

# Inventory of Shared Water Resources in Western Asia: Selected Aquifer Systems in the Arabian Peninsula for the Application of Remote Sensing Techniques



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## 1 Introduction

For millennia, sharing of water resources has been an influential feature affecting life, society and development in this mostly arid and semi-arid region. Water management and irrigation schemes, such as the underground aqueducts networks (*'qanat'* or *'falaj'* in Arabic) built centuries ago in Bahrain, Oman, Saudi Arabia and Yemen, stand as evidence for the sharing of water by different societies in the past to sustain communal needs. The concept of sharing water as a 'common resource' began to somehow dissolve with the creation of modern states in the region by political borders during the first half of the twentieth century. Most of the region's major rivers and many aquifer systems were found to extend beyond political borders and became sources of conflict as each country across the border claimed ownership of the resources.

In a region inflicted with political conflicts, severe water shortage and rapidly growing population, it is understandable why countries continued to compete rather than cooperate over the existing aquifer systems. Management of these transboundary resources became a real challenge in particular because they are non-renewable and at an increasingly high risk of being exhausted. Sustaining these "fossil" aquifer systems for future generations and for the continuation of life in this harsh environment requires a sound knowledge and cooperation among riparian countries towards joint development and management of the available resources. With this objective in mind, the preparation of the *Inventory of Shared Water Resources in Western*

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*Asia*<sup>1</sup> was jointly undertaken by the United Nations Economic and Social Commission for Western Asia (ESCWA) and the German Federal Institute for Geosciences and Natural Resources (BGR). This inventory is the first systematic effort to characterize all transboundary surface water and groundwater resources throughout the Western Asia Region. It constitutes a comprehensive reference document that encompasses water resources crossing the political borders of Arab and non-Arab states in the region. The inventory has shown the existence of several large aquifers in the Western Asia region extending across political borders. Due to the paucity of data/information, delineation of the aquifer system boundaries was based on information that was mostly outdated, obsolete, contradictory or of different nature and scale. Recent data on the majority of the aquifer systems were classified in national databases and unpublished reports to which the study team did not have access. Hence, the description and findings contained in the Inventory were meant to provide a starting point towards a more comprehensive analysis for an absolute delineation of the aquifer boundaries. This can be achieved through the application of remote sensing techniques (RS), in combination with the GIS data already available from the Inventory.

This chapter is prepared for the purpose of advocating this objective. Section 1 of this chapter is a brief description of the methodology and information sources for the Inventory. Section 2 describes the process of identifying shared aquifer systems, highlighting the main limitations to the delineation of different aquifer systems. Section 3 gives an overview of the aquifer systems identified. Finally, Sect. 4 provides a detailed information on two aquifer systems (*Saq-Ram* and *Wasia-Biyadh-Aruma-South*) selected as pilot projects for the applications of RS techniques.

## 2 Methodology and Information Sources

Information on shared groundwater resources was initially collected and summarized from data/information available in the literature (scientific publications, country papers, national and regional maps and datasets, satellite imagery, media reports) including ESCWA reports. Groundwater resources had not been previously catalogued across borders and there was no common methodology for achieving this purpose while taking into consideration the specific conditions of the region. Hence the Inventory started with the screening of all available geological/hydro(geo)logical information and its interpretation in view of identifying potentially shared aquifers/aquifer systems. The findings were discussed internally and with a panel of regional and international experts via regional expert consultations. The experts were also involved in a peer review of data sets and chapter drafts with a focus on the overall coherence and integrity, and possible shortcomings and gaps. Information packages were compiled and circulated among relevant riparian countries for any modifications and/or addition of data/information needed for completing

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<sup>1</sup> <http://www.waterinventory.org>

the chapters. Any relevant information subsequently received from the countries was incorporated into the chapter drafts to finalize them.

### 3 Shared Aquifer Systems Identification Process

Shared aquifer systems were identified through the following five steps:

#### ***Step One: Identifying Shared Aquifers in the Literature***

Based on the results of initial screening of *known* aquifers in the region, additional research was carried out on shared or potentially shared aquifers, using regional/national geological hydro(geo)logical maps, geological cross-sections, stratigraphy tables, journal articles and studies.

#### ***Step Two: Verifying Shared Aquifers Versus Shared Aquifer Systems***

The aim of this step was to verify whether water-bearing geological formations extending across specific political borders constitute shared aquifers or shared aquifer systems.<sup>2</sup> A good understanding of hydrogeological units in the area was achieved through examination of the vertical and lateral hydraulic linkages between shared aquifers and aquifer layers. Single or multiple layers of interconnected aquifers were combined into aquifer systems if the vertical and lateral hydraulic conditions allowed water flow between and across formations. Given the complexity of the region's hydrogeology and the general lack of data and information, this step was based to some extent on logical reasoning.

#### ***Step Three: Dealing with Issues of Scale***

The region covered by the inventory is predominantly a vast desert underlain by thick and widespread geological formations (Arabian Peninsula) with two chains of faulted and folded mountains in the northeast (Taurus-Zagros) and northwest (Anti Lebanon). The hydraulic setting and groundwater dynamics at the extremities of the large aquifer systems under the Arabian Peninsula may vary significantly since structural features or groundwater divides are likely to create different hydrogeological sections in the aquifer system. Hence extensive aquifer systems were geographically divided into sub-units, or sections, such that different sections would represent shared aquifer systems only for countries affected by groundwater flow in relevant section(s). By contrast, the aquifer systems in Anti-Lebanon and the Taurus-Zagros consist of small units that cross political borders in several places and generally discharge through springs such that it is difficult to determine their hydraulic relationship and/or delineate their geographical extent across political borders. These units

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<sup>2</sup> A series of two or more aquifers that are hydraulically connected. Aquifer systems are defined by continuity and characteristics rather than by the origin of the aquifer material. They may therefore be made up of several lithologies and stratigraphic units. An aquifer system may include aquitards and confining beds (UNESCO 1978).

are grouped together in separate chapters that give a description of the overall hydrogeological framework conditions and the main aquifer formations without specifying whether or not they constitute single aquifers or aquifer systems.

#### ***Step Four: Approximating Aquifer System Boundaries***

This step aimed to refine the delineation of each section of the shared aquifers and aquifer systems where found necessary. Since groundwater divides were not available in many cases, groundwater flow information was used to approximate aquifer system boundaries, taking into consideration boundaries of hydrological basins that had been delineated in previous studies on the basis of surface water drainage. However, the Inventory went beyond these boundaries for the purpose of describing the aquifer system(s), which normally extend outside the basin. Structural features (faults, graben structures, anticlines or synclines) that usually control groundwater flow were then used to approximate groundwater boundaries where possible.

#### ***Step Five: Description of Shared Aquifer Systems***

In this final step, each of the shared aquifer systems, sections, or basins was characterized with respect to hydrogeology, groundwater use, agreements and cooperation. Each of these aspects was described within a standardized chapter template containing the following information (Table 1).

Suitability for groundwater development, referred to as “exploitability” in the Inventory, was also analyzed. Exploitability, based on water quality, technical feasibility and economic viability, was determined by the following three parameters:

**Table 1** Standard template of information on each aquifer system

Heading	Content
Summary	Executive summary, basin facts
Introduction	Location, area, climate, population, other aquifers in the area, information sources
Hydrogeology—aquifer characteristics	Aquifer configuration (geometry, depth, outcrop areas, subsurface extent), Stratigraphy, Aquifer thickness, Aquifer type (confined/unconfined), Aquifer parameters (transmissivity, storativity)
Hydrogeology—groundwater	Recharge, flow regime (water levels, gradients, flow direction), Storage, Discharge (springs, vertical leakage), Water quality, Exploitability
Groundwater use	Groundwater abstraction and use (timeline of development, areas and sector use, abstraction volumes), Groundwater quality issues (return flows, salinization, pollution), Sustainability issues (trends, over-abstraction)
Agreements, cooperation and outlook	Agreements (treaties, Memorandum of Understanding, negotiations), cooperation (timeline, form, mechanism, issues of conflict), outlook (main management issues, opportunities)

- *Depth to top of aquifer*: The Inventory has adopted a depth of 2,000 m that was applied by other researchers in the region.
- *Depth to water level*: A maximum depth to water level of 250–300 m was applied in some regional studies and hence a limit of 250 m was set for the Inventory, while using the most recent data available from official sources, wherever possible,
- *Water quality*: While a salinity level of <2,000 mg/L TDS is usually desirable for “exploitability”, groundwater with this quality is rare in large parts of the region, particularly in the extensive aquifer systems of the Arabian Peninsula. Moreover, brackish groundwater in this arid and hyper-arid region is also considered an exploitable resource since it is used in combination with desalination or to grow highly salt-tolerant crops such as date palms. Therefore, a salinity level of 10,000 mg/L TDS was applied in the Inventory as a limiting factor for the exploitability of aquifer systems.

## 4 Overview of the Aquifer Systems

Geologically, the study area extends across the Arabian Plate, which has been moving incrementally from the African Plate to the north and north-east since the Miocene time, where it collides with the Turkish and Eurasian Plates along its northern boundaries. This has led to the development of different tectonic zones and geological structures that created significant differences in the hydrogeological features of the main part of the plate (*Arabian Peninsula*) and its northern areas (*Mashrek*, *Mesopotamian Plain*, and *Taurus-Zagros*). Based on tectonics and geological structure/history, the Region can be divided into four distinct main sub-regions:

- The *Arabian Peninsula* has been tectonically reasonably stable throughout different geological era such that its eastern half provided a depositional basin for thick (up to 7,500 m) and extensive sedimentary strata that form large regional aquifer systems. The largest part of the Peninsula is covered by the Kingdom of Saudi Arabia (KSA), which has political borders with 8 countries: Jordan and Iraq in the north; Bahrain, Kuwait, Qatar, and United Arab Emirates (UAE) in the east; and Oman and Yemen in the south. Aquifer systems identified across the border of KSA and neighboring countries are listed in Table 2.
- The *Mashrek* extends along the eastern Mediterranean incorporating the political borders of Israel, Lebanon, Palestine, Egypt (Sinai Peninsula) and Syria. It is characterized by high mountains in the western areas near the coast and wide plateaus further inland. The plateaus are covered by a sequence of basalt complex while the mountains consist of well exposed and highly fissured/karstified carbonate rocks, which form complex aquifers. Five transboundary aquifer systems have been identified in this sub-region, one of them extending along the Anti-Lebanon Mountain range with 3 separate catchments that discharge springs inside Syria (Table 3).

**Table 2** Aquifer systems identified across the Arabian Peninsula

Shared aquifer system	Area (km <sup>2</sup> )	Thickness (m)	Riparian countries
Saq-Ram (West)	308 000	250–700	KSA, Jordan
Tawil-Quaternary (Wadi Sirhan)	44 000	Up to 1 300	KSA, Jordan
Wasia-Biyadh-Aruma (North)—Sakak-Rutba	112 000	250–400	KSA-Iraq
Wasia-Biyadh-Aruma (South)—Tawila-Mahra-Cretaceous Sands	157 000	100–200	KSA-Yemen
Neogene (Southeast)-Dibdiba	153 000	Up to 550	KSA-Kuwait-Iraq
Umm er Radhuma-Dammam (North)	246 000	270–680	KSA-Kuwait-Iraq
Umm er Radhuma-Dammam (Centre)	281 000	265–680	KSA-Bahrain-Qatar
Umm er Radhuma-Dammam (South)	680 000	110–1040	KSA-Oman-UAE-Yemen
Wajid	455 000	100–900	KSA-Yemen

**Table 3** Aquifer systems identified across the Mashrek

Shared aquifer system	Area (km <sup>2</sup> )	Thickness (m)	Riparian countries
Anti-Lebanon (3 catchments)	248 (Anjar-Chamsine), 149 (Barada), 658 (FigeH)	900 (Anjar-Chamsine), 2 000–2 200 (Barada), 480–680 (FigeH)	Lebanon-Syria
Western Basin	9 000–14 167	600–1 000	Egypt-Israel-Palestine
Coastal Basin	18 370	60–140	Egypt-Israel-Palestine
Basalt (West)—Yarmouk Basin	7 000	100–300	Jordan-Syria
Basalt (South)—Azraq-Dhuleil Basin	8 500	100–500	Jordan-Syria

The *Mesopotamian Plain* is bounded by two major faults and has formed a depositional basin since the Neogene time. The basin extends across Iraq into Syria and Turkey and is characterized by clastic sedimentary aquifer systems. Two shared aquifer systems have been identified in this sub-region as indicated in Table 4.

The *Taurus-Zagros* extends from the northwestern border of Iran with Iraq into Turkey. This highly folded and faulted region features elevated areas made up of karstified carbonate rocks with many springs discharging good-quality water, and younger clastics that form isolated to semi-isolated aquifer systems. A single aquifer

**Table 4** Aquifer systems identified across the Mesopotamia Plain

Shared aquifer system	Area (km <sup>2</sup> )	Thickness (m)	Riparian countries
Jezira Tertiary Limestone	14 000	200–700	Syria-Turkey
Neogene (Northwest)—Jezira Basin	65 000	500–550	Iraq-Syria

**Table 5** Aquifer systems identified across the Taurus-Zagros

Shared aquifer system	Area (km <sup>2</sup> )	Thickness (m)	Riparian countries
Taurus-Zagros	11 760 ( <i>Central Diyala</i> ), 566 ( <i>Halabja-Khurmali</i> ), 1 960 ( <i>Zakho</i> )	1 000–2 500	Iran-Iraq ( <i>Central Diyala</i> , <i>Halabja-Khurmali</i> ) and Iraq-Turkey ( <i>Zakho</i> )

system with 3 different catchments (*Central Diyala*, *Halabja-Khurmali*, and *Zakho*) is identified across political borders in this zone (Table 5).

## 5 Selected Aquifer Systems for the Applications of RS Techniques

### *Saq-Ram (West)*

The Cambro-Ordovician Sandstones extending from the Tabuk-Tayma region of Saudi Arabia to the the Dead Sea area in western Jordan (Fig. 1) is known as *Saq* and *Ram* or *Rum* in the two countries, respectively. In this inventory, it is referred to as *Saq-Ram (West)* Aquifer System. The system is heavily exploited in the Tabuk-Mudawwara-Disi area, which extends from the Tabuk Plain in Saudi Arabia to Wadi Rum in Jordan as delineated in the overview map below. In Jordan, the aquifer system is widely exposed in the southern desert and is present in the subsurface throughout most of the country.

In Saudi Arabia, the *Saq* formation lies directly on the crystalline Basement and dips gradually towards the north and north-east under less permeable formations as shown in Fig. 2b. Further east and south, the *Saq* is separated from the overlying sandstones by the *Hanadir* Shale. Figure 2a shows the continuation of the *Saq* northward to Jordan where the sandstones of the *Ram* rest on the Basement. The sandstones are widely exposed in the southern desert and are present at depth throughout Jordan except for the outcrop areas of the Basement in the extreme south-west. In Jordan, the average thickness of the sequence is about 1,000 m, but increases to over 2,250 m in the southern part of *Wadi Sirhan* and more than 2,500 m in the *Risha* area near the Iraqi border. In the *Tabuk* area of Saudi Arabia, the thickness of a typical profile of the *Saq* is 800 m and reaches more than 1,000 m in some places, but thicknesses of 250–500 m are also common. The aquifer system is generally unconfined in the outcrop areas and their surroundings and becomes a confined or leaky aquifer towards the north and north-east where the sandstones dip below shales and other aquitards. A

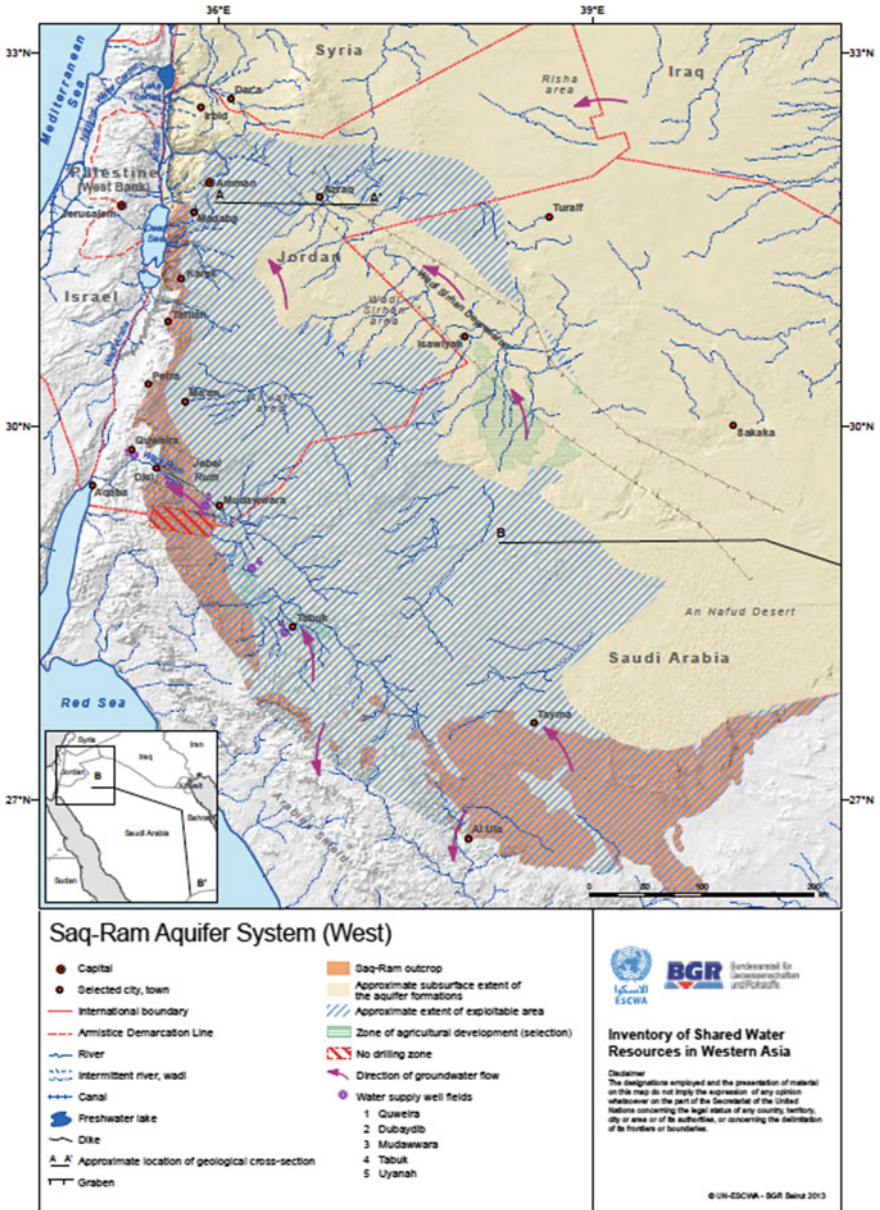
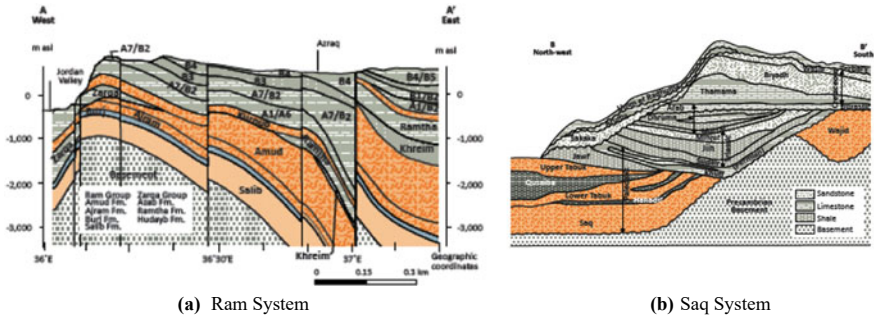


Fig. 1 Overview map of Saq-Ram (West). Source Inventory of Shared Water Resources in Western Asia. Beirut. UN-ESCWA and BGR (2013)





**Fig. 2** Geological cross section of subsurface stratigraphy of the Saq-Ram Aquifer System **a** Ram system. **b** Saq system. *Source* Inventory of Shared Water Resources in Western Asia. Beirut. UN-ESCWA and BGR (2013)

large variation in hydraulic parameters was observed in a number of studies between confined and unconfined areas and towards the northern and northeastern areas where the base of the aquifer system reaches great depths. Transmissivity values vary over a wide range for the entire system with higher values for the confined/leaky part as compared with the unconfined, while storativity/storage coefficient values show relatively less variation.

*The Resource*

Isotopic data indicate that recharge to the *Saq-Ram* Sandstones occurred between 10,000 and 30,000 years ago, as evidenced by the oldest waters now emerging from deep wells in the Jordan Valley. Modern recharge is negligible (0.03 mm/year.) in areas with no outcrops and where rainfall is less than 75 mm/year. However, in escarpment areas such as the Wadi Araba in Jordan, recharge has been shown to increase with elevation from 3 to 11 mm/year. In KSA, an average annual recharge of 2.5 mm was estimated for the *Saq* outcrops.

Until the 1980s, natural groundwater flow was directed northwards, starting from the Tayma-Tabuk area in Saudi Arabia, and across the southern desert in Jordan, towards the low-lying Dead Sea natural discharge zone. Since then, however, increased abstraction 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 as shown below. This has resulted in the occurrence of a very large and deep cone of depression, locally diverting the natural north-easterly groundwater flow direction and reducing the assumed natural flow across the border to Jordan of around 140 MCM/year. to negligible amounts. Near the border, there is basaltic dike (*Kharawi*) that forms a natural hydraulic barrier impounding the groundwater such that the flow is deflected in a south-easterly direction towards Saudi Arabia or north-westerly direction towards the Wadi Araba. Some 100 km south of Tabuk and as far as Al Ula, the groundwater flow is directed outward to the Arabian Shield (see overview map).

In the Tabuk area, available groundwater reserves in the *Saq* were estimated at 43 BCM, of which about 20 BCM is in the unconfined part. However, it was estimated that with continued pumping at the current rate of pumping, the exploitable reserve will drop from currently 75% to 38% between 2005 and 2055. In Jordan, it is estimated that available water reserve commonly ranges between 4 and 10 BCM though a maximum of 40 BCM has also been reported.

The low-lying Dead Sea area is the main discharge zone for the aquifer system is the where natural discharge occurs in the form of springs and base flow in the deeply incised wadis that discharge into the Dead Sea. The springs occur mainly in areas along the eastern side of the Jordan Rift Valley, where average rainfall is around 150–200 mm/year, and 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 though it fluctuates widely from year to year. Groundwater discharge also occurs in the Wadi Sirhan Depression and its northern extension into the Azraq Graben, as well as in the Shield. Further discharge emanates from springs in valleys draining towards the Red Sea has also been reported.

The quality of water in the aquifer system is generally good with total dissolved solids (TDS) levels of around 1,000–1,200 mg/L dominated by calcium ( $\text{Ca}^{2+}$ ) and bicarbonate ( $\text{HCO}_3^-$ ). However, a significant increase in TDS from 200 to 400 mg/L the Mudawwara-Disi area to 1,000–3,000 mg/L at the Dead Sea, where thermal springs are common, has been observed. This salinity increase has been attributed to downward leakage from the overlying formations, which contain highly saline waters (up to 35,000 mg/L TDS), and the dissolution of evaporites contained in the aquifer.

In Saudi Arabia where most abstraction takes place, elevated concentrations of boron, selenium and nitrate have been detected, mostly in wells that tap the unconfined part at a depth of less than 150 m. The occurrence of natural radionuclides is common in Cambro-Ordovician Sandstones, and their presence in groundwater within both countries has been reported. Possible sources of radioactive elements include the Basement rocks, shale layers, phosphate-bearing formations and cementing material in the sandstones such as iron and manganese oxides with other trace metal oxides, including those of uranium. A decrease in pH enhanced the dissolution of uranium and radium from the matrix and thermal springs in the Dead Sea area discharging waters with elevated concentrations of carbon dioxide, hydrogen sulfide, and radon gases. Elevation in radioactivity appears to be related to water level declines, most probably due to an increase in vertical leakage from less permeable layers that contain higher concentrations of radioactive minerals. The concentrations of radium isotopes is highest in groundwater discharging from confined areas, which can be explained by the fact that the isotopes are most mobile under reducing conditions.

### *The Exploitation*

Current abstraction in the Mudawwara-Disi area (Jordan) is 60 MCM/year. although higher values of 70–80 MCM/year. were reported in 2008. Groundwater abstraction in the Tabuk area (KSA) has increased drastically from about 29 MCM/year. in 1983

to between 1,050 and 1,700 MCM/year. in 2004, mostly in the agricultural sector, while recharge remains at 3–11 MCM/year. 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.

The water level continues to decline steadily with rising groundwater abstraction. Boreholes in the Tabuk area indicate significant declines, with total water level drops of 100 m to 160 m from 1983 to 1988, resulting in a reversal of the horizontal and vertical hydraulic gradient in some areas. Currently water level is mostly in the range of 50–150 m bgl. In the Tabuk area and continued abstraction from this 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.

There are also indications that groundwater quality deterioration may arise in the future. In particular natural sources of radioactivity may affect the entire aquifer system in the long term and limit its use, while other potential sources that may affect water quality could develop locally as a result of heavy pumping. Potential sources include leakage of saline from overlying shale formations, nitrate concentration from irrigation return flows, upconing of saline and hypersaline, and formation waters in faulted and geothermal areas.

### ***The Wasia-Biyadh-Aruma-South***

In the southern areas of Saudi Arabia, the Wasia-Biyadh Sandstones merge with the Aruma to constitute the so-called Cretaceous Sands, which extend across the Rub' al Khali Depression into Yemen where stratigraphically correlatable sandstones exist (the so-called Tawila-Mahra Group), forming a transboundary aquifer system denoted in the inventory as the Wasia-Biyadh-Aruma Aquifer System (South) and delineated as shown in the overview map (Fig. 3).

#### *The aquifer system*

The area of the Wasia-Biyadh-Aruma Aquifer System (South) is around 157,000 km<sup>2</sup>, of which 52,000 km<sup>2</sup> lies in Yemen, and 105,000 km<sup>2</sup> in Saudi Arabia. The system occurs in a largely inaccessible, arid and hyper-arid region, where the only sign of human settlement is in the Sharurah/Al Abr area. In Saudi Arabia, the sandstones lie in extensive dune areas. On the Yemeni side, the aquifer system is located in the north-eastern plateau zone, which descends gradually from the north of the Rub' al Khali Desert at an elevation of approximately 900 m.

The aquifer system is part of the Rub' al Khali structural depression that formed a depositional basin for Paleozoic and Mesozoic Formations. The main outcrops of the sandstones are found along a fault extending across the political border. They also occur on the surface at the foot of Jibal al Wajid near the western margin of the Rub' al Khali. The sandstones are overlain by superficial deposits of Quaternary age in the northern part of the study area.

During the Cretaceous period, the sea advanced into the region from the east with a series of short transgressions followed by regressions, but marine conditions never covered the western areas where terrestrial, fluvial and fluvio-deltaic conditions prevailed. Figure 4 shows that in Yemen the zone of the main lateral interdigitation of the individual formations occurs roughly between longitudes 49°30' and 50°30'. West

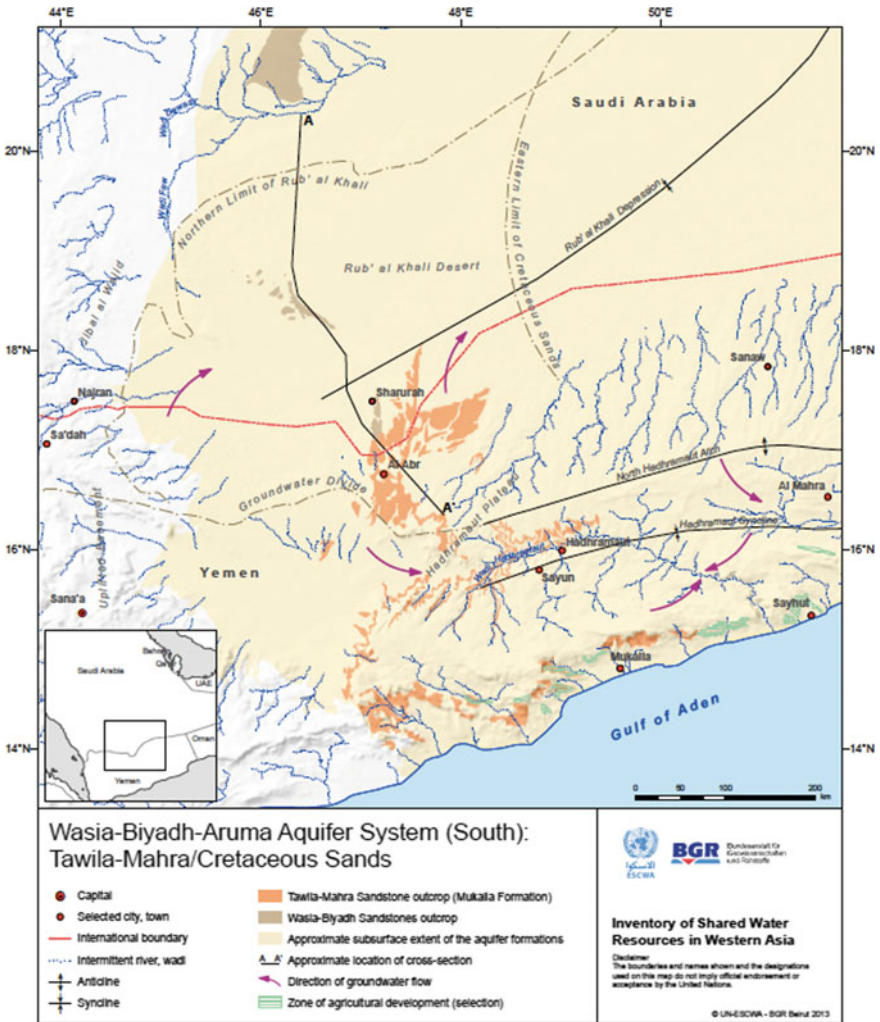


Fig. 3 Overview map of Wasia-Biyadh-Aruma Aquifer System (South). Source Inventory of Shared Water Resources in Western Asia. Beirut. UN-ESCWA and BGR (2013)

of longitude 47°, the entire Tawila Group is made up of undifferentiated clastics that constitute the major aquifer in north-western Yemen. East of this longitude, however, the Mukalla Formation constitutes the main aquifer within the Mahra Group. Similarly, in the eastern areas Saudi Arabia only the lowest unit of the Wasia-Biyadh Formations (Khafji-Safaniyah) is water-bearing whereas in the central part the sandstone deposition was much thicker and continued until the Late Cretaceous epoch (sandstone unit of the Aruma Formation not shown in Fig. 4).



Recharge of the aquifer system has also taken place in the past. Carbon-14 dating determined the age of deep water in the Mukalla Sandstone at 8,000 years, which is relatively young compared to the deep water in the Umm er Radhuma Aquifer System (20,000 years). This young age, together with the stable  $^{18}\text{O}$  isotopic composition of  $-2.0$  to  $-3.5\%$  suggest that recent recharge water must be reaching the sandstones. Similar situation has been reported for the Umm er Radhuma -Dammam Aquifer System to the north where it was found that groundwater at the main outcrop near Al Kharj is 8,000 years old as compared with water down-dip in the Khurais area, which is 16,000.

No visible signs of discharge are seen on the surface but downward flow discharge into the Upper Wajid Sandstone could occur on the Yemeni side of the border where the Khuff Formation, which separates the two aquifer systems in Saudi Arabia, seems to disappear though there is no data to confirm or negate this.

The dip of the Mukalla Sandstone in an easterly to north-easterly direction suggest that groundwater flows towards the Rub' al Khali and south-eastern Saudi Arabia. Further north, groundwater in the Wasia-Biyadh Formations flows towards the Persian Gulf under the influence of consistent hydraulic head despite being small. A comprehensive study undertaken by the Ministry of Agriculture and Water in Saudi Arabia in 1980, in which both depth and water quality limitations were taken into consideration, estimated that the total volume of water in this aquifer system with acceptable quality (TDS = 2,000 ppm) that could be extracted from a depth of 300 m (the maximum depth currently possible with pumping technology existing at the time) is in the order of 500 BCM. Groundwater from boreholes drilled into the Mukalla Sandstone south of the North Hadhramaut Arch was found to be of excellent quality, with TDS values in the range of 406–833 mg/L.

### *The Exploitation*

Information on depth to groundwater (100–200 m bgl.) and water quality (TDS of <1,000 mg/L), available for the Yemeni part of the study area, are within the limits of the criteria selected for exploitation (see above) and the top of the Cretaceous has an approximate maximum depth of 600 m bgl. across the whole area delineated in the Overview Map. Hence the entire delineated area can be considered exploitable, subject to accessibility and drilling/well stability in areas of thick sand dunes. It is expected however that groundwater exploitation would probably present logistical and access issues at such depth, thus significantly increasing unit cost per volume of groundwater extracted. If depth to water and TDS were not considered limiting factors, the area of exploitation could even extend beyond the mapped area. However, recent available data suggests that one or both parameters may be limiting factors, since practically no exploitable area is shown beyond the eastern limit of the Cretaceous Sands. At the present, the use of groundwater from the aquifer system is limited to insignificant shallow quantities available in wadi bed areas for the needs of small groups of nomadic populations.

## 6 Conclusions

Sparsely populated remote areas of the Arabian Peninsula are underlain by extensive aquifer system with abundant supplies of fresh groundwater that is hardly tapped. With the advancement of technology and scientific innovations, these freshwater resources can be extracted and transported to the growing human settlements in these areas and expanding urban centers across the Peninsula as well as made available for future generations. The application of remote sensing techniques is advocated as one of the most important tools to fine-tune the mapping of these aquifer systems and assess their potential for exploitation.

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