural flow across the border to Jordan (140 MCM/yr) to negligible amounts.⁴⁶

Near the border, the Kharawi basaltic dike forms a natural hydraulic barrier impounding the groundwater so that the flow is deflected in a south-easterly direction towards Saudi Arabia⁴⁷ or north-westerly direction towards the Wadi Araba.⁴⁸ Some 100 km south of Tabuk, flow is directed outward to the Shield areas. Further south-east, the Al Ula Valley also drains the Saq Aquifer to the Arabian Shield.⁴⁹



Wadi Rum, Jordan, 2010. Source: Andreas Renck.

STORAGE

Saudi Arabia estimates the total volume of groundwater proven-reserve (storage) throughout the Saq Aquifer at 65 BCM, without specifying how much of this reserve is in the Tabuk area that falls within the Saq-Ram shared system.⁵⁰ Other investigations in Saudi Arabia state that with continued pumping at the current rate of 5,515 MCM/yr from the Saq and 1,050 MCM/yr in the Tabuk area, the exploitable reserve will drop from currently 75% to 38% between 2005 and 2055.⁵¹ Available groundwater reserves in the Saq in the Tabuk area were estimated at 43 BCM in 1985, of which about 20 BCM is in the unconfined part, compared with 220 BCM in the Qassim area.⁵²

In Jordan, estimates of available water reserve commonly range between 4 and 10 BCM with a maximum of 40 BCM.⁵³ Only 1×10^{-1} MCM lies in the unconfined part of the aquifer, mainly within the southern desert zone.⁵⁴

DISCHARGE

The main discharge zone for the aquifer system is the Dead Sea area where the Ram and Kurnub Groups form a combined aquifer complex. Groundwater level contour maps of the sandstones indicate a groundwater inflow from Saudi Arabia into Jordan of about 50 MCM

in the Mudawwara-Disi area. Inflow increases to 140 MCM in the Dead Sea area due to additional inflow from the Kurnub.⁵⁵

Natural discharge occurs in the form of springs and base flow in the deeply incised wadis that discharge into the Dead Sea. The occurrence of springs is restricted to areas along the eastern side of the Jordan Rift Valley, where average rainfall is around 150–200 mm/yr. Of a total annual spring discharge of 27 MCM in southern Jordan, 10 MCM (37%) is from the Ram Group.⁵⁶ These springs feed the wadis along the central and southern part of the Dead Sea (mainly Wadi Ibn Hammad, Wadi Karak, Wadi Feifa). Base flow in these wadis was estimated at around 25 MCM, with wide fluctuations from year to year.⁵⁷ While this could be due to a significant variation in annual recharge, it also indicates that in many cases direct runoff and base flow have not been separated properly. Base flow may therefore be even lower (see Chap. 17).⁵⁸

Groundwater discharge also occurs in the Wadi Sirhan Depression and its northern extension into the Azraq Graben, as well as in the Shield areas as inferred from the flow lines (see Overview Map). Further discharge emanates from springs in valleys draining towards the Red Sea.⁵⁹ However, no data was available from these areas.



WATER QUALITY

The quality of water in the Saq-Ram Aquifer System (West) is generally good with Total Dissolved Solids (TDS) levels between 1,000 and 1,200 mg/L,⁶⁰ and dominated by calcium (Ca^{2+}) and bicarbonate (HCO_3^-). Salinity increases northwards along the flow path, from freshwater (200-400 mg/L TDS) in the Mudawwara-Disi area, to slightly brackish (1,000-3,000 mg/L) at the Dead Sea, where thermal springs are common. This salinity increase is most likely due to downward leakage from the overlying formations that contain highly saline waters (up to 35,000 mg/L), and the dissolution of evaporites contained in the aquifer.⁶¹ In Saudi Arabia, salinity levels are slightly elevated in unconfined areas.⁶² The chemistry of abstracted water in both the confined and unconfined areas appears to be largely unchanged over several years of operation.⁶³ Elevated concentrations of boron (B^{3+}) ($>5 \times 10^{-1}$ mg/L) and selenium (Se^{4+}) ($>1 \times 10^{-2}$ mg/L) have been detected in Saudi Arabia in about 37% and 26% of samples respectively.⁶⁴ Elevated concentrations of nitrate (NO_3^-) [25% of samples >50 mg/L] are mostly found in wells that tap unconfined aquifers at a depth of less than 150 m. However, contamination of confined aquifers through the wells themselves has also been observed.⁶⁵

The occurrence of natural radionuclides is common in Cambro-Ordovician Sandstones, and their presence in groundwater within the Ram and overlying Khreim Group in Jordan and Saudi Arabia has been reported.⁶⁶ Radioactive elements might originate from the Basement, shale layers, phosphate-bearing formations⁶⁷ and cementing material in the sandstones such as iron (Fe^{2+}) and manganese (Mn^{2+}) oxides with other trace metal oxides, including those of uranium (U).⁶⁸ In general, a decrease in pH enhanced the dissolution of uranium and radium (Ra) from the matrix and thermal springs in the Dead Sea area, discharging waters that contain elevated concentrations of

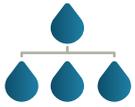
carbone dioxide (CO_2), hydrogen sulfide (H_2S) and radon (Rn) gases.⁶⁹ Radioactivity appears to be increasing as the water level declines, most probably due to an increase in vertical leakage from less permeable layers that contain higher concentrations of radioactive minerals.⁷⁰ The highest concentrations of radium isotopes in groundwater have been reported in confined areas,⁷¹ which can be explained by the fact that the isotopes are most mobile under reducing conditions. Such groundwater might pose a risk to human health when threshold values for drinking water are exceeded.⁷²

EXPLOITABILITY

The following criteria were used to delineate the exploitable areas of this aquifer system:

- **Depth to top of aquifer:** The depth to the top of the Cambro-Ordovician Formations generally increases from west to east. It is 2,000 m bgl in the vicinity of and inside the Wadi Sirhan Graben and in most areas east of the graben, except in the area of Azraq.⁷³ Hence drilling depth is a limiting factor to exploitability east of the Wadi Sirhan Depression, excluding the Azraq area.
- **Depth to water level:** Groundwater in the Tabuk area is around 200 m bgl.⁷⁴ Across the border, similar depths are found in the Mudawwara-Disi area and in the Azraq area where it can be as high as 62 m bgl.⁷⁵ Water level is therefore not a limiting factor.
- **Water quality:** The TDS of the groundwater is generally below 1,200 mg/L throughout the Saq-Ram Aquifer System (West)⁷⁶ and does not constitute any limitation to exploitability.

Based on the above, the Saq-Ram Aquifer System (West) is exploitable within a total area of 153,000 km² across the Jordanian-Saudi Arabian border as shown in the Overview Map.



Groundwater Use

GROUNDWATER ABSTRACTION AND USE

Jordan and Saudi Arabia started groundwater production from the Saq-Ram Aquifer System (West) in 1977 and 1983 respectively.⁷⁷

In Jordan, groundwater abstraction from the Saq-Ram Aquifer System commenced at an average rate of 5.4 MCM/yr and the water was used for various purposes.⁷⁸ From 1981/82 onward, a total of 8-10 MCM/yr of groundwater was abstracted, mainly from a new well field for domestic use in the city of Aqaba. Abstraction increased to around 15 MCM/yr in 2001,⁷⁹ including municipal supplies for the village of Disi.

In 1982, a Jordanian farming corporation (Rum Farms) started exploiting the aquifer at a rate of 1.2 MCM/yr.⁸⁰ Abstractions for agricultural purposes rose quickly to reach 55 MCM in 2001, bringing total abstraction to 70 MCM.⁸¹ Average annual abstraction from the Ram Aquifer oscillated between 70 and 80 MCM/yr until about 2008.⁸² Abstraction was subsequently reduced to the current rate of 60 MCM/yr, of which

40 MCM/yr is for agricultural use, 15 MCM/yr for domestic use and the remaining 5 MCM/yr for industrial use.⁸³

The following main farming corporations are currently licensed to operate in the Disi and Mudawwara areas in Jordan: Rum Company (5,000 ha), WAFA Farm (1,448 ha), ARICAT Farm (2,115 ha), Jordan Financing House Co. (1,481 ha) and GRAMCO Farm (1,638 ha), bringing the total licensed area to 11,676 ha.⁸⁴ An additional 11 MCM/yr are abstracted from the Lajjun area away from the border.⁸⁵ Further abstractions of about 100 MCM/yr are planned from the Dubaydib well field (Box 1 below).

The Jordanian Government announced plans to reduce groundwater abstraction for agricultural purposes after 2011, when its contract with the main agricultural companies expired,⁸⁶ thus stabilizing overall abstractions in Jordan.

Based on the above, the cumulative total abstraction from the Ram Group in the Disi and Mudawwara areas in Jordan between 1977 and 2011 is in the order of 1.7 BCM.⁸⁷



Agriculture in the Disi-Mudawwara area, Jordan, 2009. Source: Andreas Renck.



In Saudi Arabia, the extensive Saq Aquifer is nationally very important and currently accounts for more than half of total nationwide groundwater withdrawals from major aquifer systems. Overall withdrawals from the entire Saq Aquifer were marginal until the 1960s but have risen sharply from approximately 890 MCM/yr in 1980 to 8,727 MCM/yr in 2005. Most of these withdrawals are from the Saq Aquifer itself (5,708 MCM or 65% in 2005). The remainder is abstracted from the overlying Tawil Aquifer (876 MCM or 10%) and the Secondary-Tertiary-Quaternary Aquifer Complex (1,388 MCM or 16%).⁸⁸

More than 80% of all withdrawals from the Saq Aquifer take place in the eastern part (Qassim, Ha'il, Riyadh areas) at considerable distances from any national border. This Inventory focuses mainly on the western part of the Saq Aquifer, and more specifically on the Tabuk area which borders on the Mudawwara-Disi areas in Jordan. Practically all groundwater abstractions in the Tabuk area stem from the Saq Aquifer.⁸⁹ Significant abstraction also takes place in the northern Jawf area close to the Wadi Sirhan Graben. However these abstractions are mainly from other overlying aquifer systems (see Chap. 17).

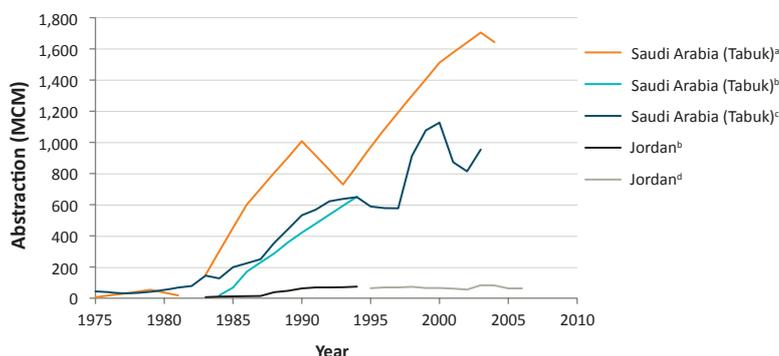
Total abstraction from the Tabuk area was limited until 1983 (less than 50 MCM/yr) but increased dramatically to between 1,053⁹⁰ and 1,700 MCM/yr⁹¹ in 2004 (Figure 2).

According to an estimate from 2008, abstraction in the Tabuk area represented nearly 20% of total abstraction from the Saq Aquifer in Saudi Arabia (5,515 MCM/yr). An estimated 990 MCM/yr (94%) were used for irrigation and 63 MCM/yr (6%) for domestic and industrial water supply in the town of Tabuk and at the nearby Tabuk airbase.⁹²

The main farming corporations in the Tabuk area include the TADCO Farms, which were established in 1986, and currently cover 35,000 ha⁹³ and the ASTRA Farms, which were established in 1979 and currently cover 3,200 ha. The latter company also owns the Rum Farms in Jordan⁹⁴ and a number of smaller concessions in Saudi Arabia.

In 1995, lands irrigated by the aquifer system were estimated at 10,600 ha and 137,800 ha in the Mudawwara-Disi (Jordan) and Tabuk-Tayma (Saudi Arabia) areas respectively.⁹⁵ Official agricultural census data for Tabuk Province in Saudi Arabia⁹⁶ shows lower total crop area for the same year and indicates that total cropped area has remained stable since 1995 at around 50,000 ha. Similar results have been obtained from other remote sensing studies, as shown in Figure 3.

Figure 2. Historical abstraction from the Saq-Ram Aquifer System (West) (1975-2007)



Compiled by ESCWA-BGR based on sources below.

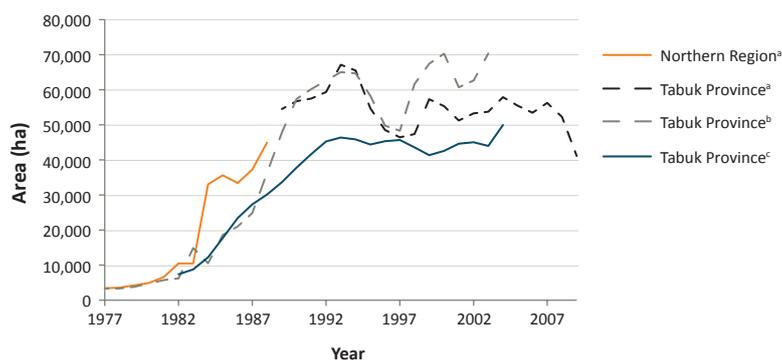
(a) Water Watch, 2006.

(b) Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.

(c) Approximate numbers only. Data digitized from Abunayyan Trading Corporation and BRGM, 2008, p. 42, Figure 24.

(d) Data for the years 1995-2006 was taken from Barthelemy et al., 2010 by adding Mudawwara and Disi area abstractions.

Figure 3. Development of total crop area in the Tabuk region of Saudi Arabia (1977-2009)



Source: Compiled by ESCWA-BGR.

(a) Central Department of Statistics and Information in Saudi Arabia, 1977-2009.

(b) Water Watch, 2006.

(c) Abunayyan Trading Corporation and BRGM, 2008.

Despite the stabilization of the total cropped area, groundwater abstraction continued to increase after 1995 (Figure 2), possibly due to a shift towards increased summer cultivation and more water-intensive crops. According to the census, most of the irrigated crop area in the Tabuk region is used for temporary crops such as wheat, which covered 71% of the cropped area in 1989.

Wheat production declined sharply after 1993, from 187,553 tons in 1989 to 15,763 tons in 1998, covering just 11% of cropped area (Figure 4). This reduction came in the wake of the government's decision to cut fixed wheat commodity prices by 25% in 1994, as well as a number of other factors including a delay in payment to producers and fuel subsidy cuts, which increased groundwater pumping costs and hence overall production cost.⁹⁷



Figure 4 shows a strong increase in the (summer) cultivation of fodder crops (mainly alfalfa), from 7% of total crop area in 1989 (total fodder production 30,111 tons) to over 45% in 1999 (329,040 tons). While these trends reversed again soon after, fodder production remained at higher levels than in the early 1990s.⁹⁸ These crops are often grown year-round and have higher water requirements of up to 3,900 mm compared to wheat, a winter crop which requires around 1,300 mm per cycle.⁹⁹ The agricultural policy changes outlined above may therefore have temporarily lowered wheat production, but did not lead to a decrease in water abstraction from the Saq Aquifer in the Tabuk area.

Based on the above figures, cumulative total abstraction from the Saq Aquifer in the Tabuk area of Saudi Arabia was roughly 32.2 BCM between 1977 and 2011.¹⁰⁰

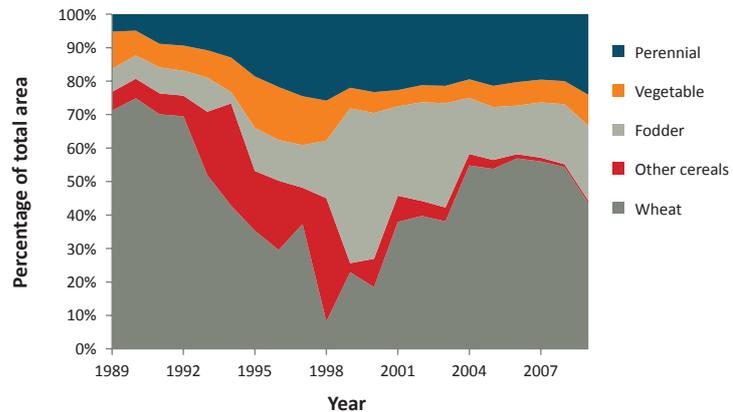
Effect of abstraction on water tables

Rising groundwater abstraction resulted in a drop in the water table in both countries from the mid-1980s onward. The average drop in water level in Jordan varied from 0.6 to 1.0 m/yr, with maximum declines of up to 5 m in some places between 1985 and 1989.¹⁰¹ The water level continues to decline steadily (Figure 5). In Saudi Arabia, data from the TADCO wells indicates significant declines in the Tabuk area, with total water level drops of 100 m to 160 m from 1983 to 1988,¹⁰² resulting in the reversal of the horizontal and vertical hydraulic gradient in some areas.¹⁰³ Currently most water levels range between 50 m bgl and 150 m bgl.¹⁰⁴ Continued abstraction from the Tabuk area could result in further head level decline in south-western Jordan, as the pressure changes in the confined system may be transferred over more than 100 km.¹⁰⁵ In principle, this also applies to abstraction in Jordan, but given that abstraction is significantly lower here than in the Tabuk area, there is less likely to be a far-reaching impact on the aquifer into Saudi Arabia.

GROUNDWATER QUALITY ISSUES

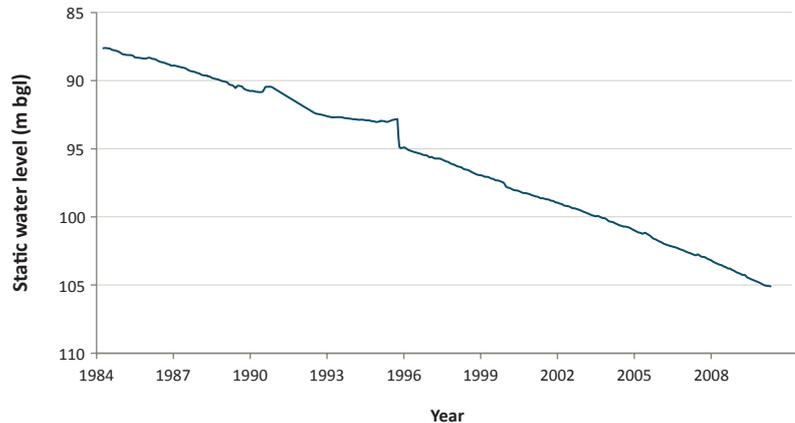
Groundwater in the Saq-Ram Sandstones is fresh and suitable for all purposes. However, there are indications that some problems may arise in the future. Natural sources of radioactivity¹⁰⁶ may affect the entire aquifer system in the long term and limit its use. Other potential sources that may affect water quality could develop locally as a result of heavy pumping. They include leakage of saline water from overlying shale formations, nitrate concentration from irrigation return flows, and upconing of saline and hypersaline formation waters in faulted and geothermal areas.¹⁰⁷

Figure 4. Main crops in the Tabuk area as a percentage of total cultivated area (1989-2009)



Source: Compiled by ESCWA-BGR based on Central Department of Statistics and Information in Saudi Arabia, 1977-2009.

Figure 5. Groundwater decline in the Ram Aquifer in the South Wadi Araba Basin in Jordan (1984-2010)



Source: Compiled by ESCWA-BGR based on Ministry of Water and Irrigation in Jordan, 2010. Note: Water level measured from ED1203L Q'A Abu Suwana Observation well.



Wadi Rum, Jordan, 2008. Source: Eileen Maternowski.



BOX 1 The Disi-Amman Water Conveyance Project

The Disi Water Conveyance Project is designed to supply the Jordanian capital Amman with 100 MCM/yr (273,973 m³/d) for at least 25 years. The projected minimum winter flow is 80 MCM/yr (219,178 m³/d) and maximum summer flow is expected at 120 MCM/yr (328,767 m³/d). Water will be drawn from the Dubaydib well field in the Ram Aquifer and pumped over a distance of 325 km to Amman, providing water to the cities of Ma'an, Tafilah, Karak and Madaba on the way. Water travelling through the Disi Conveyor will take at least 20 days to cover the distance from Mudawwara in the south of Jordan to Madaba near Amman. Groundwater will be pumped from 64 production wells, with 55 wells yielding the required flow and the remaining nine serving as piezometric wells. While the actual difference in altitude between Disi and Amman is about 250 m, the water needs to be lifted by about 800 m in total, which will require an estimated 4 kW/m³ of energy for vertical and horizontal pumping. The project's total energy requirement has been reported to be 50 MW, or 2% of Jordan's annual energy consumption.

Following the issuing of the tender in 2007, the project was awarded to GAMA Energy, a joint venture between GAMA Holding of Turkey and General Electric (GE) of the United States of America. The project, which is being built on a Build-Operate-Transfer basis over a 48-month period, has been described as the largest infrastructure project ever in Jordan, with a value of

USD 1.2 billion. In 2007, the Jordanian Government was reported to have committed USD 200 million, while GAMA has invested USD 700 million.

Construction of the wells, the pipeline and the pumping stations was initiated in August 2008, but had to be suspended several times due to security issues. In January 2011, two employees were killed and four were heavily injured during a shooting incident, as local communities protested against the project's implementation. The project was again suspended for nearly two months in October 2011 after further shooting incidents in July and September. Since then, local police forces have been enlisted to patrol the project area.

In July 2012, government sources announced that 85% of the project had been completed and that experimental pumping would start in the fourth quarter of 2012 with 20-30 MCM of water reaching Amman by February 2013. The project is scheduled for completion in July 2013. The Disi Water Conveyance Project will satisfy about 40% of Jordan's annual water demand. The price of water will range between USD 0.95/m³ and USD 1.40/m³ depending on energy consumption prices.

Sources: Compiled by ESCWA-BGR based on Consolidated Consultants (Engineering and Environment), 2004; Venture, 2012; Jordan Times, 2012; Global Water Intelligence, 2007.



The Disi Water Conveyor, Jordan, 2012. Source: Eileen Maternowski.

SUSTAINABILITY ISSUES

A 1995 compilation of yield estimates for the Ram Aquifer gave a very wide range of results predicting aquifer depletion within the space of 23 to 200 years (Table 3). Based on the simulation of production scenarios, it was concluded that it is realistic for Jordan to abstract an additional 150 MCM/yr for public supply (to reach a total supply of 225 MCM/yr from the system) for a period of 40 years, while production in Saudi Arabia could increase to 977 MCM/yr by the end of this period.¹⁰⁸ In Saudi Arabia, it was concluded that 71% of the groundwater reserves in the Saq will have been used by 2055 and that it is only a matter of time

before the exploitable groundwater resources in the Saq will be exhausted.¹⁰⁹ These projections suggest that the lifespan of the aquifer system may be limited to the first half of this century unless abstraction is reduced or technological innovation allows for the abstraction of additional reserves that cannot be accessed at present.

The simulated drawdown for the new Dubaydib well field is about 2 m/yr and the dynamic drawdown may reach 100 m in 25 years. This means that the water table depth may drop to approximately 350 m bgl, making the well field economically unviable.¹¹⁰

Table 3. Summary of Saq-Ram Aquifer System (West) yield estimates

SOURCE	QUANTITY FOR PRODUCTION (MCM/yr)	BACKGROUND INFORMATION
PRIDE, 1992.	128	Resource available for 23.5 years. Estimate based on the extent of the "Disi (surface) Basin".
UNDP, 1990.	125	Yield for 50 years provided Tabuk constant at 250 MCM/yr. Restatement of Howard Humphreys, 1986. Tabuk area already pumping approx. 478.5 MCM/yr in 1990.
Thames Water, 1988.	50-70	Economic resource for Amman supply.
Howard Humphreys, 1986.	110	Reliable yield for 200 years. Model study alone, not based on drilling/testing in the confined area, or consideration of "leakage". Model boundaries not set relative to aquifer flow lines.

Source: Modified by ESCWA-BGR based on Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.



Agreements, Cooperation & Outlook

AGREEMENTS

The riparian countries have to date not signed an official treaty, but the Jordanian Ministry of Water and Irrigation and the Saudi Arabian Ministry of Electricity and Water signed a memorandum of understanding (MoU) at the technical level in 2007. The agreement prohibits the drilling of new production wells and the expansion of agricultural activities within an area of 10 km along both sides of the border between the new Dibdib/Dubaydib and Tabuk well fields (indicated as 'no drilling zone' on the Overview Map). The MoU is non-binding as it does not constitute a treaty under international law.

COOPERATION

Based on the 2007 bilateral MoU, the two countries plan to enhance cooperation through monitoring and exchange of data.

OUTLOOK

In Jordan, continued unsustainable extractions for agricultural use in the Tabuk-Mudawwara-Disi area form the greatest threat to the aquifer system. The creation of new well fields in Dubaydib, Lajjun and east of the town of Azraq would place extra pressure on water resources. A modernized groundwater monitoring network that was installed in 2011¹¹¹ may help to assess the condition of the Ram Aquifer. In Saudi Arabia, the Ministry of Water and Electricity has suggested a reduction of up to 50% in agricultural water demand in the Tabuk area. This would not only increase the lifespan of the Saq Aquifer, but also reduce further radioactive contamination of the groundwater.¹¹² Previous studies that focused exclusively on the Jordanian or Saudi Arabian parts of the aquifer could provide a useful basis for future cooperation efforts. The establishment of a joint monitoring network on both sides of the border could verify and assess water level draw-downs across the border, and foster information exchange.



The region of Al Ula, Saudi Arabia, 2012. Source: Amru Essam.



Notes

1. More than 80% of all groundwater withdrawals from the Saq Aquifer take place in this part (Qassim, Ha'il, Riyadh areas), which is at a considerable distance from any national border and hence not considered in this Inventory.
2. BRGM and CNABRL, 1985; Abunayyan Trading Corporation and BRGM, 2008.
3. Disi, the old name for the sandstones, is not used anymore since it refers only to one formation within the Ram Group (Table 1).
4. Abunayyan Trading Corporation and BRGM, 2008.
5. The Cambro-Ordovician Sandstones extend to Iraq and Syria, where they are too deep and probably not exploitable. The description and area calculations in this chapter take the northern border of Jordan and Saudi Arabia as the limit of the aquifer system.
6. The Water Atlas of Saudi Arabia (Ministry of Agriculture and Water in Saudi Arabia, 1984) stated a total area of 225,000 km² for the whole Saq Aquifer extension (65,000 km² outcrops and approx. 160,000 km² subsurface), which is less than half of what has been calculated in this Inventory. Considering that the Inventory data is based on the Atlas Map, the discrepancy may stem from the fact that the original subsurface data was an estimate, while this Inventory based estimates on digitized data. The fact that a figure of 300,000 km² was reported for the Tabuk Basin alone (Edgell, 1997) appears to support the more recent findings.
7. Vincent, 2008.
8. Edgell, 2006.
9. Margane et al., 2002.
10. Margane, 2011.
11. Margane et al., 2002.
12. Including coastal areas that are not supplied with water from the Saq Aquifer.
13. Department of Statistics in Jordan, 2004.
14. Abunayyan Trading Corporation and BRGM, 2008.
15. Saudi Arabian Ministry of Agriculture and Water in Saudi Arabia, 1984; Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995; Christian, 2000; Abunayyan Trading Corporation and BRGM, 2008; and Barthelemy et al., 2010.
16. BRGM and CNABRL, 1985.
17. The term Tabuk Formation is gradually being replaced by the new term Qassim Formation. The names Kahfah and Quwarah are used informally for the sandstones in this formation (Abunayyan Trading Corporation and BRGM, 2008).
18. Abunayyan Trading Corporation and BRGM, 2008.
19. Hobler et al., 1991.
20. Margane et al., 2002.
21. Barthelemy et al., 2010.
22. BRGM and CNABRL, 1985.
23. Hobler et al., 1991; Andrews, 1991; Margane et al., 2002.
24. Hobler et al., 1991.
25. Margane et al., 2002.
26. Ministry of Agriculture and Water in Saudi Arabia, 1984; Sharaf and Hussein, 1996; Alsharhan et al., 2001.
27. Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995 report that, in contrast to previous descriptions, the aquifer behaves as a leaky system and not a simple confined one.
28. Margane et al., 2002; Barthelemy et al., 2010.
29. Abunayyan Trading Corporation and BRGM, 2008.
30. E.g. Ministry of Agriculture and Water in Saudi Arabia, 1984; Alsharhan et al., 2001; Tomaihy, 2007.
31. E.g. Margane et al., 2002; Hobler et al., 1991.
32. BGR et al., 1999.
33. Water Authority of Jordan, 2002.
34. Margane et al., 2002.
35. Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.
36. Ibid.
37. Abunayyan Trading Corporation and BRGM, 2008.
38. Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.
39. Abunayyan Trading Corporation and BRGM, 2008.
40. Barthelemy et al., 2010.
41. Hobler et al., 1991.
42. Ibid.
43. Abunayyan Trading Corporation and BRGM, 2008.
44. Barthelemy et al., 2010.
45. Abunayyan Trading Corporation and BRGM, 2008.
46. Barthelemy et al., 2010.
47. Hobler et al., 1991.
48. Barthelemy et al., 2010.
49. Abunayyan Trading Corporation and BRGM, 2008.
50. Ministry of Agriculture and Water in Saudi Arabia, 1984.
51. Abunayyan Trading Corporation and BRGM, 2008.
52. BRGM and CNABRL, 1985.
53. Ferragina and Greco, 2008.
54. Hydrogeological Services International, 1991.
55. Hobler et al., 1991; Barthelemy et al., 2010.
56. Hobler et al., 1991.
57. Ibid.
58. Margane et al., 2002.
59. Abunayyan Trading Corporation and BRGM, 2008.
60. Ibid.; Barthelemy et al., 2010.
61. Lloyd, 1969 cited in Barthelemy et al., 2010.
62. Abunayyan Trading Corporation and BRGM, 2008.
63. Hydrogeological Services International, 1991; Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995; Abunayyan Trading Corporation and BRGM, 2008.
64. Abunayyan Trading Corporation and BRGM, 2008.
65. Ibid.
66. Salameh and Rimawi, 1987; Abunayyan Trading Corporation and BRGM, 2008; Vengosh et al., 2009; Barthelemy et al., 2010.
67. Abunayyan Trading Corporation and BRGM, 2008.
68. Bender, 1968 cited in Salameh and Rimawi, 1987.
69. Salameh and Rimawi, 1987 [²²²Rn = 1,700 to 30,000 pCi/L (picoCuries/L)].
70. Barthelemy et al., 2010; Abunayyan Trading Corporation and BRGM, 2008.
71. Vengosh et al., 2009 [²²⁸Ra + ²²⁶Ra = up to 4 Bq/L (becquerel/L)].



72. According to WHO, 2011, the guidance levels for drinking water are the following: $^{224}\text{Ra} = 1 \text{ Bq/L}$; $^{226}\text{Ra} = 1 \text{ Bq/L}$; $^{228}\text{Ra} = 0.1 \text{ Bq/L}$.
73. Abunayyan Trading Corporation and BRGM, 2008, Vol. 13; Christian, 2000.
74. Abunayyan Trading Corporation and BRGM, 2008, Vol. 1.
75. Barthelemy et al., 2010.
76. Ibid., Abunayyan Trading Corporation and BRGM, 2008, Vol. 1.
77. Abu-Ajamieh et al., 1988.
78. Ibid.
79. Barthelemy et al., 2010.
80. Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.
81. Barthelemy et al., 2010.
82. Ferragina and Greco, 2008.
83. Ministry of Water and Irrigation in Jordan, 2011.
84. All numbers from Barthelemy et al., 2010.
85. Barthelemy et al., 2010.
86. Government of Jordan, 2010; Margane, 2011.
87. According to the data plotted in Figure 3 from Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995 and Barthelemy et al., 2010. An initial abstraction rate of 5.4 MCM/yr was assumed for the years 1977-1982, an average abstraction of 70 MCM/yr was assumed for the years 2007 to 2011.
88. All numbers in the paragraph from Abunayyan Trading Corporation and BRGM, 2008, pp. 20, 22, 40.
89. See Abunayyan Trading Corporation and BRGM, 2008, plate 4.
90. Abunayyan Trading Corporation and BRGM, 2008.
91. Water Watch, 2006. These figures were derived from remote sensing only and it is unclear whether the figures refer to the Tabuk area or to abstractions from the Saq Aquifer only.
92. Abunayyan Trading Corporation and BRGM, 2008.
93. TADCO, 2012.
94. ASTRA Food Company, 2012.
95. UN-ESCWA et al., 1996. Estimates based on landsat imageries.
96. The Tabuk-Tayma irrigated areas in Saudi Arabia lie almost entirely within the boundaries of Tabuk Province and constitute by far the largest agricultural areas in this province. In terms of geographical scope, census data for Tabuk Province is roughly comparable to estimates for the Tabuk-Tayma areas from other studies with regards to agricultural production and water use.
97. Al Sheikh, 2001, p. 307.
98. Fodder production represented around 16% of total cultivated area in 2004 and has since then continued to amount to 35%-40% of total yield of temporary crops (fodder production estimated at 145,000-200,000 tons/yr).
99. Water requirement according to Al Sheikh, 2001, p. 305, Table 14.4.
100. Based on estimated groundwater abstraction for the Tabuk area for the period 1977-2004 according to Water Watch, 2006; a constant abstraction of 1,400 MCM/yr was assumed for the period 2005-2011.
101. UN-ESCWA et al., 1996.
102. Ibid.
103. Abunayyan Trading Corporation and BRGM, 2008.
104. Ibid.
105. Barthelemy et al., 2010.
106. The occurrence of the radioactive elements (radionuclides) in the Saq-Ram Aquifer at levels higher than acceptable for human use has been reported by Al-Saud et al. 2011; Vengosh et al., 2009; Abunayan and BRGM, 2008; Salameh and Rimawi, 1987.
107. Abunayyan Trading Corporation and BRGM, 2008; Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995; Harza Group, 1996 as cited in Ferragina and Greco, 2008.
108. Haiste Kirkpatrick International and Scott Wilson Kirkpatrick, 1995.
109. Abunayyan Trading Corporation and BRGM, 2008.
110. Barthelemy et al., 2010.
111. This programme is being implemented by the ESCWA-BGR Cooperation.
112. Abunayyan Trading Corporation and BRGM, 2008.



Bibliography

- Abu-Ajamieh, M. M., Bender, F. and Eicher, R. N. 1988.** Natural Resources in Jordan: Inventory, Evaluation, Development Program. Published by the Natural Resources Authority in Jordan. Amman.
- Abunayyan Trading Corporation and BRGM (Bureau de Recherches Géologiques et Minières). 2008.** Investigations for Updating the Groundwater Mathematical Model(s) of the Saq Overlying Aquifers (Main Report) and (Geology). Published by the Ministry of Water and Electricity in Saudi Arabia. Available at: <http://www.scribd.com/doc/16845648/Saq-Aquifer-Saudi-Arabia-2008>; <http://www.scribd.com/doc/16769693/FR-Vol-13-Geology>. Accessed on March 17, 2012.
- Al Sheikh, H. M. H. 2001.** Water Resources and Development in Saudi Arabia. In **Water in the Arabian Peninsula: Problems and Policies**. Published by Ithaca Press.
- Alsharhan, A. S., Rizk, Z. A., Nairn, A. E. M., Bakhit, D. W., et al. 2001.** Hydrogeology of an Arid Region: The Arabian Gulf and Adjoining Areas. 1st ed. Published by Elsevier. Amsterdam/New York.
- Andrews, I. J. 1991.** Palaeozoic Lithostratigraphy in the Subsurface of Jordan. **Subsurface Geology**, 1(2).
- ASTRA Food Company. 2012.** ASTRA Farms, Miraculous Desert Cultivation. Available at: http://www.astrafood.com/Astra_farms.asp. Accessed on January 20, 2012.
- Barthelemy, Y., Buscartlet, E., Gomez, E., Janjou, D., et al. 2010.** Jordan Aquifers Modelling Project-Final Report.
- BGR, SGD and UN-ESCWA (Bundesanstalt für Geowissenschaften und Rohstoffe; Staatliche Geologische Dienste; United Nations Economic and Social Commission for Western Asia). 1999.** Application of Environmental Isotope Methods for Groundwater Studies in the ESCWA Region. Berlin.
- BRGM and CNABRL (Bureau de Recherches Géologiques et Minières; Compagnie Nationale d'Aménagement de la Région du Bas-Rhône et du Languedoc). 1985.** Water, Agriculture and Soil Studies of Saq and Overlying Aquifers. In **Water Studies - Main Report**. Published by the Ministry of Agriculture and Water in Saudi Arabia. Riyadh.
- Central Department of Statistics and Information in Saudi Arabia. 1977-2009.** Annual Statistics Book Volumes. Available at: http://www.cdsi.gov.sa/english/index.php?option=com_content&view=article&id=84&Itemid=172. Accessed on February 14, 2012.
- Christian, L. 2000.** Middle East Geological Map Series (MEG-Maps). Published by Gulf PetroLink. Manama.
- Consolidated Consultants (Engineering and Environment). 2004.** Environmental and Social Assessment Disi-Mudawarra to Amman Water Conveyance System. In **Main Report - Part C: Project Specific Environmental and Social Assessment**. Published by Ministry of Water and Irrigation in Jordan. Amman.
- Department of Statistics in Jordan. 2004.** Population and Housing Census by Governorate and Districts. Available at: http://www.dos.gov.jo/dos_home/census2004/cen04_3.pdf/table_3_1.pdf. Accessed on May 20, 2011.
- Edgell, H. S. 1997.** Aquifers of Saudi Arabia and their Geological Framework. **The Arabian Journal for Science and Engineering, Water Resources in the Arabian Peninsula: Part I**, 22(1C): p. 3.
- Edgell, H. S. 2006.** Arabian Deserts : Nature, Origin and Evolution. Published by Springer. Dordrecht.
- Ferragina, E. and Greco, F. 2008.** The Disi Project: An Internal/External Analysis. **Water International**, 33(4): p. 451-463.
- Global Water Intelligence. 2007.** Gama chosen for Disi. **Global Water Intelligence** 8(10): October 2007. Available at: <http://www.globalwaterintel.com/archive/8/10/general/gama-chosen-for-disi.html>. Accessed on July 26, 2012.
- Government of Jordan. 2010.** The Jordanian Experience in Cooperation with Neighboring Arab Countries. In **Proceedings for the Third Meeting of the Technical Scientific Advisory Committee of the Arab Ministerial Water Council (Annex-5)**. Cairo. Available at: http://www.arableagueonline.org/lasimages/picture_gallery/reportes29-30june2009.pdf. Accessed on January 6, 2012
- Haiste Kirkpatrick International and Scott Wilson Kirkpatrick. 1995.** Long Term Management of Aquifer Resources: Study of The Rum Aquifer of South Jordan. In **Qa Disi Aquifer Study**. Published by the Water Authority of Jordan. Amman.
- Hobler, M., Bender, H., Rashdan, J. and Schmidt, G. 1991.** Groundwater Resources of Southern Jordan. Published by the Water Authority of Jordan and BGR (Bundesanstalt für Geowissenschaften und Rohstoffe). Hannover.
- Hydrogeological Services International. 1991.** Brackish Groundwater of Jordan. Published by UNDP-DTCD (United Nations Development Programme-Department of Technical Cooperation for Development). Amman.
- Jordan Times. 2012.** Experimental pumping from Disi project scheduled to start this year. Issued on July 25, 2012. Available at: <http://jordantimes.com/experimental-pumping-scheduled-to-start-this-year>. Accessed on July 26, 2012.
- Margane, A. 2011.** Review Comments on Saq-Ram Chapter. Personal Communication.
- Margane, A., Hobler, M., Almomani, M. and Subah, A. 2002.** Contributions to the Hydrogeology of Northern and Central Jordan. **Geologisches Jahrbuch**, 68(52).
- Ministry of Agriculture and Water in Saudi Arabia. 1984.** Water Atlas of Saudi Arabia. Riyadh.
- Ministry of Water and Irrigation in Jordan. 2010.** Water Level of the Ram Aquifer. In **Country Consultations for the Inventory of Shared Water Resources in Western Asia 2011-2012**. Beirut.
- Ministry of Water and Irrigation in Jordan. 2011.** Country Consultation with the Hashemite Kingdom of Jordan. In **Country Consultations for the Inventory of Shared Water Resources in Western Asia 2011-2012**. Beirut and Amman.
- Nuqudy. 2012.** Disi Project to Be Completed on Time. Issued on January 22, 2012. Available at: http://english.nuqudy.com/Levant/Disi_Project_to_be_-623. Accessed on July 26, 2012.
- Salameh, E. and Rimawi, O. 1987.** Natural Radioactivity and Hydrochemistry of Some Jordanian Groundwater Resources. Vol.9. Published by the University of Jordan. Amman.
- Sharaf, M. A. and Hussein, M. T. 1996.** Groundwater Quality in the Saq Aquifer, Saudi Arabia / La Qualité des Eaux Souterraines de l'Aquifère de Saq, Arabie Saoudite. **Hydrological Sciences Journal**, 41(5): p. 683-696.
- TADCO. 2012.** Overview. Available at: <http://www.tadco-agri.com/english/overview.asp>. Accessed on January, 20 2012.
- Teimeh, M., Taani, Y., Lihie, O. A. and Saad, L. A. 1990.** A Study of the Paleozoic Formations of Jordan at Outcrop and in the Subsurface Including Measured Sections and Regional Isopach Maps. **Subsurface Geology**, 1(No.1).
- Tomaihy, F. A. A. 2007.** Study of Characteristics For Saq Aquifer in Two Regions in KSA. Bachelor of Science Thesis. King Saud University, Civil Engineering Department. Riyadh.



UN-ESCWA, UNEP and IDB (United Nations Economic and Social Commission for Western Asia; United Nations Environment Programme et al.). 1996. Water Resources Assessment in the ESCWA Region Using Remote Sensing and GIS Techniques. New York.

Vengosh, A., Hirschfeld, D., Vinson, D., Dwyer, G., et al. 2009. High Naturally Occurring Radioactivity in Fossil Groundwater from the Middle East. *Environmental Science & Technology*, 43(6): p. 1769-1775.

Venture. 2012. Revitalizing the Lifeline: Disi's Water Coming to a Pipe Near You. Issued on March 29, 2012. Available at: <http://www.venture-mag.com/index.php/in-depth/cover-stories/item/202-revitalizing-the-lifeline-disi%E2%80%99s-water-coming-to-a-pipe-near-you.html>. Accessed on July 26, 2012.

Vincent, P. 2008. Saudi Arabia: An Environmental Overview. Published by Taylor & Francis. London/New York.

Water Authority of Jordan. 2002. Investigation of the Present Recharge Rate and Recharge Origins in the Disi Sandstone Aquifer in Southern Jordan. In *Sixth Arab Conference on the Peaceful Uses of Atomic Energy*. Cairo.

Water Watch. 2006. Historic Groundwater Abstractions at National Scale in the Kingdom of Saudi Arabia. Published by the Ministry of Water and Electricity in Saudi Arabia, the World Bank and UNDP (United Nations Development Programme). Wageningen.

WHO (World Health Organization of the United Nations). 2011. Guidelines for Drinking-Water Quality, Fourth Edition. Geneva. Available at: http://www.who.int/water_sanitation_health/publications/2011/dwq_guidelines/en/index.html. Accessed on November 5, 2012.