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REPORT

Causes and consequences of long-term groundwater overabstraction in Jordan

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Abstract

In 2017, a comprehensive review of groundwater resources in Jordan was carried out for the first time since 1995. The change in groundwater levels between 1995 and 2017 was found to be dramatic: large declines have been recorded all over the country, reaching more than 100 m in some areas. The most affected areas are those with large-scale groundwater-irrigated agriculture, but areas that are only used for public water supply are also affected. The decrease of groundwater levels and saturated thickness poses a growing threat for drinking water supply and the demand has to be met from increasingly deeper and more remote sources, causing higher costs for drilling and extraction. Groundwater-level contour lines show that groundwater flow direction has completely reversed in some parts of the main aquifer. Consequently, previously established conceptual models, such as the concept of 12 "groundwater basins" often used in Jordan should be revised or replaced. Additionally, hydraulic conditions are changing from confined to unconfined; this is most likely a major driver for geogenic pollution with heavy metals through leakage from the overlying bituminous aquitard. Three exemplary case studies are presented to illustrate and discuss the main causes for the decline of the water tables (agriculture and population growth) and to show how the results of this assessment can be used on a regional scale.

Keywords Arid regions · Agriculture · Over-abstraction · Water supply · Jordan

Introduction

Overexploitation of groundwater resources in Jordan has been ongoing for at least 30 years and has become a growing threat to safe water supply in the country (Salameh 2008). The main reasons for the water deficit are high population growth and the intensification of irrigated agriculture, but other factors such as climate change also play a role. In all, 55% of all groundwater is used for agriculture and the remainder mainly for domestic water supply (MWI and GTZ 2005); industrial groundwater consumption is less than 5% (Margane and Almomany 1995). Many measures have been implemented to alleviate the deficit: wastewater reuse (Abdulla et al. 2016), leakage reduction (Al-Ansari et al. 2014), closure of illegal wells (MWI 2017) and desalination of brackish surface water and groundwater (World Bank 2004). Tariff hikes have also been used to make illegal wells unprofitable (Al Naber and Molle 2017b); however, those efforts have not been enough to keep pace with growing demand from agriculture and rising population (Yorke 2016). Monitoring wells all over the country record dramatic declines over the last ~25 years, on average around 50 m but up to 100 m in extreme cases (Bahls et al. 2018; Fig. 1). Total 5-year average spring discharge in all aquifers decreased from 249 million cubic meters per year (MCM/year) in 1971–1975 to 136 MCM/year in 2011–2015(MWI and BGR 2019).

Several negative consequences arise from this overexploitation. Because of the large drawdown, water for public water supply and agriculture has to be pumped from ever increasing depths. Boreholes of more than 500 m

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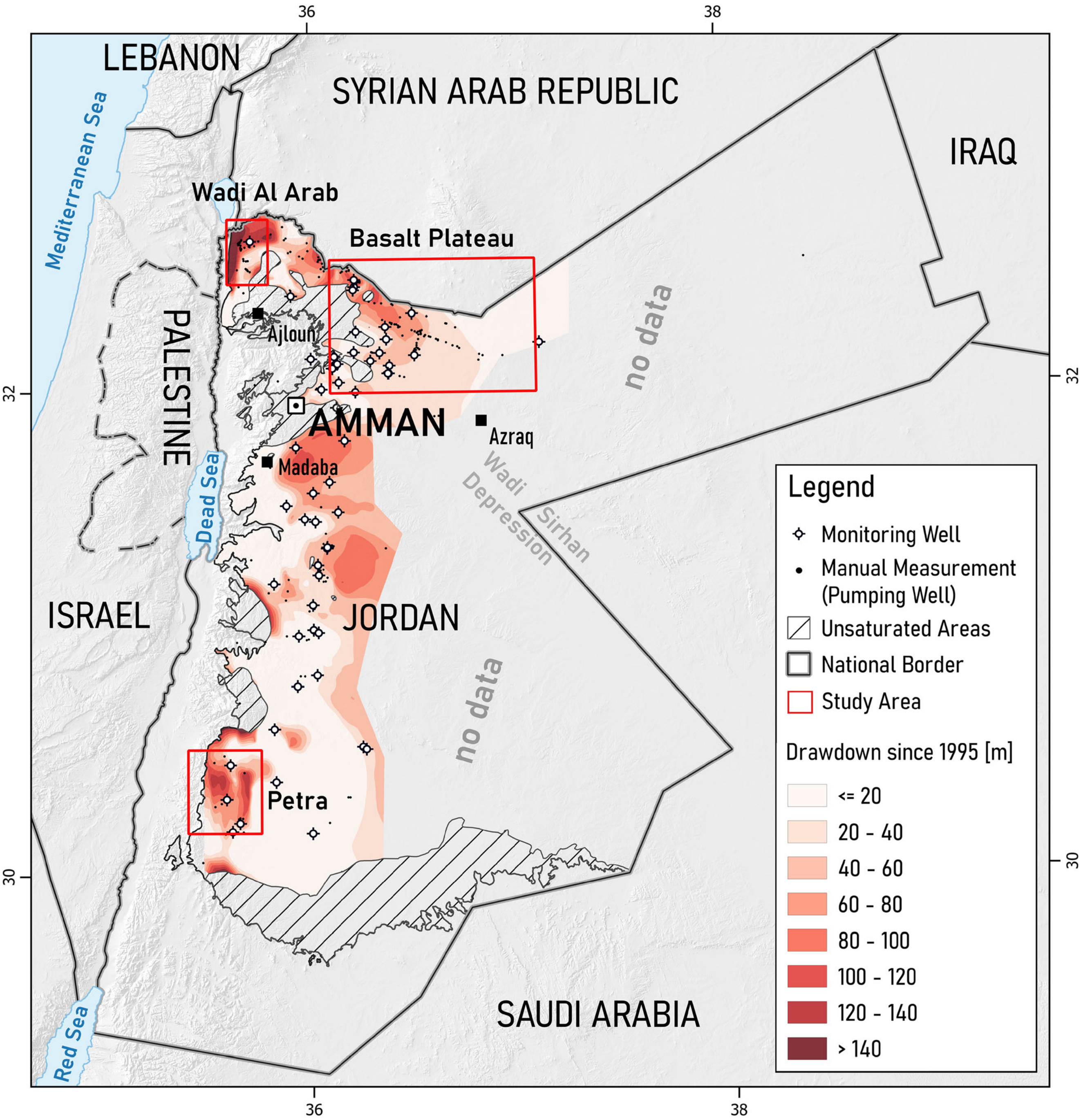


Fig. 1 Locations of case studies discussed in the text and drawdown in the main limestone aquifer (A7/B2) between 1995 and 2017 (modified from MWI and BGR 2019)

depth with a pumping lift of more than 300 m are common in Jordan (MWI 2019). Numerous wells have been drilled to depths of 1,000 m to investigate the potential of deep groundwater, some of which are now used for drinking water production, for example in the Lajjun wellfield in central Jordan (Margane et al. 2010). The electricity needed to pump groundwater already accounts for 15% of the national energy bill (NEPCO 2018). Decreasing water quality due to overabstraction has been reported in some cases (Goode et al. 2013), for example by mobilization of heavy metals due to changing redox conditions (Al Kuisi et al. 2015) or by extraction of deeper, more mineralized groundwater (Salameh 1996; Kaudse 2014). Furthermore, ecosystems are threatened by reduced baseflow and the cessation of spring flow; the most notable example for this being the springs that used to feed Azraq Wetland, an important stop for migratory birds and for ancient trade routes in the eastern desert of Jordan. The wetland is now at only

10% of its original size and is supplied with pumped groundwater (RSCN 2015). Large-scale hydraulic changes caused by overexploitation occur in many aquifers worldwide. Some well-known examples caused mainly by agricultural abstraction include the High Planes and Central Valley aquifers in the United States (Scanlon et al. 2012; McGuire 2017), the North China Plain (Foster et al. 2004; Currell et al. 2012), northern India (Kumar Joshi et al. 2021) and Yemen (Alwathaf and El Mansouri 2012). Hydraulic changes due to rapid population growth are widespread around big urban centers such as Mexico City (Carrera-Hernández and Gaskin 2007) and in many rapidly growing megacities in Asia such as Bankok in Thailand (Lorphensri et al. 2011), Dhaka in Bangladesh (Islam et al. 2021; Khan et al. 2016), Jakarta in Indonesia (Kagabu et al. 2011) and Kolkata in India (Sahu et al. 2013). In addition to the negative effects already mentioned, groundwater resource overexploitation and subsequent groundwater level decline often led to land subsidence in alluvial aquifers (Galloway and Burbey 2011) and seawater intrusion in coastal aquifers (Alfarrah and Walraevens 2018).

In spite of the consequences, attempts to quantify the scale of the problem in Jordan are surprisingly rare: the last comprehensive evaluation of groundwater resources on a (sub-)national scale dates back to the early 1990s for southern Jordan (Hobler et al. 1991) and the mid 1990s for northern Jordan (Hobler et al. 2001). Water budget calculations based on climatic data and official abstraction data widely underestimate the deficit because of limited data. As water management decisions based on these data might therefore not be sufficient, to fill this gap, a comprehensive groundwater assessment study was conducted in 2017 (MWI and BGR 2019). The study was published in 2019 with many supplemental maps, all available online (MWI and BGR 2019). The main output of this is an updated groundwater contour map (Fig. 2). From this map, secondary maps showing groundwater levels since 1995, depth to groundwater and remaining saturated thickness, were derived. Together they form an important basis for the management of groundwater resources in Jordan, showing where wells might fall dry soon and where favourable locations for replacement wells still exist. Groundwater contour lines are also the main input to delineate groundwater catchment zones. The concept of 12 "groundwater basins", introduced in the first National Water Master Plan (Vierhuff and Trippler 1977) is still widely used in literature, without taking into account the changing groundwater flow patterns due to overabstraction.

This report draws on three case studies to show what factors have contributed to the changes since the previous studies and highlight how the results of the new study can be used at the regional level. They represent some of the areas with the greatest drawdown.

Study area

Jordan is located in the northeast of the Arabic Peninsula, and the climate is Mediterranean with hot, dry summers and cool winters. Rainfall occurs only during the winter months and its distribution is mainly controlled by topography and distance to the Mediterranean Sea (Margane and Zuhdy 1995). The Jordan Valley, with elevations of up to 400 m below sea level, receives an average annual rainfall of around 300 mm and has a subtropical climate. Rainfall increases with increasing elevation and reaches up to 600 m/year in the northern Jordanian Highlands. Towards the east and the south, climate is increasingly arid, with 90% of the land area receiving rainfall of less than 200 m/year. Temperatures reach up to 40 °C in summer and can reach less than zero degrees in winter (Margane and Zuhdy 1995).

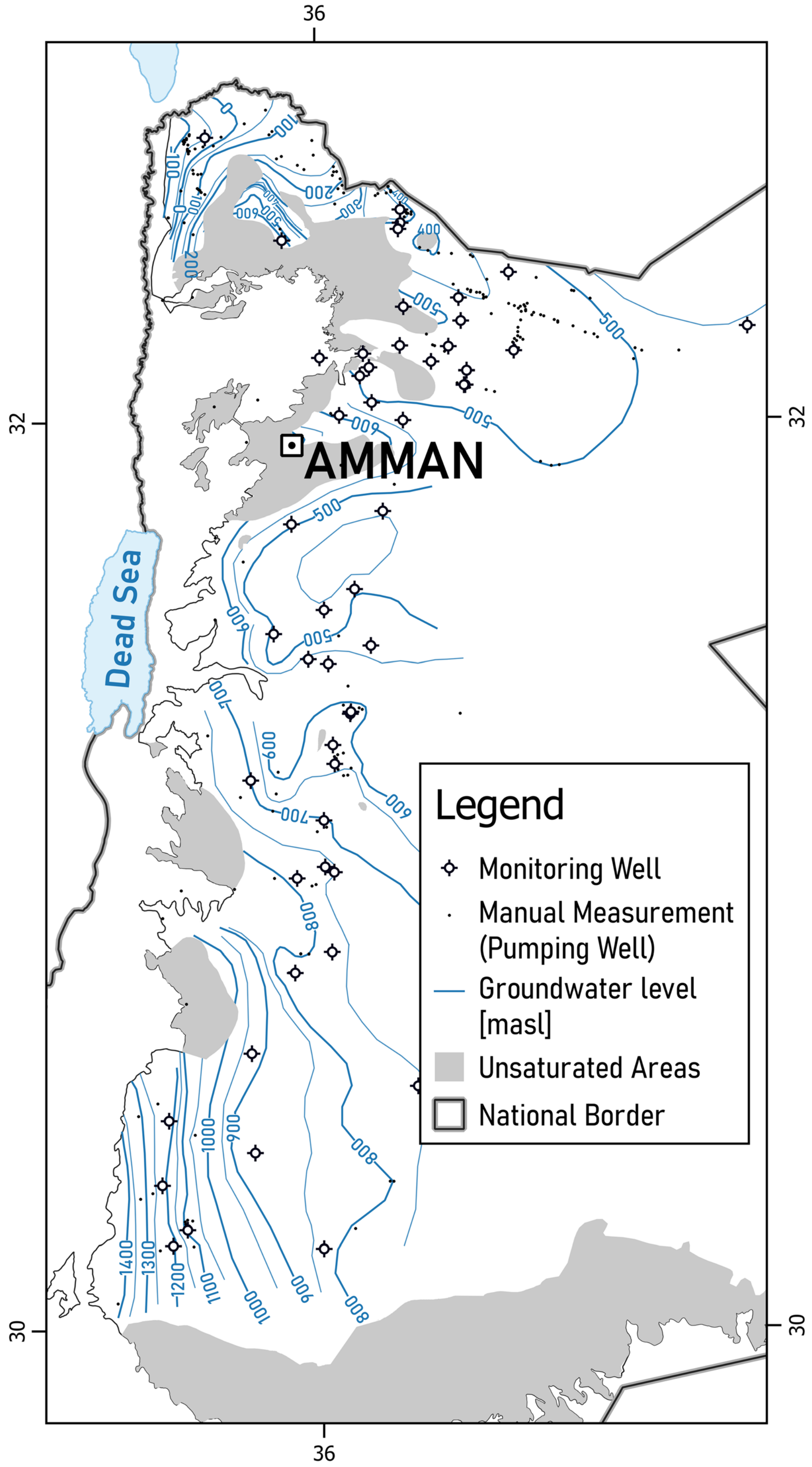
Three main aquifer systems can be differentiated in Jordan. The oldest is a Cambrian to Lower Cretaceous sandstone complex that crops out along the Dead Sea Rift and in southern Jordan. Around 20% of all groundwater in Jordan is abstracted from this aquifer system (Hobler et al. 2001), almost entirely from a single wellfield close to the border of Saudi Arabia, the Disi Wellfield (UN-ESCWA and BGR 2013). Above this aquifer complex lies an Upper Cretaceous Limestone aquifer, locally known as the A7/B2 aquifer. This is the most important aquifer in Jordan, accounting for around 50% of all abstracted groundwater (MWI 2019). The remaining groundwater come from different shallow aquifers, mostly basalt and Eocene chalks, which are becoming less and less important because many of the springs that emerge from them have fallen dry.

The focus on this study is on the main limestone aquifer (A7/B2), which occurs in most of the country with the exception of the southern desert and the escarpment of the Dead Sea Rift. It crops out along the Jordanian Highlands and dips slightly towards the Wadi Sirhan depression in the east (Fig. 1), where it reaches its maximum thickness of up to 2,200 m. The A7/B2 is principally a fractured rock aquifer but there is a moderate degree of karstification where it crops out in zones of higher precipitation, especially in the Northern Highlands. Horizontal hydraulic conductivity is generally between 10^{-6} and 10^{-4} m/s and approximately 10 times higher than vertical hydraulic conductivity (MWI and BGR 2019).

Materials and methods

Groundwater levels in Jordan are measured by the Ministry of Water and Irrigation (MWI), either manually at a monthly interval or by telemetric monitoring stations at a daily interval. Manual measurements are entered into the central database at the Ministry (Water Information System, WIS), whereas telemetric data are transmitted to an online-database (SEBA

Fig. 2 Groundwater levels in the A7/B2 aquifer in 2017. Modified from MWI and BGR (2019)



Hydrocenter). In 2017, the MWI and the German Federal Institute for Geosciences and Natural Resources (BGR) carried out an extensive field campaign to measure groundwater levels, both in monitoring wells for validation ($n = 34$) and in pumping wells stopped for maintenance or rehabilitation ($n = 64$) for a better spatial data distribution. Measurements were used to verify the values the of both the WIS and SEBA databases and data were corrected if there were obvious mistakes such as sudden shifts or outliers. The absolute elevation [m NN] of all measured monitoring and abstraction wells, as well as locations of springs, were remeasured by means of a differential global positioning system (DGPS). In areas where government groundwater data are scarce, data from consultants, water suppliers and drilling companies were also used ($n = 138$). This is particularly the case in eastern Jordan, where population density is low. Where other data were not available, the elevation of springs ($n = 10$) and extrapolated historical data from WIS were used ($n = 22$). For the latter, the linear trend of the last 5 years (2012–2016) was applied.

Groundwater contours were drawn by hand, using the same approach as in the previous studies from the 1990s in order to improve comparability. Furthermore, many factors that influence groundwater levels can be considered, such as topography, structural geology, location of production wells and wastewater treatment plants as well as known flow patterns from local studies (Brückner et al. 2015; Dorsch et al. 2020; Gassen et al. 2013; Margane et al. 2009, 2010, 2015). To calculate the differences between the data of the new and the old maps, groundwater contours were then converted into a continuous surface (raster) using a geographic information system (GIS) environment. For the calculation of depth to groundwater, the raster of the groundwater levels was subtracted from a surface elevation raster (SRTM-1; USGS 2015). Saturated thickness and areas where the aquifer is confined were calculated by combining groundwater levels with rasters of aquifer geometry (Brückner 2018). Groundwater deficit was determined by multiplying the loss in saturated thickness with the corresponding area and the porosity, which is assumed to be between 1 and 3% (Bahls et al. 2018).

Agricultural areas mentioned in section 'Materials and methods' were mapped using the normalized difference vegetation index (NDVI) calculated from Landsat images of August each year (end of dry season) to make sure that these areas are irrigated by groundwater and are not rainfed.

Results and discussion

General overview

Groundwater levels in the A7/B2 aquifer have fallen dramatically in most areas where data have been available since 1995 (Fig. 1). The greatest declines have occurred in the north along the border with Syria, south of the capital Amman and east of the archaeological site of Petra in southern Jordan (Fig. 1). The decline is not constant over time: in many wells, the trend accelerates, reaching up to 10 m/year in 2017. An acceleration of drawdown can be observed in around 30% of all monitoring well time series. In production wells, this percentage is probably higher because some areas of high drawdown are underrepresented by monitoring wells. However, groundwater levels in production wells are not measured routinely, only for specific studies.

Unsaturated areas in the A7/B2 aquifer have increased by around 20% between 1995 and 2017. The loss in saturated thickness corresponds to a yearly average groundwater deficit of between 220 and 665 MCM/year in the A7/B2 aquifer, assuming a porosity between one and 3%, respectively. In contrast, the deficit calculated with reported abstraction data is only between 170 and 210 MCM/year for all aquifers. Only roughly half of this reported abstraction corresponds to the A7/B2 aquifer, so the deficit in this aquifer alone would be significantly lower (MWI 2013, 2015, 2017).

Similar results showing that actual abstraction is higher than official abstraction are reported from other studies. Liesch and Ohmer (2016) estimated groundwater storage losses from GRACE satellite data to be 205 MCM/year on average between 2003 and 2013 in northern Jordan, compared to 145 MCM/year calculated with reported abstraction. In two out of five areas they investigated, the deficit was twice as much as officially reported and in one area even four times as much. Al-Bakri(2016) calculated that documented abstraction for agriculture in 2015 was only 57–83% of crop water demand predicted from remotely sensed cropping patterns, whereas Margane et al. (2015) estimated that actual abstraction might be two to three times as much as officially reported based on loss of saturated thickness.

These discrepancies can mostly be explained with nonrevenue water. Some of the most important issues are illegal abstractions and water theft, missing or false metering and leakage. Illegal wells and water connections have been depicted from satellite imagery by identifying irrigated crops that are far from licensed wells (Al-Bakri et al. 2016). Between 2007 and 2017, 1,443 illegal wells were backfilled by the government (MWI 2017). Fitch (2001) found that although 90% of surveyed farm wells ($n = 156$) in the Amman-Zarqa Basin had a water meter, only 61% worked properly. A survey of bulk water meters ($n = 475$) revealed even worse conditions in the public water supply. A total of 46% of the meters were not working at all and out of the remaining meters, 43% did not measure accurately (USAID 2015). Leakage is common, but difficult to detect due to the intermittent water supply. Grimmeisen et al. (2016) identified water network leakage through high-resolution monitoring of spring flow and composition. According to an analysis in Madaba governorate in central Jordan (Fig. 1), leakage makes up two thirds

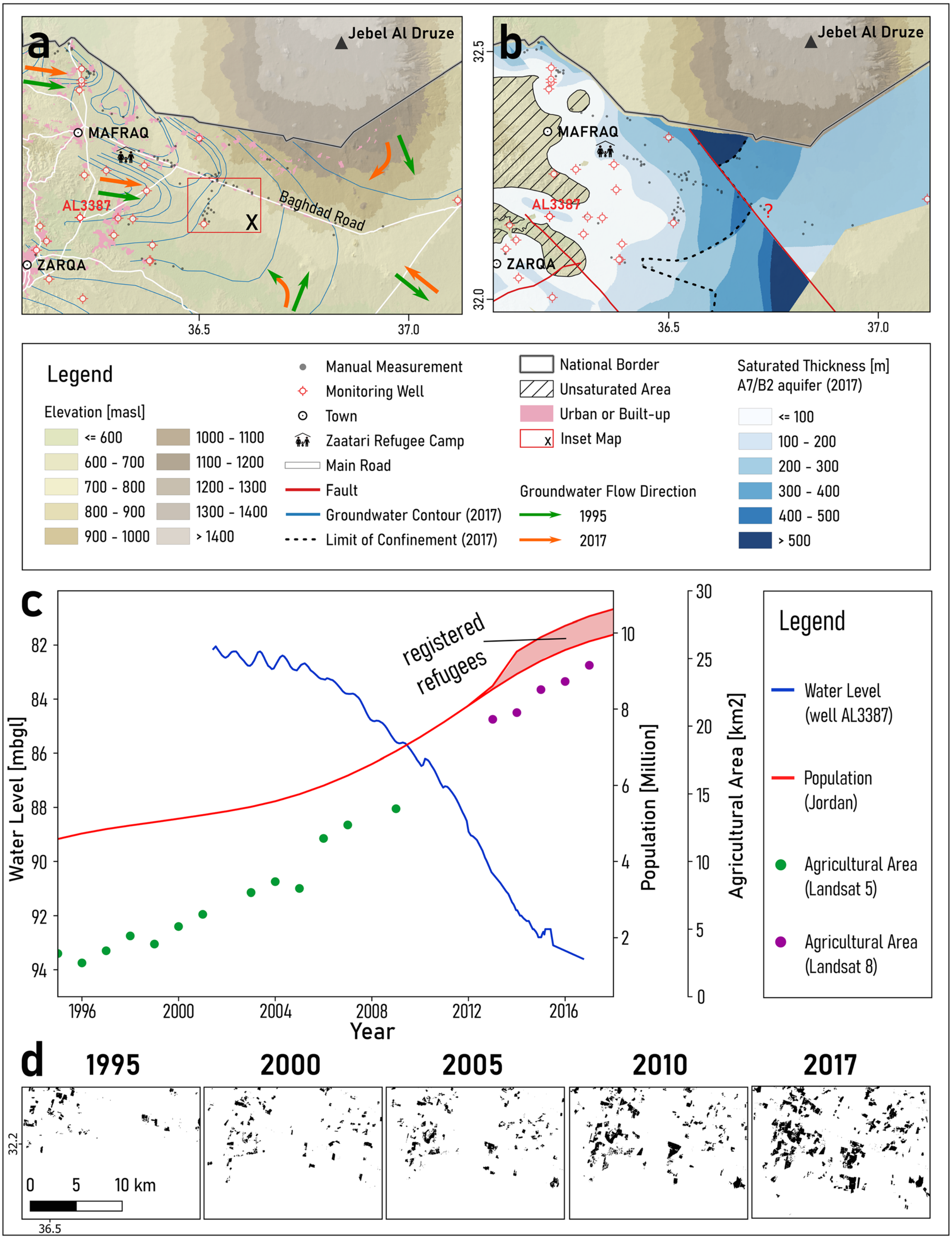


Fig. 3 **a** Change of groundwater flow direction between 1995 and 2017. **b** Unsaturated areas and remaining saturated thickness. **c** Expansion of agricultural areas between 1995 and 2017 in inset map (dots), population growth and registered Syrian refugees (red line) and groundwater level decline as measured in monitoring well AL 3387. **d** Agricultural areas between 1995 and 2017 in inset map

of nonrevenue water in the public water supply, or around 20% of total supplied water (Aboelnga et al. 2018).

The consequences of the groundwater decline vary across regions. Operational costs are increasing due to increased electricity consumption by larger, more powerful pumps and higher pumping lifts. When wells fall dry, replacement wells are often drilled deeper and far away from consumers (W. Taha, personal communication, 2019). The capital Amman receives water from the Amman Water Sewerage Authority (AWSA) wellfield near Azraq, roughly 80 km to the east and from the fossil sandstone aquifer on the southern border, almost 300 km away (and around 800 m lower in elevation).

In the following sections, three case studies are used to highlight different causes and consequences of groundwater over-exploitation. In the basalt plateau of northern Jordan, development of irrigated agriculture led to the decline of groundwater levels and large-scale reversal of groundwater flow directions. In Wadi Al Arab in northwest Jordan, extraction for drinking water supply led to the decline of groundwater levels and change in confining conditions, causing geogenic contamination of the groundwater. Near Petra in southern Jordan, recent recharge is negligible and nearly all extraction is from fossil groundwater. A paleo-groundwater gradient towards the Dead Sea increases the decline of groundwater levels caused by abstraction for agriculture, domestic use and tourism.

Basalt plateau case study

The basalt plateau is a characteristic desert landscape in northeast Jordan. Topography is mostly flat but rises gently towards the Jebel Al Druze Mountain in southern Syria, the main area for groundwater recharge. Smaller hills are formed by volcanic feeder channels, often lined along faults (Fig. 3a). The dark basalt boulders that cover the surface are a product of the erosion of Miocene-Quaternary volcanics (Allison et al. 2000).

Due to a yearly average rainfall of less than 200 mm, and absence of perennial streams or lakes, the area was traditionally populated by nomadic Beduins. The introduction of diesel pumps in the 1980s allowed groundwater-irrigated agriculture (UN-ESCWA and BGR 2013), a practice that was actively encouraged by the government in order to develop the area economically and settle the Bedouins (Fitch 2001). By the 1990s, overabstraction had already become a problem and laws were established to regulate drilling, limit abstraction through licensing and to close illegal wells (Al Naber and Molle 2017a). However, expansion of agriculture in the area is still ongoing (Fig. 3c,d), with a shift towards larger fields and high-value crops, managed by investors for the export market and run by foreign labour, often from Egypt or Yemen (Al Naber and Molle 2017b). Wells for the public water supply of the northern governorates are lined along Baghdad Road that connects Jordan and Iraq (Fig. 3a). Most wells extract water from the main limestone aquifer (A7/B2), which is hydraulically connected to the overlying shallow basalt aquifer in the western part of the study area, forming a combined aquifer. In the eastern part, the two aquifers are separated by the marls of the B3 aquitard (UN-ESCWA 1996). Groundwater-irrigated agricultural areas in the study area have increased more than sevenfold from 3.2 km^2 in 1995 to 24.5 km^2 in 2017 (Fig. 3c,d). The population in Jordan has approximately doubled from 4.8 million to 10 million in 2017 (Fig. 3c). Additionally, Jordan hosts more than 600,000 Syrian refugees, around 20% of which live in the study area, putting additional stress on the water resources. However, the accelerated decline of groundwater resources predates the onset of the Syrian Civil War in 2011 by several years. As an example, the monitoring graph of observation well AL3387 is shown in Fig. 3c, where the acceleration of the decline started in 2007.

The updated groundwater contour lines suggest that a regional drawdown cone has formed around the agricultural zone north of the city of Mafraq, which leads to a total reversal of groundwater flow direction in the eastern part of the area (Fig. 3a) compared to that in 1995. This means that groundwater catchment zones change with declining groundwater levels. The static concept of “groundwater basins” (Vierhuff et al. 1977) does not take this into account because it was developed before widespread overabstraction occurred. In addition, the concept does not consider the different aquifer systems. It has been shown that significant leakage occurs between the aquifer systems—all groundwater eventually reaches the deep sandstone aquifer and flows towards the Dead Sea—the deepest drainage level on earth. Instead of “groundwater basins”, it is recommended to use individual aquifers or aquifer systems as a point of reference.

Depth to groundwater level increases from around 100 m in the south of the study area to 500 m on the slopes of Jebel al Druze near the Syrian border. In the public water supply wells along Baghdad Road, depth to groundwater level is mostly between 250 and 300 m. The saturated thickness map (Fig. 3b) shows the remaining saturated thickness and areas where the A7/B2 aquifer has already fallen dry (unsaturated areas). Many wells located in areas with less than 100 m saturated thickness are suffering from low productivity or might fall dry in the near future, among them three wells drilled for the water supply of Zaatari refugee camp, the biggest refugee camp in Jordan (van der Helm et al. 2017).

Wadi Al Arab wellfield case study

Wadi Al Arab is a valley close to the confluence of the Jordan River and the Yarmouk River in the northwestern part of Jordan (Fig. 4a). The wellfield is located just upstream of the homonymous dam (Fig. 4b), which lies at an elevation

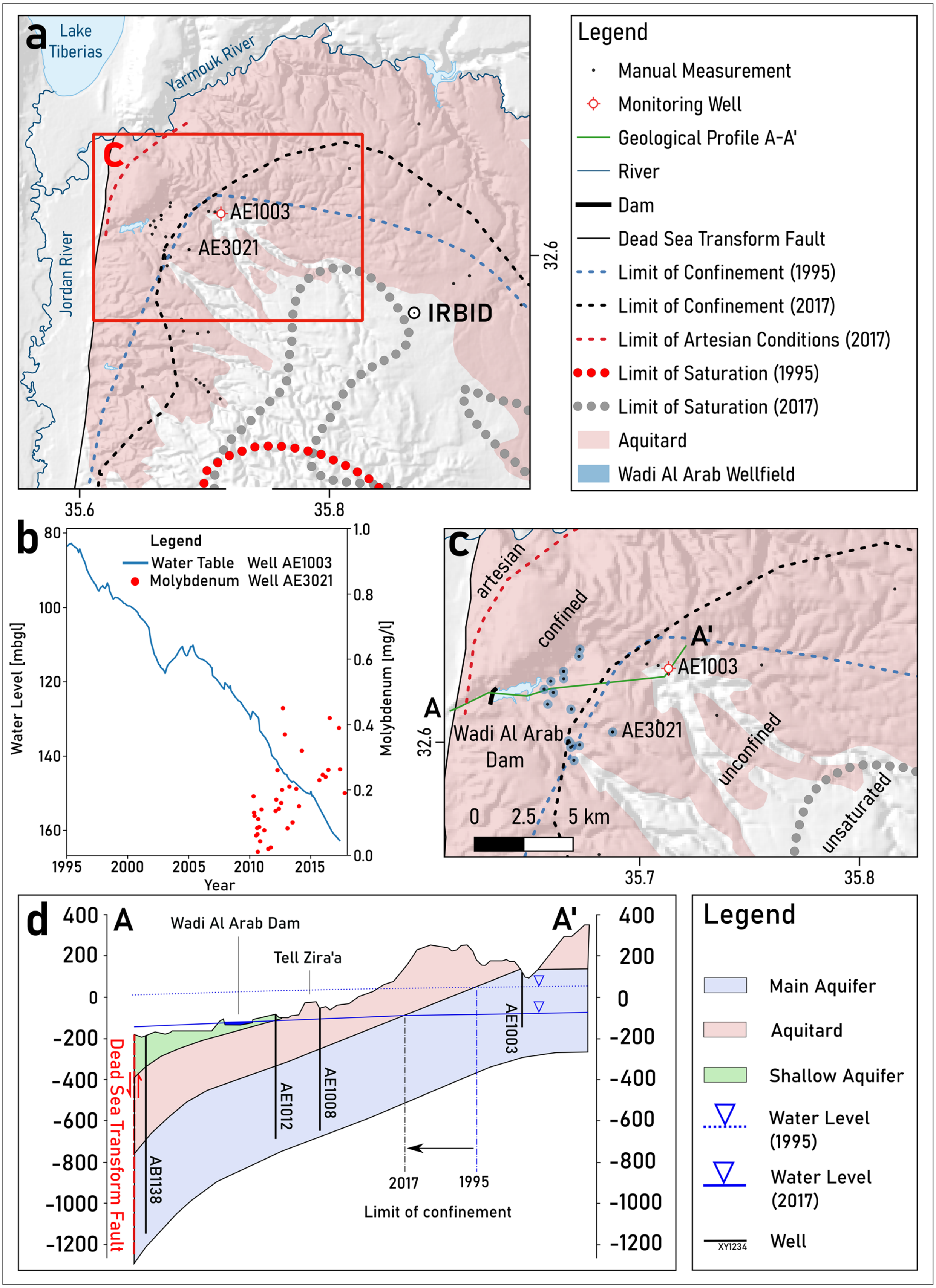


Fig. 4 **a** Wadi Al Arab Wellfield. **b** Groundwater levels in monitoring well AE1003 and molybdenum concentrations in well AE3021 (Dorsch et al. 2020). **c** Regional hydraulic conditions. **d** Hydrogeological profile A–A′ (**c**)

of 100 m below sea level. Recharge comes mainly from the Ajloun Highlands south of the study area which receive an annual mean precipitation of up to 550 mm, the highest recorded in Jordan. Rödiger et al. (2014) determined that average recharge in the area is 12% of precipitation with a hydrological model calibrated with different independent data sets.

Wadi Al Arab wellfield (Fig. 3c) provides around 40% of the drinking water supply of Irbid (Alqadi et al. 2019), one of the biggest cities in Jordan with almost 1 million inhabitants (DoS 2019). When the wellfield was established in 1982, six out of nine wells of Wadi Al Arab wellfield were artesian; however, only a few years after production started, groundwater levels started to fall and spring flow in the area ceased almost completely (Subah and Hobler 2006). Nowadays, groundwater-level decline rates in the wellfield are among the highest in Jordan. The closest monitoring well AE1003, located 5 km upstream of the wellfield (Fig. 4a,c), shows a decline of 3 m/year with a seasonal variation of around 1 m (Fig. 4b). Measurements in production wells switched off for maintenance revealed that decline rates in the wellfield are actually up to 10 m/year(Dorsch et al. 2020).

Consequently, the aquifer is becoming increasingly unconfined. Further downstream towards the Jordan Valley, artesian conditions still prevail (Fig. 4a,c,d). Patterns of stable isotopes in water samples show that water bypasses the aquitard and mixes with groundwater in the Jordan Valley (Salameh 2004), possibly via the Dead Sea Transform Fault.

The changing hydraulic conditions from confined to unconfined have implications on water quality: downward leakage from organic-rich sections in the overlying aquitard is assumed to be the main cause of rising concentrations of molybdenum (Al Kuisi et al. 2015) and heavy metals (Dorsch et al. 2020). For now, the water supplier achieves drinking water quality through dilution with water from nearby Tabaqat Fahel wellfield (Subah and Hobler 2006), but if more wells are affected, costly treatment is inevitable. Sealing the aquitard during well construction is likely to reduce concentrations but is not common practice yet. In the future, this process could affect large parts of northern Jordan that have a similar hydrogeological setup (Fig. 4a). Apart from the quality problems, hydrogeological conditions in the wellfield are favourable, with a depth to water table of around 100 m and remaining saturated thickness of around 350 m in most of the wells.

Petra case study

The ancient city of Petra is located midway between the Dead Sea and the Red Sea on top of the eastern graben shoulder of the Dead Sea Rift Valley. Petra was carved into sandstones that are overlain by the limestones of the A7/B2 aquifer east of the city in the Jordanian Highlands. West of Petra, topography falls off steeply towards the Rift Valley (Fig. 5a). Average yearly rainfall reaches up to 200 m/year in the higher elevations of the study area but decreases to less than 50 m/year towards the east (Fig. 5b). Hobler et al. (1991) determined recharge to be 10% of rainfall in areas where annual rainfall exceeds 300 m/year based on groundwater modelling. According to Hobler et al. (1991), the proportion of recharge then decreases slightly with decreasing rainfall, and in areas where rainfall is less than 75 m/year, there is essentially no recharge. Due to the steep topography around Shobak in the northern part of the study area, the proportion of recharge might be even less due to high surface runoff. This means that nearly all groundwater in the study area is fossil groundwater. As early as 300 Before Common Era (BCE), the ancient Nabateans channeled water from nearby springs to the rock-carved city of Petra as part of their elaborate water supply system for the city (Ortloff 2005). Nowadays, nearly 1 million people visit the ruins every year, generating significant income, but also putting additional stress on the water resources. (Fig. 5c).

Groundwater levels have dropped more than 90 m in the center of the study area since 1995 (Fig. 5b). In addition to the seasonal variation of 1 m/year, the monitoring graph of well G1346 shows a sustained decline of 3 m/year that increases to 5 m/year from around 2007 (Fig. 5c). Groundwater flows eastwards due to aquifer geometry, and it reaches the lower sandstone aquifer through leakage where it flows west towards the Dead Sea (Salameh and Udluft 1985; Fig. 5a). This flow pattern is closely connected to paleoclimate and tectonics: around 15,000 years ago, regional climate was humid and the Lisan paleolake occupied a large portion of the rift valley (Levy et al. 2019; Fig. 5a). Sedimentary records show evidence for a large wetland around 50 km east of Petra, now completely dry, that used to cover roughly half the size of Lisan Lake, indicating a water table significantly higher than today (Mischke et al. 2015; Fig. 5a). Since then, climate has been roughly similar to today, with the exception of two shorter and less intense humid periods at ca. 10,000 and 5,000 BP, respectively. As a result of the changing climate, the water level of Lake Lisan—drainage level for both surface water and groundwater—dropped by 200 m and the lake separated to form the Dead Sea and Lake Tiberias. The steeper gradient results in an increased outflow of groundwater towards the Dead Sea. Groundwater modelling indicates that a new equilibrium is not reached yet and water tables are still declining because of this (Hobler et al. 1991). Over the last decades, the water level of the Dead Sea has been declining at a rate of almost 1 m/year(Fig. 5c). The saltwater–freshwater interface is also retreating due to the decline, causing additional inflow of groundwater. Salameh and El-Naser(2009) calculate that an additional inflow of 461 MCM groundwater is needed every year to make up for the loss of saltwater and

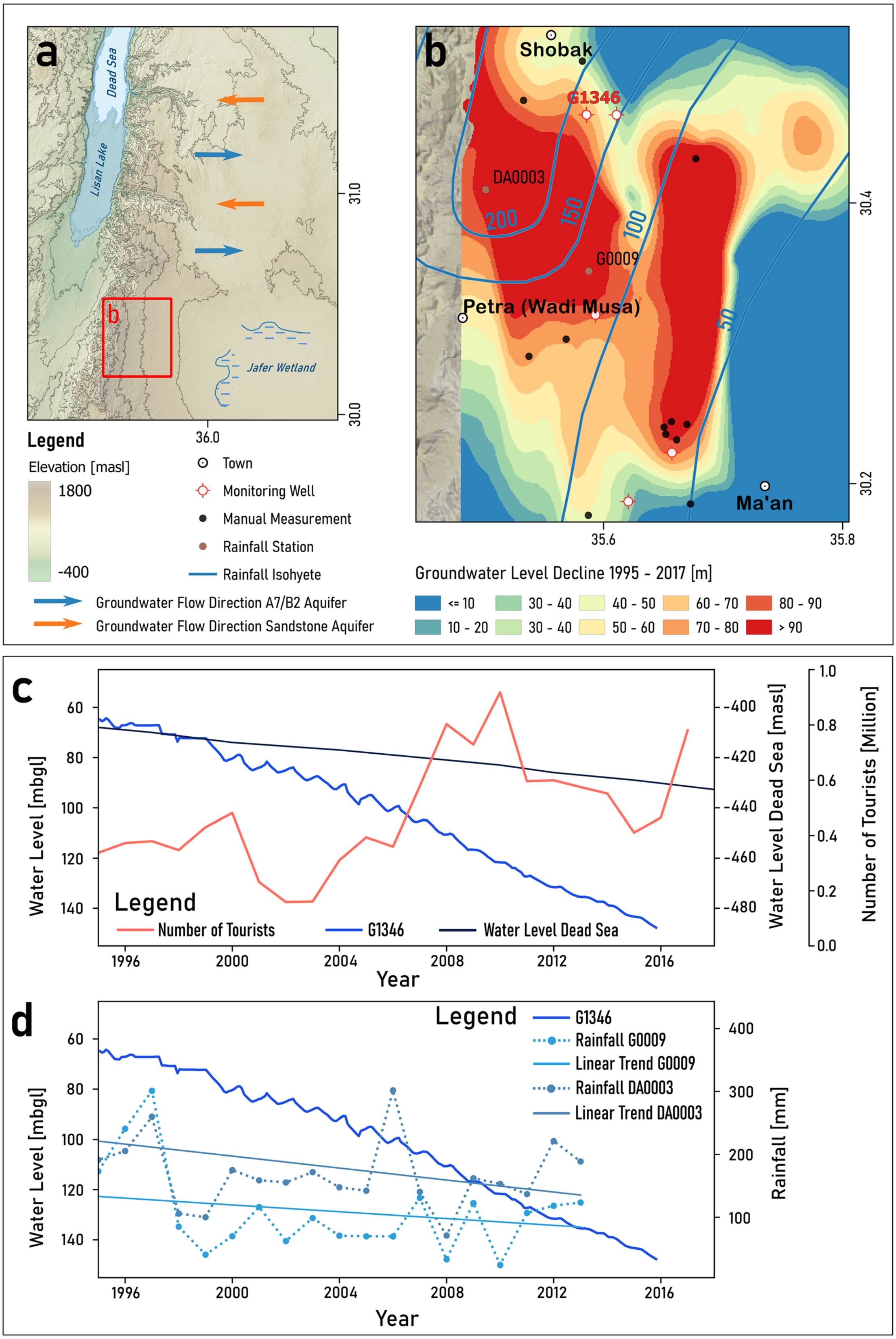


Fig. 5 **a** Location map, paleohydrological features (modified from Levy et al. 2019; Mischke et al. 2015) and regional groundwater flow direction. **b** Groundwater level decline between 1995 and 2017 and average annual rainfall (WIS database). **c** Time series of decreasing groundwater and Dead Sea water level, compared to the increase in number of tourists. **d** Time series of groundwater levels (G1346 monitoring well) and rainfall

reach hydrostatic equilibrium. In addition, sinkholes form where the freshwater dissolves salt layers that were previously saturated with saline groundwater (Yechieli et al. 2016).

Climate change is another factor that decreases water availability: the two rainfall stations in the study area show an average decline of around 1.5 m/year (G0009) and 4.5 m/year (DA0003) over the last 25 years (Fig. 5d). A similar trend can be observed in the rest of Jordan: Rahman et al. (2015) report an average decline of 0.41 m/year from 58 stations in Jordan over 44 years. Projections of future climate predict the trend to continue along with rising temperatures, thus further decreasing recharge (MoE and UNDP 2014). As of 2017, the average depth to water table in this study area is around 100 m, with about 200 m of remaining saturated thickness.

Methodological challenges and limitations

In addition to the results, important observations about groundwater monitoring were revealed during analysis. The quality of monitoring data in Jordan varies from excellent, long-term data series to short series with jumps, gaps, and shifts that can often be related to the introduction of telemetric monitoring (and the end of manual measurements) starting in 2010. The main deficit is the absence of quality control before data are entered into the database; thus, extensive and time-consuming selection, validation, and cleaning of data is necessary to ensure their usefulness. The most common errors identified were data entry errors in the case of manual measurements and wrong calibration, low battery power, vandalism and sensors above the groundwater level in the case of telemetric measurements. Coordinates and elevation of wells are frequently inaccurate: instead of measuring coordinates in the field, they are often read from a map. Furthermore, the proposed location of a well is often entered into the WIS database, rather than the location where the well was actually drilled. In telemetric wells, outlier values and sensor drift are common. Due to financial constraints, monitoring wells are usually not purposely built. Instead, decommissioned, low yield pumping wells with questionable connection to the aquifer and/or unknown well design are converted into monitoring wells. In some cases, they are not far away from active pumping wells and do therefore record dynamic groundwater levels instead of the natural groundwater level. Extrapolation of historical data has to be used carefully, because trends and seasonal variations are not systematic and can vary significantly between areas. Although the approach of drawing contour lines manually results in a more accurate representation of the hydrogeological setting, it is based on expert judgement and thus difficult to reproduce. Some of the differences between the maps from the 1990s and the 2017 update might be caused by the different interpretation of data.

Conclusions

The first comprehensive groundwater assessment in Jordan since the 1990s (MWI and BGR 2019) reveals dramatic groundwater level declines in large parts of the country. Validated data from monitoring wells and other sources give a continuous picture of the groundwater situation in large parts of Jordan's main aquifer, including flow directions, saturated thickness and drawdown since 1995.

Three case studies illustrate the major causes and consequences of long-term overabstraction, whereby in the basalt plateau, groundwater-irrigated agricultural areas increased more than sixfold since 1995, while the population of Jordan has doubled during the same time. Due to the increased groundwater abstraction, groundwater flow direction has changed significantly and decreased saturated thickness affects well yields. In Wadi Al Arab wellfield, hydraulic conditions are increasingly becoming unconfined due to the high drawdown. This is suspected to be one of the main drivers for the downward leakage of geogenic contaminants from the overlying aquitard. Around Petra, recharge is much lower than abstraction due to the arid climate. The abstracted groundwater is mostly fossil groundwater from the last humid period, leading to large drawdowns. The drivers of groundwater decline are often overlapping and difficult to separate from each other. Nevertheless, the analysis of groundwater monitoring data can help to identify important gaps in data—for example, the abstraction from agriculture is likely underestimated by a factor of at least two. The set of maps presented in this study—groundwater contours, saturated thickness and average groundwater-level decline rate—provide key information to decision-makers, researchers, and the general public. The update of groundwater data shows that large changes have occurred which make it necessary to also update conceptual models such as the concept of Jordan's 12 "groundwater basins".

In addition to the results from the assessment, a thorough analysis of the monitoring network and data revealed several shortcomings. Although the monitoring network in Jordan is extensive, there are still some gaps, especially in the east of Jordan and in the highlands where not many wells exist. In some areas, monitoring wells are located too close to pumping wells or other monitoring wells. Consequently, it was necessary to use several additional data sources to produce the maps. Locations of monitoring wells and time series were corrected in the database. Due to shifts and sensor problems, telemetric wells should be checked against manual measurements at least twice a year to check their accuracy. In order to produce groundwater assessments more frequently in the future, data quality control and quality assurance are critical to decrease the time needed for data cleaning and validation.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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