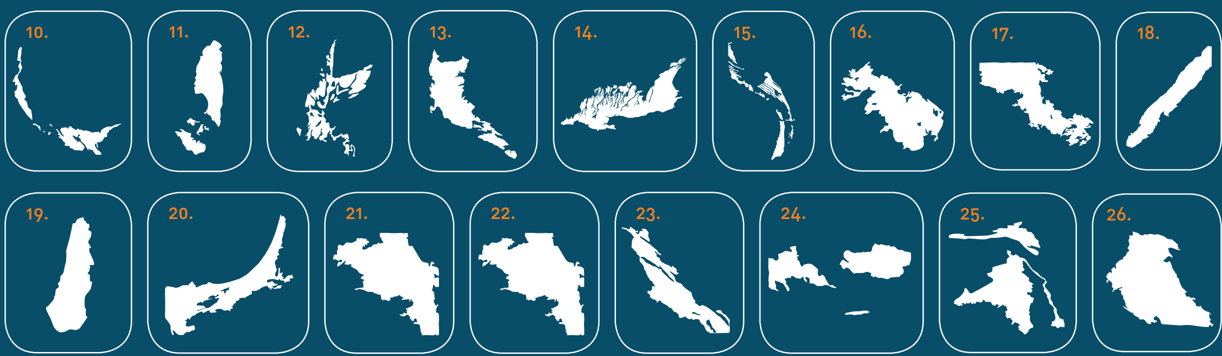
PART II

GROUNDWATER



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

german cooperation
DEUTSCHE ZUSAMMENARBEIT
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OVERVIEW & METHODOLOGY:

GROUNDWATER

Part II of the Inventory provides a comprehensive overview of shared (transboundary)[1] aquifer systems in Western Asia. This chapter defines the terminology used in the groundwater chapters and presents the methodology and approaches that helped identify, delineate, characterize and describe the shared aquifer systems in the region.[2] Each aquifer system is then categorized and briefly described. Finally, the structure of the groundwater chapters and the parameters used to characterize the aquifers and aquifer systems are outlined.

Definition of Terminology

On 11 December 2008, the United Nations General Assembly adopted resolution 63/124[3] on the Draft Articles on the law of transboundary aquifers in response to growing international concern about the use and protection of shared groundwater resources. The terminology used in the Inventory is based on the definitions used in that resolution and in the International Hydrogeology Glossary published by the United Nations Educational Scientific and Cultural Organization (UNESCO). The following key terms are widely used in the Inventory's groundwater chapters:

Aquifer: A permeable water-bearing geological formation underlain by a less permeable layer plus the water contained in its saturated zone. This implies that an aquifer could encompass part or parts of a formation. An aquifer also includes the unsaturated part of the permeable formation, although the description of hydraulic parameters such as transmissivity and storativity refer to the saturated part of the aquifer.

BOX 1

Data Availability and Implications

As explained in 'Introduction to the Inventory', information for the chapters was collected from various sources. Data and information on (shared) aquifer systems available to the public is often outdated, obsolete, contradictory or of different nature and scale. Some information, especially recent data on large aquifer systems that cross the political borders of several countries, is classified in national databases and unpublished reports to which the ESCWA-BGR team did not have access. The Inventory's Country Consultation process and consultation with experts produced only a limited amount of new data. This has affected the breadth and scope of the Inventory, especially in the area of water use and abstraction where the literature provides limited information.

The descriptions and findings contained in the Inventory should therefore be understood as the best possible approximation, based on the information available to the ESCWA-BGR team and in view of the overview character and regional scale of this desk study. The aim is to provide a starting point for future technical deliberations on shared aquifer systems in Western Asia among riparian countries and within the expert community. Rigorous scientific referencing and comprehensive bibliographies in each chapter aim to facilitate a continued debate.

Wadi Rum, Jordan, 2010. Source: Anouk Pappers.

Aquifer system: 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.[4]

Shared aquifer/Shared aquifer system: An aquifer or aquifer system that extends across political borders. The terms transboundary aquifer/transboundary aquifer system are commonly used synonyms.

Aquitard: A formation of semi-pervious rock that can store water. It can also transmit enough water to be significant in the regional migration of groundwater, but not enough water to supply individual wells. It retards but does not totally prevent the flow of water to or from an adjacent aquifer.

Aquiclude: A saturated bed, formation or group of formations which yield inappreciable quantities of water to drains, wells, springs and seeps.

Groundwater basin: A physiographic unit made up of one large aquifer or several connected or interrelated aquifers. The water in a groundwater basin flows to a common outlet and is delimited by a groundwater divide.

Other terms and concepts used in the Inventory are explained throughout the chapter.

Disi area, Jordan, 2009. Source: Andreas Renck.

Identifying Shared Aquifer Systems

Unlike rivers, which are visible linear features in the landscape, aquifers are three-dimensional structures hidden underground. This complicates the research process for the compilation of a groundwater inventory: a solid interpretation requires a wide spectrum of geological information, including geo-tectonics, geological structures, lithostratigraphy, geochemical and isotope data and groundwater dynamics. As a result, exact aquifer boundaries are often unknown and therefore not well defined. This is also the case in Western Asia, where regional hydrogeological specificities pose additional challenges to the identification and delineation of aquifer systems.

For instance, many of the region's major groundwater resources are located in deep geological strata and cover extensive areas, especially in the Arabian Peninsula. The massive water reserves contained in these aquifer systems have limited renewability (see section on Key Parameters below), and may form part of complex and partially inter-connected series of mainly confined aquiferous formations. The spatial extent and water-bearing characteristics of many of these formations are not well known. These deep aquifers are usually characterized by regional rather than local flow patterns and exhibit low natural flow gradients. Significant flow alteration may have occurred at local to sub-regional levels due to sustained abstraction and groundwater drawdown (Figure 1).

Moreover, not all parts of these aquifer systems can be considered exploitable due to poor water quality, technological limitations or inadequate saturation level. Riparian countries often do not recognize non-exploitable aquifers such as those with very high salinity levels.

The task of identifying distinct groundwater basins and defining them as groundwater management "units" at either a national or regional scale is challenging. In practice the definition of such a unit is scale-dependent, and differs in individual studies (i.e. using groundwater models) based on assumptions of boundary conditions or hydraulic connections for example. The question of hydraulic connectivity and how it affects the vertical and lateral definition of a shared resource is crucial in this context. Moreover, it is closely related to the concept of the aquifer system and the groundwater basin.

BOX 2

The Umm er Radhuma-Dammam as an Example of a Large Aquifer System in the Arabian Peninsula

The Umm er Radhuma-Dammam is the most extensive aquifer system in the Arabian Peninsula, covering a distance of 2,200 km from south-eastern Iraq to the coastal areas of Oman and Yemen (Map 2), and extending into eight Arab countries. The main geological aquiferous formations of the aquifer system (Umm er Radhuma, Dammam and Rus) vary in thickness, sequence and water-bearing characteristics but exhibit hydraulic continuity in several locations across the peninsula. Locally, the three formations exhibit significant lateral variations in lithology. For example, the Rus may be aquiferous in places while acting as an aquitard in others. Similarly, certain riparian countries no longer consider the Dammam an aquifer because the progressive decline of the water table (e.g. in Bahrain) or its hydraulic connectivity to sabkhas in desert areas (e.g. in Oman) mean that it is no longer exploitable.

Moreover, there may be a hydraulic connection to other formations, constituting an extensive and complex aquifer system equivalent to half the length of the Mediterranean Sea. While such an interpretation of a shared aquifer system may be of scientific value, it offers little guidance to the groundwater manager tasked with assessing or developing the resource across the aquifer area. In practice, groundwater abstraction from the Damman Formation in Iraq does not affect the status, dynamics or productivity of this aquifer system or any connected formation in Yemen and vice versa. This is why the Umm er Radhuma-Dammam Aquifer System has been divided into several sections for the purpose of this Inventory (see Chap. 14-16).

The region's specific hydrogeological setting gives rise to large sedimentary basins with extensive aquifer systems characterized by very low to low renewability, low flow gradients and confined conditions. Thus, an all-inclusive approach could lead to the delineation of vast and/or heterogeneous aquifer systems, in which hydraulic connectivity represents a theoretical construct that is of little practical relevance (Box 2).[5]

THE PROCESS

The process of identifying, delineating and describing shared aquifer systems in the Inventory can be broken down into the following steps:

1. Identifying shared aquifers in the literature

The first step was to list known shared groundwater resources in the study area and to gather information[6] to allow for further hydrogeological interpretation and delineation.[7] Based on the results of initial screening, additional research was carried out on shared or potentially shared aquifers using regional and national geological and hydrogeological maps, geological cross-sections, stratigraphy tables, journal articles and studies.[8] The resulting list included a brief characterization of the identified shared aquifers and a corresponding bibliography.

2. Verifying shared aquifers vs. shared aquifer systems

This step aimed to ascertain whether water-bearing geological formations that extend across the region's political borders constitute shared aquifers or shared aquifer systems. The examination of vertical and lateral hydraulic linkages between shared aquifers and aquifer layers (often individual water-bearing geological formations) led to a better understanding of hydrogeological units in the area. Sets of interconnected aquifers or aquifer layers 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. In case of doubt, an exclusive rather than an inclusive approach was preferred; the significance of hydraulic connections and the interpretation of hydrogeological data in this Inventory remain open to discussion.

3. Dealing with issues of scale

During this step, the findings of previous steps were reassessed from a transboundary perspective in order to focus research and interpretation, and refine the delineation of shared aquifers and aquifer systems.

Many of the large aquifers and aquifer systems in the Arabian Peninsula extend into areas that are far removed from country borders and therefore not relevant from a transboundary perspective (see Chap. 12-13). Moreover, the hydraulic setting and groundwater dynamics at the extremities of such large regional aquifer systems may vary significantly. Structural features or groundwater divides may create different hydrogeological sections in the aquifer system. Extensive aquifer systems were therefore geographically divided into sub-units, which are referred to as sections. Sections that are relevant from a transboundary perspective are covered in separate chapters in the Inventory (see Chap. 14-16).

By contrast, the geology and structure in the folded and faulted zones of the Anti-Lebanon and the Taurus-Zagros Mountain ranges are highly complex. The aquiferous formations in these areas consist of small units that cross political borders in several places and generally discharge through springs. This makes it difficult to determine their hydraulic relationship and/or delineate their geographical extent across political boundaries. These units are grouped together in two chapters (Anti-Lebanon and Taurus-Zagros), without specifying whether they constitute aquifers or aquifer systems. These chapters follow a different structure, with a description of the overall hydrogeological framework conditions and the main aquifer formations. Where applicable, more detailed information is provided on individual, smaller groundwater basins.

Research for the Inventory also revealed that among the hundreds of wadis in the region some extend beyond political borders and are situated above an aquiferous formation or formations. These shared alluvial aquifers are a source of freshwater at shallow depth and replenish the underlying shared aquifer system. A brief description of the main shared alluvial aquifers is featured in box texts that are included in relevant chapters, as is the case for Wadi Najran in Chapter 11.

4. Approximating aquifer system boundaries

This step served to refine the delineation of each section of the shared aquifers and aquifer systems where necessary. In principle, it would have been preferable to delineate aquifers and aquifer systems on the basis of groundwater flow systems. However, the lack of available data and issues of scale meant that this was not always feasible. As regional groundwater divides were not available in many cases, groundwater flow information was used to approximate aquifer system boundaries.

Boundaries of hydrological basins that had been delineated in previous studies on the basis of surface water drainage were taken into account. However, the Inventory went beyond these boundaries in order to describe the aquifer system(s) that normally extend outside the basin. Structural features such as faults, graben structures, anticlines or synclines, which usually control groundwater flow, were then used to approximate groundwater boundaries where possible. In such cases, the main title of relevant chapters reflects the names of the aquifer system formations; the previous basin name (e.g. Wadi Sirhan Basin) still features as a subtitle.

If there was no previous basin name and the aquifer system is divided into different sections for the purpose of the Inventory, the main title reflects the names of the aquifer system formations and the subtitle refers to the geographical location name(s) of the sections (e.g. Sakaka-Rutba).

These approximations should be understood as a basis for further discussion rather than an absolute delineation. All area figures provided in fact sheets and chapter texts refer to this approximated delineation, except where otherwise specified.

5. Description of shared aquifer systems
During this final step, each of the shared aquifer systems, sections or basins was characterized with respect to hydrogeology, groundwater use, agreements and cooperation and each aspect was described within a standardized chapter template. Suitability for groundwater development, which is referred to as "exploitability" in the Inventory (see 'Key Parameters' below), was also analysed. The results of this analysis were used to further refine the section and/or basin delineation by excluding non-exploitable parts of the aquifer.

The Inventory team had intended to classify the aquifer systems featured in the Inventory, given that no such classification currently exists for the Western Asia region. There are a number of ways of classifying aquifers and aquifer systems using information on geological/geotectonic setting, lithology, age, importance based on total exploitable volume, importance based on population dependent on the resource or a combination of categories.[9] However, as the Inventory is descriptive and not evaluative, and as information on shared groundwater units in the region was limited, no such classification has been made. Moreover, due to the lack of data some shared aquifer systems in the region have not been covered in individual chapters (see below).

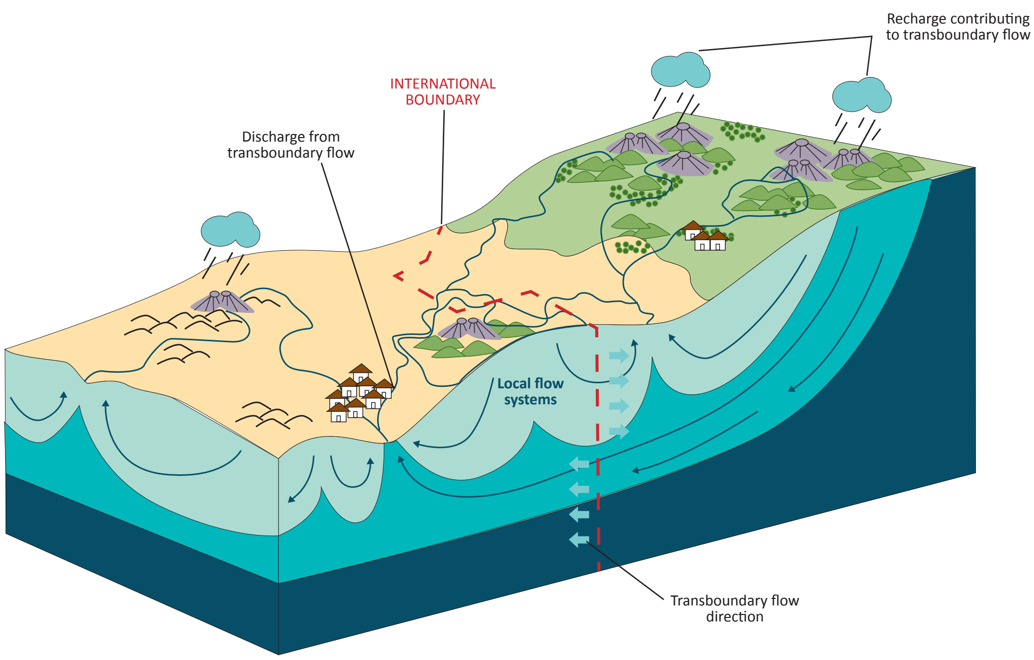
NOMENCLATURE

As shared aquifer systems in Western Asia have not been systematically delineated before, the systems do not have established names. Commonly used nomenclature could include locally known geological/geographical names, age and lithology. The nomenclature used in the Inventory is based on geological, hydrogeological and geographical information and aims to be descriptive. The name of most aquifer systems is based on the local name that riparian countries use to designate the main water-bearing formations based on lithology and age. The 'Basin Facts' table at the beginning of each chapter lists alternative names, which may also be based on lithology and/or age. Extensive aquifer systems that are divided into different sections or basins are generally designated through geographical names for the purpose of this Inventory. For instance, the Umm er Radhuma-Dammam Aquifer System (South) is situated in the Rub' al Khali Desert, which is an integrated part of Saudi Arabia and extends to Oman, UAE, and Yemen; however, reference to Rub' al Khali is meant to specify the geographical area where this section of the aquifer system is situated, but does not serve as an alternative name for the aquifer system itself.

In most cases, the nomenclature is determined as follows: Local name of the formation/age/lithology (Location): Geographic references.

However, some of the smaller aquifer systems are not divided into basins or sections and have the same name in all riparian countries.

Figure 1. Schematic diagram of a shared aquifer and its flow directions



Source: Redrawn by ESCWA-BGR based on Puri and Arnold, 2002.

Overview of Shared Aquifer Systems

The Inventory identifies 22 aquifer systems of which 17 are covered in separate chapters. These aquifer systems are located across the three Western Asia sub-regions: the Arabian Peninsula, the Mashrek and Mesopotamia (including Taurus-Zagros). Box 3 describes the regional geology of these areas. Table 1 lists the region's shared aquifer systems according to geological age: the Paleozoic, Mesozoic and Cenozoic eras.

Table 1. **Shared aquifer systems in Western Asia based on geological age**

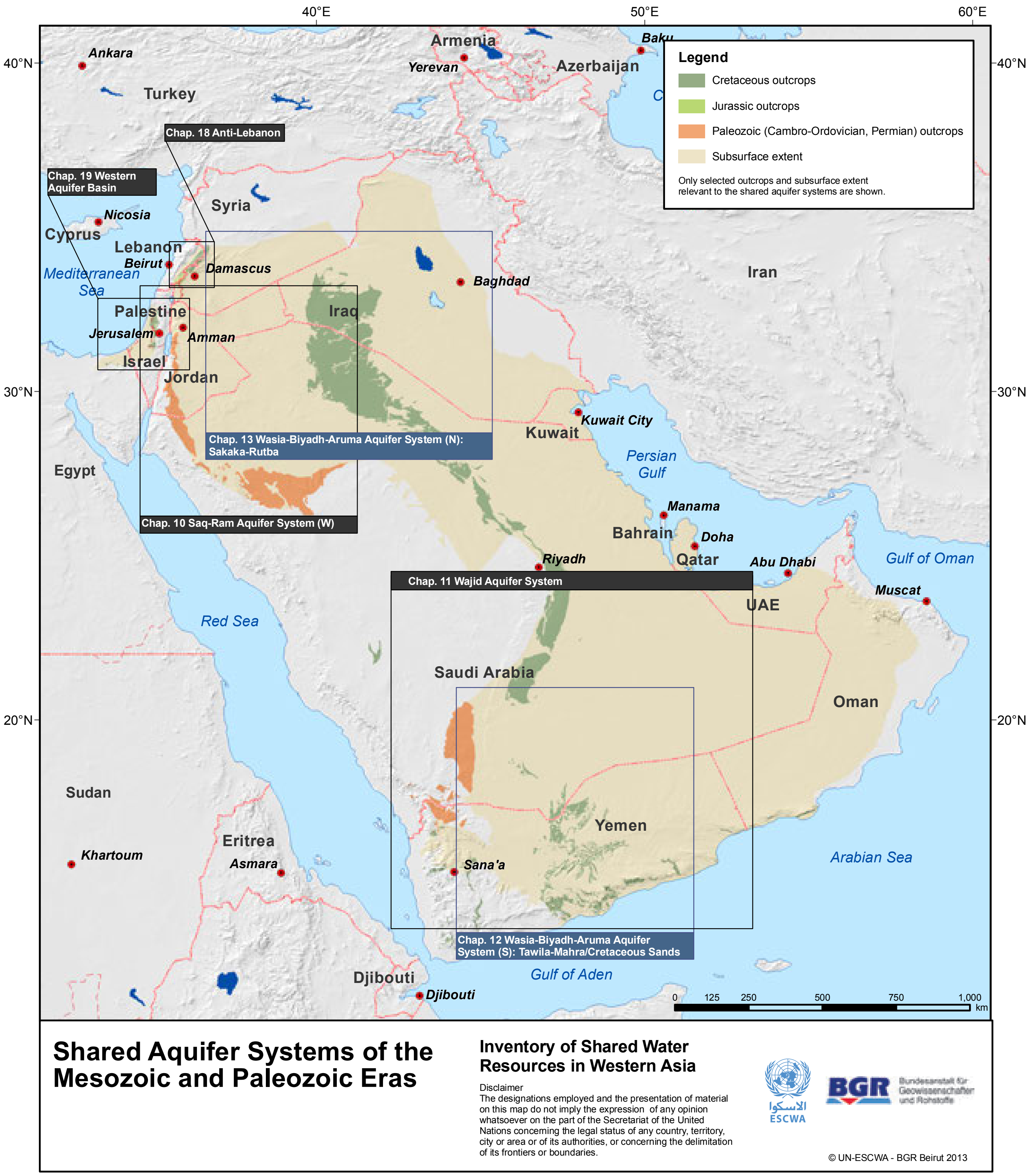
ERA	SHARED AQUIFER SYSTEM	CHAPTER	RIPARIAN COUNTRIES	ROCK TYPE	
Cenozoic	Umm er Radhuma-Dammam Aquifer System (North): Widyan-Salman	16	Iraq, Kuwait, Saudi Arabia	Fractured/karstic	Non-Renewable
	Umm er Radhuma-Dammam Aquifer System (Centre): Gulf	15	Bahrain, Qatar, Saudi Arabia	Fractured/karstic	
	Umm er Radhuma-Dammam Aquifer System (South): Rub' al Khali	14	Oman, Saudi Arabia, United Arab Emirates, Yemen	Fractured/karstic	
	Neogene Aquifer System (South-East), Dibdibba-Kuwait Group: Dibdibba Delta Basin	26	Iraq, Kuwait, Saudi Arabia	Fractured/karstic	
	Neogene Aquifer System (North-West), Upper and Lower Fars: Jezira Basin	25	Iraq, Syria	Mixed	Renewable
	Tawil-Quaternary Aquifer System: Wadi Sirhan Basin	17	Jordan, Saudi Arabia	Porous	
	Central Hammad Basin[a]	-	Jordan, Syria	Fractured/karstic	
	Basalt Aquifer System (South): Azraq-Dhuleil Basin	22	Jordan, Syria	Mixed	
	Basalt Aquifer System (West): Yarmouk Basin	21	Jordan, Syria	Mixed	
	Coastal Aquifer Basin	20	Egypt, Israel, Palestine	Porous	
	Eastern Aquifer Basin[a]	-	Israel, Palestine	Fractured/karstic	
	North-Eastern Aquifer Basin[a]	-	Israel, Palestine	Fractured/karstic	
	Jezira Tertiary Limestone Aquifer System	24	Syria, Turkey	Fractured/karstic	
	Western Galilee Basin[a]	-	Israel, Lebanon	Fractured/karstic	
	Taurus-Zagros[b]	23	Iran, Iraq, Turkey	Fractured/karstic	
Mesozoic	Anti-Lebanon[b]	18	Lebanon, Syria	Fractured/karstic	
	Western Aquifer Basin	19	Egypt, Israel, Palestine	Fractured/karstic	
	Wasia-Biyadh-Aruma Aquifer System (North): Sakaka-Rutba	13	Iraq, Saudi Arabia	Porous	Non-Renewable
	Wasia-Biyadh-Aruma Aquifer System (South): Tawila-Mahra/Cretaceous Sands	12	Saudi Arabia, Yemen	Porous	
	Ga'ara Aquifer System[a]	-	Iraq, Jordan, Saudi Arabia, Syria	Mixed	
Paleozoic	Saq-Ram Aquifer System (West)	10	Jordan, Saudi Arabia	Porous	
	Wajid Aquifer System	11	Saudi Arabia, Yemen	Porous	

Source: Compiled by ESCWA-BGR.
(a) These aquifer systems are not covered in stand-alone chapters.
(b) Aquifers in faulted and folded tectonic areas have been classified as one group. However, in practice they may represent more than one aquifer system.

PALEOZOIC AQUIFER SYSTEMS

Paleozoic aquifer systems are sandstone aquifers with very low to low renewability that only occur in the Arabian Peninsula (Map 1). The Saq-Ram Aquifer System (West), which is shared by Jordan and Saudi Arabia, is known as Ram, Rum, Disi or Disi-Mudawwara in Jordan and Saq or Saq-Tabuk in Saudi Arabia. It consists of several formations of Cambro-Ordovician age (see Chap. 10). The deposition of the formation comprising the Wajid Aquifer System (see Chap. 11), which is located in Saudi Arabia and Yemen, occured from the Cambro-Ordovician to the

Map 1. Overview Map of Mesozoic and Paleozoic shared aquifer systems in Western Asia



Source: Compiled by ESCWA-BGR.

Permian age. As a result, only its lower part, known as the Dibsiyah Formation, is correlatable with the Saq-Ram Aquifer System (West).

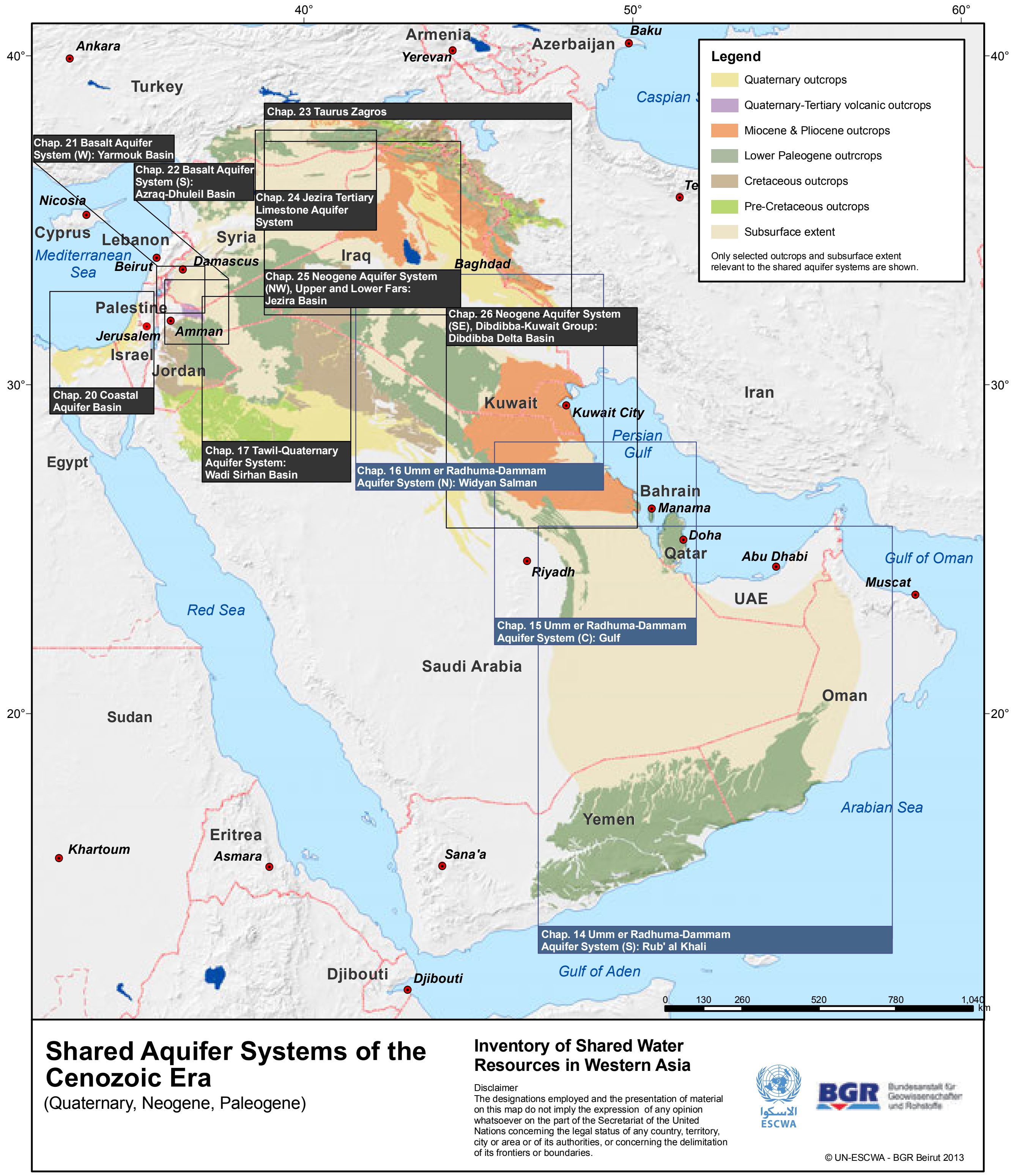
MESOZOIC AQUIFER SYSTEMS

Mesozoic aquifer systems are common throughout Western Asia (Map 1) and consist primarily of Cretaceous deposits.

In the Arabian Peninsula, the Wasia-Biyadh-Aruma Aquifer System consists mainly of sandstone and some carbonates with low renewability. It is divided into two shared sections:

In the north, the Sakaka-Rutba, shared by Iraq and Saudi Arabia and formed by the extension of the Wasia Formation (known as

Map 2. **Overview Map of Cenozoic shared aquifer systems in Western Asia**



Source: Compiled by ESCWA-BGR.

Sakaka) and the overlying Aruma Formation. The Biyadh Formation does not extend this far (see Chap. 13).

In the south, the Tawila-Mahra/Cretaceous Sands is shared by Saudi Arabia and Yemen. In this section, the Biyadh and Wasia Formations grade together with the Aruma Formation to form a thick sandstone unit known as the Cretaceous Sands in Saudi Arabia and Tawila-Mahra in Yemen, which correlate stratigraphically (see Chap. 12).

In the Mashrek, the dominant and most productive aquifers are the carbonate rocks ranging in age from Upper Cretaceous to Jurassic. They extend along the mountain chains and include the Anti-Lebanon, which is shared by Lebanon and Syria (see Chap. 18), and the Western Aquifer Basin, which stretches through parts of Egypt, Israel and Palestine (West Bank) (see Chap. 19).

The Taurus-Zagros (see also Map 2) is situated in Iran, Iraq and Turkey. It is made up of a limestone-dolomite sequence that covers large areas, mainly in the northern Taurus-Zagros Mountains. This group of aquifers also includes the Eocene-age Pila Spi Formation (see Chap. 23).

CENOZOIC AQUIFER SYSTEMS

Cenozoic aquifer systems are found across the region. They display significant differences in hydrogeological characteristics and geographical extent (Map 2).

As the most extensive aquifer system in the region, the Umm er Radhuma-Dammam extends across most of the length of the Arabian Peninsula. This system generally consists of three Paleogene (Paleocene-Eocene) carbonate formations: the Umm er Radhuma, the Rus and the Dammam. The Umm er Radhuma is the principal aquifer with the widest extent, while the Rus is the least important. The aquifer system is divided into three shared sections: the north-eastern section or Widyan-Salman (see Chap. 16) is shared by Iraq, Kuwait and Saudi Arabia; the eastern section or Gulf (see Chap. 15) is located in Bahrain, Qatar and Saudi Arabia; and the southern section or Rub' al Khali (see Chap. 14) extends across parts of Oman, Saudi Arabia, the United Arab Emirates and Yemen.

Another large aquifer system, composed of clastic Neogene formations, extends across most of the northern Arabian Platform. It is divided into two shared sections: the south-eastern section or Dibdibba Delta Basin (see Chap. 26) shared by Iraq, Kuwait and Saudi Arabia; and the north-western section or Jezira Basin[10] (see Chap. 25), which extends across parts of Iraq, Syria and Turkey and consists of Upper to Middle Miocene strata (gypsum, limestone and mudstone).

Other Cenozoic aquifer systems in the region are significantly smaller and/or highly complex. North-west of the three Umm er Radhuma-Dammam sections, the Paleogene deposits extend to the Hammad Plateau area where they are hydraulically connected with unconsolidated Neogene-Quaternary deposits or underlie

The Qandil Mountains, Iraq, 2010. Source: Stefan Jürgensen.

these deposits at greater depth. This is the case of the Tawil-Quaternary Aquifer System (see Chap. 17), which is shared by Jordan and Saudi Arabia. The Eocene- to Holocene-age clastic formations of the Coastal Aquifer Basin (see Chap. 20) are situated along the Mediterranean coast. This basin is shared by Egypt, Israel and Palestine (Gaza Strip). The Jezira Tertiary Limestone Aquifer System (see Chap. 24) that is situated in Syria and Turkey is of Middle Miocene age. Located in parts of Jordan and Syria, the Basalt Aquifer Systems in the Azraq-Dhuleil and Yarmouk Basins (see Chap. 21, 22) are completely different. They consist of complex volcanic sequences of Neogene-Quaternary age and older sedimentary formations (carbonates) of Upper Cretaceous age.

AQUIFER SYSTEMS NOT COVERED IN INDIVIDUAL BASIN CHAPTERS

A number of shared aquifer systems in the region have not been covered as stand-alone chapters in the Inventory for the following reasons:

(a) Insufficient data made it impossible to describe potentially shared aquifer systems (e.g. in the area between the city of Aleppo in Syria and Turkey), and certain transboundary linkages may not yet have been discovered.

(b) The scale of the Inventory was too large to allow for the description of local aquifer systems (e.g. the Western Galilee Basin and the North-Eastern Aquifer Basin) or aquifer systems that are only shared to a minor extent by some riparian countries (e.g. the Eastern Aquifer Basin)

(c) Certain larger aquifer systems change facies and are no longer considered aquifers (e.g Ga'ara Aquifer System)

(d) The system is not based on hydrogeological boundaries but on geographical basins including a number of different flow systems (e.g. Central Hammad Basin).

Table 2 lists the lithology and location of aquifers/aquifer systems/basins that have not been covered in individual basin chapters in the Inventory.

Table 2. Lithology and location of shared aquifers not covered in individual basin chapters

NAME	LITHOLOGY	RIPARIAN COUNTRIES
Central Hammad Basin	Basalt, carbonates and marl	Jordan, Syria
Eastern Aquifer Basin	Limestone	Israel, Palestine
Ga'ara Aquifer System	Sandstones/ carbonates	Iraq, Jordan, Saudi Arabia, Syria
North-Eastern Aquifer Basin	Predominantly limestone	Israel, Palestine
Western Galilee Basin	Limestone and dolomite	Israel, Lebanon

Source: Compiled by ESCWA-BGR.

Information in the Basin/Aquifer System Chapters

The Inventory identifies and characterizes shared aquifer systems in Western Asia, describing basic hydrogeology and groundwater use, environmental aspects, as well as agreements and cooperation projects between riparian countries. Each groundwater basin chapter follows the standard structure outlined in Table 3 and provides information on all relevant keywords, to the extent possible. As applied in the methodology, the information on hydrogeology is covered in two sub-headings, the first focusing on the characteristics of the rock bearing the water, and the second examining the status and dynamics of the groundwater.

Table 3. Chapter structure

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) and 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 of use, abstraction volumes), Groundwater quality issues (return flows, salinization, pollution), Sustainability issues (trends, over-abstraction).
Agreements, Cooperation & Outlook	Agreements (treaties, Memoranda of Understanding, ongoing negotiations), Cooperation (timeline, form, mechanism, issues of conflict), Outlook (main management issues, opportunities).

Source: Compiled by ESCWA-BGR.

KEY PARAMETERS

This section provides further detail on some of the parameters used to characterize aquifer formations, groundwater resources and groundwater use in the groundwater chapters.

Recharge and renewability

Renewability describes the rate of replenishment of the aquifer system through present-day recharge water. Present-day groundwater recharge is primarily dependent on the volume and timing of precipitation. Very limited recharge occurs if precipitation is below 75 mm/yr; direct recharge takes place when precipitation exceeds 350 mm/yr[11] (see 'Overview: Shared Water Resources in Western Asia', Figure 3). Indirect recharge through wadi beds is therefore often more important than direct recharge through soil infiltration in arid regions. While direct quantification of recharge is often hindered by a lack of hydrological and meteorological field data, indirect methods like isotopic signature, groundwater dating and sometimes chloride mass balance[12] in the groundwater can provide an insight into present recharge rates. In general, recharge via infiltration can only occur in the unconfined part of the aquifer system, while the confined part can only receive inflow through vertical or horizontal leakage.
For the purpose of the Inventory, renewability is categorized according to the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP)[13] into very low (0-2 mm/yr), low (2-20 mm/yr), medium (20-100 mm/yr) and high (>100 mm/yr). The Western Asia region is predominantly subjected to very low/low recharge rates of 0-20 mm/yr, though medium recharge does occur in mountainous areas such as the Taurus-Zagros and Anti Lebanon Mountain ranges.[14] Regardless of how they are used, aquifers that receive only limited recharge are vulnerable to groundwater mining.

Rock type

Rock type describes the aquiferous formations in terms of their water-bearing openings (i.e. primary voids vs. secondary fissures). All rock types exist in Western Asia:

Porous aquifer systems are dominated by primary voids (pores).They are mainly sandstones and alluvial sediments along river or wadi channels and in the foothill areas of the Arabian Peninsula.

Fissured/karstic aquifer systems are dominated by fractures and karstic features, resulting in high flow anisotropy. These are mainly carbonate rocks occurring in the eastern part of the Arabian Peninsula and in mountainous areas in the Mashrek and Taurus-Zagros regions.

Mixed pore/fissure aquifer systems contain mixed pores and fissures. Different types of rocks occur in relatively unstable areas in which sedimentation is interrupted by magmatic activities and/or volcanic events, mainly in the northern part of the region.

Table 1 above provides information on the rock types found in each of the identified shared aquifers and aquifer systems.

Aquifer type

The aquifer type indicates whether an aquifer that forms part of an aquifer system is unconfined, confined or semi-confined. In general, larger aquifer systems exhibit unconfined conditions at and around the outcrop areas and become more confined as the depth of the aquifer increases. Shallow aquifers are commonly unconfined and deep aquifers are confined. Unconfined aquifers have high storativity[15] as they release the stored water by draining the voids. The resulting drop in the water table is limited to a localized area. By contrast, confined aquifers have a low storativity and release water stored through matrix expansion and water compressibility. Hence, a change in piezometric head can be transmitted over a much larger distance, as it does not involve the physical movement of water molecules but is only a transmission of pressure. This is also relevant in the context of shared water management as the impact of abstraction in one country is potentially much greater in confined aquifers than in unconfined settings.

Exploitability

Exploitability is used to assess whether groundwater stored in an aquifer system is viable for use, based on water quality, technical feasibility and economic viability.

The presence of groundwater in an aquifer system does not necessarily imply that it can be readily abstracted and used. Economic viability and technical feasibility determine whether or not these resources are exploitable. Moreover, resources that are exploitable now may not be exploitable in the future if water tables continue to decline and groundwater quality deteriorates as a result.

Three parameters were used to determine the exploitability of aquifer systems in Western Asia: depth to top of aquifer, depth to water level[16] and water quality. The parameters were used as criteria to delineate exploitable areas within the identified aquifer systems, as explained below.

Depth to top of aquifer: Researchers who have worked in the region have applied a maximum depth to top of aquifer of 2,000 m.[17] The Inventory has adopted the same criterion and applied it to the upper formation of the geological units that constitute an aquifer system. The Middle East Geological Map Series (MEG maps) were used to determine the depth to the top of these formations.[18] For formations not covered in the MEG maps (Neogene and Paleogene), the top of the underlying Cretaceous formations is considered the lowest level at which they can be tapped. For example, if the top of the Cretaceous is less than 2,000 m bgl, then the exploitation of any younger aquifer overlying the Cretaceous is not considered limited by drilling depth.

Depth to water level: Some regional studies apply a maximum depth to water level of 250-300 m.[19] The Inventory sets the limit at 250 m, using the most recent data available from official sources wherever possible.

Water quality: Groundwater with a salinity of less than 2,000 mg/L TDS is usually desirable for exploitability. However, this type of water is rare in large parts of the region, particularly in the extensive shared aquifer systems of the Arabian Peninsula. Moreover, as the water is used in combination with desalination or to grow highly salt-tolerant crops such as date palms, brackish groundwater is also considered an exploitable resource. Hence, the Inventory applies a salinity level of 10,000 mg/L TDS as a limiting factor for the exploitability of aquifer systems.

In addition to the three parameters mentioned above, transmissivity[20] has been used in two cases (Umm er Radhuma-Dammam Aquifer System south and central sections) where the Umm er Radhuma Formation is discontinuous and/or unsaturated and can therefore not sustain production of economically viable water through well extraction.

Unfortunately, in many cases the information required to assess exploitability does not cover the whole aquifer system. Therefore, any reference to the extent and volume of the exploitable resource should be considered as an estimate.

Groundwater abstraction and use

Little is published on groundwater abstraction in the study region. In most Western Asia countries, groundwater abstraction is not measured and governmental data sets are usually approximations based on remote sensing, groundwater modelling studies and/or extrapolations from surveys. Official data on groundwater abstraction was only sporadically made available for the Inventory. Given that agriculture is by far the largest water consumer in the region, official agricultural statistics were sometimes used to provide historical context and highlight trends and the scale of irrigation and groundwater development. In arid desert areas in particular, there is a direct link between groundwater abstraction and agricultural development, as in the Tabuk, Al Jawf or Wajid areas in Saudi Arabia, where agricultural areas can easily be identified and rely entirely on groundwater irrigation due to the low annual precipitation rates. However, as agricultural statistics are usually based on administrative units, they could not always be precisely matched with the extent of agricultural areas within the identified aquifer systems. In this case, agricultural data only shows an overall trend for the administrative unit.

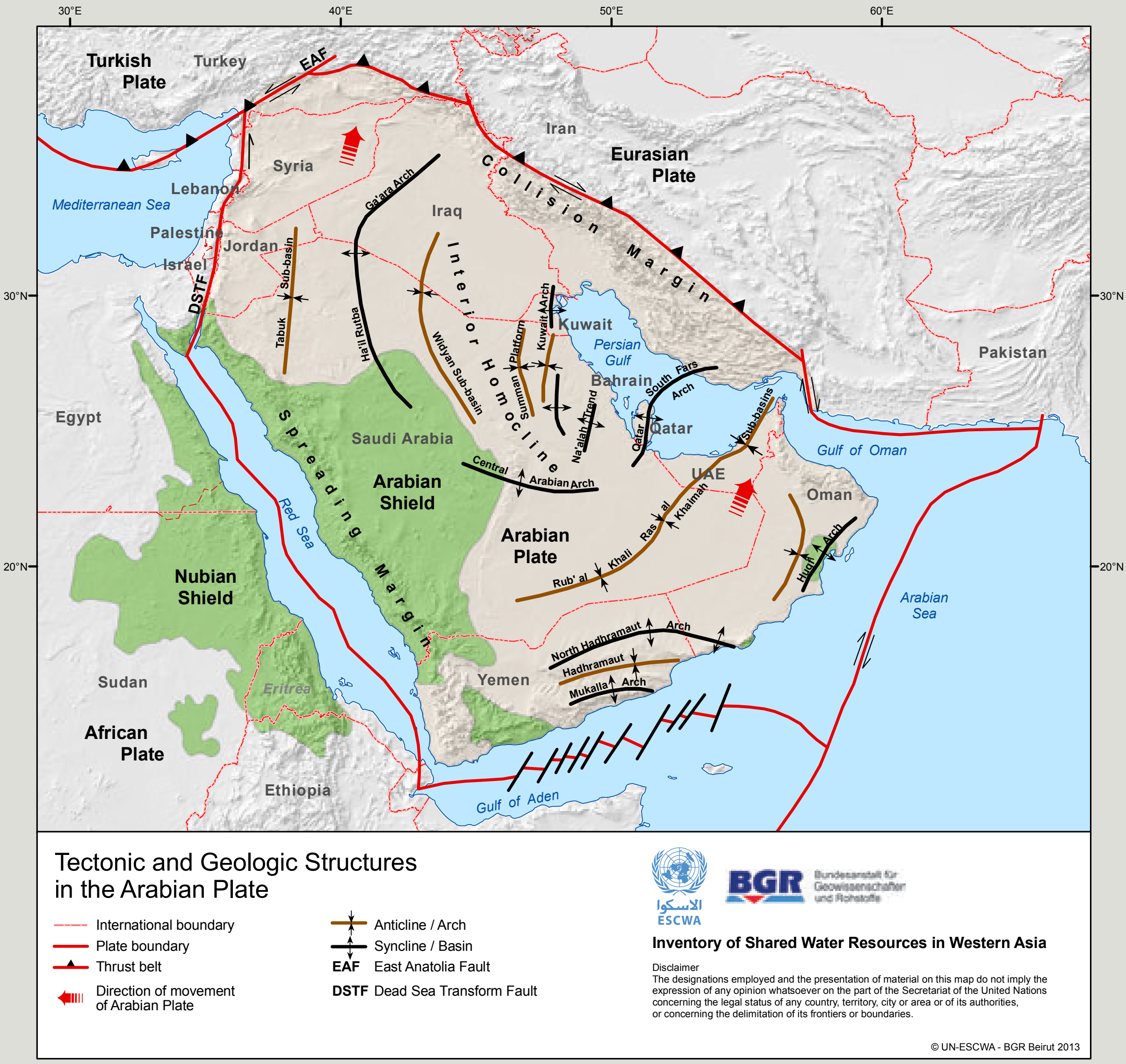
The most relevant agricultural parameters used in the Inventory are total crop area (which is practically equivalent to irrigated areas in dry areas) and yields and/or area of individual crops and/or crop groups (i.e. perennial and seasonal; cereals, fruits and vegetables).

BOX 3

Geological Setting

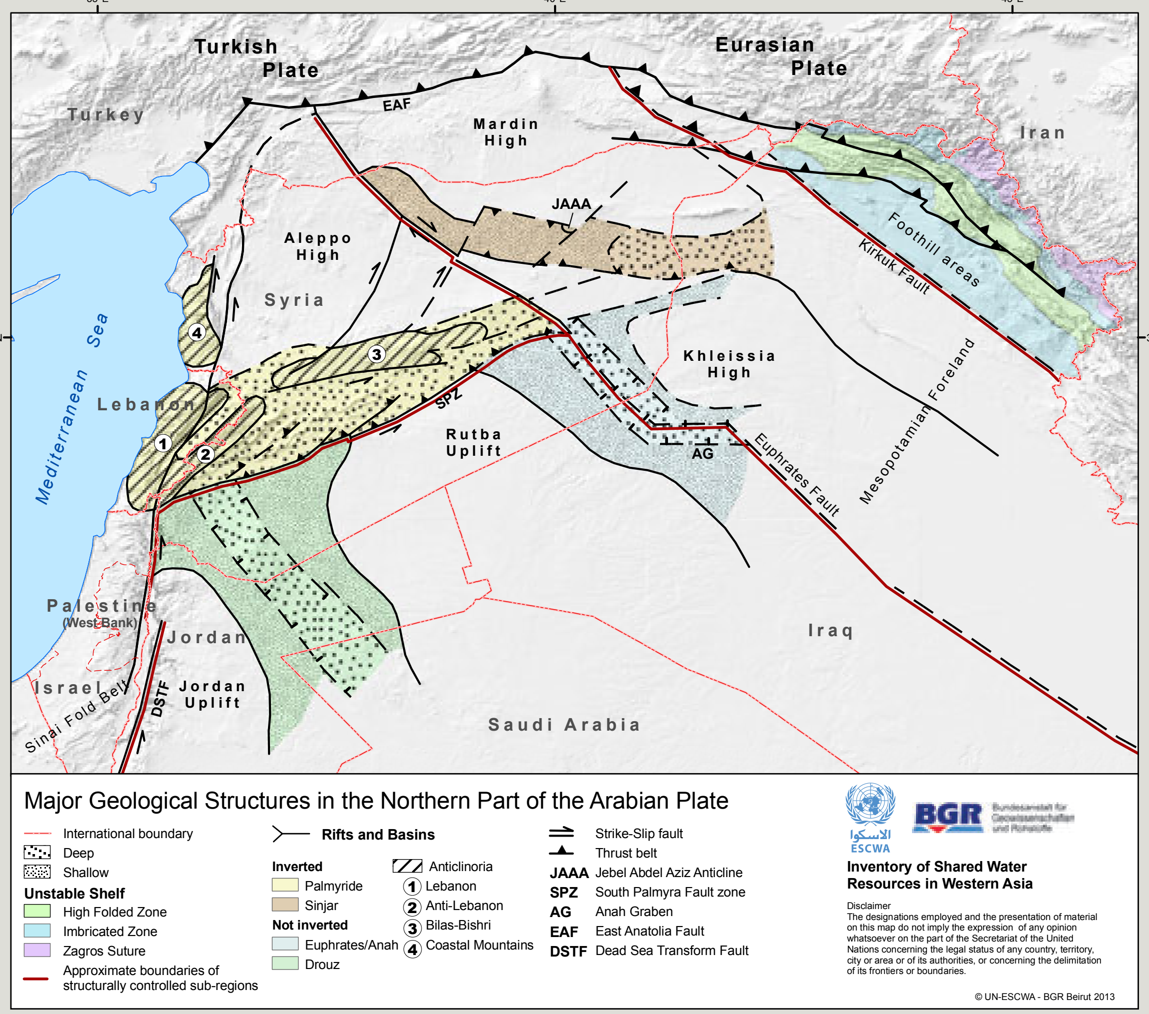
Geologically, the Western Asia region extends across the Arabian Plate, which has been moving incrementally from the African Plate to the north and north-east, where it collides with the Turkish and Eurasian Plates (Figure 2). This collision along the northern boundaries of the plate has led to the development of different tectonic zones and geological structures.

Figure 2. Tectonic and geologic structures in the Arabian Plate



Source: Compiled by ESCWA-BGR based on Edgell, 2006; Vincent, 2008.

Figure 3. Major geological structures in the northern part of the Arabian Plate



Source: Compiled by ESCWA-BGR based on Kazmin, 2002.

The southern boundaries of the Arabian Plate are passive margins, while the northern boundaries are active margins with lateral movements[21] and/or compression forces[22] (Figure 3). As a result, the sedimentation of thick deposits in the northern part was interrupted and the deposits were folded, compressed, metamorphosed, subsided, uplifted, laterally displaced and/or inverted in three main tectonic phases (Late Carboniferous-Early Triassic, Late Permian-Early Cretaceous and Paleogene).[23] The region is now dominated by rift-related structures like troughs and grabens, as well as high folded mountains[24] and tectonic forces (e.g. strike-slip transformations) which are still active today.

In addition to these geological and structural factors, the northern areas are influenced by the Siberian Anticyclone/Mediterranean regime and receive significantly higher precipitation than the southern areas. Based on this, four main sub-regions can be distinguished:

a) The **Arabian Peninsula**, which extends from the Palmyride Mountains in the north to the Indian Ocean in the south and from the Jordan Uplift in the west to the Rutba High in the east. The peninsula has been tectonically reasonably stable since the Pre-Cambrian era[25] and the Arabian Shelf in the eastern part provided the depositional basin (thickness: ≤7,500 m) for extensive sedimentary strata (continental and marine deposits, punctuated by evaporitic events) from the Paleozoic to the Neogene eras. Since they form large regional aquifer systems,[26] these sediments were only subjected to minor folding and faulting along extensive anticlines and arches, and the lithological character is maintained over large areas. The Arabian Shield (Pre-Cambrian Rocks, Basement) that covers the western part of the Arabian Peninsula has seen some uplifting.[27] It is characterized by local fissured aquifers that do not provide extensive flow into neighbouring countries. Hence, it is not covered in the Inventory. Chapters 10 to 17 cover the shared aquifer systems in the Arabian Peninsula.

b) The **Mashrek** extends west of the Dead Sea Rift and the South Palmyra Fault zone to the Mediterranean Sea, incorporating Israel, Lebanon, Palestine, the Sinai Peninsula, large parts of Syria and small parts of southern Turkey. The mountainous areas are characterized by high precipitation falling on extremely well-exposed and highly karstified carbonate rocks of Early Jurassic to Late Cenozoic era (e.g. Anti-Lebanon). Many of these fissured and complex aquifers supply springs that sustain important river systems. The low-lying coastal areas, on the other hand, are more arid and are characterized by Cenozoic porous aquifer systems. Chapters 18 to 22 address the shared aquifer systems in the Mashrek.

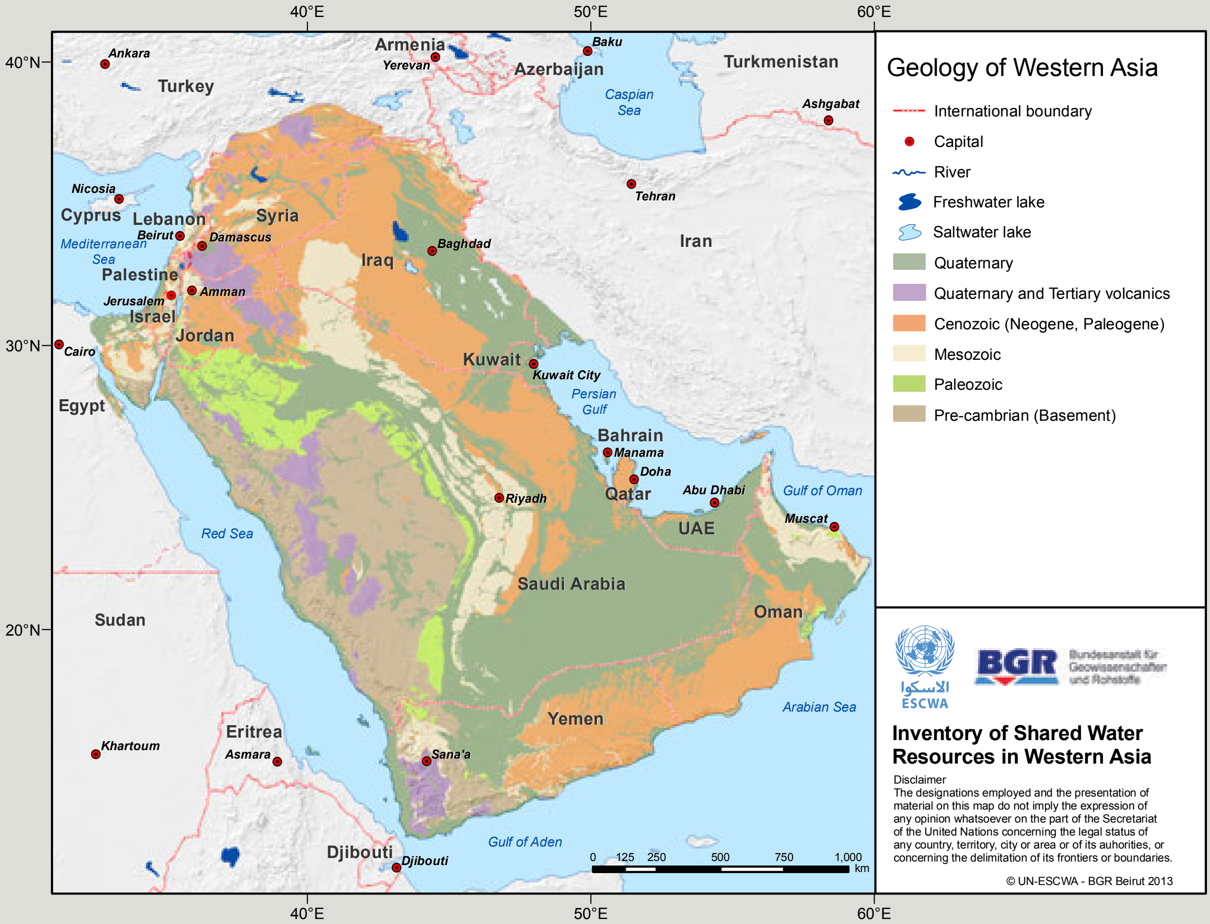
c) The **Mesopotamian Plain** is bounded by two major faults, the Euphrates Boundary Fault and the Kirkuk Fault (Figure 3). It has formed a depositional basin since the Neogene time. The basin extends across Iraq into Syria and Turkey and is characterized by Cenozoic clastic sedimentary aquifer systems. The shared aquifer systems in Mesopotamia are discussed in Chapters 24 to 26.

d) The **Taurus-Zagros** extends north-east of the Kirkuk Fault from Iran through Iraq into Turkey. This highly folded and faulted region features elevated areas made up of karstified Tertiary and older carbonates with many springs discharging good-quality water, and younger clastics that form isolated to semi-isolated aquifer systems (Chap. 23).

In conclusion, tectonic forces and structural settings have created significant differences in the geological and hydrogeological features of the main part of the plate (Arabian Peninsula) and the northern part.

Figure 4 shows that the western part the Arabian Plate, which is tectonically more stable, exposes Pre-Cambrian-age rocks, whereas the geological formations in the eastern part are younger. The youngest sediments, including volcanic outcrops, are exposed in the northern part of the Arabian Platform, in the highly faulted and tectonically active area.

Figure 4. Geological map of the Arabian Plate



Source: Compiled by ESCWA-BGR based on USGS, 2004.

Notes

1. The terms "transboundary" and "shared" are used interchangeably in the Inventory. See 'Overview: Introduction to the Inventory', Box 1 for more information.
2. Only shared aquifer systems on the Arabian Plate (i.e. the western part of Western Asia) feature in the Inventory; those on the African Plate are not addressed. See 'Overview: Shared Water Resources in Western Asia' for more information.
3. This resolution is based on the draft articles of the law of transboundary aquifers prepared by the International Law Commission (United Nations General Assembly, 2008).
4. An aquifer system may include aquitards and confining beds (UNESCO, 1978).
5. Direct transboundary impacts may involve measurable physical flow of water or the propagation of groundwater pressure changes across boundaries as well as the induction of water quality changes through spreading of pollutants via mass flow or diffusion, or other chemical alterations such as upconing of saltwater, seawater intrusion etc.
6. Initial data collection was based on existing regional compilations including ACSAD, 1983; Khoury and Droubi, 1990; UN-ESCWA, 1990; UN-ESCWA and BGR, 1999 and Alsharhan et al. 2001.
7. Previous investigations (e.g. ACSAD-UNESCO, 1988) have used the geographical extent of specific geological formations to delineate aquifers across the Western Asia region.
8. Ministry of Agriculture and Water in Saudi Arabia, 1984; ACSAD and UNESCO, 1988; Van der Gun and Ahmed, 1995; Edgell, 1997; Jassim and Goff, 2006 among others.
9. Van der Gun, 2008 describes a hierarchical system (region – province – aquifer/aquifer system) that is considered useful for collecting information on global groundwater regions.
10. Also known as Fatha-Injana Aquifer System.
11. Lloyd, 1997.
12. Allison et al., 1994.
13. Struckmeier and Richts, 2008.
14. In most cases, recharge estimates in mm/yr were not available. Instead, estimates were based on models for individual sub-areas and estimates from isotope studies, among others. Category designations were therefore somewhat arbitrary.
15. Storativity or the storage coefficient is a physical property that characterizes the capacity of an aquifer to release groundwater. It is defined as the volume of water released per unit change of hydraulic (pressure) head. Storativity is a dimensionless quantity, and ranges between 0 and the effective porosity of the aquifer. In confined aquifers, storativity is usually much less than 0.01. There are various other related parameters to characterize aquifer storage properties, such as specific storage, specific yield or specific capacity (Freeze and Cherry, 1979).
16. E.g. Abunayyan Trading Corporation and BRGM, 2008.
17. Ibid.
18. Christian, 2000.
19. E.g. Abunayyan Trading Corporation and BRGM, 2008.
20. The rate at which groundwater flows through an aquifer and is dependent on the hydraulic conductivity and the saturated thickness of the aquifer.
21. Brew et al., 1999.
22. Jassim and Goff, 2006.
23. Ibid.
24. Ibid.
25. Powers et al., 1966.
26. Alsharhan et al., 2001.
27. Ibid.

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