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Groundwater Resources Management in Jordan

Groundwater Resources Assessment of the A7/B2 Aquifer in Northern Jordan for 2022

Technical Report

Amman, June 2024

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Acknowledgments

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Abbreviations

Abbreviation	Meaning
A7/B2	Hydrostratigraphic aquifer unit of the Upper Cretaceous
a.s.l.	Above Mean Sea Level (here referring to ellipsoidal height within EGM96)
B3	Hydrostratigraphic aquitard unit of the Upper Cretaceous
b.g.l.	Below Ground Level
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BWF	Basalt Wellfield
DWL	Dynamic Water Level (pumping water level in a well)
EC	Electric Conductivity
Fm.	Formation (Stratigraphic Unit)
GWRM	Groundwater Resources Management Project
GW	Groundwater
h	Hour
km^2	Square Kilometers
MCM	Million Cubic Meters
MWI	Ministry of Water and Irrigation of the Hashemite Kingdom of Jordan
NWS	National Water Strategy
m^3	Cubic Meter
mm	Millimeter
PBE	Palestine Belt East (Coordinates)
PBN	Palestine Belt North (Coordinates)
SWL	Static Water Level
WAJ	Water Authority of Jordan

1 Introduction

Groundwater is the main source for the water supply in the Hashemite Kingdom of Jordan. Extraction from groundwater contributes to about 57 % of the gross annual water use of approximately 1,100 million cubic meter (MCM) for domestic, industrial and agricultural supply. Just regarding the domestic water use, groundwater even makes up more than 70 % of the total amount (MWI, 2023).

The National Water Strategy (NWS) 2023 – 2040 names the sustainable management of groundwater resources and the restoration of safe yields to protect the resources in the aquifers as a major concern. This is defined as Goal 1 under the strategy for the Intergrated Water Resources Management (IWRM) and Environmental Protection (see textbox).

In order to define safe yields for the extraction from the various aquifer systems, an up-to-date and detailed knowledge about the status of the groundwater resources is necessary. The effective management of groundwater resource requires a reliable database to enable fact-based decisions and it must be founded on the thorough and on-going investigation and monitoring of the aquifers. Above all, the water level (or better the hydraulic head) is the key parameter to be observed in a sufficient spatial and temporal resolution for the different groundwater bodies.

The most important groundwater body exploited in Jordan for water supply is the so-called A7/B2-aquifer. This report aims to provide updated information about the status of this aquifer.


Goal 1

Sustainably manage groundwater resources to restore safe yield levels and protect Jordan's aquifers.

Target

Annual abstraction reaches and sustains safe yield levels from 2035.

Key Objectives and Approaches

- Strengthen enforcement measures to reduce over-abstraction with reliable analysis of safe yield levels.
- Link wells licensing limits and the water budget to safe yield levels.
- Shift to groundwater conservation and aquifer recharge when desalination supplies are available.
- Minimize pollution risks to protect groundwater quality.

Figure 1: Definition of Goal 1 under the IWRM approach described in the NWS (MWI, 2023b).

The study was carried out within the German-Jordanian technical cooperation Groundwater Resources Management II (GWRM II, BGR No.: 05-2419, BMZ No.: 2020.2211.9) and in close collaboration with the Ministry of Water and Irrigation of the Hashemite Kingdom of Jordan (MWI).

1.1 Objectives and project framework

A comprehensive assessment of the groundwater resources of Jordan was conducted in 2017 by the German Federal Institute for Geosciences and Natural Resources (BGR) and the Ministry of Water and Irrigation (MWI) (MWI and BGR, 2019; *https://www.bgr.bund.de/EN/Themen/Wasser/Produkte/Downloads/gw_resource_assessment_jordan.html*). It included all major groundwater bodies within the main hydrogeological units throughout the country (except for the Jordan Valley). The corresponding groundwater maps illustrate the hydraulic heads at that time for the main aquifers as contour lines, as well as the depth to groundwater and the saturated thickness for each aquifer layer. Additionally, further detail on the status of the A7/B2 aquifer system was provided in a separate BGR report on the *"Groundwater Resources Assessment of the A7/B2 Aquifer in Jordan"* (Bahls et al. 2018).

Referring to the results from 2017, the report on hand gives an update on the groundwater situation within the A7/B2 aquifer five years later. In the winter season 2022/23, field data on well water levels was collected and used to update the groundwater maps for the northern part of Jordan (see chapter 2). The results are shown in the revised maps in the annex, which display the hydraulic head isolines, depth to groundwater and saturated thickness (see chapter 3 and annex). The extend of the newly revised maps is limited to the northern part of Jordan, roughly north of the line between Madaba and Azraq, as groundwater monitoring was only carried out in this region during the respective BGR project. Based on the maps, the current water level situation is discussed in this report and compared with the 2017 assessment (see chapter 3). Furthermore, recommendations for the improvement of groundwater data availability and quality will be given to support a development towards an effective management of the groundwater resources.

1.2 Brief overview of the hydrogeology of northern Jordan

The geological and hydrogeological inventory and structure of Jordan have been described in numerous reports and publications (e.g. Margane & Hobler 1994, 1995). The geological information in the following short overview is based on the work of Bender (1974), El-Naser (1991) and Margane et al. (2002). This report furthermore refers to the BGR Technical Report of Brückner (2018) on the Structure Contour Maps of the Ajloun and Belqa Groups, which provides the essential structural elevation data for the major rock units. The given description of the geology refers to the highlands of Northern Jordan; the Jordan Valley and the southern deserts are not included.

1.2.1 Geological overview and stratigraphy

The hydrogeologically and economically most important strata in Jordan (MWI 2005) are sedimentary rocks of marine origin, which consist mostly of limestones, dolomites and marls, intercalated with cherts and phosphorites. Lithostratigraphically, they are summarised in the Ajloun and Balqa groups of Upper Cretaceous to Paleogene age (see Figure 2 and Figure 3). The deeper sandstone aquifer system, known as Kurnub Group (Lower Cretaceous), is not discussed in this report.

The mostly calcareous, marine succession forms extensive, fractured hardrock aquifers that extend over large parts of the country (see Figure 3 and Annex 1). It may reach thicknesses of up to several thousand meters in areas which have been affected by synsedimentary tectonics and downfaulting (e.g. in the east around Azraq) but the thickness may vary quite significantly (Brueckner, 2018). Layers of lower permeability interrupt the aquifers, where the marls become more chalky and clayey, sometimes fading into mudrocks and shales. Those aquitards divide the succession into several groundwater layers of varying thickness.

Traditionally, the Ajloun and Balqa Group sequence has been hydrostratigraphically subdivided by numbering the succession of aquifers and aquitards (El-Naser, 1991), starting with layer A1 referring to the Naur Formation (Fm.) at the base of Ajloun Group (see Figure 2). This subdivision ends with B4/5 (Wadi Shallala Fm., Eocene) as the uppermost member of the marine succession. The most important and most extensive aquifer system within this scheme are the limestone layers referred to as A7, B1 and B2, reaching from the Wadi As Sir Fm. to the Amman Fm. and Al Hisa Phosphorites. They are mostly addressed in a comprehensive way as the A7/B2 aquifer.

In some regions, there are volcanic rocks and alluvial deposits of younger age which form groundwater-bearing layers overlying the marine, calcareous formations. Especially the basaltic rocks of Neogene and Quaternary age form vast sheets in the most north-easterly parts of Jordan, which can be locally important aquifers (e.g. around and north of Azraq). Their role is discussed, as far as necessary, in the presentation of the results in chapter 3.

1.2.2 The Amman to Wadi As-Sir Formations (A7/B2 Aquifer)

Detailed descriptions of the formations constituting the A7/B2 aquifer can be found in the references mentioned at the beginning of this chapter. The following account is taken from Bahls et al. (2018):

The uppermost member of the Ajloun Group and the lower members of the Belqa Group are considered as one hydrogeological unit, comprising from bottom to top, the Wadi As Sir Limestone Formation (A7), the Wadi Umm Ghudran Formation (B1) and the Amman Silicified Limestone and Al Hisa Phosphorite Formations (B2) from the Upper Cretaceous. Massive limestone, dolomitic limestone and dolomite with intercalated beds of sandy limestone, chalk, marl, gypsum, chert, and phosphorite are predominant in the A7/B2 unit. The A7 and B2 formations are characterised by a variable degree of karstification and are locally separated by a thin marly layer of the B1 formation.

The main outcrop areas of A7/B2 are located around the structural high of the Ajloun Dome [Figure 3 and Annex 1]. From here, it extends all the way south along the highland east of the Rift Valley. [...] The outcrop areas in the highlands are also the recharge areas with the highest amount of precipitation. The partly [...] karstification of the aquifer is supporting the recharge.

Based on the Update of Structure Contour Maps of the Ajloun and Belqa Groups (Brückner, 2018) the thickness distribution of the A7/B2 unit [Figure 5] varies from less than 100 meters to more than 1000 meters. [...] The highest thickness can be found in the block between the NW-SE striking Fuluk Fault, the W-E striking Siwaqa fault, the WSW-ENE striking Zarqa Main-Azraq fault. Immediately west of the Fuluk Fault, the Hamza Graben shows the highest thickness of A7/B2 with more than 2000 meters. South of the Siwaqa fault, the thickness is decreasing towards the south and the southeast to less than 100 meters. Also, east of the Fuluk fault, the thickness rapidly decreases from 250 to less than 100 meters, with only 40 meters in the Risha area. In the northwestern part of the country, around Irbid, the A7/B2 thickness trends to increase towards the north and the Rift Valley.

In general, the A7/B2 dips [away] from the outcrop areas in northerly to easterly directions and underlies the entire country area further to the east. Figure 4 shows the base of the A7/B2 unit. The deepest point of the base of the aquifer is [located] in the Hamza Graben, west of the Fuluk Fault, where the aquifer also has its highest thickness. Around Irbid and towards the Jordan Valley, the A7/B2 aquifer dips down sharply to more than 2000 m bgl [related to block tectonics and downfaulting of the Jordan graben].

In the highest elevations, the aquifer is unconfined but towards the east, where it is overlain by the B3 aquitard, groundwater occurs partially in confined conditions. In several wells of Wadi Al Arab wellfield, in the Yarmouk river area, artesian conditions occur (Margane et al., 2002). Due to the intense exploitation of the aquifer, the line of confinement is moving continuously further east. *[end of citation]*

ERA	SYSTEM	EPOCH	GROUP	FORMATION	LITHOLOGY	THICK-NESS	AQUIFER UNIT
CENOZOIC	QUATERNARY	Holocene	JORDAN VALLEY	Alluvium	clay, silt, sand, gravel		ALLUVIUM (AQUIFER) / BASALT (AQUIFER)
		Pleistocene		Lisan	marl, clay, evaporites	>300	
	NEOGENE	Pliocene, Miocene		Samra	conglomerates	100-350	
	PALEOGENE	Oligocene		Neogene	sand, gravel		
		Eocene	BALQA	Wadi Shallala	chalky and marly limestone with glauconite	0-550	B4/5 (AQUIFER)
				Umm Rijam	limestone, chalk, chert	0-310	
		Paleocene		Muwaqqar	chalky limestone, marl, shale, chert	80-320	B3 (AQUITARD)
MESOZOIC	CRETACEOUS – Upper	Maastrichtian					
		Campanian		Amman-Al Hisa	limestone, chert, chalk, phosphorite	20-140	A7/B2 (AQUIFER)
		Santonian		W. Umm Ghudran	dolomitic limestone, marl, chert, chalk	20-90	
		Coniacian	AJLUN	Wadi as Sir	dolomitic limestone, limestone, chert, marl	60-340	
		Turonian		Sheib	marl, limestone	40-120	A5/6 (AQUITARD)
		Cenomanian		Hummar	limestone, dolomite	30-100	A4 (AQUIFER)
				Fuheis	marl, limestone	30-90	A3 (AQUITARD)
				Naur	limestone, dolomite, marl	90-220	A1/A2 (AQUIFER)
	CRETACEOUS – Lower	Albian, Aptian, Barremian	KURNUB	Subeihi	sandstone, shale	120-350	KURNUB (AQUIFER)
		Hauterivian, Valanginian, Berriasian		Aarda	sandstone, shale		
	JURASSIC		ZARQA	Azab	siltstone, sandstone, limestone	0->600	ZARQA (AQUIFER)
	TRIASSIC			Ramtha	siltstone, sandstone, shale, limestone, anhydrite, halite	0->1250	
PALEOZOIC	PERMIAN			Hudayb	siltstone, sandstone, limestone	0->300	
	SILURIAN		KHREIM	Alna	siltstone, sandstone, shale	0->1000	KHREIM (AQUITARD)
				Batra	mudstone, siltstone	0->1600	
				Trebeel	sandstone	0-130	
	ORDOVICIAN			Sahl as Suwwan	mudstone, siltstone, sandstone	0-200	
			RAM	Amud	sandstone	0->1500	RAM SANDSTONE (AQUIFER)
	CAMBRIAN			Ajram	sandstone	0-500	
				Burj	siltstone, dolomite, limestone, sandstone	~120	
				Salib	arkosic sandstone, conglomerate	0->750	
PRECAMBRIAN				Saramuj & Aqaba	Several clastic units above igneous rocks	0-1500	BASEMENT

Figure 2: Stratigraphic chart for Jordan with hydrostratigraphic classification. (from Bahls et al. 2018 after Margane et al. 2002 and El-Naser 1991)

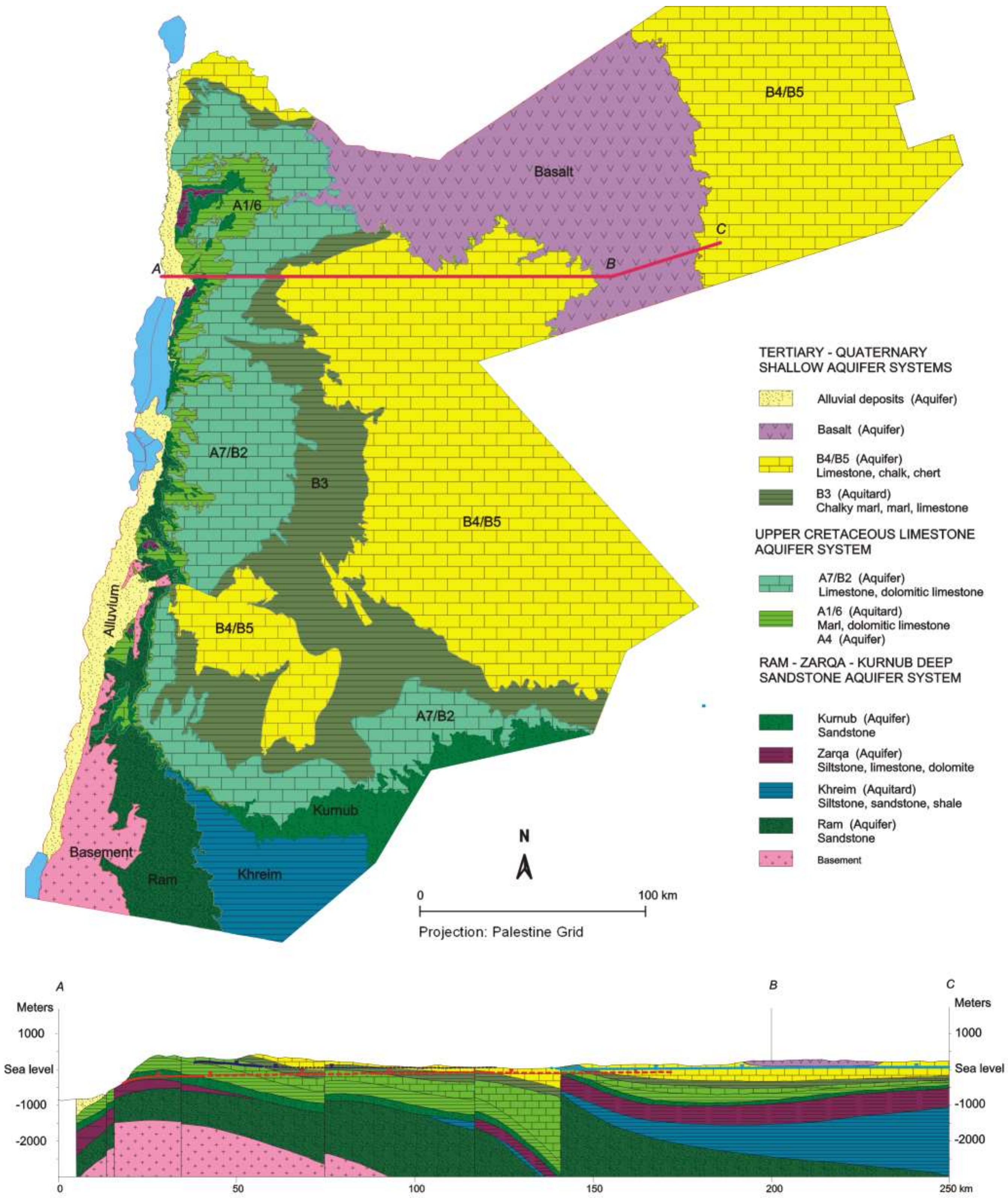

Figure 3: Simplified hydrogeological map of Jordan and W-E cross section depicting the main hydrostratigraphic units. Profile line runs partly through the study area south of Amman (compare annex 1) (from MWI 2005).

As a hydrostratigraphic unit, the A7/B2 layer is regarded as a continuous aquifer in this study, although it is known to be tectonically heavily disturbed in some areas, especially near the Jordan Graben and around Azraq. The hydraulic properties of the calcareous hardrocks may vary quite significantly vertically and laterally. They can be described as a predominantly fracture-controlled aquifer in all parts, but with significant changes in hydraulic permeability. Pump tests in numerous wells and boreholes have shown very variable permeability, with some wells being very productive and others finished almost unusable for water production. The latter being the case in two recently drilled exploration wells for the planned new well field in the basalt area east of Aqeb towards Azraq. Although both wells penetrate well into the aquifer, reaching 650 m and 700 m below ground, the specific yield proved to be small (exploration well BW-21: 158 m drawdown at 50 m^3/h; exploration well BW-4: 146 m drawdown at 40 m^3/h). These examples illustrate the lateral variability over the large area of these layers. This must be taken into account in any analysis or planning for the further development of the aquifer.

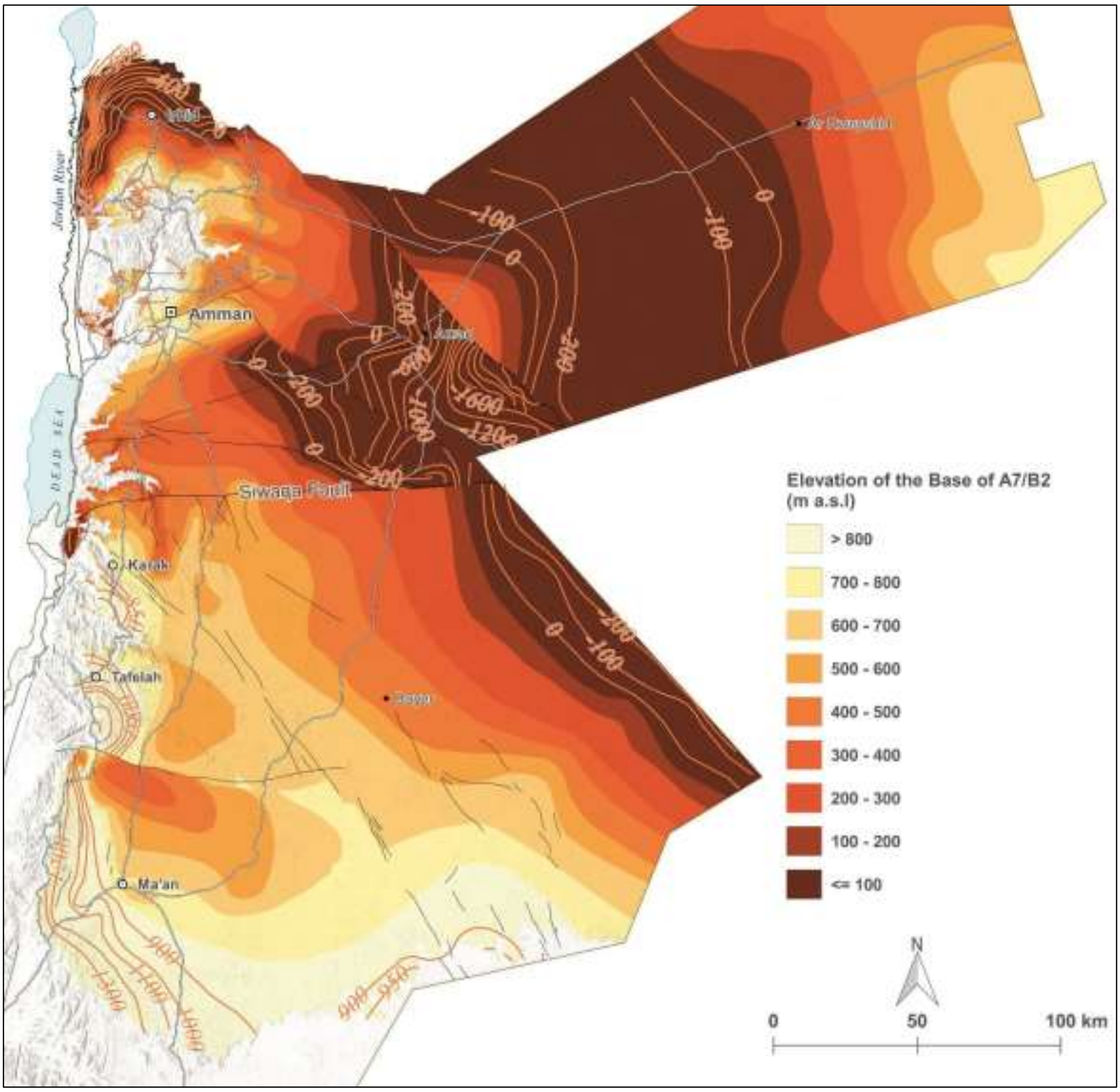

Figure 4: Occurrence and elevation of the A7/B2 layer in Jordan. Colours and contour lines refer to the base of the Wadi as Sir Fm. (after MWI & BGR 2019).

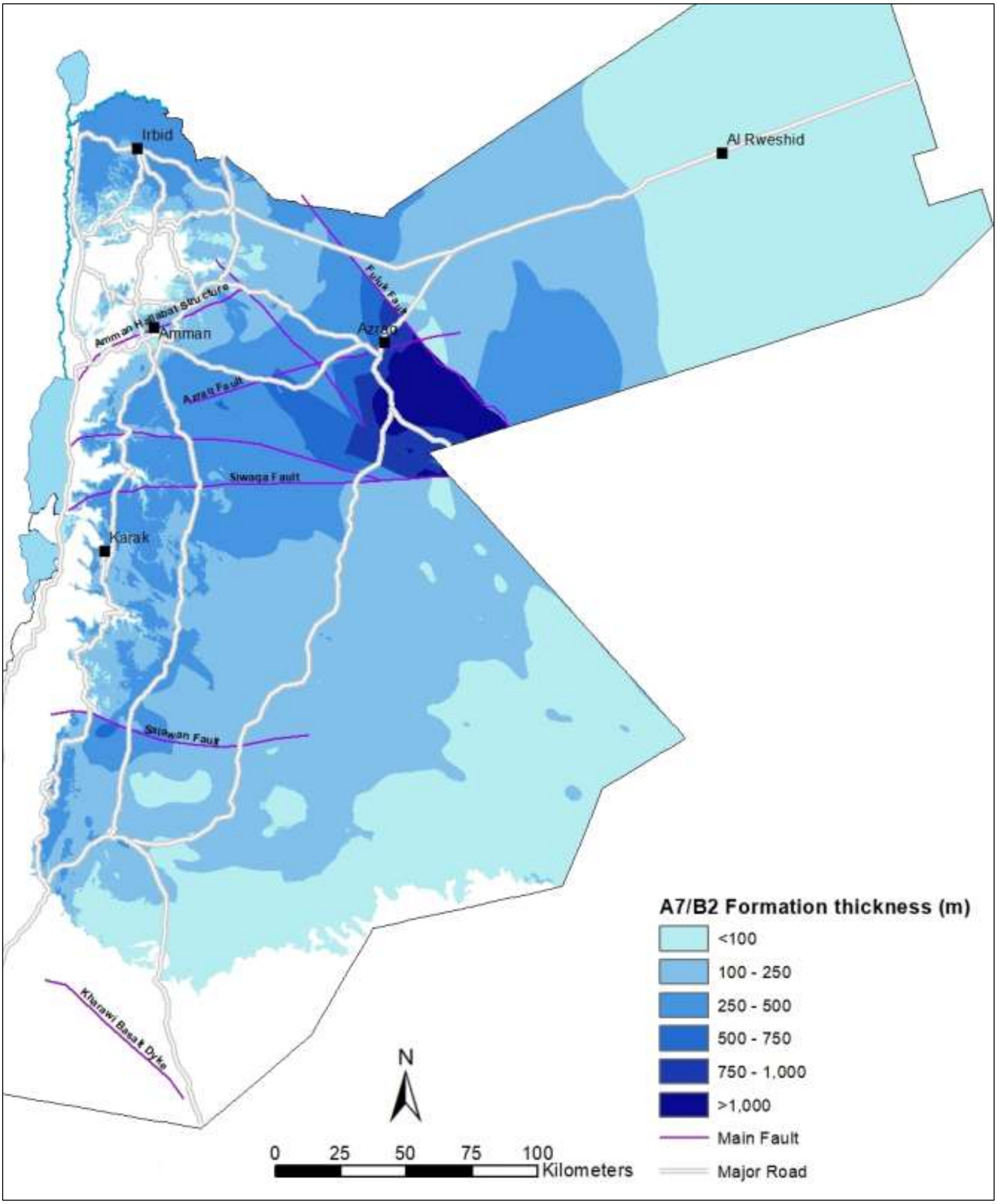

Figure 5: Thickness of the A7/B2 aquifer on basis of the structure contour maps by Brückner (2018). (from Bahls et al. 2018).

2 Methodology

The revised groundwater maps for the A7/B2 layer in Northern Jordan are an output of the German-Jordanian cooperation project “Groundwater Resource Management II”, implemented from August 2021 to June 2024. The groundwater level data used for these maps was collected within the framework of the component “Management of Domestic Wells”. The main focus of this component was the monitoring of the governmental wells, which are operated by the three Jordanian water companies. The measurements of static water levels in these wells were obtained during field campaigns for this project component. The update of the maps was therefore an outcome of the efforts to improve the well monitoring in Northern Jordan, rather than a self-standing study on the groundwater reserves. The process from data collection to map compilation is described in the following subchapters.

2.1 Study area

The area covered comprises the northwestern part of Jordan, excluding the Jordan valley (see maps in Annex 1-5). In the North-South extend, it stretches from the northern border to Madaba. The southern delineation runs along the Azraq-Fault towards town of Azraq. In the east, it ends roughly 10 kilometers east of the road between Azraq and Bishriyyah. The easternmost data points considered, were water level measurements from the exploration wells for the planned “Basalt Wellfield” (BWF) along this road to the north of Azraq (see Annex 5).

The study on hand only provides information on the A7/B2 aquifer. Therefore the interpolation of water levels is limited to the regional extend of the Wadi As-Sir, Umm Ghudran and Amman / Al-Hisa Formations (see Figure 2, Figure 4 and Annex 1).

2.2 Data collection and data sources

All water level readings were collected in a field campaign carried out in fall and winter 2022/23, between October and March. All groundwater level information presented here is based on the measurement of water levels in wells, either in production or monitoring wells. In production wells, readings of the static water level were only taken where the pump was stopped at the time of measurement. To assure static conditions, measurements were only considered if water pumping was halted for at least 24 h before.

To obtain measurements from stopped wells, the BGR team kept close contact with the staff of Miyahuna Water Company and Yarmouk Water Company during the time of the field campaign. Each week, the well operation units and pump station managers were contacted to ask for any scheduled work on the well sites and if there were any wells that would be eventually stopped. The field team then travelled to the well sites where the pump was stopped or was pulled and took the reading of the static water level by hand using a dipmeter. In some cases, recordings were provided by service companies doing pump service for the water companies or working on the rehabilitation of wells. In very few cases, water levels readings from CCTV logs were included.

In total, a number of 111 water level measurements was collected over a period of six month. All observations are listed in the appendix, together with the information on each well location.

The water level records from governmental monitoring wells, which were provided by the Monitoring Department of the MWI, were partly difficult to verify. In fact, the quality of groundwater monitoring data available was not always sufficient to confidently use the data points for interpolation. Therefore, only hand measurements from monitoring wells taken during this campaign were finally considered in the interpolation. Further details and implications are discussed in the final chapter. Consequently, this study relies solely on hand measurements taken during the field campaign or water level values received from the well operators.

2.2.1 Well coordinates and reference system

The locations of all measured wells were retrieved from a list that was exported from the Water Information System (WIS) database provided by the MWI. Horizontal coordinates are given as easting and northing in the Palestine Belt 1923 (EPSG: 28192) coordinate reference system. The geographic Lat/Long coordinates added in the list in the appendix were calculated from the Palestine Belt coordinates and are only displayed for additional information and easier entry in web tools.

The vertical elevation of each well point was extracted from a digital elevation model (DEM), in this case the SRTM 1 arc-second global dataset, which has a resolution of approx. 30 m cell size (USGS 2018). Thus, all absolute elevation values for the wells and the static water levels are coupled to the SRTM-DEM elevations, which refer to the EGM96 as the vertical datum within the WGS84 reference system. As most wells in Jordan have not been levelled by geodetic land surveying, elevations could only be obtained from the satellite-derived elevation model.

2.3 Processing and analysis of water level data

Out of the 111 readings in total, only 62 points were finally used for the interpolation. Among those are 16 monitoring wells and 46 production wells (see table below and Appendix A1). A number of 20 monitoring wells and 29 production wells had to be rejected (Appendix A2).

Table 1: Number of used and discarded water level observation points.

Water Level Observation Points:	**Used** (Grade 1 & 2)	**Discarded** (Grade 3)
Monitoring Wells:	16	20
Production Wells:	46	29
Total quantity:	**62**	**49**

A classification of the data points into three quality grades was applied to distinguish between reliable data points and those that are most probably not representing the actual hydraulic head of the targeted aquifer. The grades were assigned to each data point during the data processing and discussion of the results in the working group of MWI and BGR. The grading of each point is shown in the data tables in the appendix.

Three grades were defined, referring to “good”, “acceptable” and “unusable” data points. The following criteria correspond with each grade:

Table 2: Data point classification scheme.

Grade 1: (*“good”*)	Information on basic well data sufficient, static conditions fulfilled, water level reading plausible. ➔ Representative for hydraulic head of target aquifer.
Grade 2: (*“acceptable”*)	Information on well may be insufficient but static conditions are fulfilled, and water level reading is plausible. ➔ Regarded as representative for hydraulic head of target aquifer.
Grade 3: (*“unusable”*)	Information on well insufficient and/or static conditions not fulfilled and/or water level reading implausible. ➔ Not representative for hydraulic head of target aquifer.

Finally, all data points with grade 3 were discarded and not used for the interpolation and map compilation (compare Annex 2). Only grade 1 and 2 measurements were used for the delineation of the groundwater isolines.

2.4 Interpolation and compilation of maps

For the scope of this study, it was presumed that the rock layers forming the A7/B2 unit are actually a continuous aquifer, for which a corresponding hydraulic head can be calculated. This is an important assumption for the interpolation of water levels and the delineation of contour lines over a larger area. An aquifer continuum is required to allow spatial autocorrelation of the measured water level values. This assumption should always be reconsidered when looking at the groundwater surface in specific areas on a larger scale. Local geological structures may disrupt the aquifer continuum and the interpolation across such structures as faults may not be adequate. However, a continuous aquifer can be assumed for most parts of the study area (compare Figure 3). Where faults occur, these do not fully disrupt the permeable rock layers. Therefore, faults were not regarded as hydraulic barriers within the study area. Only one fault between Ramtha and Mafraq was considered to have an effect on the hydraulic heads with different levels on either side, which is discussed in chapter 3.5.3.

Any results and interpretations regarding the interpolation of the water level measurements were discussed in regular workgroup meetings between MWI and BGR during the implementation period of the project. Data processing and map cartography was done using QGIS 3.28.

2.4.1 Groundwater contour lines

After the water level measurement points were classified in grades and the trustworthy locations were selected (grade 1 and 2), the isolines for the piezometric head were created by interpolation of the points. Automatic, GIS-supported interpolation proved to be not fully sufficient to delineate contour lines for the purpose of this study. Instead, interpolation was mostly done by hand and is based on the hydrogeological interpretation of the field data. Only for the central and eastern parts of the study area, isolines created automatically by Inverse Distance Weighted (IDW) interpolation were used as a starting point for further interpretation and elaboration of the groundwater surface contour lines.

After drawing and discussion of the isolines, these were digitised in QGIS and saved as georeferenced line shapefiles. The final isolines depicting the hydraulic head of the A7/B2 aquifer are shown in Annex 2 and 5.

In a further interpolation step, a rasterised dataset for the piezometric head was created. It contains the interpolated groundwater level information for the entire extend of the study area. To create a continuous raster based on the isolines, a triangulated irregular network (TIN) was generated in a first step. TIN surfaces are used to display the morphology of surfaces, in this case the theoretical pressure head surface of the aquifer. Finally, a TIFF raster file for the piezometric head with a cell size of 90 m of was created using the TIN.

The raster data for the piezometric head is not shown on the maps attached. It was used for further processing to create the derivative raster layers for the depth to groundwater and saturated thickness described below.

2.4.2 Depth to groundwater

The depth to groundwater map displays the vertical distance between the earth's surface, in this case the DEM surface, and the interpolated hydraulic head surface of the aquifer. The hydraulic head surface is not necessarily the groundwater surface, as it lies above the aquifer top in the confined areas.

The depth to groundwater layer was created by subtracting the hydraulic head raster from the SRTM-DEM GeoTIFF with a cell size of 90 m (SRTM 3 arc seconds global; USGS 2018). Each cell value represents the distance between ground level and piezometric surface. In unconfined areas it shows the actual depth to the groundwater surface. The derived raster file is a GeoTIFF with a cell size of 90 m.

The results are depicted on the map in Annex 3.

2.4.3 Saturated aquifer thickness

In a similar way, the theoretical thickness of the water filled parts of the A7/B2 layer was calculated using the hydraulic head raster file and the base elevations of A7/B2 from the structure contour maps. Here, confined and unconfined areas have to be distinguished, as the saturated thickness equals the aquifer thickness in the confined parts. Thus, for confined areas, the thickness is derived from the difference between the top of A7/B2 and its base (as available from the structure contour maps). On the contrary, the saturated thickness in unconfined areas is derived from intersection of the layer base with the hydraulic head surface.

The classified output is shown on the map in Annex 4.

2.4.4 Unsaturated area

In some regions of the study area, the saturated thickness becomes very small, as the base level of the aquifer rises towards the high-lying outcrop areas in the western mountain ridges (compare section in Figure 3). Eventually the saturated thickness will become marginal and the aquifer will be technically unsaturated where to theoretical hydraulic head surface comes close to the base or even falls below the base of the aquifer. Hence, the unsaturated areas were calculated by intersecting the hydraulic head surface with the base of the A7/B2 layer. Areas in which the theoretical hydraulic head lies below the elevation of the aquifer base are regarded as unsaturated. Here the saturated thickness would be zero. Those areas are delineated in red on all the updated groundwater maps in the annex.

It has to be mentioned that for the purpose of this study, the theoretical hydraulic head surface derived from interpolation was used. In this case, unsaturated means that the water-filled thickness becomes so small, that water extraction on a larger scale is no longer feasible. These areas are not suitable for the development of wellfields. Still, it might be possible that wells with small extraction rates can be successful. Especially in structurally favourable locations, localised or perched groundwater bodies might be found. Such localised areas have to be investigated separately and cannot be displayed in the small scale maps created for this study.

Generally, it has to be expected that the A7/B2 aquifer does not store enough water within these areas to support further groundwater production or development. Also it should be considered, that the aquifer base as constructed in the structure contour maps, also underlies a certain uncertainty. And that only local investigation or exact borehole information will give clue to the exact aquifer depth.

2.4.5 Limit of confinement

To delineate the limit of the confined areas, the rasterised water level data was intersected with the elevation rasters for the base of the B3 layer, obtained from the structure contour maps (Brückner 2018). After that, all areas in which the hydraulic head lies above the base of the confining B3 layer were outlined, resulting in the limit of confinement line shown on the map (Annex 2-5).

2.4.6 High salinity area

The high salinity areas depicted on the updated maps were taken over from the 2017 assessment (Bahls et al. 2018 after Margane & Hobler 1995) and are only shown for information. The threshold for the delineation is an electric conductivity of 1500 µS/cm. During this study, no new data about the groundwater salinity was obtained.

3 Discussion of the results

The main output of this study are the groundwater maps found in the annex to this report. The reference date for the maps is October 2022. Thus, the groundwater levels depicted reflect the situation at the end of the hydrological year 2021/22.

3.1 General remarks on the intended use and its limitations

The attached maps are presented in a scale of 1:250,000 and the study area covers roughly 10,370 km^2. The north-south extend of the study area is 118 km and the east-west extend 130 km. On this scale, the maps may serve as an overview depicting the general groundwater situation. The maps can be used to understand the distribution of major groundwater bodies in the more densely populated parts of Jordan. Areas of depletion or even unsaturated conditions can be distinguished from areas with a higher saturated thickness. In comparison with the assessment of 2017, general trends in the groundwater decline and the flow direction changes can be concluded. In this context, it has to be mentioned that the current study does not include a difference map. Instead, the groundwater level contour map in annex 5 displays the isolines from the 2017 study for comparison.

As described above, the contour lines for the hydraulic head and the derived layers, like the saturated thickness, are based on the interpolation of single point measurements. For the interpolation, a spatial correlation of the measured water level values has to be assumed, which requires the assumption of a continuous aquifer. However, these conditions may not always be fulfilled in structurally complex areas, e.g. like the mountainous highlands south of Irbid. To establish better spatial correlation, and consider structural geological features, a higher density of observations points is needed

The maps should not be used to assess the groundwater dynamics and availability for smaller areas on a larger scale. The resolution is not high enough to provide detailed information on the hydraulic head or the flow direction in specific areas like well sites or wellfields. They are also not suitable to predict the drilling depth for individual boreholes or the productivity of a new well site. In any such cases, further investigation on the specific site and the local hydrogeological situation need to be conducted. Any interpretations should be carefully cross-checked with further information on a local level, like drilling reports and up-to-date monitoring data, if available.

3.2 Groundwater level contour maps

The primary map in annex 2 shows the contour lines for the interpolated piezometric surface of the A7/B2 aquifer. The occurrence of the A7/B2 aquifer within the study area can be seen on the hydrogeological map in annex 1 and the depictions in Figure 4 and Figure 5. A second version of the contour line map is included in annex 5. That version displays additional information on the used measuring points (see also chapter 2.3). It also contains the isolines for the piezometric surface calculated in the 2017 assessment (Bahls et al. 2018) for comparison. Additionally, five hydrographs of selected monitoring wells are included, which can also be found in Appendix C.

In general, one can distinguish several zones in the study area, regarding the groundwater situation. Some areas of special interest will be discussed in chapter 3.5, including the area marked as unsaturated.

Principally, the eastern highlands and Badia regions show different characteristics than the mountainous regions closer to the rift valley. In the Badia regions, east of Mafraq, Amman and Madaba, the A7/B2 is dipping slightly eastward and becoming increasingly thicker (see Figure 4 & Figure 5). The isolines show a rather wide spacing, reflecting low gradients. In the north-eastern part, groundwater flow is directed south and south-westward, flowing into Jordan territory from recharge areas near Jebel Al Druze in Syria. The flow direction then turns west towards the Aqeb and Zaatari area, due to the large groundwater depressions that have developed in these highly exploited areas. Here numerous public and agricultural wells extract water from the A7/B2 aquifer, resulting in a regional sink around Bagdad Road and Salhiyya village in the vicinity of the Aqeb wellfield (Yarmouk Water Company). Further south, towards Azraq, far less wells are operating in the Basalt desert and the gradient is very shallow. The extensive Basalt desert north of Azraq even contributes to some groundwater recharge during winter month, which became evident during water level observations for the so called Basalt Wellfield. This new wellfield is currently in the exploration and design phase and shall be developed in the east of the Aqeb wellfield.

Further west of the Aqeb-Zaatari area, the groundwater flow is directed to the west or north-west. Around Mafraq, the potentially unsaturated area has increased and is extending eastward towards Zaatari (see also chapter 3.4). Further north towards Ramtha and Irbid the flow direction is more or less unidirectional in the same northwestern to western direction.

In the southern part of the study area, the flow direction is mostly south-east, from the mountains around Amman towards the eastern desert plains. Around Amman, many parts of the aquifer are unsaturated, with only the Zarqa valley along the Amman-Hallabat structure holding groundwater. It has to mentioned that further south and east a higher salinity of the groundwater has to be expected. In the attached maps, the high salinity distribution of the 1995 study is shown for reference. No new data for the salinity was gathered during this study.

3.3 Depth to groundwater map

The depth to groundwater map in annex 3 depicts the vertical distance between the ground surface and the groundwater level of the aquifer, i.e. the piezometric surface (Figure 6). It is derived by the subtraction of the piezometric surface from the digital elevation model, like described in chapter 2.4.2. Therefore, the results are highly dependent on the topography.

On the map, regions with a high depth to the water table can clearly be distinguished from regions where the water table is closer to the ground surface. The smallest depth is found around Azraq to the south of the basalt cover. The adjacent areas along the basalt sheet margins are also areas with shallow groundwater depth, like for example around Hallabat in the governorate of Zarqa. Another area were the water table is close to the surface (less than 100 m), is found along the Zarqa valley northeast of Amman. In this favourable setting, many wells are situated, e.g. domestic wells for Miyahuna Amman and Miyahuna Zarqa like in the Russeifa/Awajan wellfields.

Areas with a greater depth to the water table are found around Muwaqqar and in the very north, in regions with a thicker basalt cover. The thick basalt sheets in the north-eastern corner of the study area make it more difficult to reach the aquifer, although a good thickness can be expected (compare annex 4).

In the northernmost part of the study area, near Irbid, the topography is very variable. While most of the highland areas have a relatively large depth to groundwater with distances of more than 300 m and sometimes more than 400 m, the groundwater is much shallower in the deeply incised valleys. Along the Yarmouk River and its tributary wadis the aquifer can be reached in less than 100 m depth.

In the eastern part and most northern part of the study area, the A7/B2 aquifer is overlain by the B3 aquitard (compare Figure 2 and Figure 3), resulting in confined conditions. The limit of the confinement is outlined on the maps. In the confined areas, the hydraulic head lies above the top of the aquifer. Therefore the isolines reflect the piezometric surface, not the groundwater surface. The concept is illustrated in Figure 6, depicting (a) one well penetrating only the aquitard and not the aquifer; (b) one well penetrating the aquifer with the water table rising in the well as a result of the hydrostatic pressure of the groundwater in the aquifer. This is important for the estimation of the drilling depth required to reach the aquifer. The minimum drilling depth to reach water within A7/B2 is the depth to the top of the layer in the confined areas, rather than the depth to the piezometric surface. The depth to groundwater map therefore also shows the isolines for the elevation of the top surface of the aquifer.

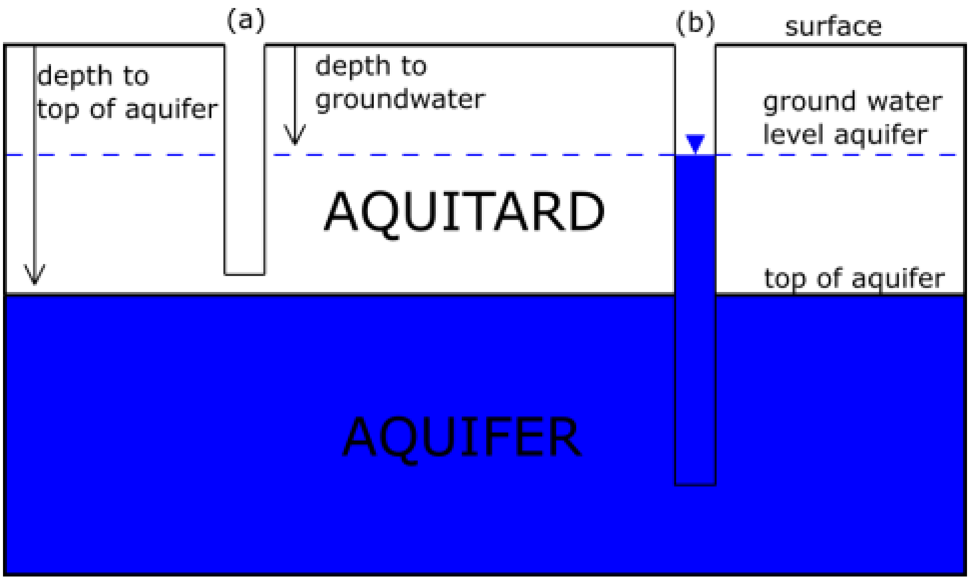

Figure 6: Illustration of the depth to groundwater under confined conditions.

3.4 Saturated thickness map

The saturated thickness of the aquifer was determined in a similar way as the depth to groundwater, calculating the vertical distance between the piezometric surface and the base of the aquifer (see chapter 2.4.3). The map in annex 4 shows how large the water column in the A7/b2 aquifer is. Just as the depth to groundwater is strongly influenced by the topography, the saturated thickness is mostly determined by the geological structure of the specific layer. This becomes very obvious when looking at the west to east development of the saturated thickness in the middle part of the study area. The thickness increases steadily from the unsaturated areas in the mountainous highlands towards the badia. The highest saturated thickness can be found in the graben structures associated with the Fuluq fault around Azraq.

Another region with high saturated thickness, and partly confined conditions, is found in the very north towards the Yarmouk valley. On the contrary, the highlands around Irbid city are already partly unsaturated or have a saturated thickness of less than 100 m.

The annex 4 map displays the unsaturated areas determined in this study in comparison with the 2017 results. Most of the mountainous regions along the rift margin must be regarded as unsaturated. If the A7/B2 strata are existent in this areas, they are not favourable for water production. Like mentioned above, this does not mean that there is no water within these rock layers. But it may only be stored in localised perched aquifer parts or structural depressions and therefore large scale water extraction is not feasible.

The unsaturated areas seem to have extended at the eastern margin. Especially around Mafraq and towards Zaatari, the boundary progressed eastward over the last five years. From measurements in the Zaatari area and also the Zaatari camp wells it is evident, that the saturated thickness decreased here and is now less than 100 m. Moving west from Zaatari, the aquifer quickly becomes unsaturated. The same seems to be the case around Khaldiyeh and Dhuleil.

3.5 Areas of special interest

3.5.1 The confined zones

In some regions of the study area, the A7/B2 aquifer is overlain by rocks with lower permeability. These are the chalky and locally bituminous marls of the B3 aquitard (see Figure 2, Figure 3 and Annex 1) (Margane et al., 2002). Wherever the B3 layer exists, it can be assumed that it minimizes vertical permeability and thus confines the A7/B2 aquifer. All areas in which the hydraulic head in the aquifer lies above the base of the B3 layer, the groundwater body would be pressurised and confined.

There are two zones within the study area where this is the case. One lies north of Irbid, where the strata dip northward and the B3 layer is existent over a larger area. Confined conditions can be assumed towards the Yarmouk valley as the hydraulic heads lies above the top of the aquifer. However, in some exploitation hotspots like the Wadi Al Arab wellfield and around Ramtha, the water level is drawn down by water extraction and the wells may not be under confined conditions any more (Dorsch et al., 2020).

The second, much larger, confined zone is the Eastern Badia region with occurrence of the B3 layer. Here, confined conditions prevail for all areas with B3 cover. This may change in the future, when exploitation continuous and new wellfields are developed. Areas that are now still confined but may turn to unconfined due to water table drop are lying east of Hallabat and in the eastern part of the Aqeb wellfield.

3.5.2 The unsaturated zones

Because of the broader geological structure of the Cretaceous system, the rock layers of the A7/B2 aquifer are generally dipping eastwards and northwards from the mountainous, high-lying terrain along the graben shoulder north of Amman and around Ajloun (compare Figure 3). Moreover, the Cretaceous succession is becoming thicker towards the east and towards the Yarmouk River. Because of this structural configuration, the outcrop areas of the A7/B2 layers in the mountains are also the areas where the aquifer has its highest absolute elevation and from where water flows eastwards and northwards. Therefore the saturated thickness becomes thinner to the west and thicker to the east and north.

All areas, in which the interpolated piezometric surface lies at or below the base of the A7/B2 aquifer (according to the structure contour map), were marked as unsaturated, as described in chapter 2.4.4. Figure 7 displays a section of the saturated thickness map in the central part of the study area. For comparison, the unsaturated zone from the 2017 study is included. During the last five years, since the assessment of 2017, the areas with a water column close to zero have expanded. Especially east of Mafraq and Khaldiyah, the water table in the A7/B2 aquifer recedes to the east. In the future, the most western wells of the Aqeb wellfield and the wells of Zaatari camp will likely suffer from a reduced water column. In the Khaldiyeh area, a number of wells has already fallen dry. North of Zarqa, the unsaturated zone is also extending, which may affect production rates in Tamoween. Although it has to be mentioned that the Tamoween wells draw water from different aquifers.

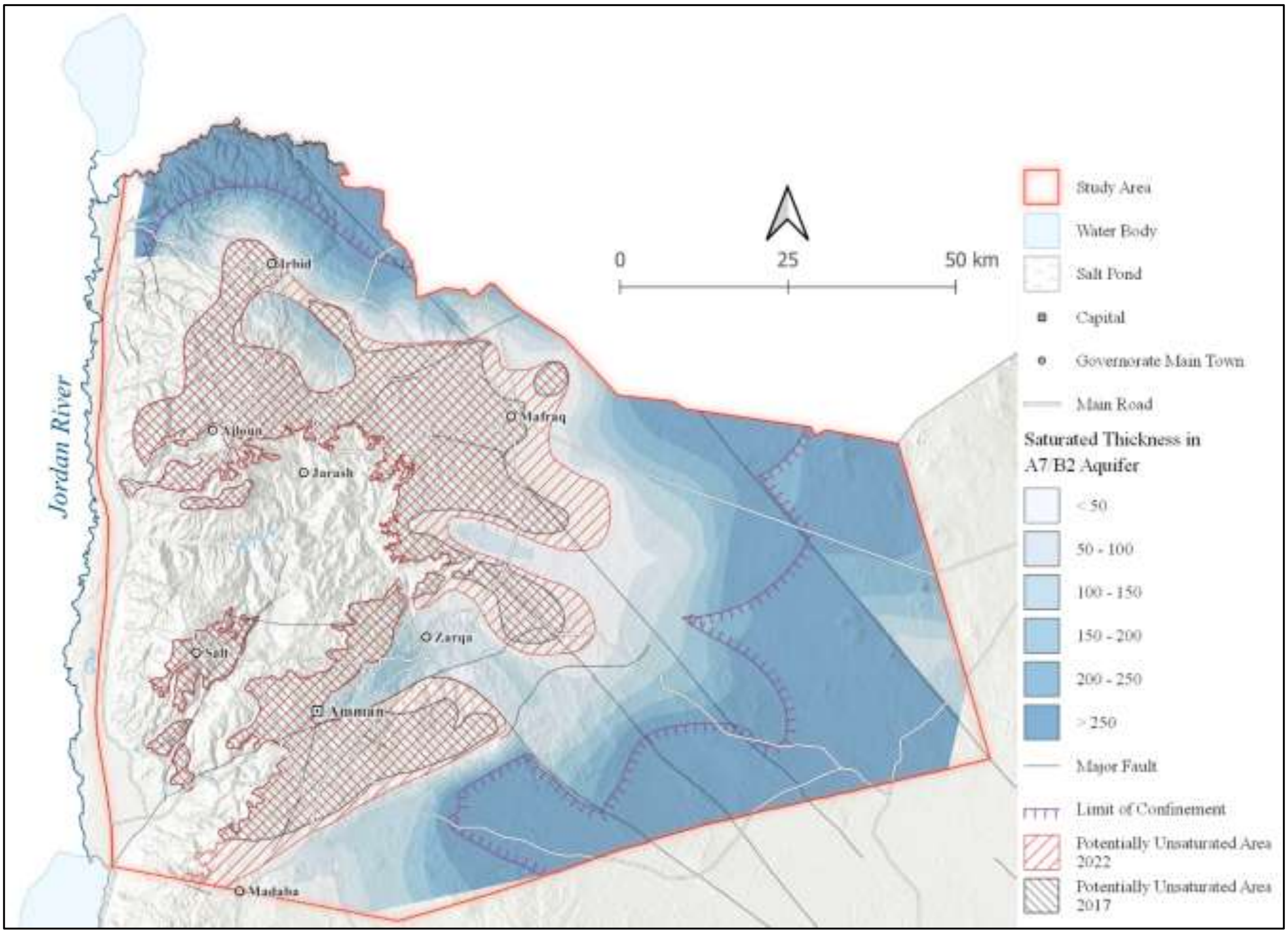

Figure 7: Section of the saturated thickness map showing the progression of unsaturated areas.

3.5.3 Irbid, Ramtha and Sirhan area

In the northernmost part of the study area, around Irbid, the A7/B2 aquifer dips towards the Yarmouk valley and the Jordan valley and is mostly overlain by the B3 aquitard (Figure 3 & Annex 1). Still, not all areas overlain by B3 are confined since the water level does not always reach the top of the aquifer. Generally, the flow direction is northward or northwestward from the higher mountainous regions of the Ajloun dome and then turning west to the Jordan valley. There is a rather steep gradient towards the Jordan valley as the ultimate base level resulting from the large elevation difference. The area towards the rift becomes structurally more complex, which may result in locally changing conditions regarding the confinement. One example for a highly exploited area with fast changing groundwater flows is the Wadi Al Arab wellfield, a major water contributor for the governorate of Irbid. For more details on this area refer to previous studies on the Wadi Al Arab area (e.g. Dorsch et al., 2020).

Compared to the 2017 situation (Annex 5), the general flow pattern has not changed significantly in this region, but a clear drop of the hydraulic head can be observed. Around Irbid, the decline may be around 20 m in the last five years, while it increases to alarming 50 – 60 m around Ramtha and towards the Sirhan area north of Mafraq. This is also visible in the hydrograph of one of the few operational monitoring wells: AD1301/Mahasi 8 (Deep) (Appendix C & Annex 5).

The Sirhan area, close to the Jaber as-Sirhan border crossing, seems to be affected by faults that influence the groundwater flow. During the assessment, a sudden change of water levels was observed at the southwest-northeast trending faultline between Mafraq and Ramtha. Possibly, the high declines of water levels in the Ramtha area are not only a result of overexploitation, but are exacerbated by a geological structure that reduces the groundwater flow from the eastern and southern directions.

3.5.4 Eastern Badia and the Aqeb wellfield

As mentioned above, the Aqeb wellfield and its surroundings are a hotspot for groundwater overexploitation. This is also evident in the measurements taken in this study. The static water levels collected in this area are often difficult to interpolate, because they may be influenced by adjacent wells. Also seasonal effects play a role in this area, due to the high number of irrigation wells. Therefore the isolines for the central Aqeb area had to be smoothed during interpolation of the point measurements (compare Appendix A & Annex 5). Still, it is evident that there is large scale depression, formed by intersecting drawdown cones of the numerous wells. The central part of the Aqeb wellfield, together with surrounding private wells, forms a local groundwater sink. Water levels may vary in the decameter range over time and during seasonal change and are often influenced by other operating wells.

Further east, towards Ashrafiyyah along Bagdad Road, the water tables get more stable and there is less drawdown of the piezometric surface. Further east of Ashrafiyyah, the aquifer is overlain by B3 and still confined. That is the reason why the easternmost wells of the Aqeb wellfield (e.g. K123/124) are much more stable in the production and the dynamic water level.

To the south of Bagdad road and towards Azraq, groundwater conditions are more stable and favourable for the drilling of news wells. The area of the newly planned Basalt wellfield seems to be only slightly affected by the overexploitation so obvious in the western part of Aqeb wellfield. Thus the proposed location for the new wellfield still seems to be expedient.

3.5.5 Zarqa valley and Tamoween wellfield

In the capital area of Amman, the Ajloun and Balqa groups are exposed and store very little water. Over large areas around the capital, the A7/B2 aquifer is unsaturated (compare Annex 4 & Figure 6). Water production from wells capturing A7/B2 water is happening along the valley of the Zarqa River, e.g. within the Russeifa-Awajan wellfield. The availability of water in this area is a consequence of the structural setting, with a synclinal structure to the north of the Amman-Hallabat fault line.

The Tamoween wellfield, located east of Zarqa city, is of importance for the water supply. Its wells are partly capturing water from A7/B2 but also from other layers, e.g. the A4 aquifer. It was difficult to interpolate the water table in the vicinity of this wellfield. Partly, because the wells intersect different layers, partly because of instationary conditions and intersection of drawdown cones. The saturated thickness of the A7/B2 aquifer in the Tamoween area can be expected to be around 50 m or less, which is at the tipping point for water production. But the well water levels are most likely sustained by water influx from underlying formations. A close monitoring of the areas water levels will be necessary in the near future to observe a further depletion in the Tamoween area and react accordingly by well management.

3.6 Status of the groundwater monitoring network

This updated groundwater assessment is based on manual water level measurements taken at monitoring wells as well as production wells. The reason for including static water levels from production wells is the insufficient spatial density of monitoring wells. A higher density is indeed challenging to achieve, considering the depth and spatial extent of the aquifers. Still, monitoring wells are the best data source for gaining water level records. It became evident during the study that there are major problems with the data availability and reliability of the official monitoring wells. Of only 36 monitoring wells for A7/B2 available within the study area, 20 had to be rejected due to quality concerns (see chapter 2). A share of 55% of the wells were found to be unusable for water table interpolation or timeline analysis. Hence, the urgent need for the improvement of the monitoring network is still prevailing. However, the known challenges concerning the groundwater monitoring system could not be improved since the last groundwater assessment of 2017. To illustrate the problems, some typical issues are described below with the help of four examples of hydrographs from monitoring wells within the study area. All data for these monitoring wells was obtained from the WIS database at MWI in October 2022.

Disrupted or discontinuous records

One of the most abundant issues found are incomplete or discontinuous data sets. Often timelines are interrupted after a certain date, like for example at the well ‘A’QIB DAM OBS.1’ (AL1926), of which a hydrograph is shown in Figure 8. In the same graph, the reduction of the measuring interval after 2015 is clearly visible. Nearly all monitoring wells show a decline of the measuring intensity after 2015.

This example is one of the more useful hydrographs, because the still available data at least allows an extrapolation for the time after the abandonment. In other cases, the timelines are totally fragmentary and cannot be used for any analysis at all. In such cases, it is not worth to conduct any further measurements unless the interval can be shortened and data quality can be assured. In general, the effort to take manual readings should only be done at wells where there is a benefit.

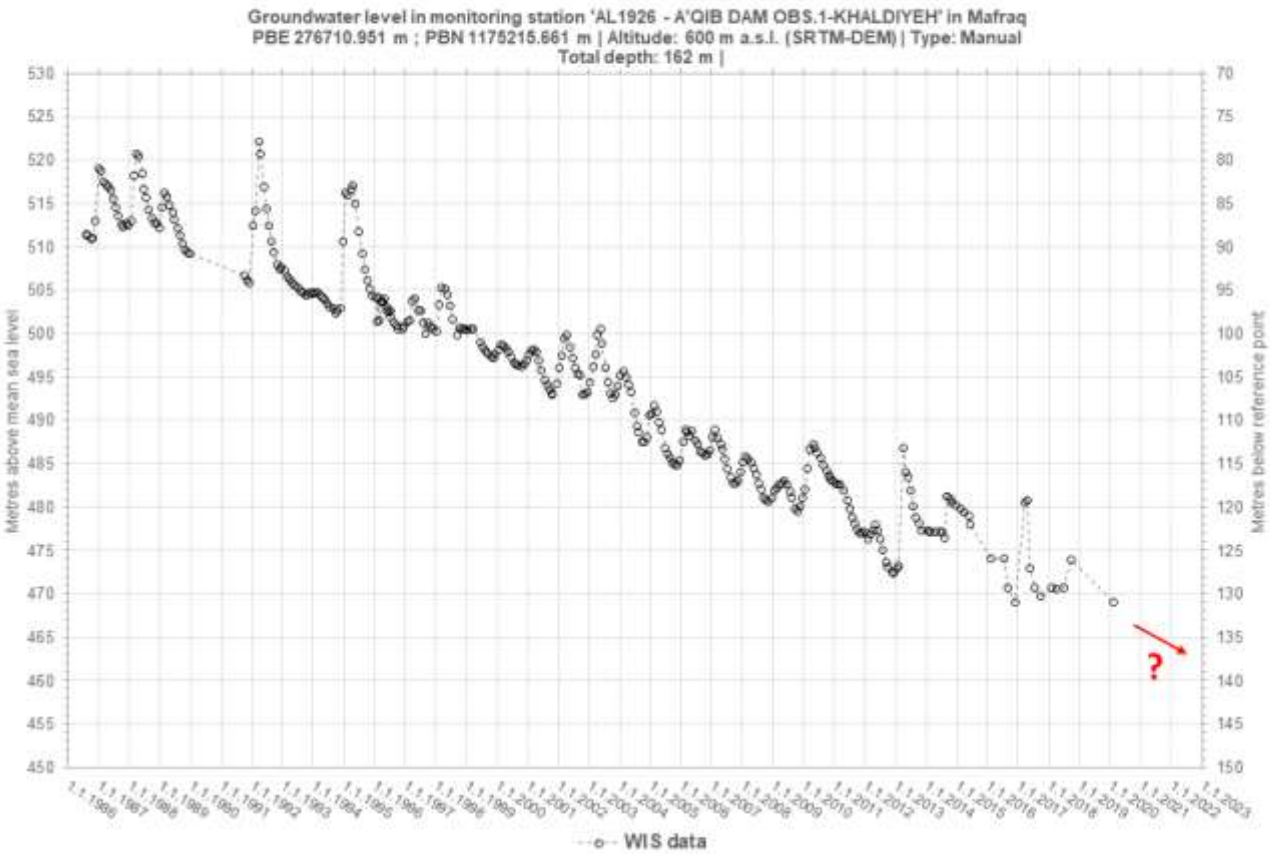

Figure 8: Hydrograph of monitoring well AL1926 - A'QIB DAM OBS.1.

Implausible measurements

By plotting the measurement timelines as hydrographs, measurement points that must be faulty quickly become obvious. For example the hydrograph of well 'QASTAL NO 7 (OBS.)' (CD1075) shows a conspicuous development between 2015 and 2021, which cannot be explained. Here the reason for these elevated values is most certainly to be found in the data acquisition process. Moreover, the less frequent measurements make it difficult to see seasonal trends that were obvious in that monitoring location before.

Another example is 'Swailmeh Observation' (AD3272). The measurement taken during the 2022 field campaign is more than 100 m deeper than the previous points. Because all previous measurements are on a straight line, it is possible that the values were submitted without any real hand measurement.

These are two examples of wells which can provided very useful data, but the reliability of the latest measurements is questionable. Still, the reasons for the quality deterioration might only be of organisational nature and an improvement of data quality can be achieved by a revision of the process.

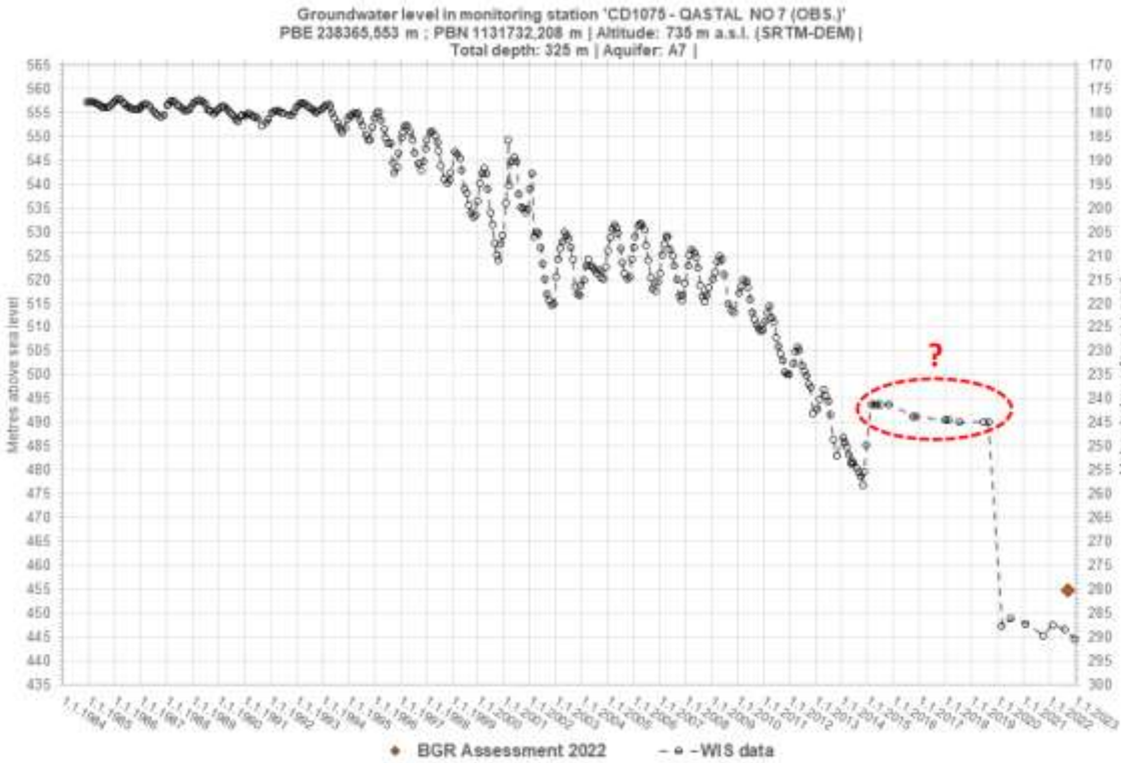

Figure 10: Hydrograph of monitoring well CD1075 - QASTAL NO 7 (OBS.).

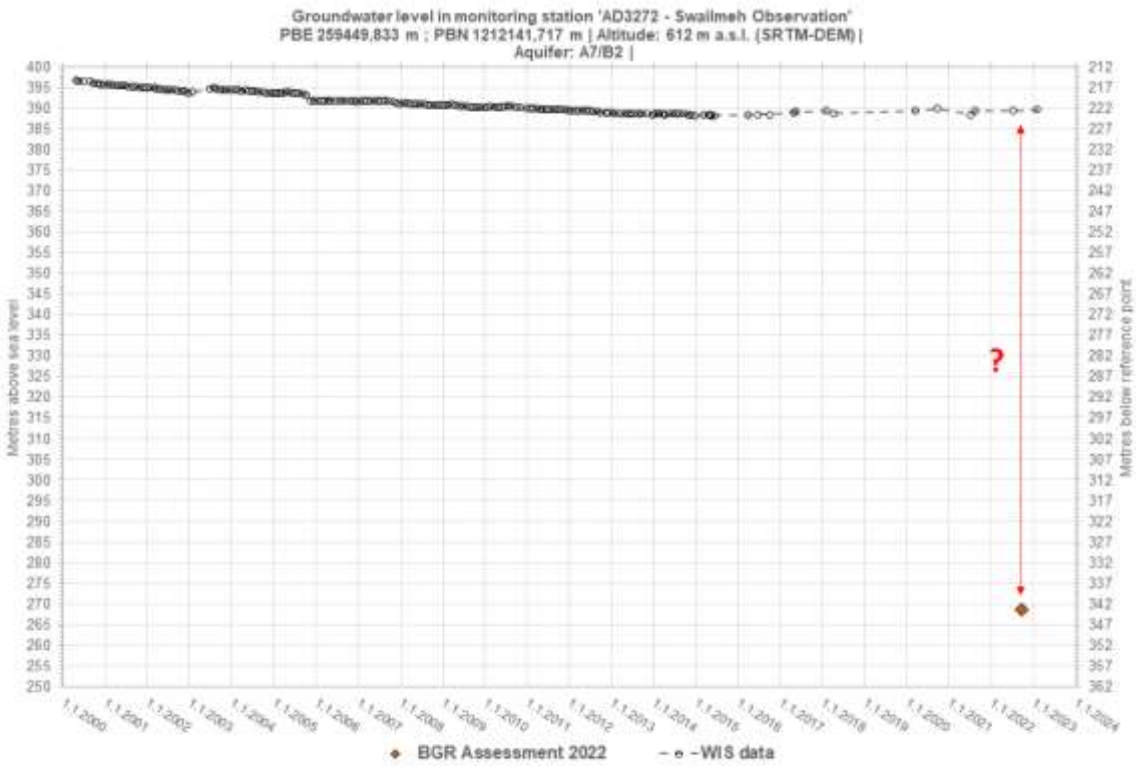

Figure 9: Hydrograph of monitoring well CD1075 - QASTAL NO 7 (OBS.).

Well depth insufficient

In some monitoring wells, the hydrograph shows a clear trend that approaches a certain depth and after that measurements become odd. One such example is the 'HALLABAT 6' monitoring station. Again, the data quality deterioration starts after 2015. Moreover, the water level seems to have reached the bottom of the well. Nevertheless, some measurements have been continued, although the well does not reflect the actual water table any more. Maybe there is some water left in the lowest casing section at the well bottom, which prompts a signal by the dipmeter sensor that doesn't actually reflect the real water level. The actual water table probably has fallen below the bottom of the well. In this case, the current well should be taken out of the monitoring programm and one option would the replacement of the well on the same site with a greater drilling depth. Anyhow the measurements should be used very carefully, as they do not reflect the actual groundwater situation. The data from this well could even be interpreted in a misleading way, suggesting a shallow water table, which is not actually true.

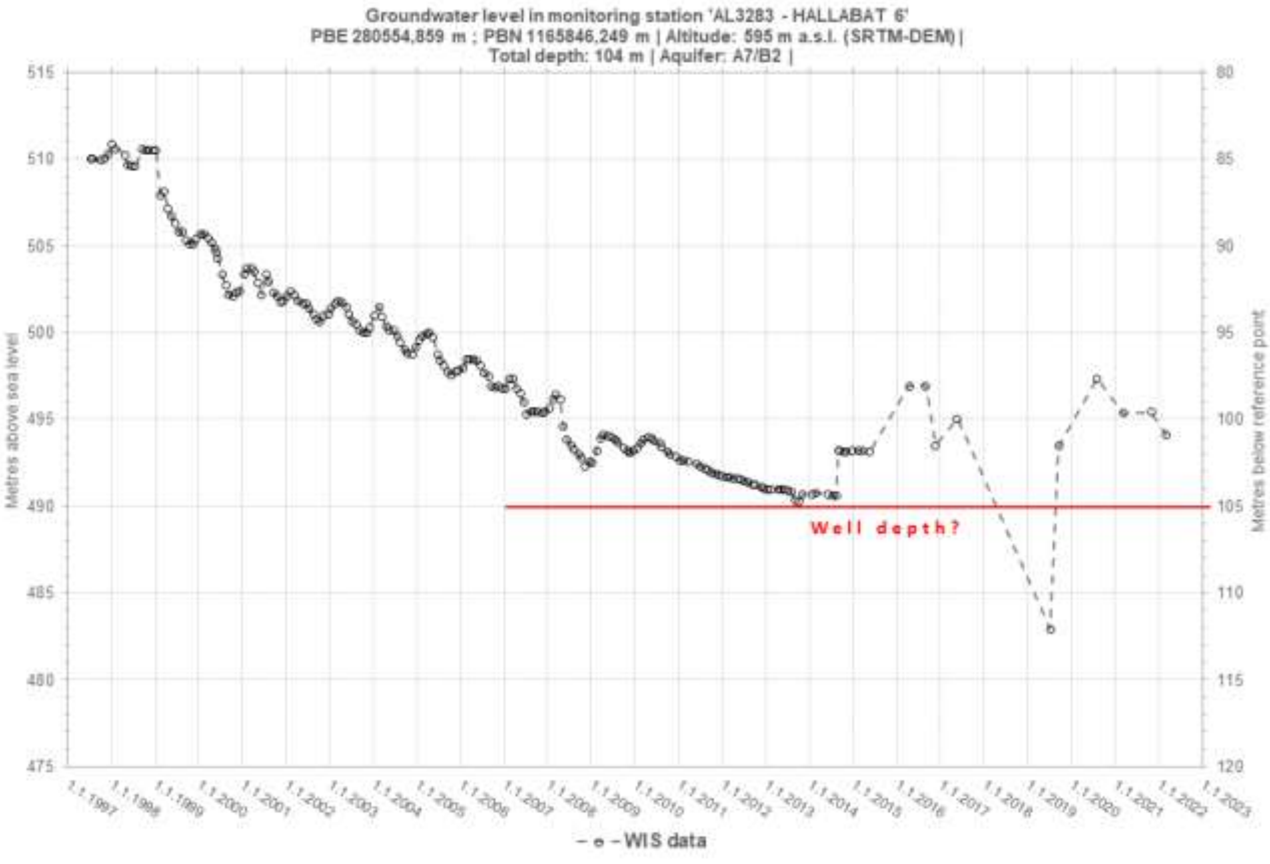

Figure 11: Hydrograph of monitoring well AL3283 - HALLABAT 6.

4 Conclusions and recommendations

4.1 Status of the A7/B2 aquifer in northern Jordan

The 2022 groundwater assessment evidently shows that the trends of falling water tables have continued since 2017, at least for the area examined in this study. The obtained information is documenting an ongoing depletion of the A7/B2 aquifer in northern Jordan. At the same time, the areas in which the saturation is becoming minimal have expanded (Figure 7). In this context, it is suggested to discuss and reaffirm the goals of the groundwater monitoring concept. The objectives and possible interventions should be clearly defined. In Jordan, groundwater monitoring cannot be understood as an approach to preserve the groundwater reserves. It is out of question that the depletion will continue and therefore preservation cannot be an objective, at least until other sources are available (see also chapter 1.1). Groundwater monitoring should rather be used as a tool to raise the efficiency in the groundwater exploration and production and control future costs. A comprehensive monitoring concept can help a lot in prescient planning.

4.2 Development of well fields

The presented maps, in particular the saturated thickness map, may help to identify areas that are still promising with regard to further exploration and exploitation. In the context of the developments described before, the only region offering a substantial potential for additional groundwater exploitation is the Eastern Badia. To the east of a line from Muwaqqar over Hallabat to Salhiyyah, the saturated thickness of the A7/B2 layer is high and the aquifer is confined where the B3 aquitard is existent. Nevertheless, high salinity is a risk factor that was not examined in this study, but which is known from various other studies. Also, the risk of contamination by water leackage from B3 rocks need to be considered more thoroughly in future.

Already, there are several donor funded groundwater development project in the Badia region happening at the time of writing. The Miyahuna water company has begun to build a new wellfield of approximately ten new wells in the eastern extension of the Hallabat wellfield. At the same time, the WAJ is implementing a large scale wellfield project for an estimated 20 wells to the southeast of Aqeb, supported by funding of the German KfW bank. Once operational, these two projects will raise the production from this region by several million cubic meters per year, posing a great impact on the remaining water reserves. A thorough monitoring of the effects will be crucial for a long term operation of the new infrastructure.

For all other areas with A7/B2 distribution within the study area, the potential for additional water extraction from A7/B2 is minimal.

4.3 Monitoring concept

Groundwater monitoring is a crucial precondition for the pursuit of the goals and objectives for groundwater management defined in the updated National Water Strategy (see chapter 1 and Figure 1). Reliable data on the piezometric water levels of the aquifers is indispensable and needs to be available in a spatial and temporal resolution that supports further analysis, e.g. geostatistical interpolation.

Nothing works better than quality-checked water level timelines and hydrographs when it comes to the assessment of groundwater bodies.

The monitoring of the water table through wells is the most reliable way to gather the needed information about the development of the groundwater resources. Monitoring wells with dependable static water level measurements have to be the primary data source. Production wells can contribute further valuable information, if they are monitored carefully and the pump status is recorded.

There are a number of monitoring wells in operation, which could principally provide the much needed data. Still their spatial distribution is far from ideal and needs to be further improved. Looked at closely, many of the stations do not provide measurements that are good enough to be used for interpolations, e.g. groundwater contour maps. During this study, 55 % of measurements from official monitoring stations had to be rejected (see Table 1), as the values were not plausible. Additionally, a number of monitoring wells were found to be damaged or fell dry in recent years. The process of data acquisition still needs improvement, as already mentioned in the groundwater assessment report published in 2017.

The reasons for the setback can be summed up in the following three categories:

Table 3: Apparent reasons for shortcomings in groundwater monitoring.

Reason 1:	**Physical condition of monitoring wells**	Monitoring wells have suffered from vandalism, aging of materials, sedimentation, drying up or other physical reasons for failure.
Reason 2:	**Frequency and reliability of measurements**	The measurement intervals have extended or the reading has been given up. Additionally, many measurements seem to be false or imprecise.
Reason 3:	**Missing quality check of data**	Where timelines exist, deviations in the graphs show that data has been entered and kept without quality check, even if irregularities can be detected.

Based on the identification of these issues, a recommended first step towards an improved groundwater management would be the revision of the monitoring concept for groundwater levels. Most of the problems described above seem to be process related, meaning that it is a question of organisation and institutional management to mitigate them. Obviously, the great depth to the groundwater and the resulting well depth are often an obstacle and complicate all tasks related to the measuring, construction and maintenance. But nevertheless, physical reasons seem to be of far less importance than process related reasons in this context.

The following recommendations describe steps that could lead to a direct improvement of the groundwater monitoring:

Table 4: Possible steps to overcome shortcomings in groundwater monitoring.

Step 1:	**Revision of the objectives**	At the beginning, the need for information and the corresponding objectives for the monitoring should be defined clearly.
Step 2:	**Revision of the budget**	To establish a monitoring routine, including manual measurements and check-up of wells, the equipment as well as vehicles and fuel are needed. To ensure the necessary equipment and staffing, the funding of the responsible units should be revised.
Step 3:	**Examination of the data acquisition process**	Before further investments in infrastructure, the whole monitoring process should be examined regarding reliability and efficiency. The practical approach to obtain the measurements must be determined, e.g. how often manual measurements need to be taken to support and validate automatic measurements. Automatic measurements alone are not enough to ensure data quality.
Step 4:	**Introduction of quality checks at several levels**	Each step in the data acquisition process needs to be checked. Quality checks for the data must at least be done when water levels are entered into a database.
Step 5:	**Restoration of monitoring stations**	The existing monitoring wells need to surveyed, repaired or replaced. This should be done step by step in only one area / governorate at a time not over all of Jordan at once.
Step 6:	**Expansion of the monitoring network**	After completing the steps before and improving the routines for data acquisition, new wells should be drilled. The locations for new monitoring wells must be picked strategically and be aligned with development projects for new wellfields.

Ultimately, the groundwater monitoring should be regarded as a process cycle, as depicted in the schema in Figure 12. It is an ongoing and repetitive task of the water authorities, which does not only include the measuring. Rather it can be seen as an organisational process, starting with the definition of the goals and the available technical options needed to gather the needed information. The monitoring systems continuously needs to be adapted and amended, as more and more information is gathered. Most importantly, the task does not end with the collection of the data. A well designed system to store and aggregate the data produced needs to be set up and the quality check of the incoming data is essential for the reliability. Finally, the data needs to be evaluated and interpreted to extract information from it, which can then again be introduced into the management process.

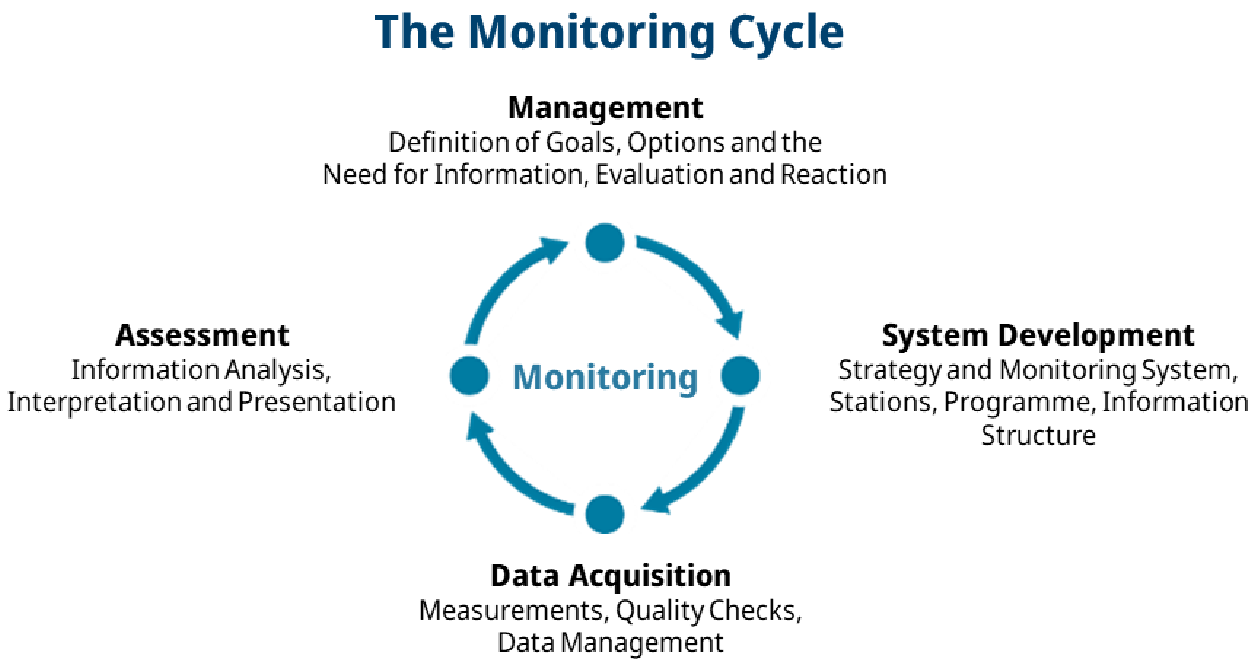

Figure 12: Illustration of the monitoring cycle.

4.3.1 Groundwater assessments in the future

The limitations of studies like the one on hand have been discussed in the previous chapters and shortcomings have been pointed out that limit the informative value of the presented results. In this situation, the repetition of a similar groundwater level assessment in some years would only make sense as long as the groundwater monitoring routine is improved beforehand. With the very limited number of measuring points and the low temporal resolution, interpretations cannot be accurate. Therefore, it is highly recommended to address the issues described above first, before carrying out further studies on the development of groundwater resources in Jordan.

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