Chapter 15

Gulf

Umm er Radhuma-Dammam Aquifer System (Centre)

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

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Umm er Radhuma-Dammam Aquifer System (Centre)

Gulf

EXECUTIVE SUMMARY

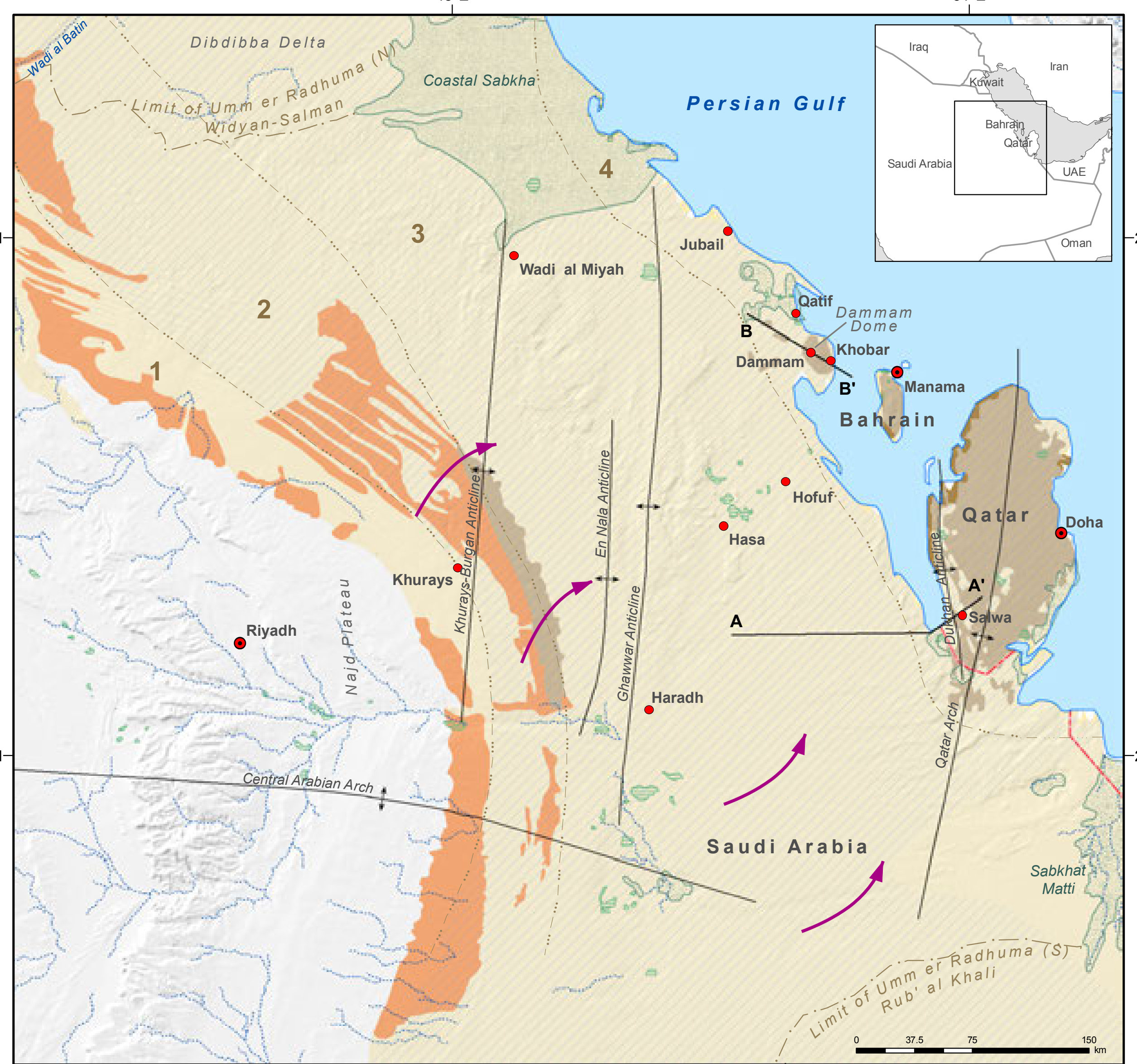
The central section of the Umm er Radhuma-Dammam Aquifer System extends over a 400 km-wide structural platform that stretches across three Gulf States: Bahrain, Qatar and Saudi Arabia. In the western low-plateau areas, the aquifer system is dominated by the Umm er Radhuma, while in the eastern plains it becomes more complex as the Umm er Radhuma and the Dammam are separated by the Rus Formation and overlain by Neogene-Quaternary units. Limited recharge occurs mainly through the Umm er Radhuma outcrops. The general direction of groundwater flow in the aquifer system is from west to east in Saudi Arabia.

The aquifer system is heavily exploited for agricultural development projects in Saudi Arabia, with most water abstracted from the Dammam. The Dammam is also the main source of irrigation water in Bahrain, while the Umm er Radhuma supplies most of the water for domestic and industrial purposes. In Qatar, water is drawn from the Umm er Radhuma and Rus in the north. The Umm er Radhuma-Dammam Aquifer System in the Gulf region is increasingly threatened by salinization as a result of seawater intrusion and over-pumping.

BASIN FACTS

RIPARIAN COUNTRIES	Bahrain, Qatar, Saudi Arabia
ALTERNATIVE NAMES	Alat, Khobar, Dammam, Rus, Umm er Radhuma
RENEWABILITY	Very low to low (0-20 mm/yr)
HYDRAULIC LINKAGE WITH SURFACE WATER	Weak
ROCK TYPE	Fissured/karstic
AQUIFER TYPE	Unconfined to confined
EXTENT	~281,000 km^2
AGE	Cenozoic (Paleogene)
LITHOLOGY	Mainly limestone and dolomite, with some evaporites
THICKNESS	Dammam: 35-180 m Umm er Radhuma: 240-500 m
AVERAGE ANNUAL ABSTRACTION	Bahrain: Dammam: 97 MCM (2010) Umm er Radhuma: 54.3 MCM (2006) Qatar: 91 MCM (1983) Saudi Arabia: ~608 MCM (2006)
STORAGE	Bahrain: 90 MCM (safe yield) Qatar: 2.5 BCM Saudi Arabia: 235 BCM
WATER QUALITY	Fresh (mostly <1 g/L TDS) to hypersaline in some coastal areas
WATER USE	Mainly agricultural, also domestic, industrial and urban irrigational use
AGREEMENTS	-
SUSTAINABILITY	Over-exploitation and salinization

OVERVIEW MAP



Umm er Radhuma-Dammam Aquifer System (Centre): Gulf

- Capital
- Selected city, town
- International boundary
- Intermittent river, wadi
- Sabkha
- Anticline
- A A' Hydrogeological cross-section
- Direction of groundwater flow
- Umm er Radhuma Formation outcrop
- Dammam and Rus Formation outcrop
- Approximate subsurface extent of the aquifer formations
- Approximate extent of exploitable area
- Zone of agricultural development (selection)
- Physiographic boundary

1 Dahna Desert
2 Summan Plateau
3 Hasa Plain
4 Gulf Coastal Plain

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Inventory of Shared Water Resources in Western Asia

Disclaimer
The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

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The Umm er Radhuma-Dammam Aquifer System in this Inventory

The Umm er Radhuma-Dammam Aquifer System extends from northern Iraq to the southern coast of the Arabian Peninsula over a distance of 2,200 km. Overall, it covers an area of more than 1,220,000 km^2, of which 363,000 km^2 is covered by outcrops. The total area of this aquifer system in Saudi Arabia, which shares the northern, central and southern sections with neighbouring countries, is 662,000 km^2 (see 'Overview and Methodology: Groundwater' chapter, Map 2).

This system generally comprises three Paleogene (Paleocene-Eocene) Formations: the Dammam, the Rus and the Umm er Radhuma. These formations stretch across Iraq, Yemen and the six Gulf Cooperation Council countries.[1] However, the water contained within these formations cannot be considered shared between all countries. For example, a well pumping from the Dammam Formation in Iraq cannot affect the productivity of this formation in Yemen and vice versa. Furthermore, there is significant variation in the lithostratigraphy of these three formations, particularly the Rus, which is water-bearing in some areas, while acting as an aquitard in others.

Because of the large geographical extent and the lithostratigraphic variations within the formations, the aquifer system has for the purpose of this Inventory been divided into three sections: a northern section (see Chap. 16), a central section (see current chapter) and a southern section (see Chap. 14).[2] This division, which is primarily based on the geographical extent of the formations, also takes relevant geological information into consideration to define the section boundaries.

Hofuf Oasis, Saudi Arabia, 2011. Source: Chris Helmkamp.

Introduction

LOCATION

The central section of the Umm er Radhuma–Dammam Aquifer System lies in a nearly flat 400 km-wide structural platform (Interior Platform) stretching from the eastern edge of the Najd Plateau to the Qatar Peninsula. It is bound to the north by Wadi al Batin, the Dibdibba Delta and coastal sabkha. In the south, it borders on the northern limit of the Rub' al Khali Desert and the Sabkhat Matti. This section extends across three Gulf states: Bahrain, Qatar and Saudi Arabia (see Overview Map).

AREA

The central section of the aquifer covered in this chapter represents around 23% of the aquifer system's total area. Within the boundary of the suggested delineation, the aquifer covers a total area of 281,000 km^2, of which about 560 km^2 are located in Bahrain, 11,300 km^2 in Qatar and 269,000 km^2 in Saudi Arabia.

The largest outcrop of the Dammam Aquifer covers almost all of Qatar, with smaller outcrops across Bahrain and around the city of Dammam in Saudi Arabia. The Umm er Radhuma only crops out in Saudi Arabia. The Rus is found in the subsurface across the whole region, separating the two main aquifer units. Outcrops of this formation occur in structurally elevated areas such as the Dammam and Bahrain Domes.

CLIMATE

The eastern part of this section falls within the Southern Gulf Coast agro-climatic zone,[3] while the western part extends to the Summan Plateau and south-eastern Najd agro-climatic zones. Temperatures range from a low of around 14°C in winter to a high of about 36°C in summer, though higher temperatures are not uncommon during this season.[4] Mean annual rainfall lies at 90-95 mm,[5] and is concentrated in winter and spring.

POPULATION

Around 4 million people live in the east of Saudi Arabia, a region which has flourished since the discovery of large quantities of oil in the 1930s. Key cities include Dammam, Dhahran, Khobar and Qatif.[6] Around 3 million people live in Bahrain (1.2 million)[7] and Qatar (1.7 million).[8]

OTHER AQUIFERS IN THE AREA

Large parts of the aquifer system are overlain by Neogene-Quaternary sediments, which constitute a relatively shallow aquifer in this area. This aquifer system is also to varying degrees connected with the Umm er Radhuma-Dammam system. The Wasia-Biyadh Formations underlie the whole area but constitute a source of freshwater only in Saudi Arabia, mainly in the Summan Plateau where it acts as an unconfined aquifer.

INFORMATION SOURCES

The Umm er Radhuma-Dammam Aquifer System constitutes a major aquifer system in Bahrain, Qatar and eastern Saudi Arabia and has been the subject of extensive studies in the three riparian countries. It is the only source of groundwater for Bahrain and Qatar. Most of the information in this chapter is drawn from government documents, United Nations reports and scientific studies. The Overview Map was delineated based on various local and regional references.[9]

Hydrogeology - Aquifer Characteristics

AQUIFER CONFIGURATION

Four main physiographic regions can be identified in this section of the aquifer system:

- **Dahna Desert:** A narrow belt of complex linear dunes with topography that comprises a cuesta landscape of cover rocks that dips gently eastwards towards the Gulf.[10]

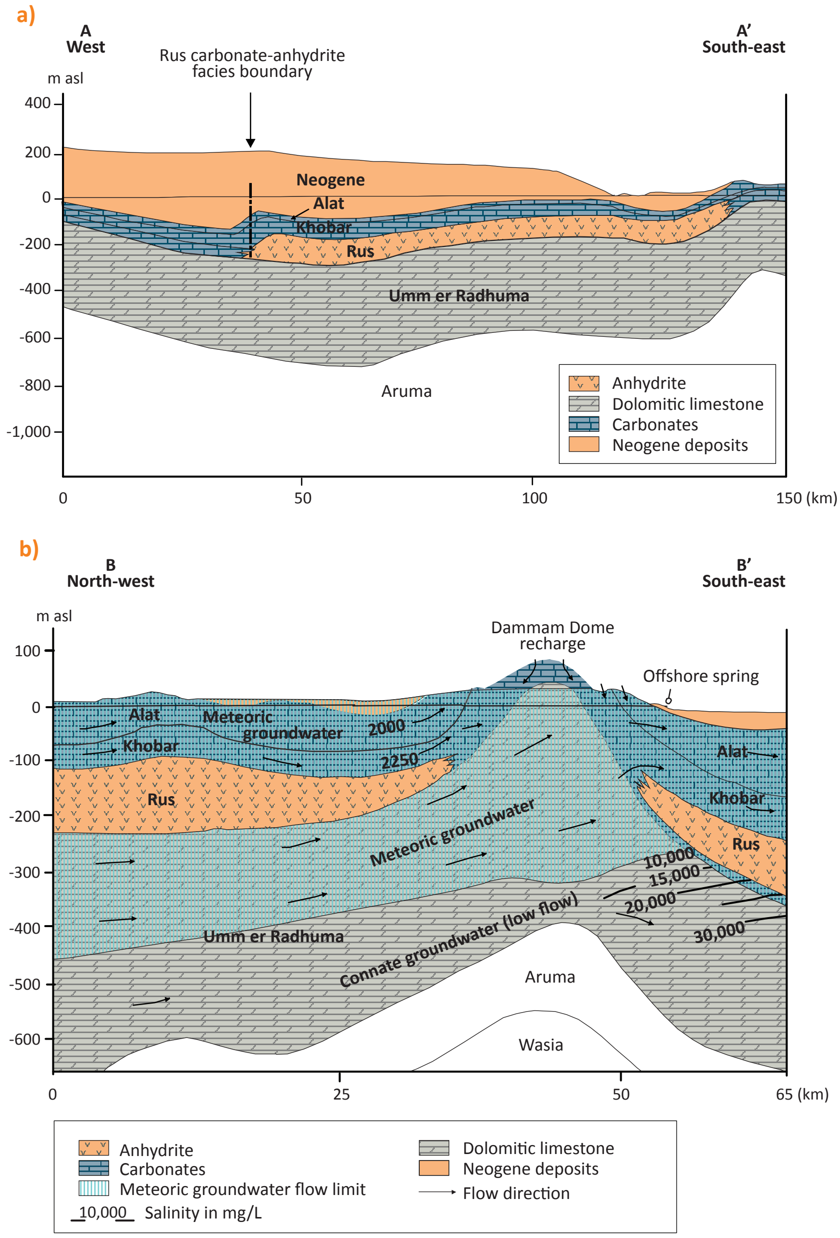
- **Summan Plateau:** A relatively low (200-400 m) karstified limestone plateau, barren and extensively eroded, containing hundreds of sinkholes, many of which extend into structurally controlled cave systems of up to 1.1 km in length.[11]

- **Hasa Plain:** A wide plain characterized by locally abundant supplies of freshwater from wells and artesian springs and fertile oases such as Hasa and Hofuf. In the west, the plain is bounded by a prominent east-facing escarpment that cuts into the eastern margin of the Summan Plateau.[12]

- **Gulf Coastal Plain:** An extensive sabkha area constituting the southern part of the Hasa-Kuwait Plain, which extends from the western edge of the Shatt al Arab Delta to the Gulf of Salwa south-west of Qatar.[13]

In the western low-plateau areas, most of the aquifer system is made up of the Umm er Radhuma Formation. The system becomes more complex in the plains where it consists of the Umm er Radhuma and the Dammam, intercalated with the Rus Formation and overlain by the Neogene (Figure 1). Outcrops of the Umm er Radhuma exist only in the Dahna Desert and Summan Plateau in Saudi Arabia. The Dammam outcrops are more common in Qatar and Bahrain, and around the Dammam Dome, from which the formation takes its name. The Dammam Formation is largely eroded in these dome areas which are aligned along a Fault Line. In this area the Rus changes to carbonate facies and acts as an aquifer (Figure 2). The lateral extent of the two main aquifer units (Umm er Radhuma and Dammam) is defined by the saturation limit in the west and by a saline water front to the east.[14]

Figure 1. Hydrogeological section across the Gulf-Coastal Plain (a) near the Saudi-Qatari border, and (b) near the Dammam Dome in Saudi Arabia



Source: Compiled by ESCWA-BGR based on Harhash and Yousif, 1985.

STRATIGRAPHY

In general, the aquifer system consists mainly of alternating layers of limestone and dolomitic limestone with intercalations of anhydrite and argillaceous shales that increase in clay content in the lower layers. The main lithological and stratigraphic features of the aquifer system can be summarized as follows (Table 2, Figure 1):

- The Umm er Radhuma consists predominantly of dolomitic limestone, limestone and calcarenite.
- The Rus Formation ranges in composition between anhydrite facies and carbonate facies so that it can act as an aquifer (mainly in the Dammam and Bahrain Dome areas) or as an aquiclude/aquitard, depending on its composition and thickness in different places.[15]
- The Dammam Formation consists of five units: the lower three units are non-aquiferous shales and the upper two units (Khobar and Alat) are aquiferous carbonates.[16] Although the latter two units are sometimes referred to as one aquifer (Dammam Aquifer), they are in some areas separated by a marl bed (Orange Marl) which plays an important hydraulic role and acts as a leaky confining layer between the Khobar (Lower Aquifer) and the Alat (Upper Aquifer).[17]

Because of their wide extent and thickness, the Umm er Radhuma and Rus Formations make up the main aquifer in this part of the system, particularly in structurally high areas (e.g. Dammam Dome) where the Rus is composed of carbonate facies and is hydraulically connected with the Umm er Radhuma (Figure 1b).

Throughout most areas in this region, the aquifer units of the Paleogene carbonates are overlain and hydraulically connected with Neogene detrital rocks so that they form one aquifer system.[18] By contrast, the vertical connection to the underlying Wasia-Biyadh Formation is so insignificant that the two aquifer systems behave essentially independently, although the intercalated Aruma Formation acts as an aquitard allowing limited upward leakage.[19]

AQUIFER THICKNESS

In Saudi Arabia, the thickness of the Umm er Radhuma decreases from 500 m in the area north of Hofuf to about 300 m over the Ghawwar Anticline,[20] while the Dammam is about 70 m thick around Wadi al Miyah and 35-65 m in the area of Hasa.[21] In Bahrain, the Rus Formation has an average thickness of 105 m, while the Umm er Radhuma is 350 m thick. Both aquifer units of the Dammam (Khobar and Alat) disappear over the crest of the Bahrain Dome, but their thickness increases to the east and west, averaging 15-25 m for the Alat and 20-45 m for the Khobar.[22] In Qatar, the Rus is 28-44 m thick in the northern and central areas, and reaches 110 m in the south-western zone.[23]

AQUIFER TYPE

The presence of intercalated marls, shales and argillaceous limestones means that the Umm er Radhuma Formation does not constitute a complete interconnected aquifer.[24] In areas where it crops out or is covered only by dunes, it acts as an unconfined aquifer. This occurs mainly along the Summan Plateau. It is also unconfined in structurally high areas such as the Dammam and Bahrain Domes, where the overlying Rus Formation is of carbonate facies and in hydraulic connection with the Umm er Radhuma. In these uplifted areas, upward vertical leakage occurs where the Rus Formation is thin. More commonly though, the Umm er Radhuma is confined by the evaporitic unit of the Rus and the shales of the Dammam.

In most of the Gulf region, the Dammam Aquifer is confined from below by the lower shales of the Dammam and from above by the siliceous layers of the Neogene deposits. The latter displays wide vertical and lateral variations and consists of three main formations: the Hadrukh, Dam and Hofuf. Within the aquifer unit itself, the Orange Marl separates the lower Khobar member from the upper Alat. However, the aquifer is unconfined in a number of places due to erosion of one or more of the confining layers and/or the development of karst structures. In south-western Qatar (Abu Samra area), for example, the upper Abarug member of the Dammam exists under both confined and unconfined conditions.[25] Similarly, in Bahrain, the Dammam Aquifer is mostly confined, but its lower Khobar member is unconfined in the northern and south-western parts of the country due to erosion.[26]

AQUIFER PARAMETERS

The Umm er Radhuma-Dammam Aquifer System (Centre) is characterized by several major north-south anticlinal axes that rise above the general level of the platform.[27] Argillaceous fine carbonates of the aquifer units were deposited in the structurally low areas, while deposition of coarser carbonate sediments occurred in high areas.[28] Two other key features affect the water-bearing characteristics of the rock formation in this area:

- Karstification and the development of secondary permeabilities, due to the high intensity of intersecting fissures and other lineaments of different trends.

- Dolomitization, a process that increases porosity and improves the aquiferous nature of the formations.

These lithological and structural features have caused large variations in the hydraulic properties (transmissivity and storativity). In general, elevated areas display higher values than structurally low areas. Available data for the aquifer units in this system has been collected from various sources.[29] Table 1 compiles available data for the aquifer units in this system and summarizes the main findings and observations. Based on the data presented in the table, it can be concluded that:

- Hydraulic parameters of the two main aquifer units (Umm er Radhuma and Dammam) vary by several orders of magnitude, with values in the range of $6.4x10^{-1}$ to $3.0x10^{-6}$ m^2/s for transmissivity and $2.0x10^{-1}$ to $2.0x10^{-9}$ for storativity.

- The higher values are generally from areas where confinement of the aquifer units is removed by uplifting (the crest of the Dammam and Bahrain Domes) or solution collapse (mainly the north-eastern areas). These structures trap local surface runoff[30] and provide "windows" in the virtually impermeable evaporite confining beds through which flow from one aquifer to another may occur.[31]

- In Qatar, the Rus has a lower transmissivity and higher storativity than the Umm er Radhuma.

- In eastern Saudi Arabia, the Alat member, a granular aquifer, has a lower permeability than the Khobar member, which is highly karstified and fissured, particularly in structural highs.[32] In places where the Rus Formation is thin and considerable upward leakage from the Umm er Radhuma occurs (Wadi al Miyah), the Khobar exhibits higher transmissivity values.

Table 1. **Hydraulic parameters of the Umm er Radhuma-Dammam Aquifer System (Centre)**

COUNTRY		DAMMAM				UMM ER RADHUMA	
		ALAT MEMBER[a]		KHOBAR MEMBER[b]			
		TRANSMISSIVITY (m^2/s)	STORATIVITY	TRANSMISSIVITY (m^2/s)	STORATIVITY	TRANSMISSIVITY (m^2/s)	STORATIVITY
Bahrain		AVG:[c] $4.0x10^{-3}$	$5.3x10^{-4}$-$1.3x10^{-1}$ AVG: $6.5x10^{-2}$	$5.4x10^{-4}$-$4.8x10^{-1}$ AVG: $2.4x10^{-1}$	$5.0x10^{-5}$	$1.3x10^{-3}$-$4.6x10^{-1}$ (Umm er Radhuma-Rus)	$2.0x10^{-1}$ (unconfined), $2.0x10^{-4}$ (confined)
Qatar		$1.1x10^{-4}$-$1.1x10^{-2}$ AVG: $4.1x10^{-3}$	$1.0x10^{-3}$ (south-western)	..	..	Umm er Radhuma: $2.7x10^{-3}$-$9.8x10^{-2}$ Rus: $2.3x10^{-5}$-$5.2x10^{-2}$	Umm er Radhuma: $2.0x10^{-9}$-$2.2x10^{-8}$ (confined, southern) Rus: $6.0x10^{-5}$-$8.6x10^{-1}$ (unconfined to semi-confined)
Saudi Arabia	Coastal region	$2.9x10^{-1}$-$3.1x10^{-4}$	$1.3x10^{-4}$	$9.0x10^{-2}$	$5.3x10^{-4}$	$7.0x10^{-2}$-$6.4x10^{-1}$	$3.5x10^{-5}$-$1.4x10^{-2}$
	Wadi al Miyah region	$2.7x10^{-5}$-$9.0x10^{-4}$	..	$1.4x10^{-4}$-$8.9x10^{-3}$	..	$1.4x10^{-2}$-$4.2x10^{-1}$	..
	Dammam Dome region	$3.1x10^{-4}$-$2.3x10^{-3}$	$1.5x10^{-4}$-$2.6x10^{-4}$	$2.9x10^{-5}$	AVG: $2.1x10^{-5}$	..	..
	Hasa region	$2.6x10^{-5}$-$5.1x10^{-3}$	$2.6x10^{-5}$-$1.3x10^{-4}$	$3.0x10^{-6}$-$1.0x10^{-2}$	$1.0x10^{-4}$-$1.0x10^{-3}$ (confined)	$2.4x10^{-3}$-$6.6x10^{-2}$	..
	Hofuf-Salwa region	..	..	..	..	$5.0x10^{-5}$	..

Source: Compiled by ESCWA-BGR based on UN-ESCWA and BGR, 1999b; Alsharhan et al., 2001; Al-Nouaimy, 1999.
(a) The equivalent of the Alat in Qatar is the Abarug.
(b) The equivalent of the Khobar in Qatar is the Umm Bab (formerly the Simsima Member. See Harhash and Yousif, 1985).
(c) AVG refers to average values.

Table 2. Lithostratigraphy and water-bearing characteristics of the Umm er Radhuma-Dammam Aquifer System (Centre)

COUNTRY	DAMMAM				RUS		UMM ER RADHUMA	
	ALAT MEMBER[a]		KHOBAR MEMBER[b]					
	LITHOLOGY	WATER-BEARING CHARACTERISTICS	LITHOLOGY	WATER-BEARING CHARACTERISTICS	LITHOLOGY	WATER-BEARING CHARACTERISTICS	LITHOLOGY	WATER-BEARING CHARACTERISTICS
Bahrain	Dolomitic limestone.	A secondary aquifer of low productivity.	Dolomitic limestone and dolarenite (dolomitic sandstone).	Major aquifer of high permeability within the upper 5-10 m.	Chalky dolomitic limestone, shale, anhydrite and gypsum.	Forms a continuous hydraulic head with Umm er Radhuma in central Bahrain; otherwise an aquitard.	Dolomitic limestone, calcarenite, partly argillaceous and bituminous.	Upper part: aquifer connected to Rus. Lower part: low permeability and saline.
Qatar	Dolomitic limestone.	A secondary aquifer of low productivity.	Chalky limestone, partly dolomitized.	Forms a continuous aquifer with the Rus Formation in northern Qatar, which contains freshwater lenses above saline water (except for the areas where it is dry or dewatered).	Dolomitic limestone, anhydrite and gypsum.	Aquiferous, but also thinner in the north-central part of the peninsula where hydraulic continuity exists between calcareous deposits within this formation and the Umm er Radhuma.	Dolomite with chert, marl/shale intercalations and anhydrite beds.	Aquifer in the south and in the north where it is hydraulically connected with the Rus.
Saudi Arabia	Limestone, fissured with cavities filled with Neogene.	Moderate aquifer.	Calcarenite and dolomitic limestone, locally fissured.	Aquifer	Anhydritic facies: massive anhydrite, gypsum, marl and limestone layers. Carbonate facies: limestone in places, dolomitic and marly, locally fissured.	Aquiclude Aquifer in hydraulic connection with the Umm er Radhuma.	Limestone and dolomite; calcarenitic in the south, argillaceous and evaporitic in the north.	Calcarenites: good aquifer. Dolomitic zones: moderate aquifer. Anhydritic facies: poor aquifer. Basal shales: aquitard.

Source: Compiled by ESCWA-BGR based on UN-ESCWA and BGR, 1999b; Al-Nouaimy, 1999; Harhash and Yousif, 1985.
(a) The equivalent of the Alat in Qatar is the Abarug.
(b) The equivalent of the Khobar in Qatar is the Umm Bab (formerly the Simsima Member. See Harhash and Yousif, 1985).

Hydrogeology - Groundwater

RECHARGE

Recharge to any aquifer within the system can occur from rainfall (directly or via runoff) or transfer of water by vertical flow from shallower or deeper aquifers. Estimated rainfall-related recharge in eastern Saudi Arabia varies significantly from year to year as a result of erratic rainfall patterns. Between 1952 and 1977, 82% of freshwater replenishment occurred via the Umm er Radhuma, compared to only about 16% via the Neogene and less than 2% via the Dammam. The estimated mean annual recharge from rainfall for the three aquifers (Umm er Radhuma, Dammam, Neogene) was 1,272 MCM[33] (approx. 5.9 mm/yr)[34] for this period, with a minimum of 8 MCM in 1970 and a maximum of 5,423 MCM in 1955. [35]

For the Umm er Radhuma alone, an estimated mean annual recharge between 547.1 MCM (6.7 mm/yr) and 287.6 MCM (9.4 mm/yr) has been estimated for the northern (82,100 km^2) and southern (30,600 km^2) areas of the Gulf section respectively (Figure 2). The highest recharge occurred in 1955 (3,348 MCM), with 2,705.7 MCM (33 mm/yr) in the northern areas and 642.7 MCM (21 mm/yr) in southern areas. In 1970 and 1978 there was no recharge at all.[36]

In Bahrain, recharge was estimated at a mean annual rate of 0.5 MCM (approx. 0.7 mm/yr). [37] Direct recharge here is not only insignificant, but also varies considerably from year to year. The lateral inflow from eastern Saudi Arabia into the Dammam Aquifer is more significant here and is estimated at 83-90 MCM/yr.[38]

Recharge data from Qatar indicates an average of 27 MCM/yr (approx. 2.4 mm/yr) for the period 1962/1963-1979/1980, with a minimum of 0.5 MCM and a maximum of 85.75 MCM. Recharge is about 2% from direct rainwater infiltration and 10% by indirect infiltration through wadis.[39]

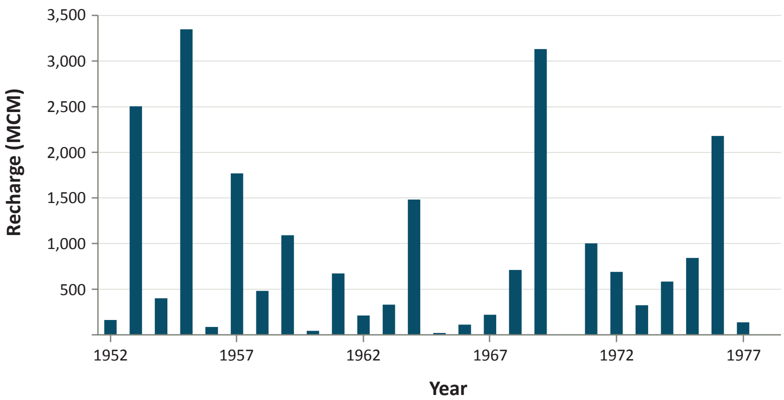
FLOW REGIME

The flow regime of the Umm er Radhuma and Dammam Aquifer Systems points to the east, generally following the dip of the aquifer system from the outcrop areas in western Saudi Arabia to the Gulf coastline.[40] Potentiometric contour lines for the two aquifer units show that the water level generally lies at about 200-300 m asl in wells tapping the aquifer system in western areas, whereas it may be only tens of metres above sea level in the coastal areas. Within this general trend, there are large variations in the magnitude of the gradient, which can largely be explained in terms of recharge/discharge zones and transmissivity changes. For example, the hydraulic gradient in the Umm er Radhuma Formation is steep in the outcrop areas and becomes quite flat in the central areas before it steepens again suddenly in the coastal area. Other anomalies in the gradient can be explained by the complexity of vertical conditions, which are affected by hydraulic properties of the aquitards, but also by the horizontal flow conditions, which are affected by the presence of stagnant saline water bodies at the lower limit of the Umm er Radhuma.

In Bahrain, groundwater flow in the Dammam follows the regional flow direction from north-west (in the recharge area in Saudi Arabia) to south-east. However, in central and southern Bahrain, the hydraulic gradient of the Umm er Radhuma-Rus does not reflect this general trend, mainly due to the upward circulation of groundwater.[41]

In Qatar, groundwater flows radially outwards from recharge areas, centred over higher land surfaces in the northern and southern zones, and discharges into the adjacent low-lying sabkhas and the Gulf. The main anomalies occur in the north, where the general groundwater direction is interrupted by pumping, and in the

Figure 2. Recharge estimates from rainfall for the Umm er Radhuma Aquifer in eastern Saudi Arabia (1952-1977)



Source: Compiled by ESCWA-BGR based on Faulkner, 1994.

south-western zone, where the Dukhan Anticline creates a physical barrier to groundwater movement.

STORAGE

Assuming a pumping depth of 300 m bgl as a limiting factor, groundwater reserves in eastern Saudi Arabia were estimated at 190 BCM for the Umm er Radhuma and 45 BCM for the Dammam.[42] Other sources estimated the proven reserves of slightly brackish water in the aquifer system to be lower (Table 3).[43] Freshwater reserves (<2,000 mg/L TDS) in the Umm er Radhuma-Rus system in Qatar were reported to be about 2.5 BCM.[44] In Bahrain, storage is estimated on the basis of safe yield, which is 90 MCM.[45]

DISCHARGE

Most of the natural discharge takes place in eastern Saudi Arabia (Hofuf-Hasa-Qatif-Dammam area) where a large number of karst springs discharge about 285 MCM/yr.[46] In low-lying areas, sabkha lakes occur as a result of upward groundwater leakage (mainly through fissures in the confining layers) to the surface due to artesian pressure.

Onshore and offshore springs in the north of Bahrain also discharge groundwater. Sabkha evaporation is about 22% of the potential evaporation rate and occurs on about 80% of the sabkha surface area. [47]

Discharge also takes place via direct transpiration of groundwater from date palm trees in the coastal strip of Saudi Arabia and northern Bahrain (about 158 MCM/yr).[48] The total annual discharge from the system was estimated at 1,311 MCM, of which 65% (855 MCM/yr) occurs via sabkhas.[49] A comparison of this value with the total recharge suggests that the central part of the Umm er Radhuma-Dammam Aquifer System was roughly in balance – at least before abstraction from wells started 40 to 50 years ago.

WATER QUALITY

In general, changes to groundwater quality in the Gulf Coastal Plain reflect the regional groundwater flow from the outcrop (recharge) areas in the west to the coastal (discharge) areas in the east, with increasing salinity as the groundwater evolves from bicarbonate (HCO_3^-)-sulphate (SO_4^{2-}) to chloride (Cl^-) type. Three main factors contribute to significant anomalies within the system:

- The occurrence of evaporites and their exposure in several locations (Figure 1a) has resulted in the prevalence of significant amounts of wind-blown and aeolian gypsum particles on the land surface that are dissolved and carried along wadi courses. This often results in elevated sulphate concentrations in the recharge waters.
- Upward leakage of saline water (very slow process) and recharge from the surface along preferential paths (fast process) as inferred from the anomalously young and anomalously old waters in different places.
- The existence of a remarkable inland sabkha line (Figure 3) marks the shore of an ancient seawater body,[50] the imprint of which has not yet been flushed out completely due to the occurrence of low-permeability aquitards and aquicludes between the aquifer units.

The major ion composition of the Umm er Radhuma and Dammam Aquifer units is characterized by comparable concentration levels (Figure 4). Sodium (Na^+) and chloride (Cl^-) are the most common cation and anion respectively, followed by calcium (Ca^{2+}) and sulphate (SO_4^{2-}). Sodium chloride/sulphate water is dominant in most areas, while calcium-bicarbonate water is commonly found in the western area, where the Umm er Radhuma Formation is at the surface or near surface environments.

Table 3. Groundwater reserves in the eastern Umm er Radhuma-Dammam Aquifer System in Saudi Arabia

AQUIFER	SALINITY (mg/L TDS)	GROUNDWATER RESERVES (BCM)		
		PROVEN	PROBABLE	POSSIBLE
Dammam	2,600-6,000	5	25	..
Umm er Radhuma	2,500-5,000	16	40	75

Source: Compiled by ESCWA-BGR based on Sadiq and Hussain, 1997.

Agriculture in Bahrain, 2011. Source: Michele Solmi.

Also, although most of the groundwater abstracted across the region has a salinity level below 5 g/L, much higher salinities (80-100 g/L) were found in wells in certain coastal areas where there is present-day seawater intrusion or ancient sabkhas exist.

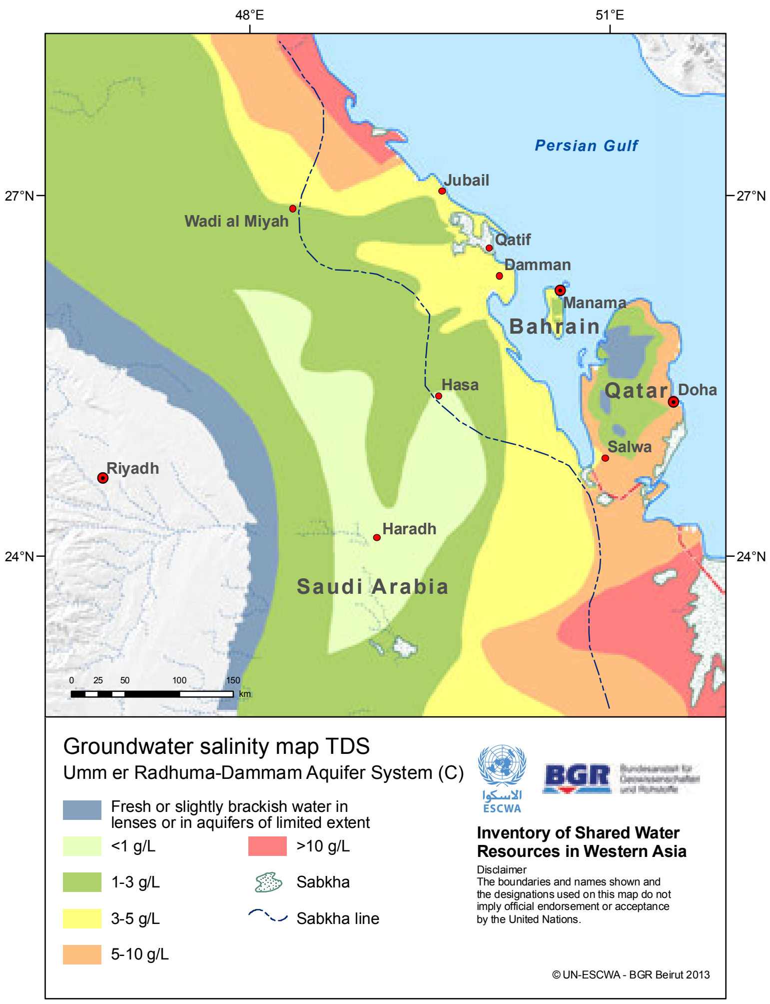
EXPLOITABILITY

The following criteria were used to assess the exploitability of this aquifer system:

- **Depth to top of aquifer:** The depth of wells abstracting water from the Dammam-Khobar area in eastern Saudi Arabia ranges between 300 and 400 m bgl.[51] In structurally elevated areas such as the Dammam Dome and the northern/central parts of Bahrain and Qatar, groundwater can be extracted from much shallower depths. For example, the depth of all wells used for estimating the hydraulic parameters of the aquifer system in Qatar in 1982 ranged between 6 and 69 m bgl.[52] Hence, drilling depth is not a limiting factor.
- **Depth to water level:** Depth to water, which was generally less than 25 m bgl in the early 1980s, has probably dropped over the years. However, as the Dammam Formation has limited thickness it is unlikely that the water level would drop below 200 m bgl. Water levels of the Umm er Radhuma Formation may drop much further, particularly where the aquifer is characterized by solution collapse features. For example, by the early 1980s the water level was already at 160 m bgl in wells located in the north-eastern Hofuf area.[53] This would mean that exploitation of the Umm er Radhuma may locally be limited by depth to water.
- **Water quality:** Exploitation of the aquifer system in the eastern areas of this region is limited by the presence of saline and hypersaline waters and the facial change of the Rus Formation to anhydrites (see Overview Map; Figure 1).
- **Transmissivity:** The aquifer system is practically not exploitable in the Dahna Desert since the Dammam Formation is not present and the Umm er Radhuma is discontinuous and does not have enough thickness and storage properties to yield substantial amounts of groundwater.

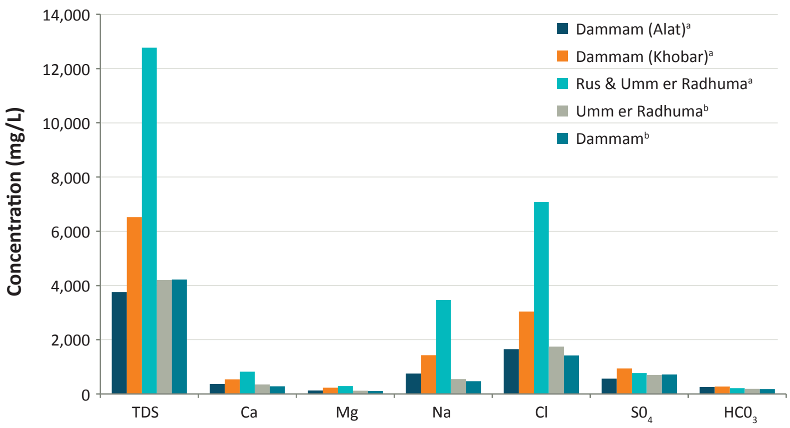
Based on the above, it seems that the aquifer system is exploitable in most parts, except in the coastal areas and other localized zones which are not specified on the map due to their small scale and the lack of specific data.

Figure 3. Groundwater salinity map - Umm er Radhuma-Dammam Aquifer System (Centre)



Source: Compiled by ESCWA-BGR based on UN-ESCWA and BGR, 1999a; UN-ESCWA and BGR, 1999b.

Figure 4. Major element concentrations in the Dammam and Umm er Radhuma Aquifers



Source: Compiled by ESCWA-BGR based on (a) Ministry of Municipalities Affairs and Urban Planning in Bahrain, 2011; (b) Ministry of Agriculture and Water in Saudi Arabia, 1984.

The total exploitable area in the suggested delineated basin is 243,360 km^2, of which 360 km^2 is in Bahrain, 11,000 km^2 in Qatar and 232,000 km^2 in Saudi Arabia.

Groundwater Use

GROUNDWATER ABSTRACTION AND USE

The use of wells to abstract water from the aquifer system began in the 1920s in Bahrain, the 1930s in Saudi Arabia,[54] and in the 1950s in Qatar.[55] Since then, groundwater levels are constantly declining, which has resulted in alarming drawdown in both the Dammam and the Umm er Radhuma Aquifers. In the area of Hasa, for example, a decline of 30 to 77 m was reported over a six-year period between1978 and 1984.[56] Water levels in the Dammam Aquifer have dropped at a rate of 4 m/yr and this aquifer is now mostly dewatered in Bahrain and Qatar.[57]

Saudi Arabia

The Umm er Radhuma Aquifer is exploited intensively for agricultural development projects around Haradh, Hofuf and Wadi al Miyah. The King Faisal Bedouin Settlement project, 10 km south-east of Haradh relies heavily on the aquifer, with an annual withdrawal of about 90 MCM. The water is pumped from 51 bore-holes that were drilled by the Ministry of Agriculture and Water in the 1980s.[58] In the northern parts of the aquifer around Wadi al Miyah, the Al Sharqiyah Agricultural Development Company (SHADCO) extracts 38 MCM/yr of groundwater.[59] The aquifer is also used to supply water to industrial and domestic users in the Greater Dhahran urban area (the cities of Dhahran and Khobar), including for landscape irrigation purposes. Over 70 bore-holes were drilled in this area in the vicinity of the Dammam Dome.

The Dammam Aquifer is mainly used in the coastal cities of Dammam, Qatif and surrounding smaller towns such as Sayhat, Anik, Safwa, Umm al Sahik and Ras Tanurah.[60] More than 80% of the extracted water is used for irrigation purposes; the remainder is used for domestic and industrial purposes and to water livestock.

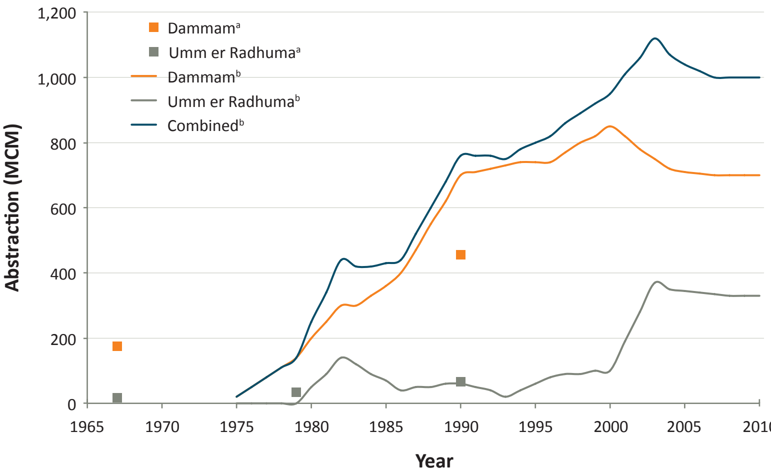
The limited thickness of the Dammam (25-65 m) makes it highly vulnerable to dewatering, which is a real risk in the area of Hasa[61] where there is a long history of groundwater exploitation, particularly from the Dammam Aquifer. Hence, the Umm er Radhuma and Dammam Aquifers are currently only used to a limited extent for irrigation and domestic purposes in the area of Hasa, and springs emanating from the Neogene provide the main supply of groundwater here.

As the Dammam Aquifer has a relatively shallow water level and reasonably good permeabilities, it has been exploited more intensively than the Umm er Radhuma (Figure 5).[62] Pumping records indicate a continuous increase in abstraction rates from the Dammam since 1940 and a marked upward trend after 1965. By 1966, most withdrawals from the Dammam along the coast were from artesian wells that tapped both the Khobar and Alat members. Abstraction from the Alat was reduced in the early 1980s due to decreasing yields in most areas. Instead the Khobar was developed along the coast and in the area of Hasa.[63] In 1990, abstraction from this unit had increased to more than three times the abstraction from the Alat.[64]

Abstraction from the Umm er Radhuma lagged behind, mainly because the average depth to the top of the aquifer was around 220 m in the late 1960s.[65] Total abstraction from this aquifer has increased gradually, particularly since 1979, to reach 66 MCM/yr in 1990 compared to 427 MCM/yr from the Dammam (see Dammam[a], Figure 5). After 2000, when the abstraction from the Dammam reached its highest level (850 MCM/yr), abstraction decreased by about 100 MCM until 2004. This was however compensated by increased abstraction from the Umm er Radhuma, from 100 MCM/yr in 2000 to 370 MCM/yr in 2002 (see Umm er Radhuma[b], Figure 5).

Cumulative total abstraction from the Umm er Radhuma-Dammam Aquifer System in eastern Saudi Arabia was roughly 24.3 BCM between 1967 and 2010.[66]

Figure 5. Historical abstraction from the Dammam and Umm er Radhuma Aquifers in eastern Saudi Arabia (1967-2010)



Source: Compiled by ESCWA-BGR based on (a) Abderrahman et al., 1995; (b) Water Watch, 2006.

Bahrain

Bahrain withdraws groundwater from the highly productive Khobar unit in the Dammam Formation, and, to a lesser extent, from the Umm er Radhuma Formation. Development activities in the 1960s significantly increased abstraction, and total withdrawal from the Dammam almost doubled between 1952 and 1966 and continued to rise from then on to reach 218 MCM in 1994. Figure 6 suggests that abstraction may have stayed at this level until 2000 before it started dropping as withdrawal for the agricultural sector was reduced. By 2010, abstraction levels had declined to 97 MCM/yr and 54.3 MCM/yr for the Dammam and the Umm er Radhuma respectively.[67] In general, abstraction points for domestic and irrigation purposes are concentrated in the western and northern areas, where the best-quality groundwater is found, while industrial wells are mostly limited to the eastern coast and south-central areas.

The cumulative total abstraction from the Dammam Aquifer in Bahrain was roughly 3.8 BCM between 1952 and 2010.[68]

Qatar

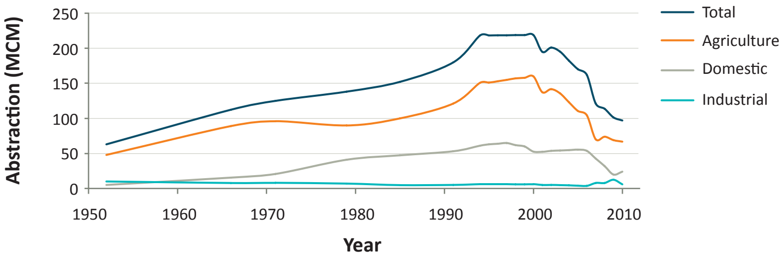
Groundwater abstraction has steadily increased in Qatar since 1971. This is mainly due to the expansion of agricultural activities, which consumed 98% of the groundwater in 1993.[69] The remaining 2% was used for domestic purposes. Abstraction more than doubled between 1971 and 1983, from about 43 to 91 MCM/yr.[70] More than 70 MCM/yr (77%) of this abstraction is from the Umm er Radhuma and Rus Aquifers and takes place in the north of the peninsula where many farms are located and water quality is better.[71] The remaining 23% is withdrawn from the Rus Formation in the south of the peninsula.

GROUNDWATER QUALITY ISSUES

Continuous over-exploitation of the Umm er Radhuma-Dammam Aquifer System has rendered the groundwater prone to salinization. This may make the aquifer unsuitable for use in the future. Several factors contribute to groundwater salinization in this area:

- Formation (connate) water at depth is rising to shallow environments in the eastern part of the Arabian Peninsula (Dammam and Bahrain Domes and central Qatar) and mixing with the groundwater in the aquifer system.

Figure 6. **Historical abstraction from the Dammam Aquifer in Bahrain (1952-2010)**



Source: Compiled by ESCWA-BGR based on Zubari et al., in UN-ESCWA and BGR, 1999b; Ministry of Municipalities Affairs and Urban Planning in Bahrain, 2011.

- The progressively declining water table heightens the risk of saline connate water upconing along major fault systems such as the En Nala and Khurays-Burgan Anticlines in Saudi Arabia and the Qatar Arch in Qatar.
- Water-level decline would also enhance the formation of more solution collapse features and hence provide new "windows" through which saline water could rise and mix with the relatively freshwater along the coast of Saudi Arabia.
- Changes in hydraulic gradients of the aquifer system due to over-pumping in inland areas could further enhance the advance of the seawater wedge along the coast of eastern Saudi Arabia, eastern Bahrain and around Qatar.
- Over-abstraction enhances the migration of saline sabkha water into unconfined areas of the coastal parts of the aquifer system, for example in the southern parts of Bahrain.

Overall, salinization of the aquifer system in the near future is a threat.

SUSTAINABILITY ISSUES

The unsustainable use of the aquifer system over the past 30 to 40 years, and the resulting salinization and drop in water table have already restricted the use of this aquifer system in Bahrain and possibly in some parts of Qatar and Saudi Arabia. The Dammam and Rus Formations, which used to be the only source of freshwater in Bahrain and Qatar respectively, are particularly at risk of salinization and/or total depletion.

Agreements, Cooperation & Outlook

AGREEMENTS

There are no water agreements in place for Umm er Radhuma-Dammam Aquifer System (Centre) which is shared between Bahrain, Qatar and Saudi Arabia.

COOPERATION

No information was available regarding cooperation between the riparian countries on the aquifer system. However, there are cooperation activities under the umbrella of the Gulf Cooperation Council which include investments in water infrastructure projects. Bahrain has also underlined its need and interest to cooperate over the management of shared groundwater resources.[72]

OUTLOOK

Joint management of the aquifer system would help ensure its long-term sustainability, as this section of the aquifer system is threatened by complete salinization in the near future.

Jebel al Qarah, Saudi Arabia, 2011. Source: Chris Helmkamp.

Notes

1. Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates.
2. This division was based on UN-ESCWA and BGR, 1999b.
3. As delineated by the Ministry of Agriculture and Water in Saudi Arabia (Ministry of Agriculture and Water,1995 as cited in Vincent, 2008).
4. PSRCE, 2007.
5. Al-Jerash, 1985 as cited in Vincent, 2008.
6. Central Department of Statistics and Information in Saudi Arabia, 2011.
7. Central Informatics Organisation in Bahrain, 2010.
8. Statistics Authority in Qatar, 2012.
9. UN-ESCWA and BGR, 1999b; UN-ESCWA and BGR, 1999a; Alsharhan et al., 2001; and Alsharhan and Nairn, 1997.
10. Vincent, 2008.
11. Edgell, 2006, p. 18-19.
12. Chapman, 1978.
13. Edgell, 2006, p. 12.
14. UN-ESCWA and BGR, 1999b.
15. Alsharhan et al., 2001; UN-ESCWA and BGR, 1999b.
16. Ministry of Agriculture and Water in Saudi Arabia, 1984.
17. Alsharhan et al., 2001.
18. Ibid.
19. BRGM, 1977 cited in Alsharhan et al., 2001.
20. Ministry of Agriculture and Water in Saudi Arabia, 1984.
21. Alsharhan et al., 2001.
22. Al-Nouaimy, 1999.
23. Harhash and Yousif, 1985.
24. Alsharhan et al., 2001.
25. UN-ESCWA and BGR, 1999b.
26. Al-Nouaimy, 1999.
27. Powers et al., 1966.
28. Alsharhan et al., 2001.
29. Ibid; UN-ESCWA and BGR, 1999b.
30. Alsharhan et al., 2001.
31. Bakiewicz et al., 1982.
32. UN-ESCWA and BGR, 1999b.
33. Bakiewicz et al., 1982.
34. The recharge calculation was done for an area of 215,800 km^2 in eastern Saudi Arabia. This includes most of the northern and central part of the study area, but not all areas stated in Faulkner, 1994.
35. Bakiewicz et al., 1982.
36. Faulkner, 1994.
37. UN-ESCWA and BGR, 1999b.
38. Al-Nouaimy, 1999.
39. Harhash and Yousif, 1985.
40. UN-ESCWA and BGR, 1999b.
41. Al-Nouaimy, 1999.
42. Dabbagh and Abderrahman, 1997 as cited in UN-ESCWA and BGR, 1999b.
43. Sadiq and Hussein, 1997 as cited in UN-ESCWA and BGR, 1999b.
44. Parker and Pike, 1976 as cited in UN-ESCWA and BGR, 1999b.
45. Ministry of Municipalities Affairs and Urban Planning in Bahrain, 2011.
46. Bakiewicz et al., 1982.
47. GDC, 1980 as cited in UN-ESCWA and BGR, 1999b.
48. Bakiewicz et al., 1982.
49. Ibid.
50. FAO Near East Cooperative Program, 1979.
51. Ministry of Agriculture and Water in Saudi Arabia, 1984.
52. Harhash and Yousif, 1985.
53. Ministry of Agriculture and Water in Saudi Arabia, 1984.
54. Ibid.
55. Zubari et al. 1993 cited in UN-ESCWA and BGR, 1999b; UN-ESCWA, 1981.
56. UN-ESCWA and BGR, 1999b.
57. Zubari et al. 1993 cited in UN-ESCWA and BGR, 1999b.
58. Dabbagh et al., 1988 cited in UN-ESCWA and BGR, 1999b.
59. Abderrahman et al., 1995.
60. Not shown on the Overview Map due to scale.
61. Ministry of Agriculture and Water in Saudi Arabia, 1984.
62. Ibid.
63. Ibid.
64. Abderrahman et al.,1995.
65. Italconsult, 1969 cited in Abderrahman et al., 1995.
66. Based on estimated groundwater abstraction for the period 1967-2004, according to Water Watch, 2006; a constant abstraction of 1,000 MCM/yr was assumed for the period 2005-2010.
67. Ministry of Municipalities Affairs and Urban Planning in Bahrain, 2011.
68. A constant abstraction of 218.6 MCM/yr was assumed for the period 1995-1999 in Bahrain based on Zubari et al 1993, cited in UN-ESCWA and BGR, 1999b; Ministry of Municipalities Affairs and Urban Planning in Bahrain, 2011.
69. Joudeh, 1994.
70. Harhash and Yousif,1985.
71. Ibid.
72. Ministry of Municipalities Affairs and Urban Planning in Bahrain, 2011.

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