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Groundwater Resource Assessment of Jordan (2017)

Ministry of Water and Irrigation (MWI)
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This document was mainly elaborated based on information currently available in the database of the MWI or provided by third parties. Additionally, new data were gathered during field work in 2017. The findings of this study result from the analysis of available information in combination with newly gathered field data. **Because it is not possible to validate the historical information, no warranty can be given for the accuracy or veracity of the results of this study.**

LAYOUT

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COVER PHOTO

Wadi Mujib in the Madaba Governorate, 2018. In the center, the Mujib dam and in the background the A7/B2 hydrogeological unit overlaying the A1/6 layers. Source: Bashar Tabbah, www.mapandlens.com

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Foreword

Prof. Dr. Ralph Watzel

President, Federal Institute for Geosciences and Natural Resources

(Source: BGR)

Being one of the German implementing agencies for technical cooperation on behalf of the German Federal Ministry for Economic Cooperation and Development, the Federal Institute for Geosciences and Natural Resources (BGR) conducts currently more than 25 projects in countries throughout the world. Of these, there is no other country in which BGR has been longer active as in the Hashemite Kingdom of Jordan. Over the years, BGR has built very fruitful and trustful partnerships with our Jordanian partners.

It is a great pleasure for me to commemorate 60 years of successful international cooperation between BGR and the Hashemite Kingdom of Jordan. Areas and partners of cooperation have changed over the years. Activities in the early years concentrated on geological surveys and the exploration of oil shales. For the last thirty years, the focus has shifted more and more towards groundwater management and protection.

Jordan is one of the most arid countries in the world. Due to very limited surface water resources, it is heavily dependent on groundwater. BGR has and will assist the Jordanian Government – especially through our main cooperation partner, the Ministry of Water and Irrigation (MWI) – in building knowledge and awareness about Jordan's precious but limited groundwater resources, as well as strengthening the management skills for the best use of this resource of great strategic importance for the countries water security.

This publication assesses the current groundwater status in Jordan and compares it to the situation in 1995. I am convinced that this updated baseline on groundwater resources is a valuable source of information for everybody active in the water sector of Jordan and that it will support informed decisions in response to the challenges in Jordan's water supply.

On behalf of BGR, I would like to thank all our Jordanian partners for the long and trustful cooperation and look forward to keeping up our good and fruitful relationship with the Hashemite Kingdom of Jordan also in the future.

Prof. Dr. Ralph Watzel
President, Federal Institute for Geosciences and Natural Resources

H.E. Eng. Raed Abu Soud

Minister of Water and Irrigation

(Source: MWI)

It is highly evident and well known that water resources in Jordan are very scarce. All previous strategic studies and official documents have identified that scarcity of water resources is one of the major barriers facing sustainable development in Jordan that will be further magnified by the impacts of climate change, drought and other socioeconomic circumstances.

The availability of information regarding water resources is one of the most important determinants when dealing with this situation and the development of strategies, policies and plans. Information availability contributes to making the right decisions and helps all concerned sectors to understand and accept the decisions that will impact development and growth of this sector.

Consequently, considering the water scarcity challenges and to achieve our goal of the successful integration of Jordan's water resource development and management practices, the Ministry of Water and Irrigation has been active in issuing reports and studies that improve the understanding of our existing water resources and provide information to all stakeholders.

In the light of 60 years German-Jordanian Cooperation, the MWI would like to thank the German people and the German Government for their continues support and especially the BGR for their longlasting and highly valuable assistance. Personally, I am thankful to the whole team of BGR and MWI for putting great efforts to enhance the availability of information about Jordanian water resources.

We hope that the published information will assist the stakeholders in the water, public and private sectors and the public that may have an interest in the water sector.

H.E. Eng. Raed Abu Soud
Minister of Water and Irrigation

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Source: BGR

EXTENDED EXECUTIVE SUMMARY

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Extended Executive Summary

Jordan is one of the most water-scarce countries in the world, and groundwater is the main source to meet domestic, industrial and agricultural water demands. Significant groundwater abstractions have resulted in declining groundwater levels within nearly all aquifers, which is evidence that the abstraction rates exceed the natural recharge. The observed substantial decline in groundwater levels began in the 1980s and has been exacerbated by increased abstraction to address the water demands of a growing population and intensified agricultural development in recent decades.

Source: BGR

The last comprehensive nationwide study of groundwater resources was conducted in the 1990s by the BGR (Margane & Hobler, 1994, Hobler et al., 1991). Since then, only local studies of different topics have been performed. In 2016, the BGR and MWI made efforts towards updating groundwater information for the entire country, involving all of the aspects needed to assess the current groundwater conditions. These activities focused on groundwater quantity rather than quality. This book comprises the main outcomes of the many tasks involved in this comprehensive study, including structure contour maps (SCM) and cross-sections of the subsurface aquifer systems, groundwater contour maps, several thematic maps, such as the depth to groundwater and saturated thickness, and an evaluation of all springs in Jordan. Various decision support tools were developed, including a nationwide groundwater model that was coupled with a nationwide WEAP model to predict the outcomes of different groundwater resource management decisions as well as a vulnerability map that highlights areas where groundwater resources require a high level of protection.

To assess the overall groundwater conditions, it is necessary to understand the aquifer geometry. Subsurface information is needed to estimate the probability of encountering water as well as the costs of well construction when siting a new borehole. Therefore, updating the SCMs was among the first project activities undertaken (Chapter 3). SCMs are two-dimensional representations of the surface elevation of each geological unit and are based on available borehole information. Nationwide SCMs were first produced in 1995, combining the findings for southern (Hobler et al., 1991) and northern (Margane & Hobler, 1994) Jordan. Many new wells have been drilled since then, and the SCMs urgently needed to be updated. The new maps show the estimated bases of the major hydrogeological units and serve as an important tool for new borehole planning, resource estimations (Chapter 4) and groundwater vulnerability mapping (Chapter 8). In addition, separate maps for the A3, A4 and A5/A6 formations were developed for the first time.

All available geological and hydrogeological drilling data were collected and analyzed to update the SCMs (Chapter 3.2) and draw new subsurface cross-sections (Chapter 3.1.3). Unfortunately, the WIS data quality is often limited. There is no system in place for quality control to prevent data entry errors. The coordinates and elevations are frequently incorrect or inaccurate, and systematic errors derived from coordinate conversions occur. Additionally, neighboring boreholes often have conflicting lithological information. Therefore, other data sources were used when available, including drilling reports from water suppliers, drilling companies and oil, oil shale and uranium exploration boreholes. These are generally well documented and often include geophysical logs that allow cross-checking of geological descriptions. Drilling records for the numerous private water wells from the WAJ database were not used because of their low data quality.

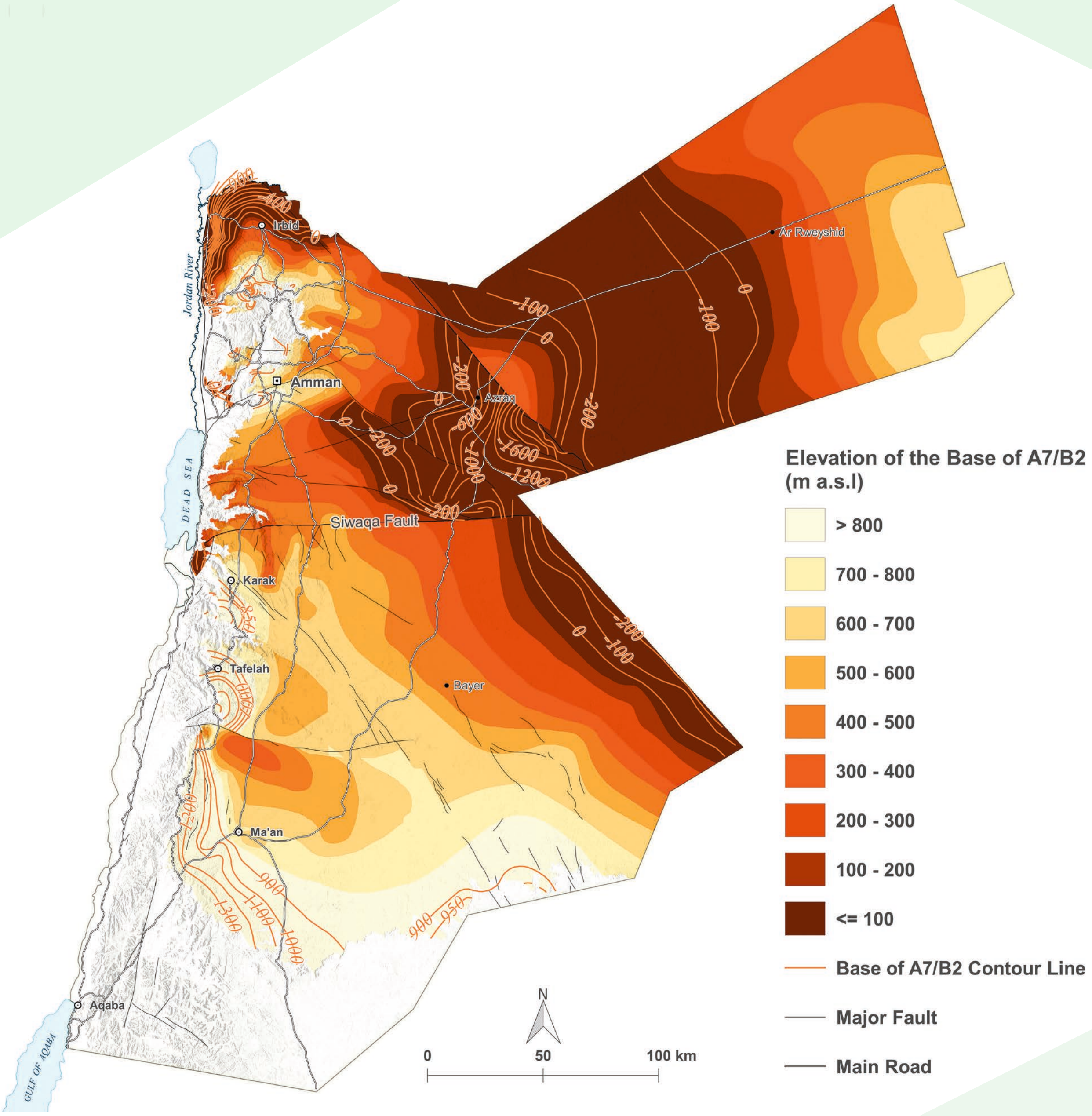


Figure 1 Structure contour map of the A7/B2 aquifer

In summary, the hydrogeological units with updated structures (A1/A2 and younger) are as follows:

- The deep sandstone aquifer system consists of several units: Ram, Khreim, Zarqa and Kurnub. The Ram Group is an important porous aquifer that extends across all of Jordan and dewaters towards the Dead Sea (Chapter 3.2.1). The name “Disi Sandstone” is sometimes used in reference to this group, although it is simply one of the formations in the Ram Group. In this book, the name Ram/Disi aquifer is used when referring to the Ram Group. In western Jordan, the Kurnub aquifer (Chapter 3.2.4), which increases in thickness to the northeast (Barthelemy et al., 2010), directly overlies the Ram/Disi aquifer and forms a combined aquifer complex (Margane et al., 2002). However, in eastern Jordan, the low-permeability Silurian Khreim Group (Chapter 3.2.2) separates the two sandstone aquifers. The Permian to Triassic Zarqa Group (Chapter 3.2.3) forms a minor aquifer that is hydraulically connected to the Kurnub sandstone in some areas.

- At the country scale, several formations in the Upper Cretaceous Ajlun Group are usually grouped together as the “A1/A6 aquitard”. However, the A1/A2 and A4 aquifers are important for local water supply, especially in areas where the overlying A7/B2 aquifer has nearly dried up. The A3, A4 and A5/A6 units cannot be distinguished from each other south of the Siwaqa Fault. The Naur Limestone aquifer (A1/A2) thins from nearly 300 m thick in the north to approximately 150 m thick in Wadi Mujib and only 25 m thick at the Ras en Naqb escarpment in the south (Chapter 3.2.5). In general, the A1/A2 and overlying formations dip gently to the east due to the uplift of the Dead Sea Rift graben shoulders. The A3 aquitard (Fuhais Formation) has an average thickness of approximately 50 m and thins to the south (Chapter 3.2.5.2), and it structurally follows the underlying A1/A2 Formation. There are no indications of the A3 aquitard in the lower Zarqa River, the Baqa’a Valley northwest of Amman or between Amman and the northern Dead Sea. East of the Fuluq Fault, there are no data about the presence of the A3 aquitard. Due to facies changes, the borders between A3, A4 and A5/A6 are unclear south of the Siwaqa Fault, and these units are mapped as one unit. The thickness of the A4 aquifer (Hummar Formation) is comparable to that of the A3 aquitard (Chapter 3.2.5.3), and it discharges though several springs. This aquifer is hydraulically connected to the underlying A1/A2 aquifer or the overlying A7/B2 aquifer due to faulting and karstification (Brückner et al., 2015; Margane et al., 2009; Subah & Hobler, 2004). The A5/A6 aquitard, or Shueyb Formation (Chapter 3.2.5.4), separates the A4 aquifer from the overlying A7/B2 aquifer, although there is some evidence that this separation does not always exist, likely due to karstification (Brückner et al., 2015).

- The A7/B2 aquifer consists of three formations from the Upper Cretaceous Ajloun (Wadi as Sir) and Balqa (Wadi Umm Ghudran and Amman-Al Hisa) Groups. Most of the wells that fully penetrate the A7/B2 aquifer are located in northern Jordan between Amman, Mafraq, and Ajloun. The thickness increases towards the Sirhan Graben, where it can reach 2200 m (Chapter 3.2.6). The units generally dip towards Wadi Sirhan and away from Ajloun Dome (Figure 1), which is a prominent structural high in northern Jordan.

- The Paleogene B3 (Muwaqqar) aquitard is the most important aquitard in Jordan. Most of the proven oil shale reserves in Jordan are located in the lower part of this formation due to locally elevated contents of bitumen (Ziegler, 2001). Because the majority of the water wells in Jordan tap the underlying A7/B2 aquifer, the base of this formation is generally well documented (Chapter 3.2.7).

- The Paleogene B4 (Umm Rijjam) and B5 (Wadi Shallala) formations form a combined aquifer at the regional level, although the marls in B4 can act as aquitards in some areas (Margane & Hobler, 1994). The average thickness of the B4/B5 is approximately 230 m, and the maximum thickness of 970 m, including the overlying alluvium, is located in the Sirhan Graben (Chapter 3.2.8).

- The Harrat Ash Shams basalt (Tertiary to Quaternary) is the Jordanian part of the North Arabic Volcanic Province. The greatest thickness of approximately 1500 m is located at the Jebel al Arab volcano (1803 m asl) in Syria, and the thickness decreases to the south (Chapter 3.2.9), with a maximum estimated thickness of 500 m in Jordan (Margane et al. 2002), as shown in Figure 2. Jebel Mountain is the main recharge area for the basaltic aquifer. The groundwater flow is highly anisotropic with higher horizontal conductivities between the individual 3-m- to 25-m-thick lava flows (BGR/ESCWA, 1996) that host local perched aquifers. The basalt is hydraulically connected to the underlying formations in some areas through faults and cooling cracks that allow downward leakage. Several important wellfields for the water supply of Amman are located in this basalt, including the Aqeb and Corridor wellfields (Borgstedt et al., 2007).

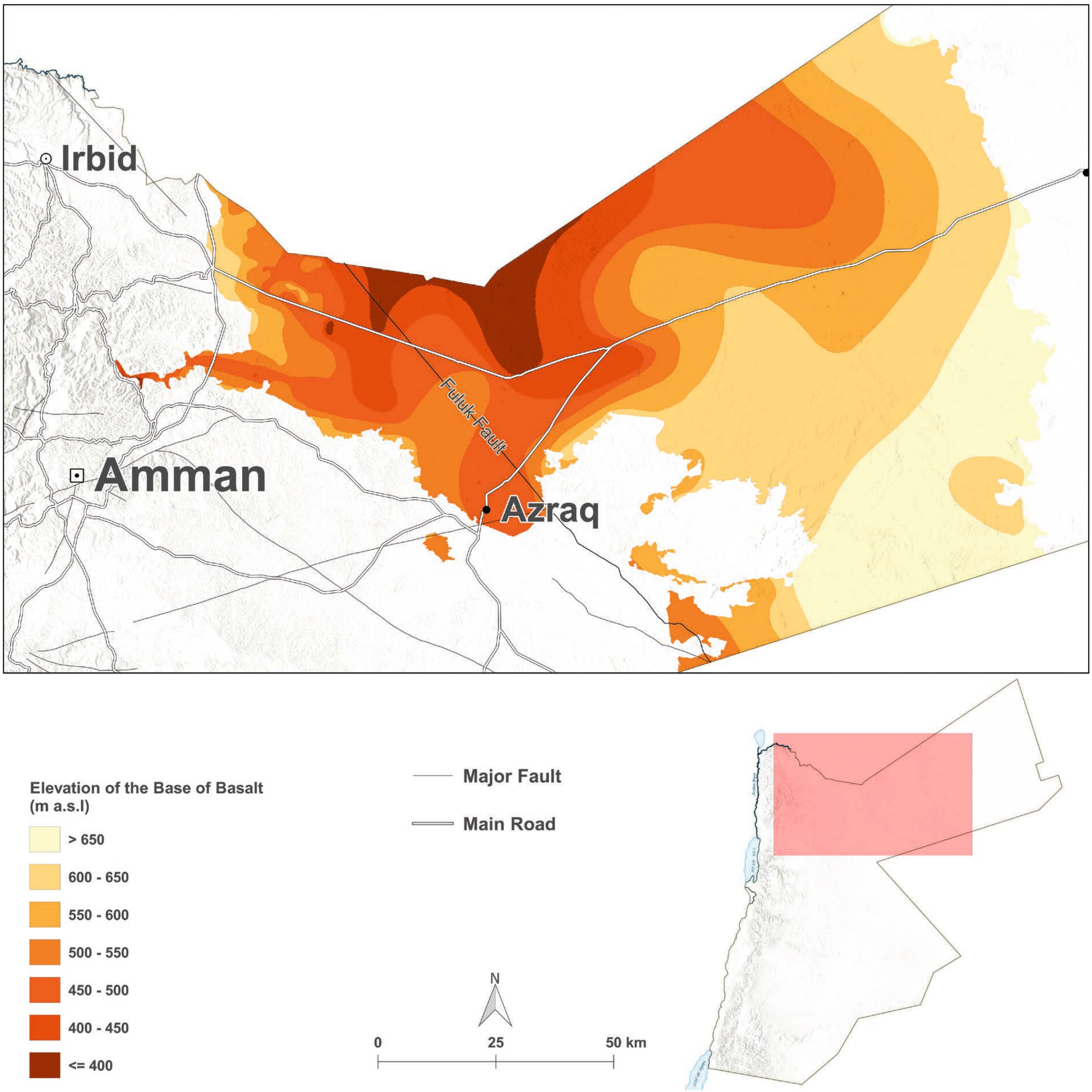


Figure 2 Structure contour map of the Basalt aquifer

Based on the updated digital SCMs, new cross-sections (Annex 2, Figure 3) of the subsurface were drawn at a horizontal scale of 1:322000 and a vertical exaggeration of 1:25. Due to data gaps, only the upper part of the aquifers and major faults are displayed. Depressions and bulging areas in the SCMs are indicated, which could potentially be the result of tectonic shifting; however, faults are not plotted. When using SCMs or cross-sections for hydrogeological exploration, the shortcomings of the data and tools must be considered.

After updating the structural subsurface information, the BGR supported the MWI to assess the current groundwater resources of Jordan. Furthermore, the changes in the groundwater conditions were evaluated using the last comprehensive study from the 1990s as a baseline reference (Chapter 4). One of the main outputs is the 2017 groundwater level contour map for the A7/B2 aquifer in addition to the first groundwater level contour map of the A1/A2 and A4 aquifers. A groundwater contour map was also developed for the deep sandstone aquifer system. Additional thematic maps, such as a depth to groundwater map, saturated thickness map, and map of the difference in groundwater levels from the 1990s to 2017, were derived from these main maps.

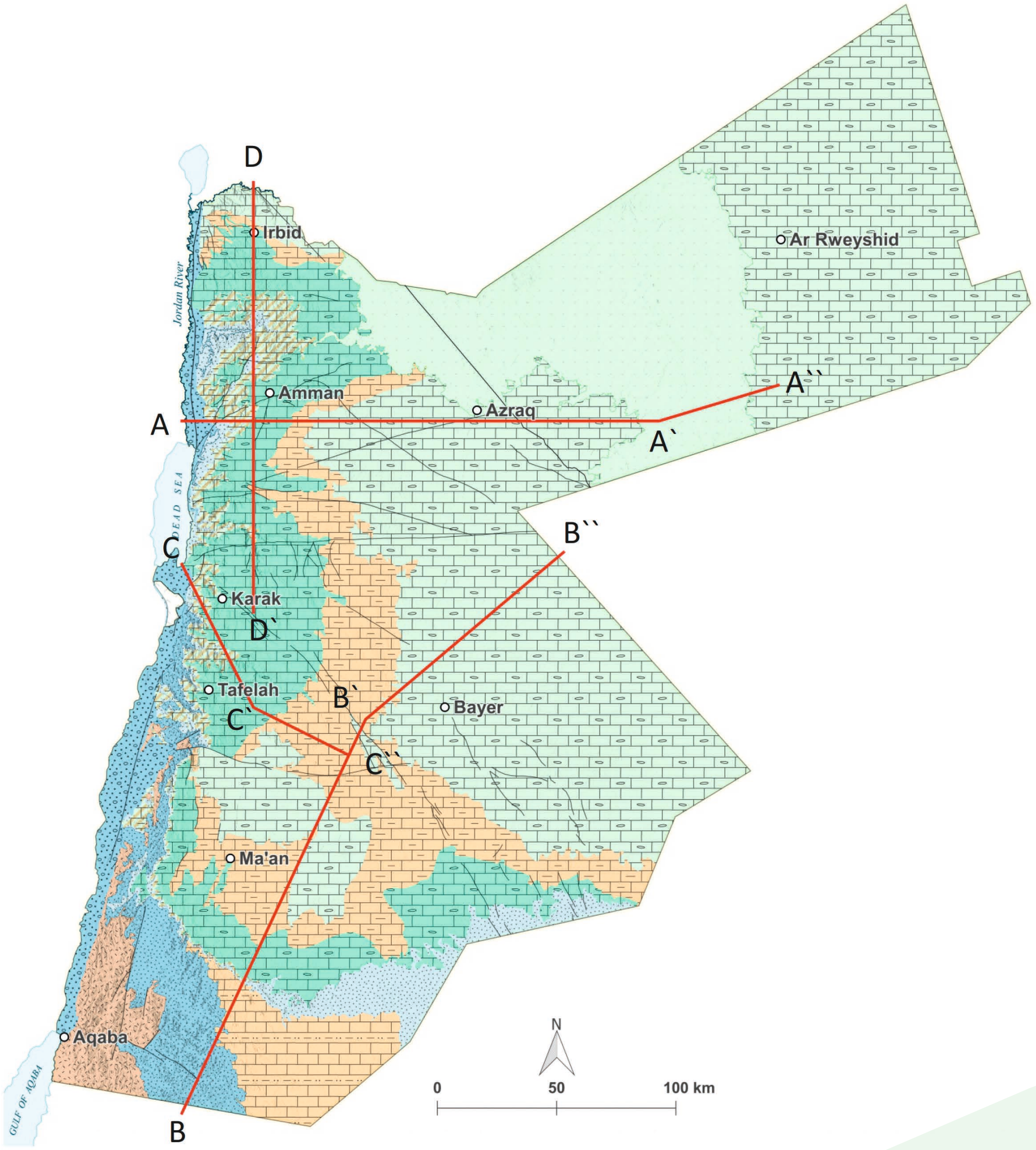


Figure 3 Locations of cross-sections

Before preparation of the groundwater level contour map, historical data were retrieved, plotted, validated and categorized as a function of the information source reliability. In addition, extensive fieldwork was carried out to collect actual water level data in monitoring and nonoperating production wells as well as to determine the exact coordinates and elevations of all wells and springs used for the interpolation of the groundwater level contours.

The A7/B2 aquifer is one of the most important aquifers in Jordan (Chapter 4.2.3). The 2017 water level contour map (Figure 4, Annex 8) shows that the natural groundwater flow conditions are rarely observable anymore, especially in northern Jordan, where a regional groundwater depression has developed north of Mafraq. A comparison of the flow directions observed in the 1990s and 2017 indicates that the regional flow patterns have changed significantly. The groundwater flow direction between Mafraq and Azraq has become inverted: groundwater originating from the north (Jebel al Arab in Syria) flowed to the endorheic basin of the Azraq Oasis in the 1990s, whereas in 2017, the groundwater turned to the west and now flows towards the regional depression cone at Mafraq.

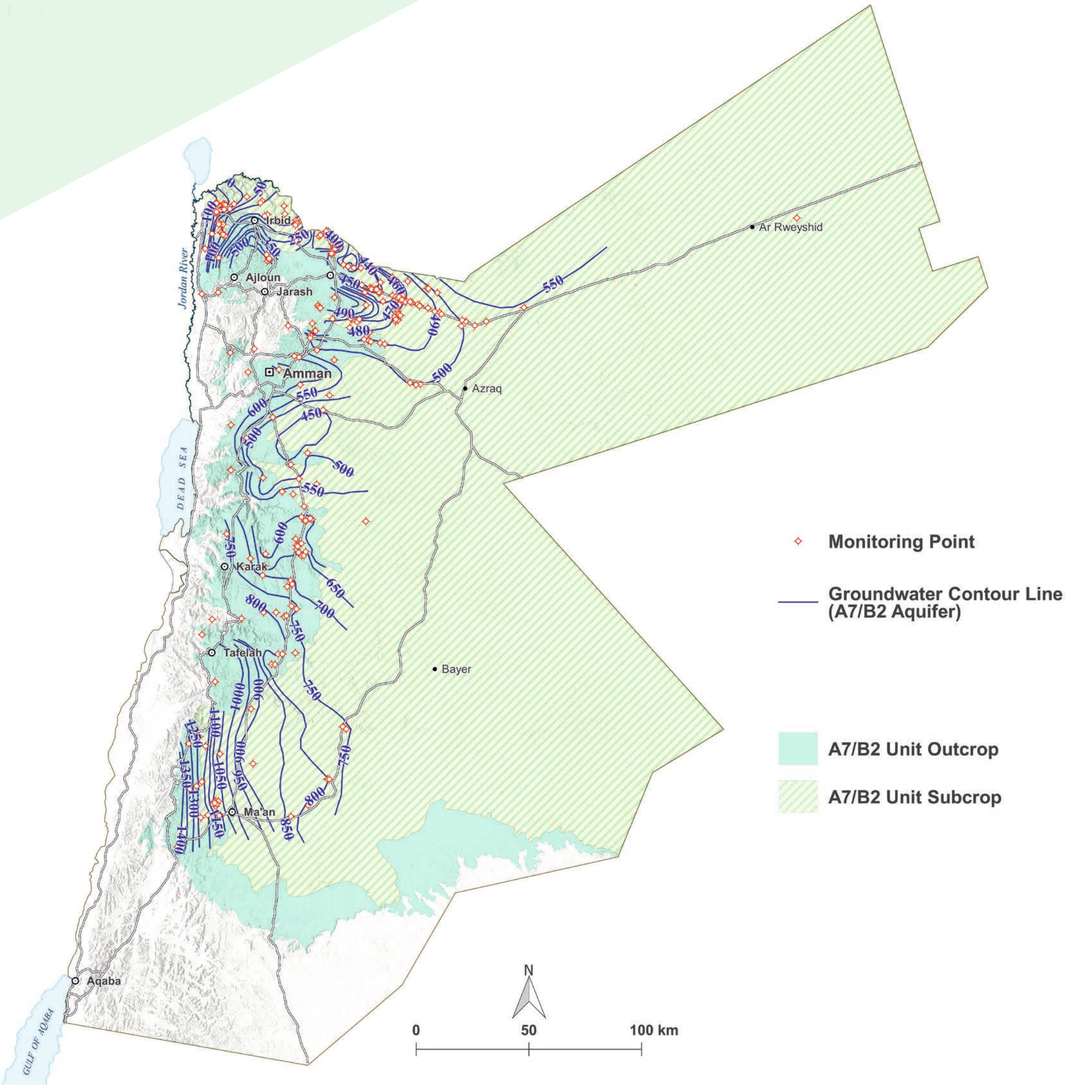


Figure 4 Groundwater level contour lines for the A7/B2 aquifer, October 2017

The saturated thickness map (Figure 54, Annex 10), which was derived from the groundwater contour map and updated geological structure map (Chapter 3.2), shows that the A7/B2 aquifer is partly dry, especially in the outcrop areas near the escarpment. The map of the groundwater level difference from the 1990s to 2017 (Chapter 4.1.4, Annex 11) indicates that the drawdown over the past 20 years is alarmingly high; in general, the decrease in saturated thickness varies between 20 and 50 meters (Figure 5). Locally, such as east of Petra, south of Amman and north of Mafraq, the drawdown reaches more than 100 meters. In the areas where the aquifer is still under confined conditions (western Wadi Al Arab and southern Yarmouk Valley), the groundwater equipotential surface has decreased by more than 150 meters.

Unsaturated areas were already mapped in 1995 west of Mafraq, but these areas have strongly expanded towards the west since 1995. The saturated thickness appears to be greater than 300 meters only in small parts of the country, such as the very northern part around Irbid, east of the Fuluq Fault, and south of the Salawan Fault. However, groundwater exploitation in these areas should be carefully considered because the base of the A7/B2 aquifer is more than 2500 meters below the ground surface.

In areas where the A7/B2 aquifer is no longer saturated, especially in northern Jordan, wells have been deepened into the deeper A4 or A1/A2 aquifers, enhancing the local importance of these aquifers. For this reason, the BGR and MWI produced the first groundwater contour map for the A1/A2 and A4 aquifers, reflecting the conditions as of 2017 (Chapter 4.2.2).

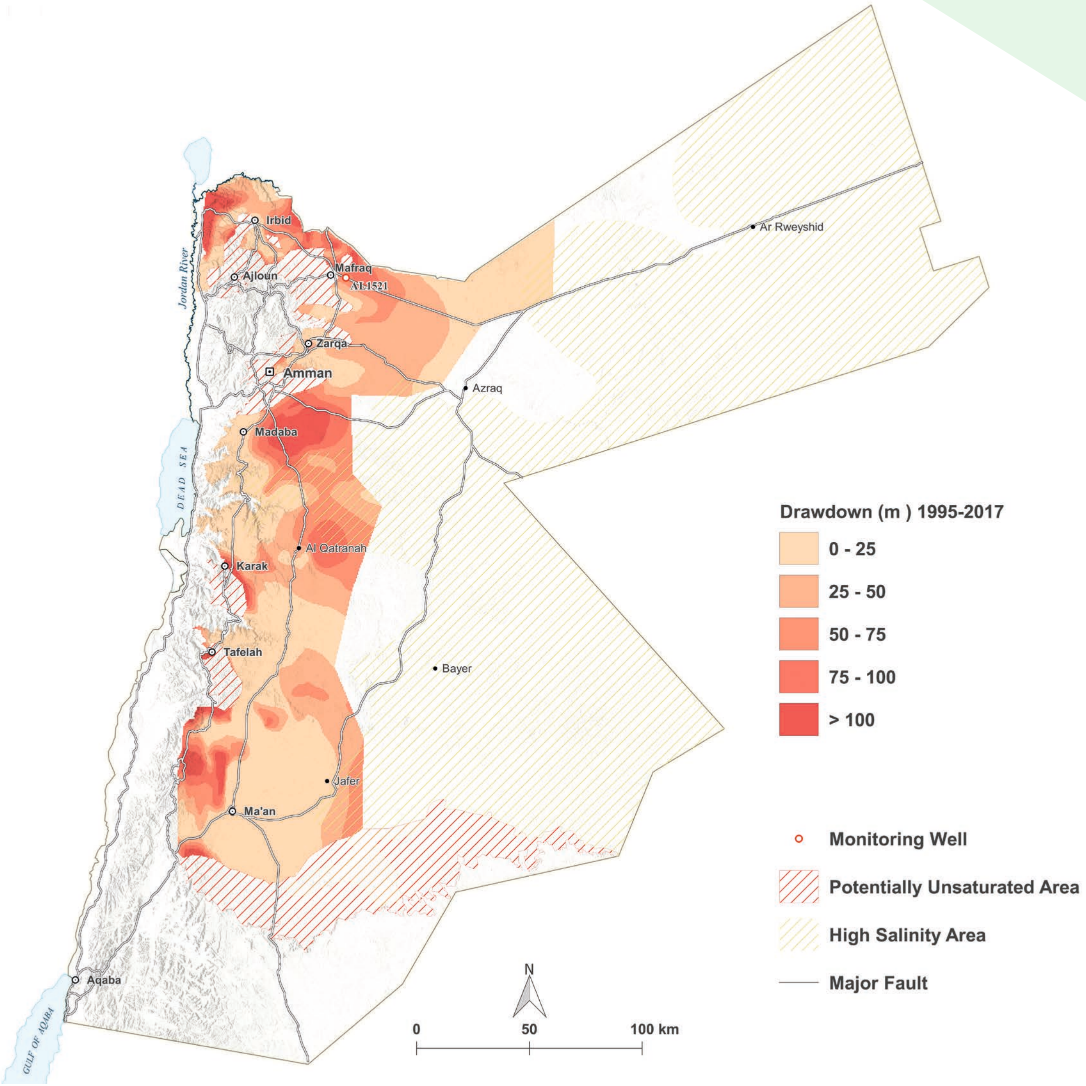


Figure 5 Difference in groundwater levels of the A7/B2 aquifer between 1995 and 2017

The groundwater contour map of the A1/A2 and A4 aquifers (Figure 6, Annex 5) indicates recharge in the northern outcrop areas, from which the groundwater flows mainly towards the Jordan Valley, north, and east. Recharge also likely occurs at Jabel al Arab in Syria and flows into the country towards the south/southwest. The data density decreases substantially to the south, but the groundwater flows from outcrop areas around Karak are assumed to be dominantly towards the east.

Based on the saturated thickness map (Chapter 4.2.2.3, Annex 7), which was derived from the groundwater contour map and the updated geological structure map, the A4 and A1/A2 aquifers appear to no longer be saturated, especially in the outcrop near the escarpment in northern Jordan, although verification through measurements is needed. The saturated thickness south of the Siwaqa Fault mainly mirrors the thickness of the A1/A6 aquifer under confined conditions with values between 200 meters and more than 400 meters. However, not all of the thickness is considered to be economically usable because less permeable layers are included in the thickness. Most of the still-saturated area north of the Siwaqa Fault is under confined conditions. Around Amman, the thickness varies between 100 meters and 300 meters. However, in this area, the thickness is for the A4 and A1/A2 aquifers because the A5/A6 and A3 aquitards are not included. The area between Mafraq and Irbid has saturated thicknesses of 300 meters to 400 meters and more. However, the A4 and A1/A2 aquifers are very deep (more than 400 meters) and are not likely economically feasible. The ongoing exploitation of the A7/B2 aquifer will increase the exploitation of the A1/A2 and A4 aquifers, especially in areas where it is already exhausted.

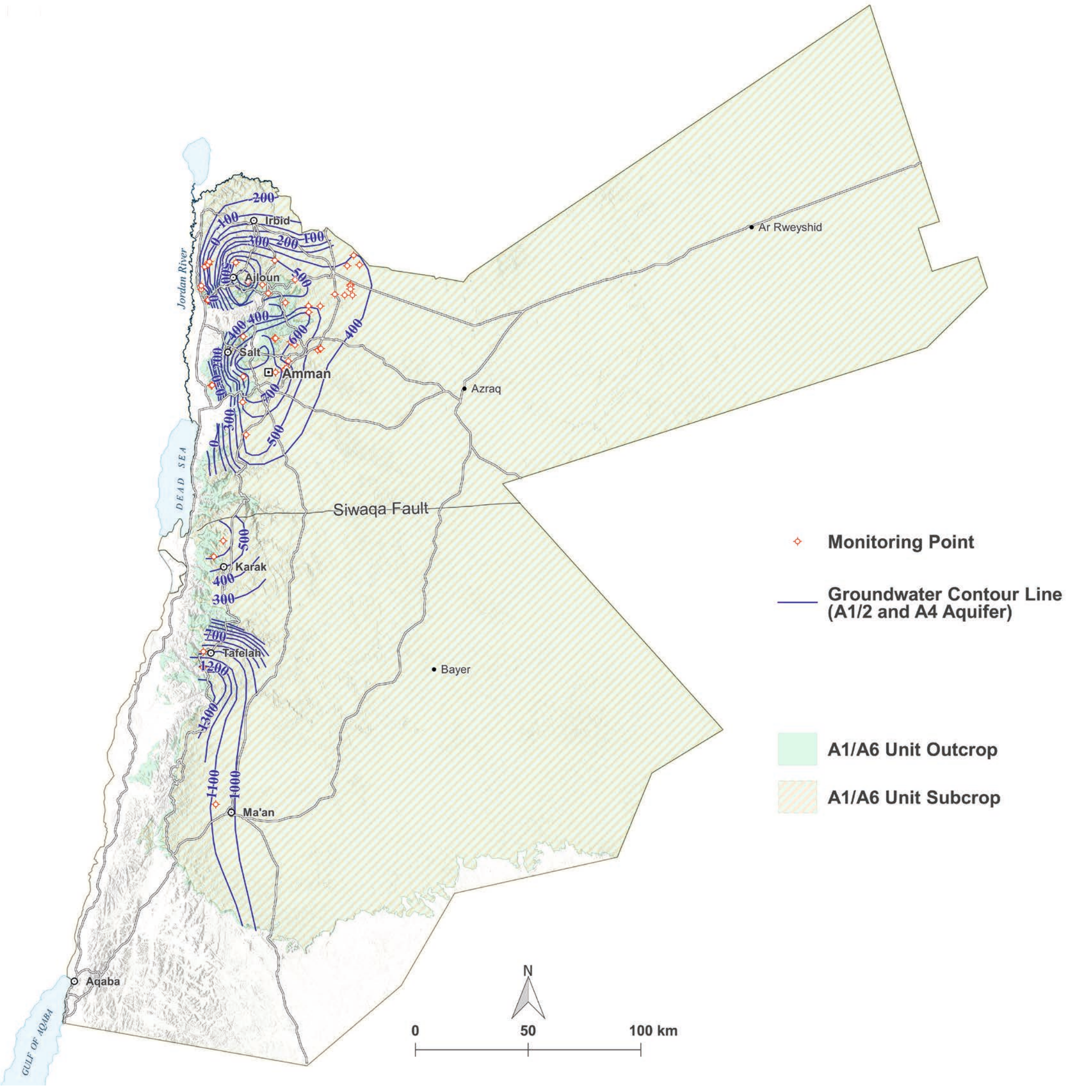


Figure 6 Groundwater level contour lines for the A1/A6 aquifer complex, October 2017

In addition to the A7/B2 aquifer, the deep Sandstone aquifer system is another large reservoir of fossil groundwater and is very important for the water supply of Jordan (Chapter 4.2.1). In particular, the Ram/Disi and Kurnub aquifers are locally important. In the central and southern parts of Jordan, the Kurnub and Ram/Disi aquifers are considered to be one hydraulic unit. Around Amman, the Zarqa Group separates the Kurnub and Ram/Disi aquifers, which can be recognized by a difference of more than 100 meters in the hydraulic heads of the aquifers. Due to the inadequate data distribution, not all parts of the aquifer can be represented (Chapter 4.2.1.1). In southern Jordan, groundwater flows from Saudi Arabia towards the northeast, turns to the northwest around the Ras en Naqb escarpment and continues farther towards the Dead Sea, where it discharges (Figure 7). In the far southeast, the water inflow from Saudi Arabia is oriented towards the northwest. The area around Salt and Ajloun, where the Kurnub aquifer outcrops, appears to be a recharge area for the Kurnub aquifer. From there, groundwater flows in all directions but dominantly towards the Jordan Valley.

Since 2013, the Disi wellfield in southern Jordan has had a major impact on the general domestic water supply, with a contribution of approximately 100 MCM per year. The effects of the Disi wellfield on the groundwater conditions in the Ram/Disi aquifer are indicated in the groundwater level difference map between the 1990s and 2017 (Chapter 4.2.1.4). Here, the overall drawdown in the region is less than 25 meters, but the drawdown in the wellfield area is higher.

The Basalt and B4/B5 aquifers are only of regional importance in the area around Azraq. The AWSA wellfield located

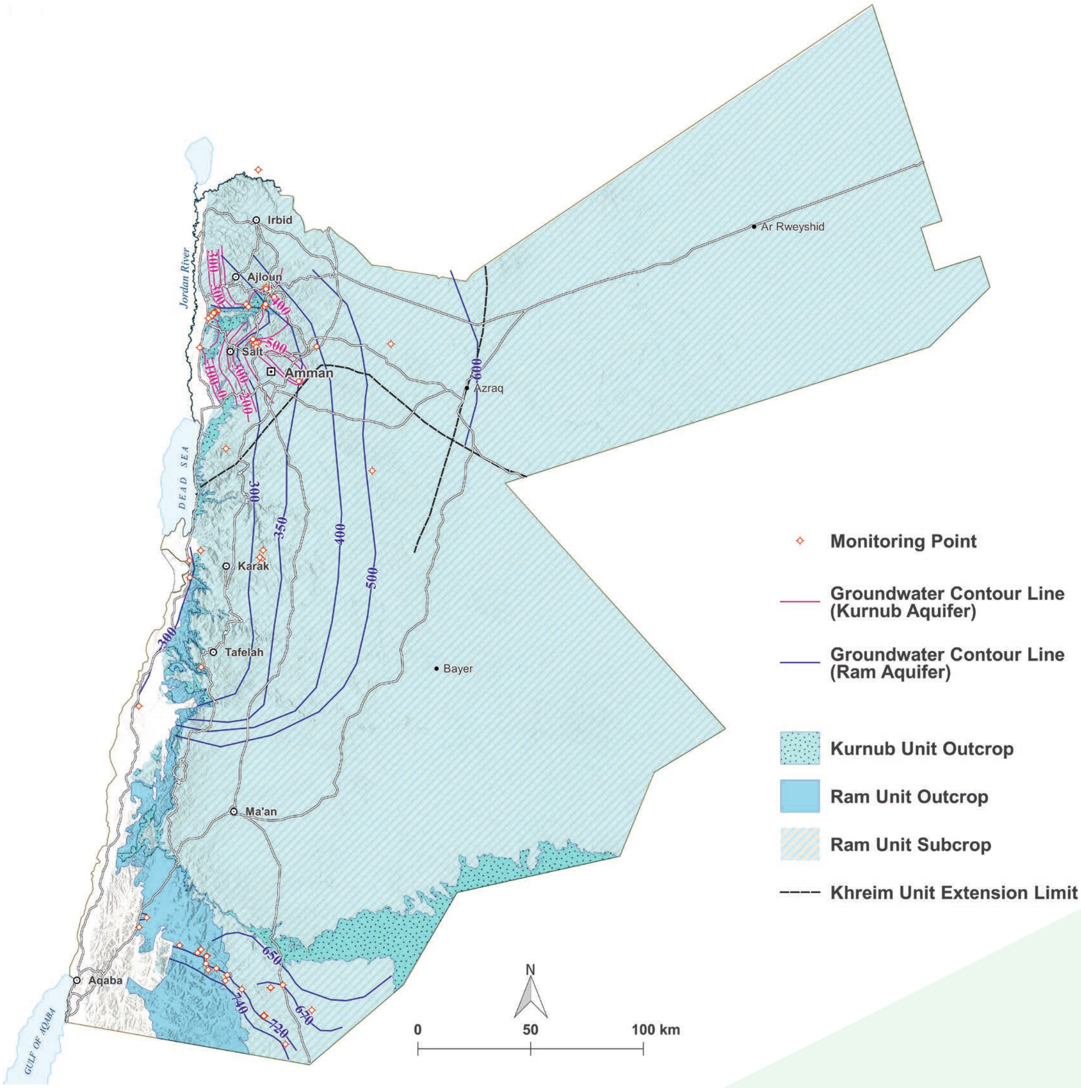


Figure 7 Groundwater level contour lines for the deep Sandstone aquifer system and the Kurnub aquifer, October 2017

north-northwest of Azraq produces a cone of depression that affects the regional groundwater flow. In this area, because the hydraulic heads of the A7/B2 aquifer are similar to those of the B4/B5 and Basalt aquifers (Figure 61), a hydraulic connection is assumed (Chapter 4.2.4.1).

All of the information presented above indicates that the available groundwater resources are very limited in Jordan, which makes the proper use of the available surface water resources more important. For comprehensive water resource management, springs should be considered, especially in Jordan, which has many springs in the highlands. A total of 861 springs are recorded in the WIS database of the MWI for the different aquifers, although there are no recent data for many of these springs. During the project, a nationwide assessment of the springs was conducted to identify their current status (Chapter 5). The results showed that 361 springs are perennial, 23 are intermittent, and 195 are dry. The flow conditions for an additional 12 springs are unknown because it was impossible to identify these springs in the field. The number of dry springs varies yearly with an overall increasing trend since 1987, but an large number of these springs were dry in 1988, 1995, 1999, and 2014, which consequently affected the water supply. In 2016/ 2017, only 23 springs were used for the drinking water supply. Many of the running springs cannot be used because of bacterial pollution, despite a large amount of discharge. The water from the important springs is treated to remove the bacterial contamination. In 2017, approximately 20 MCM of water was provided by springs for the drinking water supply.

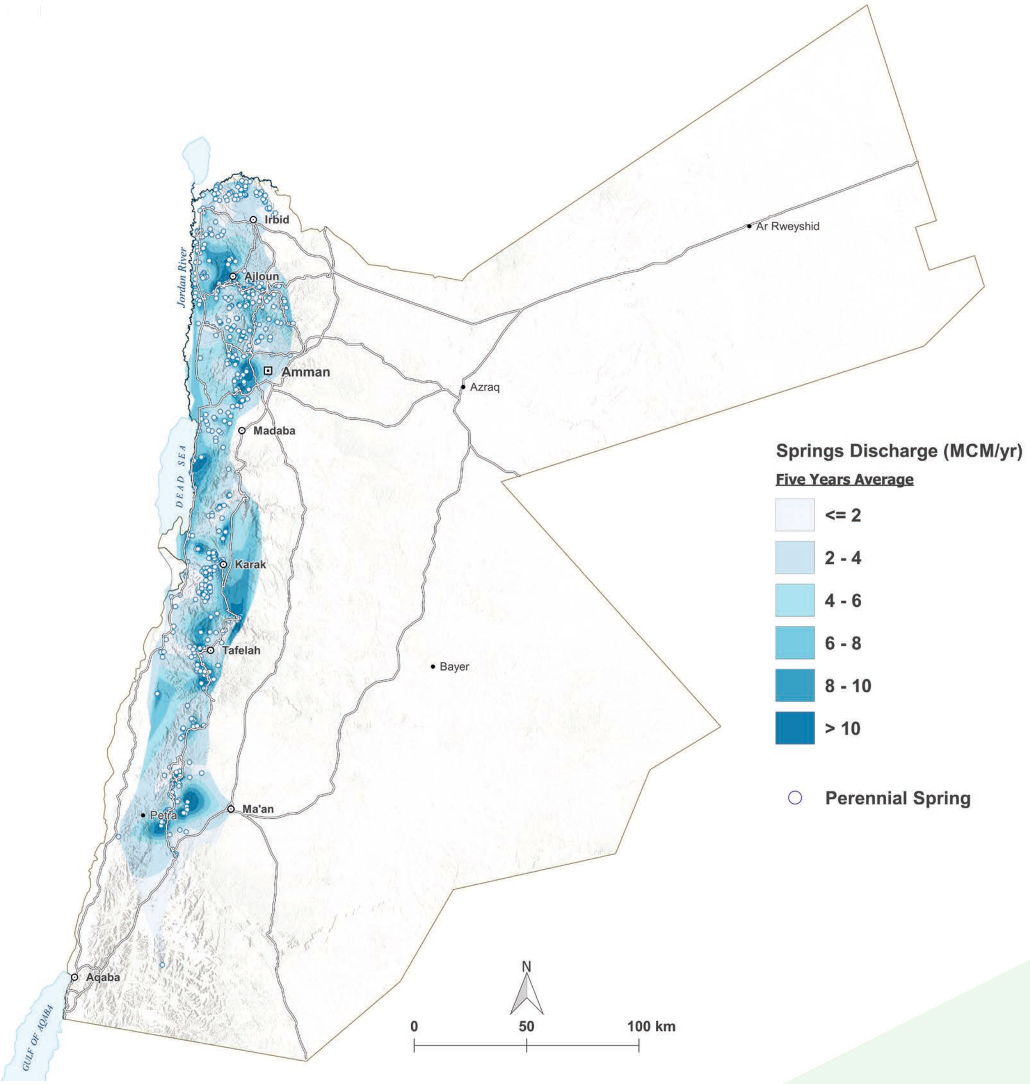


Figure 8 Five-year average discharges of the perennial springs in MCM

The distribution of the 5-year average spring discharge (Figure 8) identified high discharge areas, which could possibly be used for water supply after further investigations. In the high recharge areas in Ajloun, north and west of Amman, areas of large spring discharge (approximately 10 MCM/yr) are located south-southwest of Madaba and around Karak and Tafelah as well as south of Petra.

The maximum total yearly spring discharge was 249 MCM/yr in the early 1970s, and the discharge has decreased constantly since that time except during in the early 1990s, when a sudden increase was observed. The total spring discharge decreased by more than 115 MCM/yr to 136 MCM/yr by the early 2010s. Springs from individual aquifers follow the same trend.

These analyses illustrate the historical groundwater resource development until 2017. All of these factors are important in deciding future groundwater management measures. However, decision makers also need to know how various possible measures would affect the resources in the future.

With this aim, a nationwide groundwater flow model was established, which adequately represents the groundwater development in the past and forecasts future developments under different circumstances (Chapter 6). Coupled with the nationwide WEAP model (Chapter 7), the effects of various water planning options can be evaluated to support decision-making processes. The groundwater model comprises all relevant hydrogeological units from Ram/Disi to Alluvium. The model is based on structural models from BRGM (2010) and Margane et al. (2002), as shown in Figure 9.

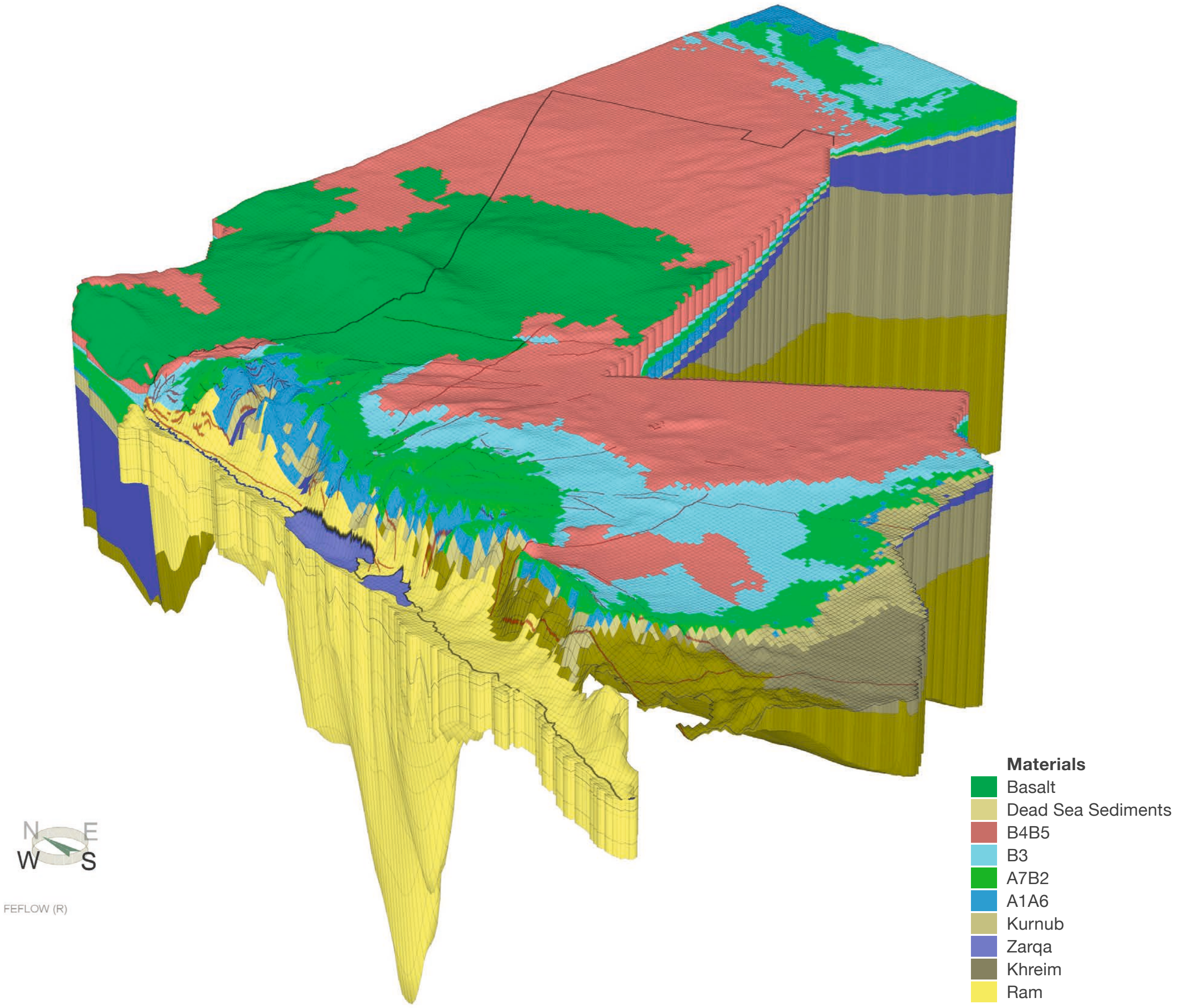


Figure 9 Three-dimensional groundwater model

The numerical groundwater flow model can be applied as a stand-alone tool for assessing the effects of management strategies on groundwater resources, such as to predict the impacts of

→ decreasing groundwater levels in existing wellfields,
→ new or currently unaccounted for groundwater abstractions, and
→ water use reductions in different sectors and/or locations.

The model was calibrated for steady state conditions and validated under transient conditions using the results of the groundwater assessment (Chapter 4). The steady state calibration provides results under predevelopment conditions. The hydraulic heads and flow directions of the modeled groundwater contours for the most intensively used aquifers (A7/B2 and Ram/Disi) are consistent with the results of BRGM (2010) and MWI (2005).

The hydraulic heads and parameters of the steady state calibration were used as initial conditions for the transient modeling that simulates the 1960-2017 period. The data applied to the transient model comprise the water level of the Dead Sea, groundwater recharge, and pumping rates of more than 5000 abstraction wells available in the WIS. The results of the transient simulation were verified using the observed historical groundwater levels in selected monitoring wells, the discharge rate of the Azraq springs, and the groundwater contour maps of the groundwater resource assessment.

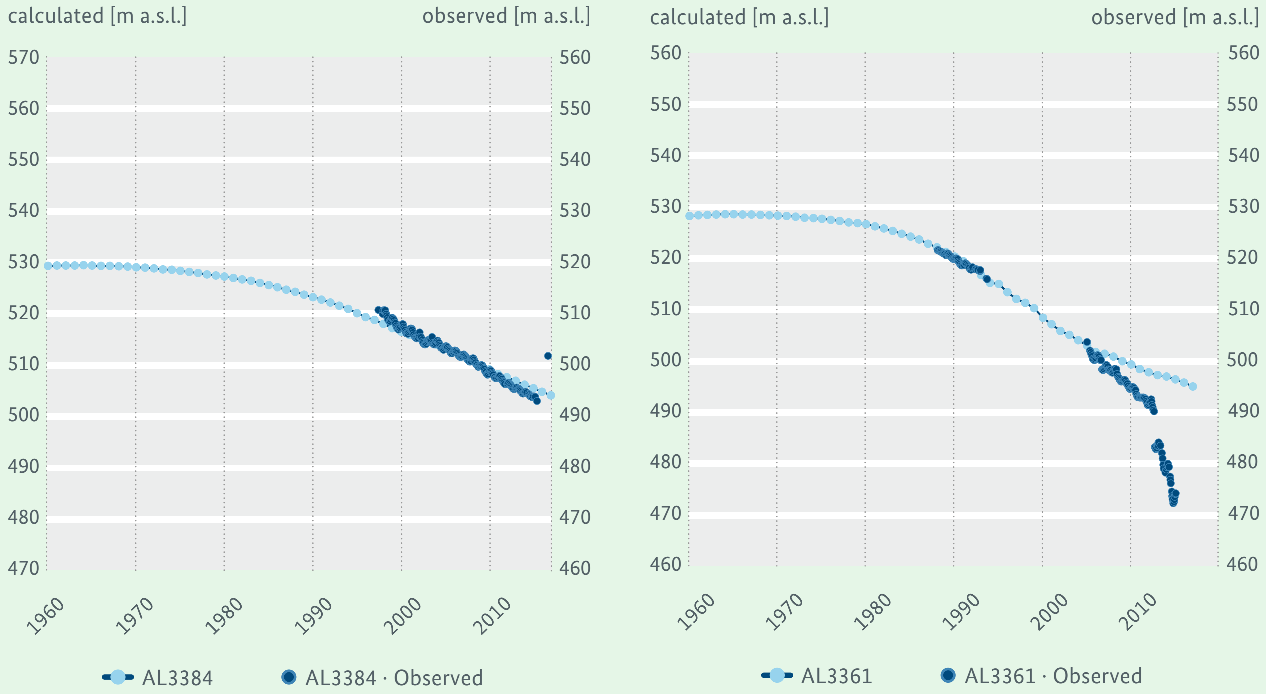


Figure 10 Simulated and observed hydraulic heads for selected monitoring wells

In general, the simulated hydraulic heads reproduce the observed groundwater levels of the aquifers, such as in well AL3384 for A7/B2 (Figure 10, left), but the simulations fail to reproduce the observed increased drawdown since 2000 caused by the increasing extraction rates, which are not recorded in the WIS, such as in well AL3361 for the Basalt aquifer (Figure 10).

For decision makers, it is always important to understand what will occur in the future under different management measures. After transient validation, the model was used to forecast the drawdown for 2000-2050 based on different assumptions. Two groundwater abstraction options were considered:

1. Baseline scenario: abstraction for domestic and industrial uses from the WIS. The groundwater abstractions for irrigation are from the WEAP model, which are based on the mapped irrigated areas for 2015 and 2017 using remote sensing data (Al-Bakri, 2016).

2. Enforcement of the groundwater bylaw scenario: abstraction for domestic and industrial uses from the WIS. The groundwater abstraction volumes are based on the current abstraction rates documented in the WIS.

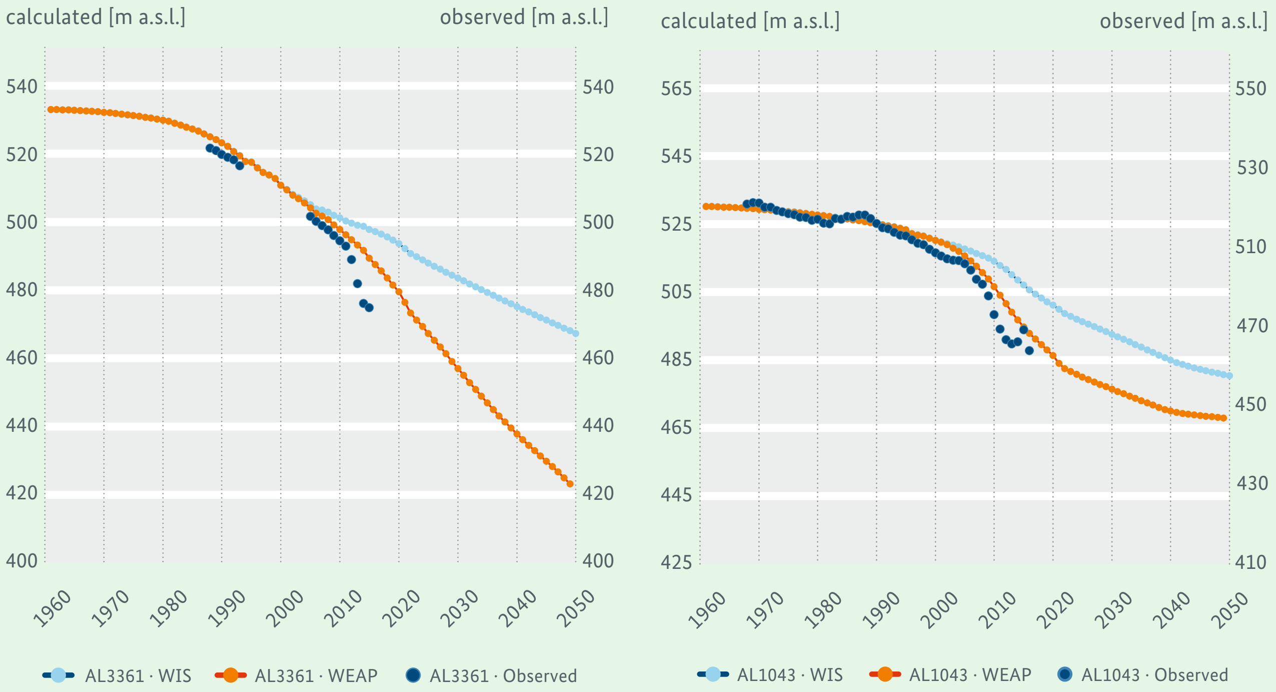


Figure 11 Simulated and observed hydraulic heads for selected monitoring wells in the A7/B2 aquifer for scenarios 1 (orange curves) and 2 (blue curves)

Figure 11 shows that a significantly better fit of the trends recorded through 2017 is achieved for scenario 1 (orange curves) compared to scenario 2 (blue curves).

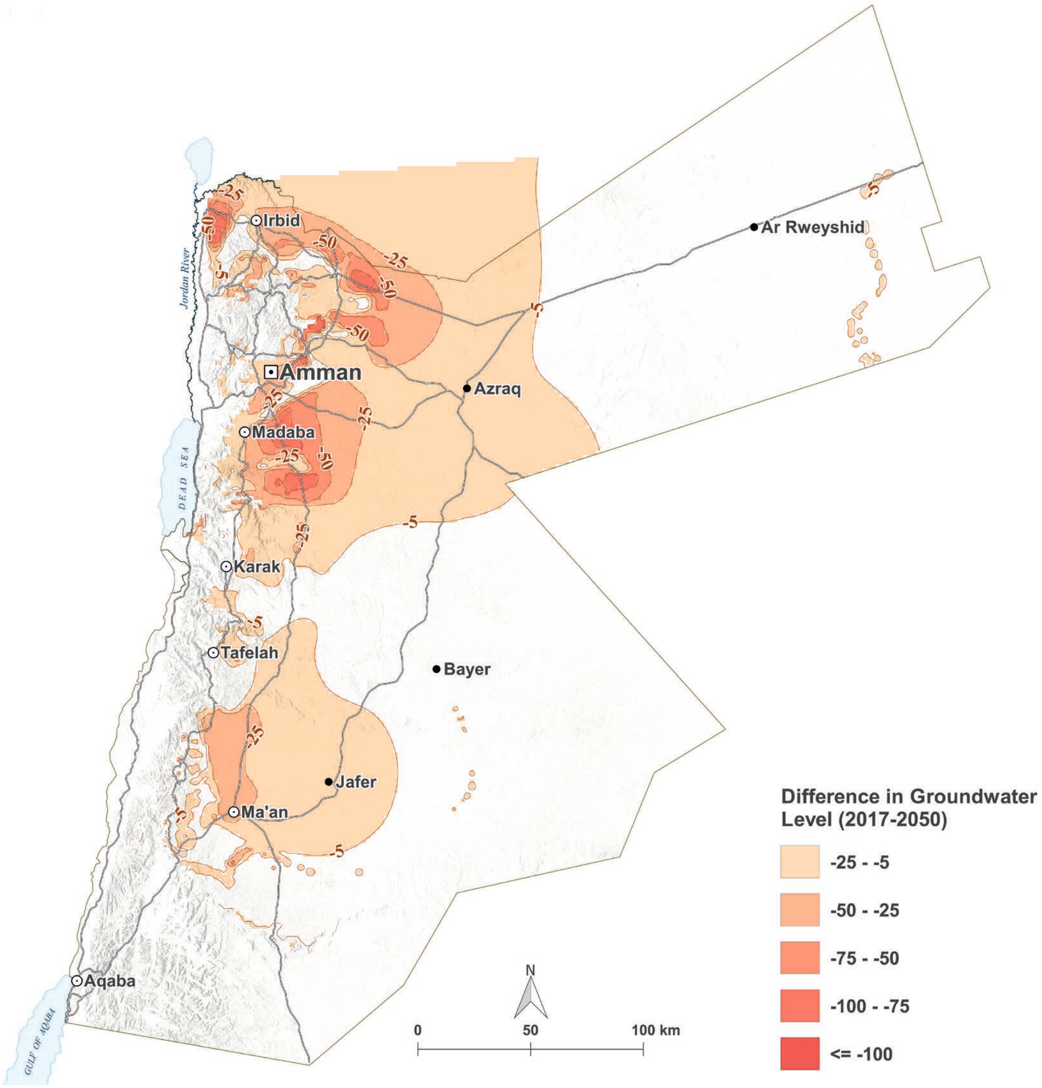


Figure 12 Simulated drawdown in the A7/B2 aquifer for 2017-2050 under scenario 1

Generally, in the A7/B2 aquifer, scenario 1 shows a better fit of the calculated and observed values than scenario 2, especially in the observation wells close to irrigation areas. For 2017-2050, the model under scenario 1 predicts drawdowns of up to 100 m (Figure 12). However, the maximum drawdown predicted for the same period under scenario 2 reaches approx. 65 m (Figure 13). In both scenarios, the areas with major drawdowns are Wadi Al Arab, Ramtha/Mafraq, northeast of Amman, east of Madaba and east of Al Shubak and Jafer.

Decreasing groundwater levels have an impact on groundwater availability and groundwater production costs. The availability is reduced because wells become dry, whereas groundwater production costs increase due to the higher pump lift and thus higher electric energy consumption. Furthermore, the need to deepen or replace wells leads to additional costs.

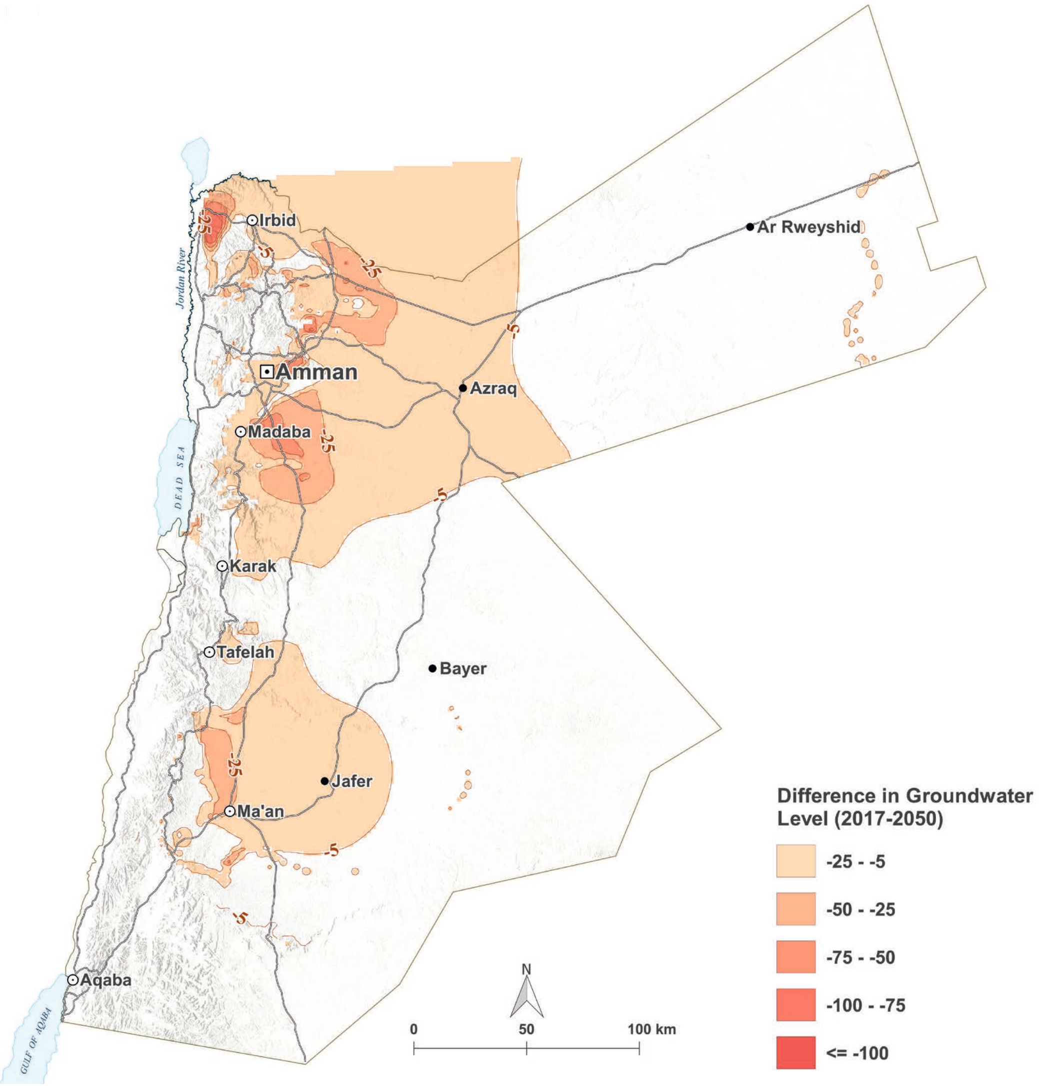


Figure 13 Simulated drawdown in the A7/B2 aquifer for 2017-2050 under scenario 2

By coupling the groundwater model with the existing WEAP model, a decision support system was created (WEAP-MODFLOW-DSS) that assesses groundwater-related processes as well as the spatial and volumetric limitations of the available water resources in detail. Without a groundwater model, the WEAP model neglects spatial information and considers aquifers as infinite groundwater resources, which contradicts the natural conditions. Therefore, the coupled WEAP-MODFLOW model constitutes a necessary improvement of the WEAP model, and the MWI is now capable of improving the strategic management of groundwater resources and water supply infrastructure.

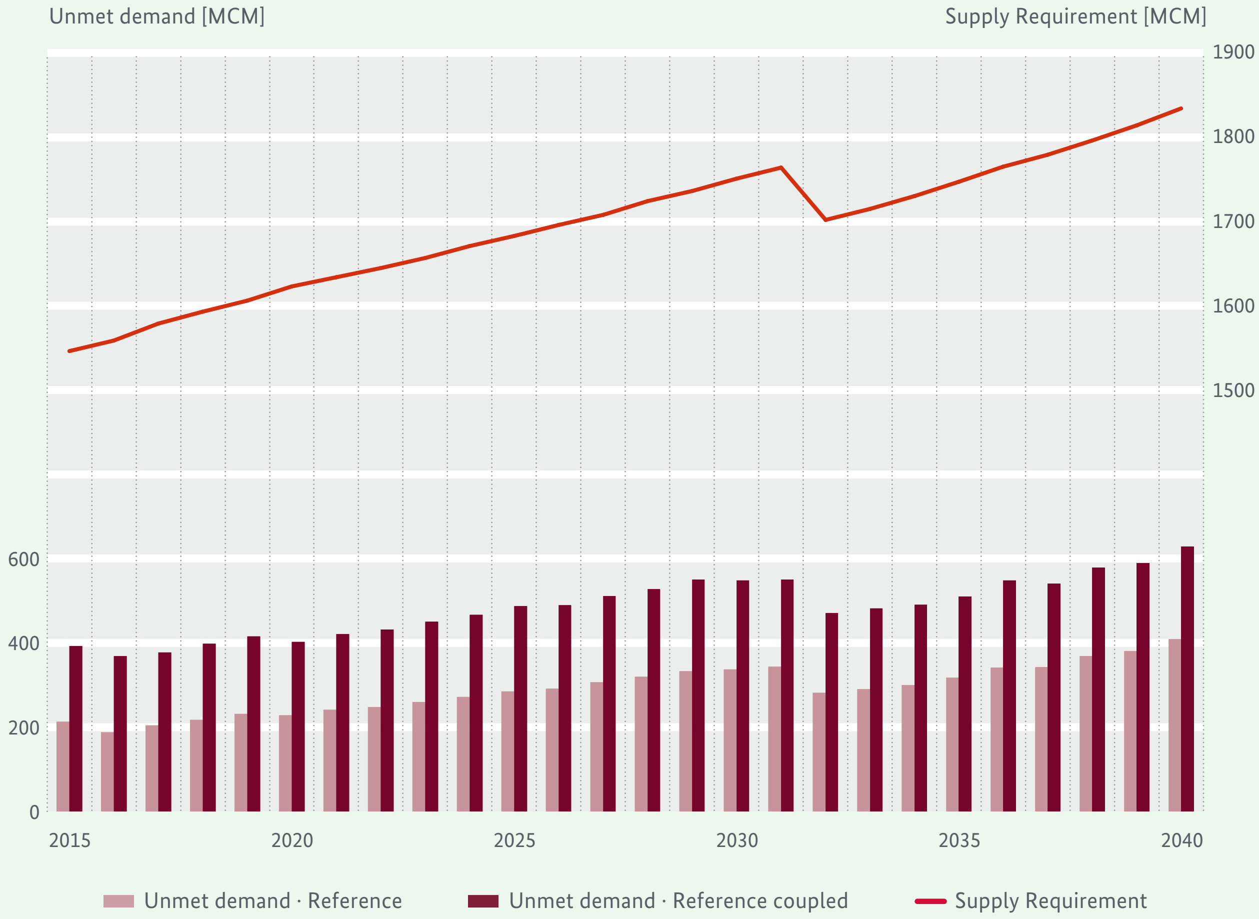


Figure 14 Calculated unmet demands with and without coupling for scenario 1 and the supply requirements for all demand sites in Jordan

The results of the coupled WEAP model show that groundwater production is lower than required in the uncoupled WEAP master model. Figure 14 illustrates the unmet demand, which is the difference between the supply requirements and supply delivered.

As expected, the unmet demand is higher in the coupled model because of the lower groundwater production as a result of declining groundwater levels. According to the simulation results, the coupled model leads to an unmet demand that increases from 400 MCM in 2015 to approximately 630 MCM in 2040, which demonstrates the increasing water supply deficits in Jordan and the importance of more accurately assessing groundwater availability.

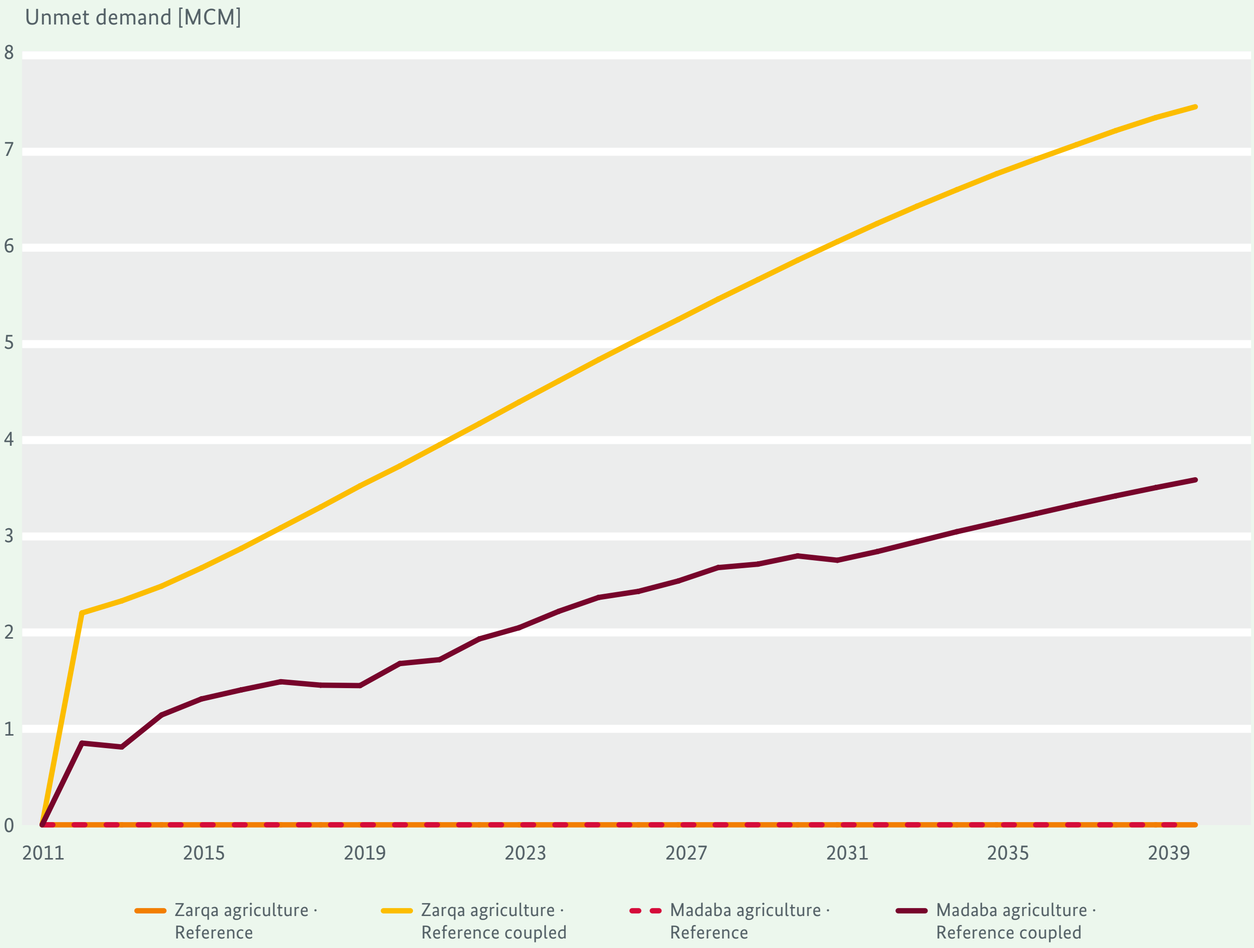


Figure 15 Unmet irrigation demands at Zarqa and Madaba with and without coupling for scenario 1

The impact of limited groundwater availability can also be visualized for individual demand sites, such as Zarqa and Madaba (Figure 15). While the uncoupled model calculated permanent coverage of supply at both sites, the coupled model estimated an unmet demand that steadily increased over the period to approximately 7.5 MCM for Zarqa and 3.7 MCM for Madaba in 2040.

All of these assessments show that the groundwater resources in Jordan are very limited. The still-available resources require urgent protection against surface pollution, which appears to be a serious problem. Many springs with large discharges cannot be used as water supplies because of pollution. To protect these resources, groundwater protection zones were implemented in a previous BGR project. Another important tool for assessing pollution hazards is the groundwater vulnerability map (Annex 13). This map highlights areas where aquifers are naturally unprotected (Chapter 8). Any pollutant can easily reach the groundwater

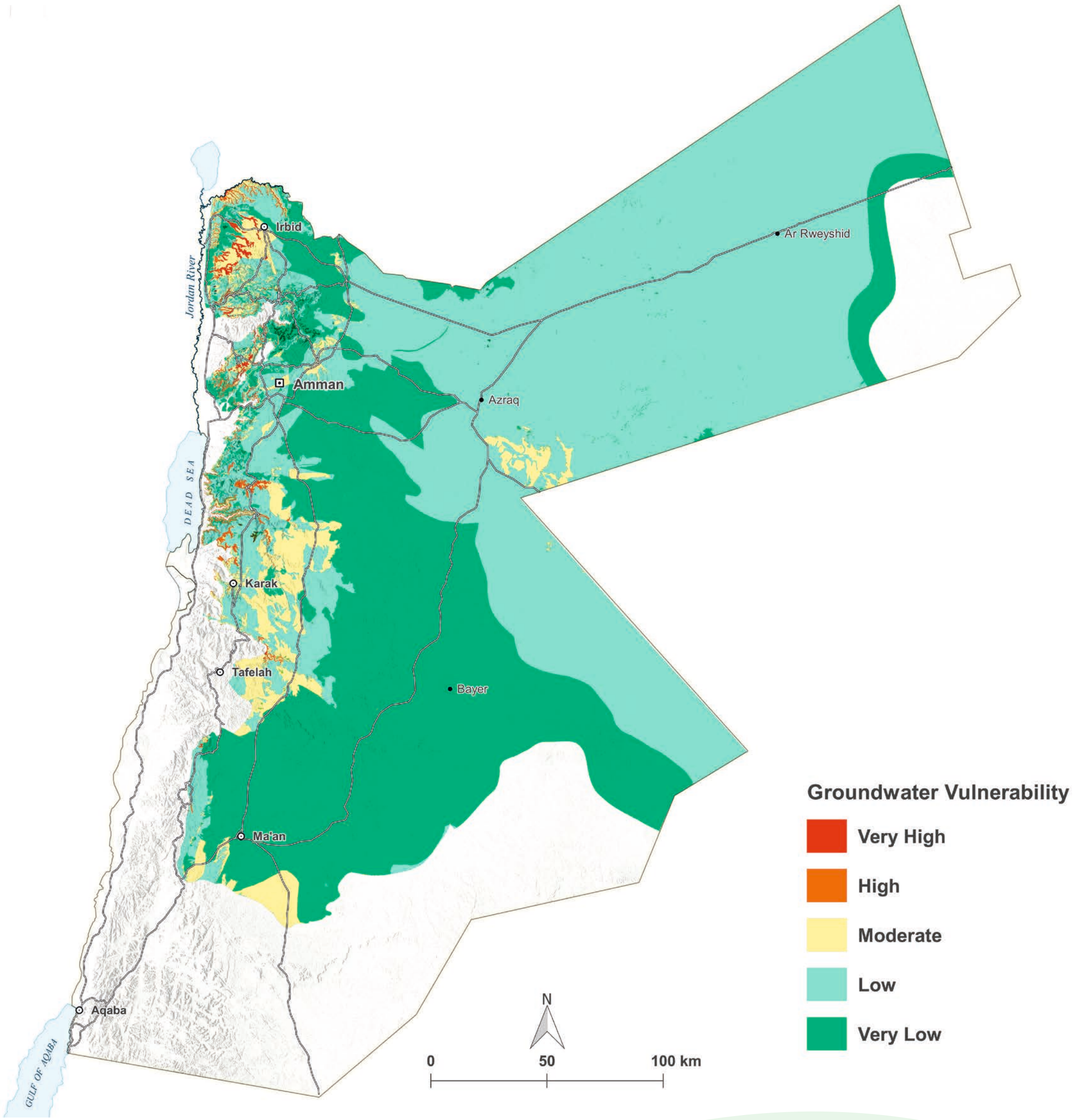


Figure 16 Groundwater vulnerability map

table and spread quickly. To develop this important tool, the structure of the subsurface aquifer system combined with the actual groundwater levels are key information.

The COP method (Vías et al., 2006) was used in this study because it considers the rapid flow through the karst features that are present in northern Jordan. Three groups of factors are considered in this method: overlying layers (O), concentration of flow (C) and precipitation (P). The processes that govern infiltration and transport are parametrized, combined and shown on a map (Figure 16) in an easy-to-understand form with qualitative classes from high vulnerability (fast transport) to low vulnerability (slow transport).

The map shows that the vulnerabilities are highest near the outcrops of the aquifers because there is little or no protective cover. This is especially the case in the deeply incised waters that run from the highlands towards the Dead Sea Rift basin. In contrast, the vulnerability along the outcrops of the B3 aquitard is very low because of its high thickness and low permeability.

The vulnerability map leads to purposeful protection of critical areas and must be considered in any further land-use planning, such as to avoid the installation of critical industries in highly vulnerable areas.

In conclusion, significant efforts have been made to update the subsurface information and vulnerability map, to collect and analyze current field data for groundwater and springs and to develop decision-making tools. Recent water level data were collected at 550 measurement points. The resulting assessment of groundwater resources, especially the A7/B2 aquifer and the comparison to the conditions in the 1990s, shows that the groundwater conditions in Jordan are very critical. The generally significant drawdown of the water levels, development of regional depression cones, loss of saturated thickness and growing extension of unsaturated zones, inversion of flow directions towards areas of extensive groundwater exploitation and increasing number of dried springs are clear indicators of the severe overuse of groundwater resources.

The results of the transient groundwater flow model coupled to the WEAP model predict continued significant declines in groundwater levels in certain areas. Decreasing water levels and increasing unsaturated areas will have serious economic and operational consequences on water abstraction for both private and public use. Water levels at greater depths require higher energy consumption to lift water and consequently increase operational costs. Furthermore, existing wells must be deepened, riser lines must be extended, and pumps must be exchanged with more powerful and expensive pumps to adapt to lower water levels. A significant number of wells will dry up in upcoming years. Because salinity and mineralization of abstracted groundwater increases with depth, water quality will become a major cost factor, eventually requiring water treatment by cost-intensive technologies and disposal of brines.

To mitigate these conditions and slow or reverse the continuous increase in water supply costs as well as secure the future water supply, decisive measures by the Jordanian government are urgently needed. Potential effective measures that could contribute to mitigating or overcoming the Jordanian (ground)water crisis are as follows:

1. One of the most effective measures for addressing the water crisis is increasing awareness among national, regional, and local decision makers as well as among the most important private water users, such as water companies and farmers. All institutions related to the water sector must have access to this studyAny potential for saving water should be fully exploited. Water companies must reduce water losses due to leaking pipes to a minimum. Continuous maintenance or, where necessary, modernization of the water supply network is needed. In the agricultural sector, water-saving technologies and processes together with the cultivation of low-water demand crops must be promoted. In critical areas, the licensed water volumes must be reduced, or the licenses should not be extended.

2. Groundwater resources must be protected from any kind of contamination that could reduce their availability and exacerbate the water crisis. Urban planning and project licensing must consider groundwater vulnerability (Brückner, Hamdan, Breazat, 2018) to reduce the risk of the negative impacts of potentially contaminating activities in highly vulnerable areas.

3. It is highly recommended to identify alternative water sources, such as the desalination of sea water or brackish groundwater, as well as to study the economic feasibility of these methods for the domestic water supply by comparing their costs with the steadily increasing costs of groundwater exploitation. The development of new sources reduces the drinking water supply sector's dependency on decreasing groundwater resources, increases drinking water supply sustainability, and improves water security.

4. Through analysis of the groundwater resources based on field investigations and the groundwater model, areas of illegal well operations have been identified, and the difference between the groundwater model results

Source: BGR

Source: BGR

and the field measurements provides an initial estimate of the amounts of illegally abstracted water. Illegal wells should be closed, especially in northern Jordan. Additionally, stricter control of abstracted volumes, revoking of licenses, and application of higher water fees need to be implemented.

5. Despite the extremely high costs of pumping and energy consumption in the Jordan highlands, extensive agriculture is widespread, probably because of the subsidization of electricity for irrigation. Further studies are needed to fully understand why irrigation in the highlands is still profitable, and subsidies must stop.

6. Management decisions on a local level cannot be made with the scarce data availability. Additional field investigations and local data collection are recommended to enhance prediction reliability. The MWI needs to continue regular monitoring of its water resources, including regular field inspections at least every 6 months. This basic information is indispensable for successful water resource management.

7. The coupled WEAP-MODFLOW model improves the ability to forecast the effects of future developments. Because the model allows for the quantification of wellfield productivity and identifies the origin of supply deficits, it must be used for water supply management and planning in Jordan.

8. Maps can be used together with the groundwater model to identify favorable areas for siting new wellfields for public water supply. These areas must have a good saturated thickness and a low depth to groundwater. However, the final decisions must be based on exhaustive feasibility studies.

INTRODUCTION

2

2

Introduction

Jordan is one of the most water-scarce countries in the world. Groundwater resources are the main water supply source, and they are used for domestic, industrial, and agricultural purposes. Due to population growth and the expansion of industrial and agricultural activities, the need for water resources is continuously increasing. Decreasing groundwater levels in monitoring wells and drying of production wells and springs are indicators of extremely critical groundwater resource conditions in Jordan.

Funded by the Federal Ministry for Economic Cooperation and Development of Germany, as part of the Jordanian-German technical cooperation, the BGR and MWI are jointly working on several topics in the field of groundwater resources in the Hashemite Kingdom of Jordan (Figure 17). For Jordan's future, it is crucial to understand the present conditions, how they have developed over the years, and what the effects of different future management strategies (scenarios) will be on resource availability. By doing so, a sound base for making drastic but necessary decisions for safeguarding Jordan's scarce groundwater resources can be established.

The last nationwide study on groundwater resources was conducted in the 1990s by the BGR. Since then, only local studies of different topics have been performed. The results of these studies show that the groundwater conditions in Jordan are rapidly deteriorating. Although several donors have developed multimillion-dollar programs to improve the water supply situation in Jordan, the nationwide analysis of the available resources have not been updated. The BGR decided to take over this task in 2016 with a study that covers the entire country and involves the different aspects needed to analyze and understand the current groundwater conditions. The focus is on groundwater quantity rather than quality.

First, all available geological or hydrogeological drilling data were collected and analyzed to update the SCMs and draw subsurface cross-sections. The maps describe the aquifer geometries down to the Upper Cretaceous aquifers and thus to identify areas with groundwater potential. The structural information in combination with the current groundwater levels can be used to define unsaturated areas or estimate the amount of groundwater still available in an aquifer.

In the second step, the project activities concentrated on the definition of the actual groundwater conditions in Jordan. Two nationwide surveys were carried out in 2017 to collect precise groundwater level data, including a DGPS survey to obtain the most accurate coordinates and elevation information. Groundwater contours were drawn for October 2017 using all available data for the main aquifers in Jordan. For each aquifer, the resulting groundwater contour lines were combined with the corresponding updated structure contour map to develop different thematic maps, such as the depth to groundwater and the saturated thickness maps.

The depth to groundwater and the resulting delineation of confined and unconfined areas are important information with economic implications because they reflect the required amount of pump lift. In unconfined areas, the water level indicates the minimum necessary drilling depth, but in confined areas, the water level may be hundreds of meters above the top of the actual aquifer. However, the drilling must reach at least the top of the aquifer. The saturated thickness map describes how much water remains in an aquifer. This information is relevant to identifying areas for new drilling sites or other cost-intensive operations, such as well deepening. Without information about the subsurface structure, none of these estimations would be possible.

To visualize the regional trends, the groundwater conditions encountered in October 2017 were compared with the results of the 1995 nationwide study. Groundwater level changes between 1995 and 2017 were identified, and areas of significant drawdown over the last 22 years can easily be seen. These regions in Jordan require urgent action if the groundwater resources are to be preserved.

To decide on future groundwater management measures, decision makers also need to know how these measures will affect the resources. With this aim, a nationwide groundwater flow model was established, which adequately represents the past groundwater developments, forecasts future developments under different scenarios and allows for the rough assessment of illegal abstractions. Coupled with the nationwide WEAP model, the effects of various water planning options can be evaluated, and the decision-making processes for strategic water management can be supported. Without a groundwater model, the WEAP model neglects spatial information and considers aquifers to be infinite groundwater resources, which is not consistent with the natural situation.

For comprehensive groundwater resource management, springs must be included, especially considering the large number of springs in Jordan. The BGR together with MWI conducted two nationwide surveys to assess the present status of all springs that had not been measured in the last two years but where flow measurements had been obtained in the previous two years. The results of the surveys show how many springs are now dry and how the average discharge of the still-running springs has changed as a direct effect of decreasing groundwater levels.

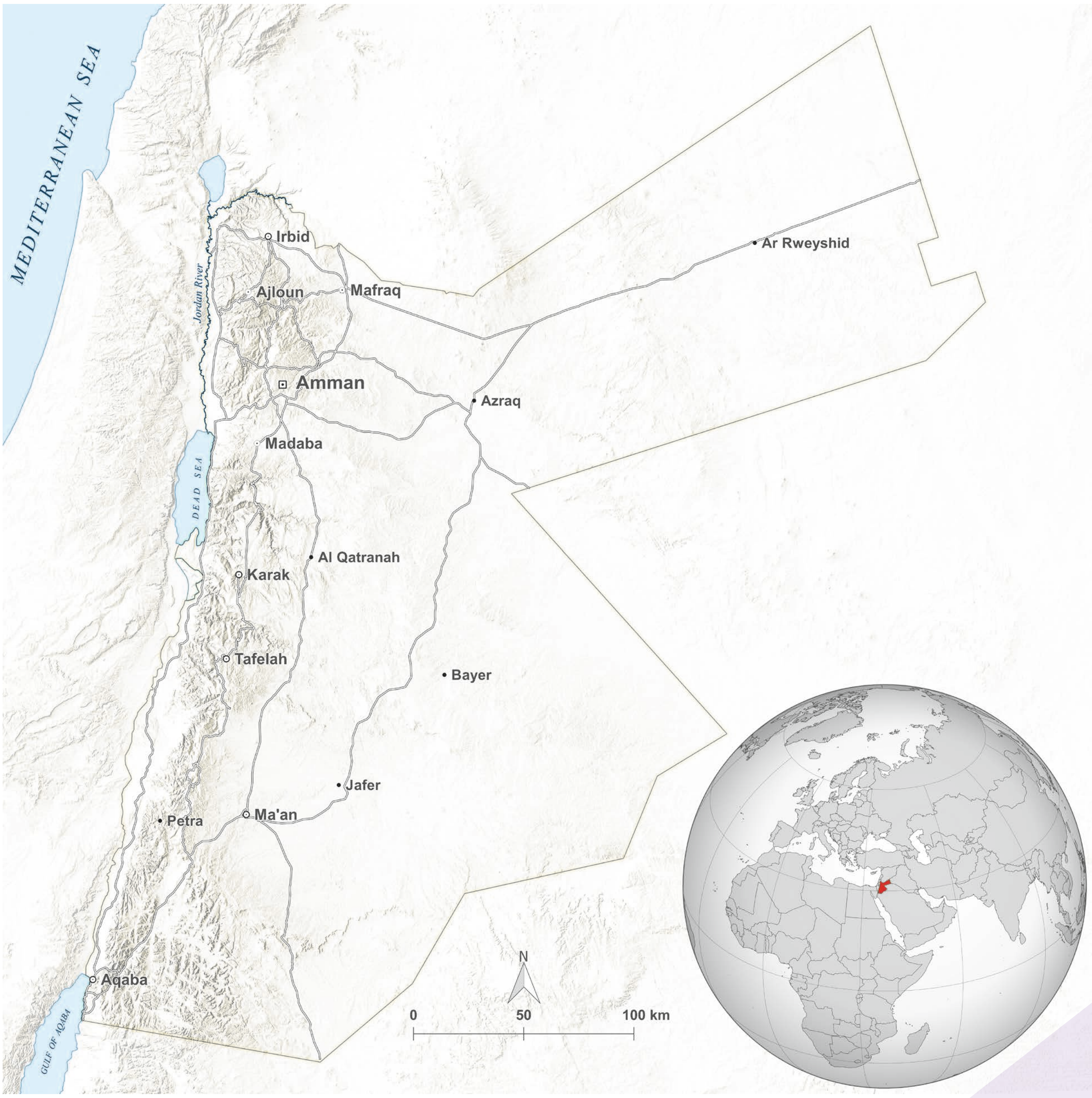


Figure 17 The Hashemite Kingdom of Jordan

Source: Bashar Tabbah Photography

The groundwater resources in Jordan are scarce and need protection against pollution from the surface, which appears to be a serious problem. Many springs with large discharges cannot be used for water supplies because of pollution. To protect these resources, groundwater protection zones were implemented in a previous BGR project. Another important tool needed to assess pollution hazards is the groundwater vulnerability map. This map highlights areas where aquifers are naturally unprotected. Any pollutant can easily reach the groundwater table and spread quickly. To develop this important tool, the structure of the subsurface aquifer system and the actual groundwater level are again key information. Based on these two factors (structure and water level), the speed at which polluted water can infiltrate and contaminate the resources in different areas can be estimated. The vulnerability map leads to the purposeful protection of critical areas and must be considered in any further land-use planning, such as to avoid the installation of critical industries in highly vulnerable areas.

The authors of this study believe that all of the products presented here should be used to manage and protect the scarce water resources of Jordan in the best possible way.

HYDROGEOLOGICAL SETTING AND UPDATES TO THE STRUCTURE CONTOUR MAP

3

3

Hydrogeological Setting and Updates to the Structure Contour Map

Florian Brückner & Mohammad Alhyari

For any kind of groundwater resource management, subsurface information is needed to estimate the availability of groundwater. To site a new groundwater well, the hydrogeologist requires subsurface information to estimate the probability of encountering water as well as the costs of well construction. Several methods exist to visualize the subsurface geological conditions, such as single borehole logs, cross-sections and SCMs, and complex 3D geological models.

SCMs are geostatistical interpolations of borehole information about geological or hydrogeological layer variations and represent the current knowledge about the subsurface groundwater systems. SCMs are two-dimensional representations of the elevations of geological units in the subsurface, and this information is usually obtained from borehole data.

Nationwide SCMs were first produced in 1995 and combined the results of studies in southern Jordan (Hobler et al., 1991) and northern Jordan (Margane & Hobler, 1994). Since then, many new wells have been drilled, and the SCMs urgently required updating. The new maps show the estimated bases of major hydrogeological units and serve as important tools not only for planning new boreholes but also for resource estimations (Chapter 3) and groundwater vulnerability mapping (Chapter 8). For the first time, separate maps for the A3, A4 and A5/A6 formations were developed. Based on the new SCMs, several subsurface profiles were drawn using GIS and manual methods.

3.1 Methods and Data

3.1.1 Updated Structure Contour Maps

The 1995 contour lines remained unchanged unless new information was available, which was mostly from governmental water wells stored in the WIS database of the MWI. The data quality of the WIS is often limited; there is no system in place for quality control or to prevent data entry errors, coordinates and elevations are frequently incorrect or inaccurate, and systematic errors occur due to conversion of coordinates. Additionally, neighboring boreholes often have conflicting lithological information. Therefore, other data sources were used where available, such as drilling reports from the water suppliers and drilling companies as well as exploration boreholes for oil, oil shale and uranium. These features are generally well documented, often with geophysical logs that make it possible to cross-check geological descriptions. Drilling records of the numerous private water wells from the WAJ database could not be used because of their low data quality.

The boundaries of the geological layers are based on 1:50,000 scale geological maps of the NRA, except in the eastern desert, where 1:250,000 scale maps from the German Geological Mission were used (Bundesanstalt für Bodenforschung, 1966, 1968).

The main faults (Figure 18) were identified through a literature review, remote sensing data, and major displacements between neighboring boreholes, but their exact positions and orientations often remain unclear; therefore, all fault

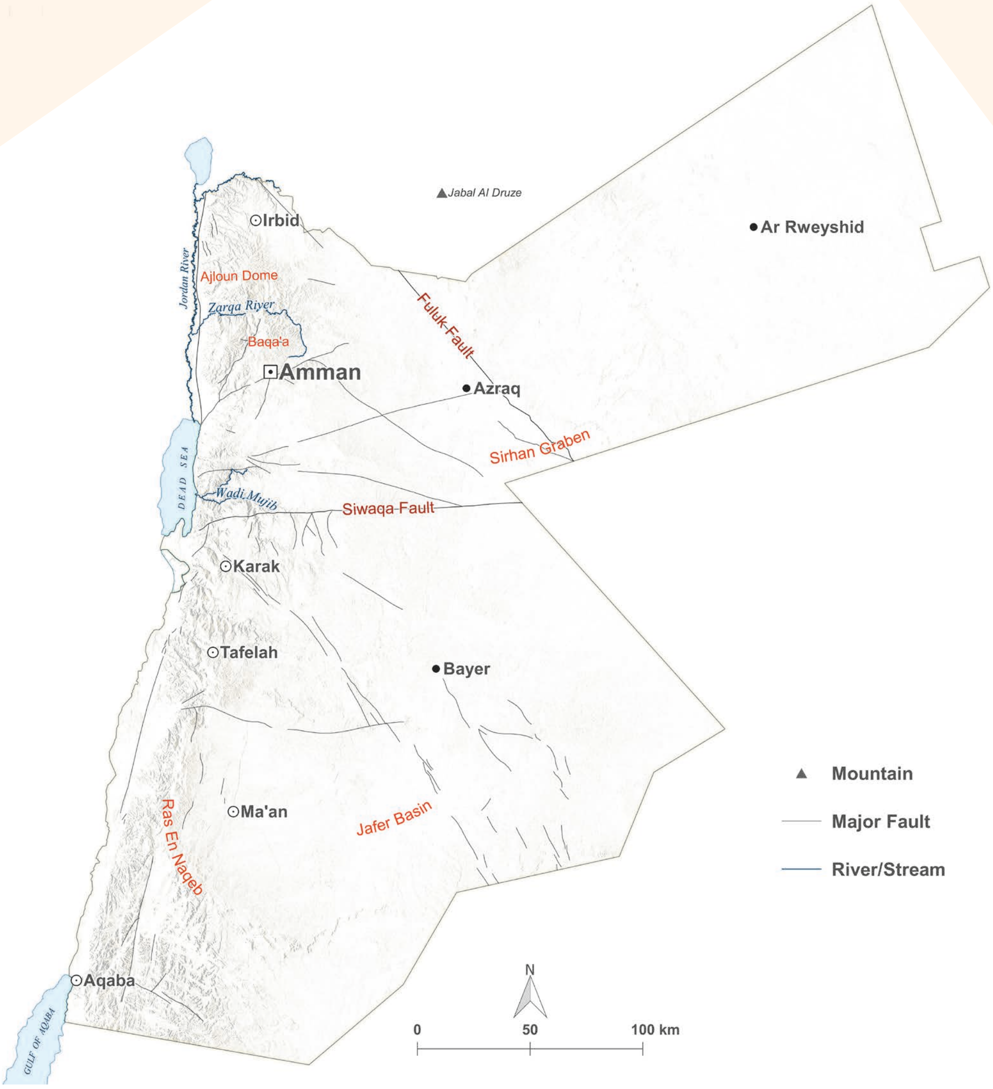


Figure 18 Overview of faults in Jordan

planes were simply considered to be vertical. Consequently, the maps are less accurate near the faults. Smaller faults were not considered, even though they may be relevant at the local scale. The country was divided into several "fault blocks" that were interpolated independently in ArcGIS from the structure contour lines and then merged together to account for displacements along faults.

3.1.2 Hydrogeological map

The hydrogeological map (Annex 1) is a simplified map of the outcrops of the hydrogeological units in Jordan (Figure 19). The map was originally created by the MWI and combines the geological formations with their respective hydrogeological characteristics. To simplify this map, formations with similar hydrogeological characteristics and/or hydraulic connections were merged to represent a single hydrological unit.

The hydrogeological setting of Jordan has been described in detail in many previous studies. This section is based on "Groundwater Resources of Northern Jordan – Contributions to the Hydrogeology of Northern Jordan" (Margane et al., 2001), Geology of Jordan (Bender, 1974) and the Groundwater Resources of Northern and Southern Jordan (Margane et al., 2002).

The geological sequence in Jordan is subdivided into lithostratigraphic units based on hydrogeological relevance (Figure 23). These units describe the succession of aquifers and aquitards and have been a well-established system since the 1970s (GTZ/NRA 1977, Abu Ajamieh et al., 1988, BGR/WAJ 1991).

The series of sedimentary rocks is up to 3000 m thick because the base levels for some of the aquifers are very deep due to downfaulting of the Dead Sea Rift valley. A complex aquifer system developed with 3 major hydraulic complexes, which are important for the entire region and are separated by marly and clayey aquitards:

Source: BGR

Basalt: The shallow (upper) aquifer system, consisting of Tertiary and Quaternary sedimentary and igneous rocks (alluvium, basalt, B4-B5)

Source: BGR

Limestone: The Upper Cretaceous A7/B2 limestone aquifer (the most important aquifer in Jordan) and the A1-A6 limestone-marl aquifer-aquitard group

Source: BGR

Sandstone: The Kurnub-Zarqa-Ram/Disi Sandstone aquifer system

This long-term established aquifer grouping is only a general description and can vary locally. In some areas, the A7/B2 aquifer is directly connected to the overlying basalt aquifer. In areas where the A7/B2 aquifer is already unsaturated, the deeper A4 or A1/A2 aquifer can be locally important. In addition, this aquifer-aquitard group separates the two important aquifer systems of A7/B2 and the deep sandstone aquifer system. In the central part of Jordan, the Kurnub Formation and Ram Group are hydraulically connected. However, this connection cannot be assumed for the entire country because in northern and eastern Jordan, these groups are separated by the Khreim aquitard and/or the low-permeability Zarqa Formation.

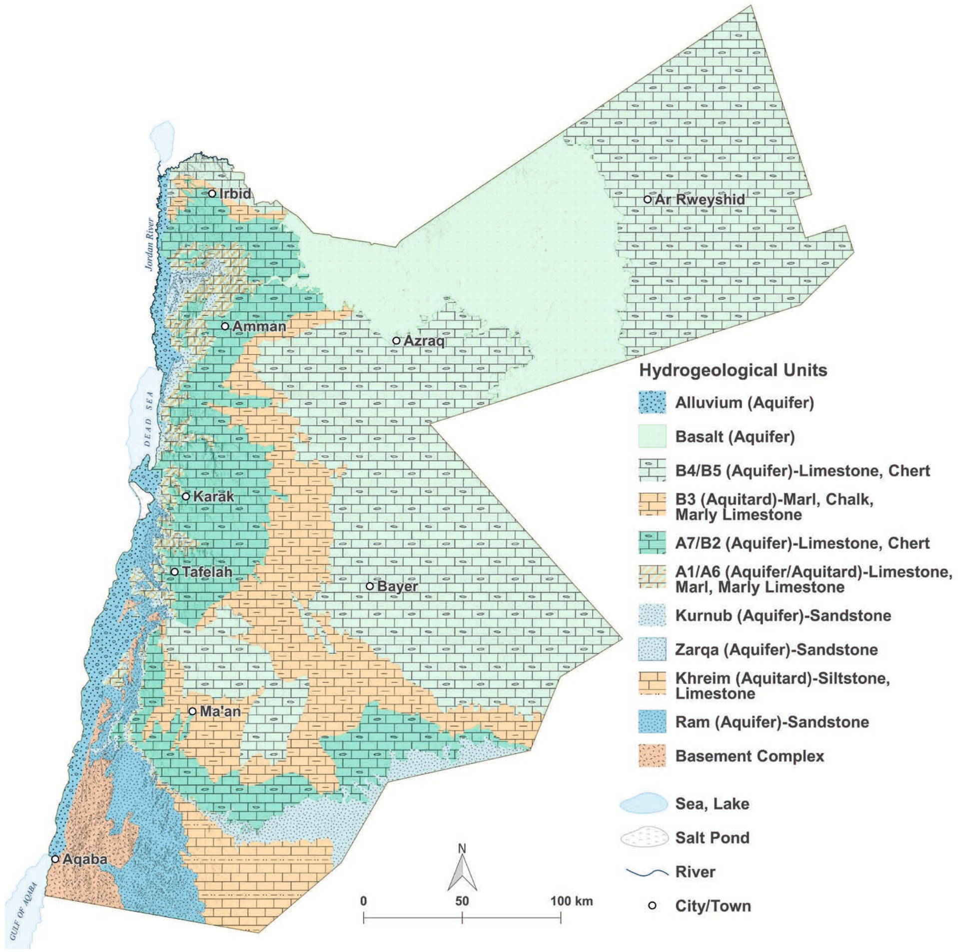


Figure 19 Simplified hydrogeological units of Jordan

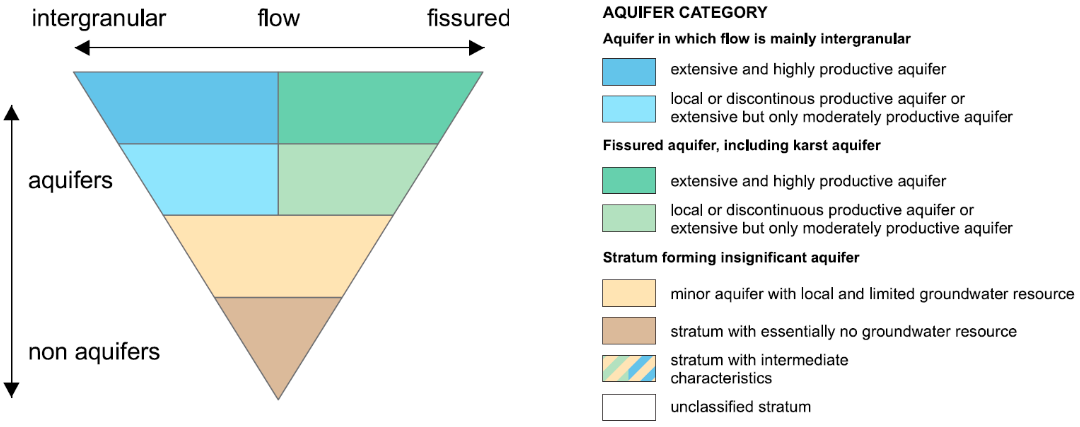


Figure 20 Aquifer classification system (after Struckmeyer & Margat, 1995)

The colors of the hydrogeological units in the map were selected based on the aquifer classification system of Struckmeyer & Margat (1995). Blue and green represent aquifers, and the darker the color is, the greater the potential for aquifer exploitation is. Formations with limited potential are show in light brown, while strata with essentially no groundwater are indicated by dark brown. For groundwater systems with high or moderate potential, the color scheme also considers the dominant type of groundwater flow within the rock: blues are used for systems in which the flow is mainly intergranular, while greens represent systems formed by hard rock, including karst, where the flow occurs in fissures, fractures or dissolution cavities (Figure 20).

3.1.3 Hydrogeological Cross-Sections

Four cross-sections were constructed using the new SCMs (Figure 21) along the cross-section lines from Hobler et al. (1991) in southern Jordan and Margane & Hobler (1994) in northern Jordan (Annex 2). SRTM (USGS, 2015) grid data with 90 m x 90 m resolution were used to describe the surface topography. The SCMs and groundwater contour maps are displayed at the same grid resolutions. The cross-sections have a vertical scale of 1:25 and a horizontal scale of 1:322,000.

In contrast with the previous cross-sections, which were idealized representations of the subsurface, the updated SCMs were used here. Due to data gaps, only the upper parts of the aquifers and major faults are shown (Figure 22).

Depressions or uplifted areas in the SCMs that could be the result of possible tectonic movements are indicated, but the faults were not drawn. When using the SCMs or cross-sections for hydrogeological exploration, the shortcomings of the data and tools must be considered.

3.2 Results

The hydrostratigraphic classification of the geological units in Jordan is shown in Figure 23. In the following sections, the major hydrogeological characteristics of the main aquifer and aquitard systems are described, and their SCMs are presented. The SCMs were only updated for those units with sufficient new information.

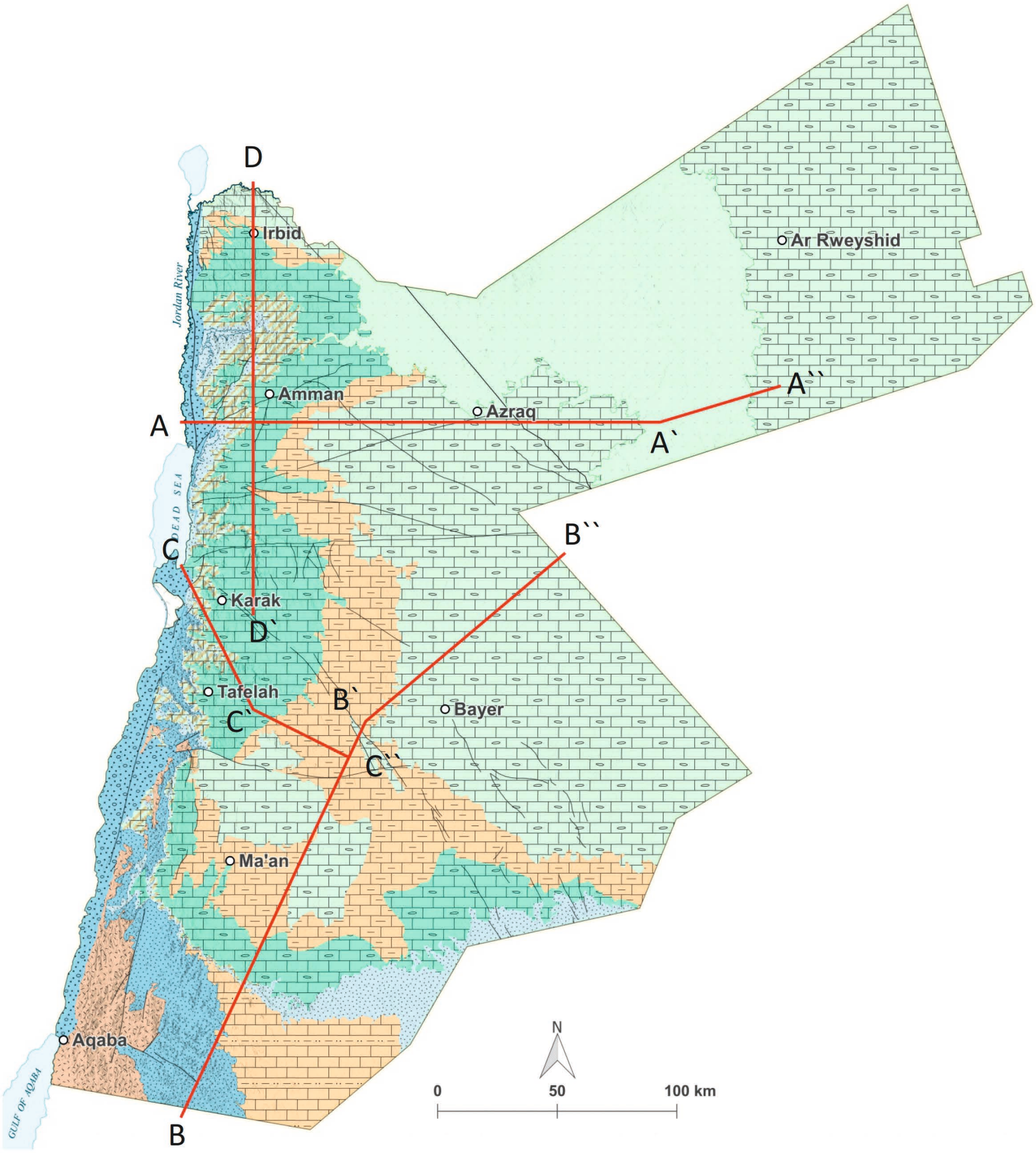


Figure 21 Overview map with locations of cross-sections

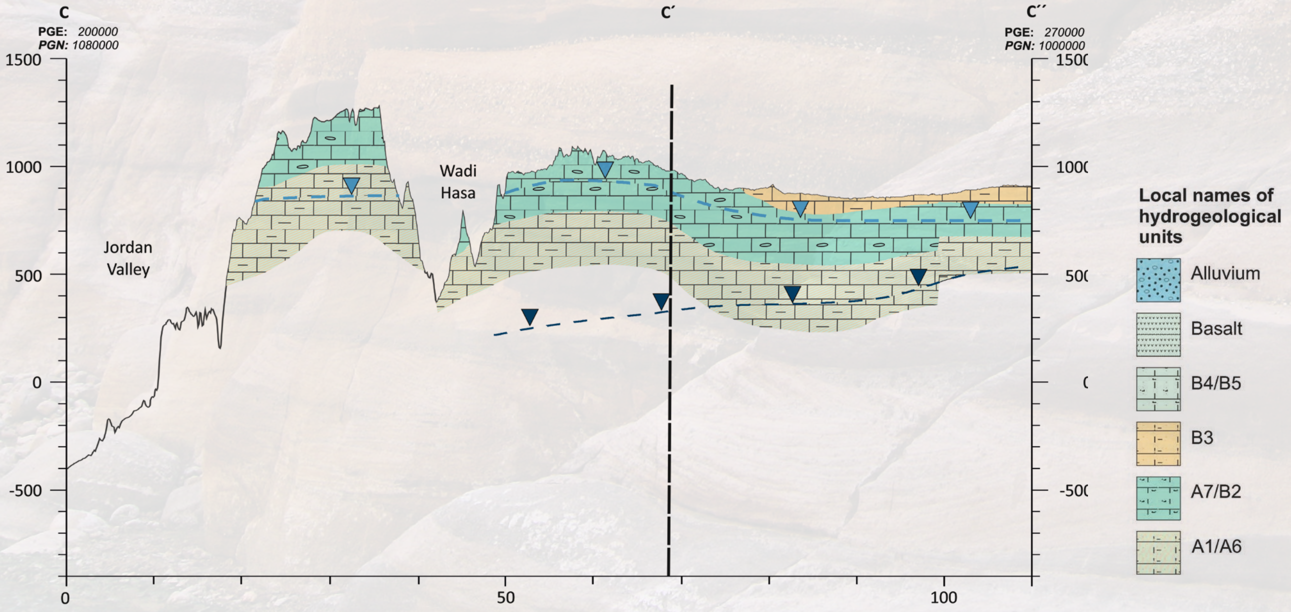
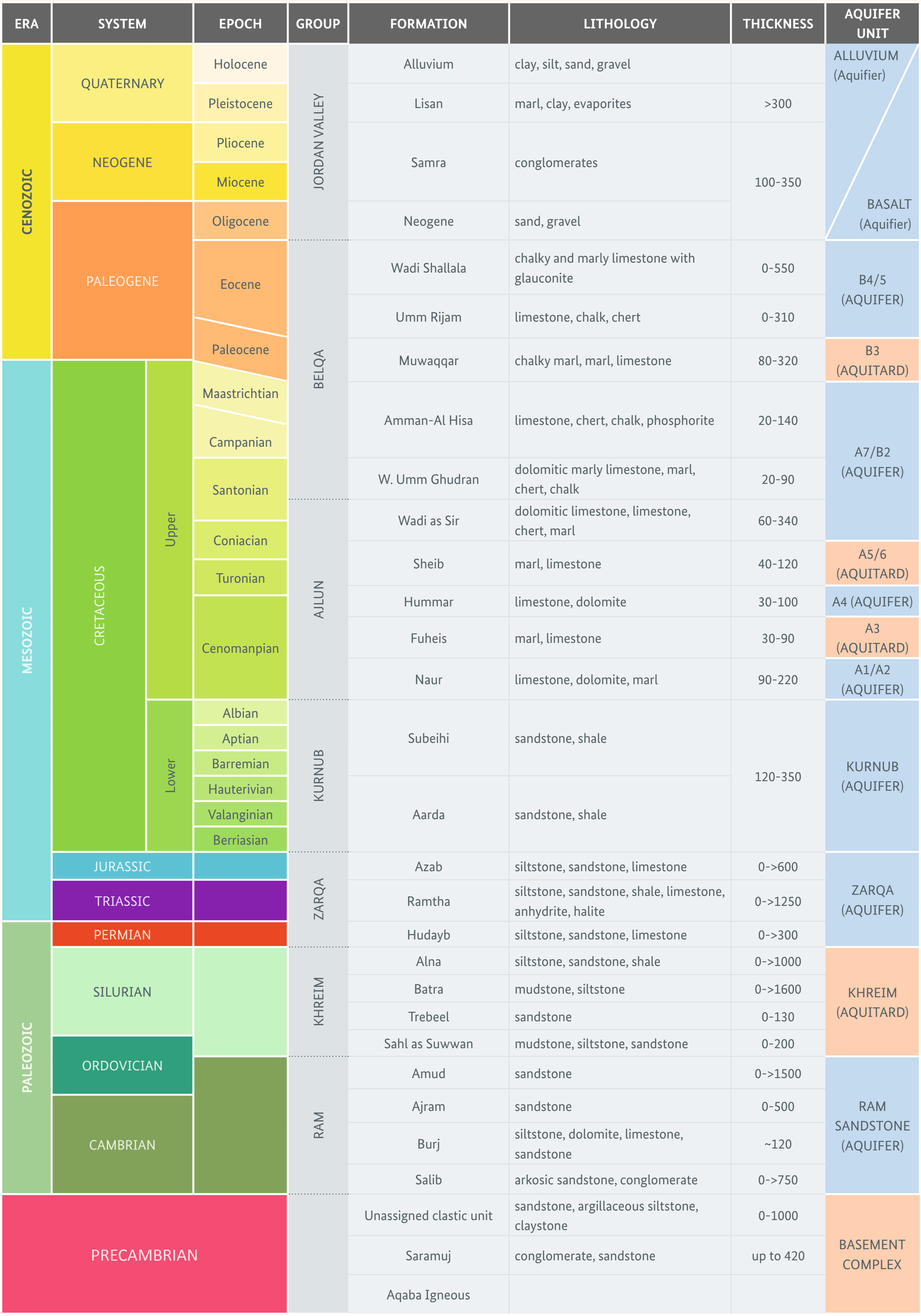


Figure 22 Cross-section C-C‘-C“ from the Jordan Valley to the southeast



ERA	SYSTEM		EPOCH	GROUP	FORMATION	LITHOLOGY	THICKNESS	AQUIFER UNIT
CENOZOIC	QUATERNARY		Holocene	JORDAN VALLEY	Alluvium	clay, silt, sand, gravel		ALLUVIUM (Aquifier) BASALT (Aquifier)
			Pleistocene		Lisan	marl, clay, evaporites	>300	
	NEOGENE		Pliocene Miocene		Samra	conglomerates	100-350	
	PALEOGENE		Oligocene		Neogene	sand, gravel		
			Eocene	BELQA	Wadi Shallala	chalky and marly limestone with glauconite	0-550	B4/5 (AQUIFER)
					Umm Rijam	limestone, chalk, chert	0-310	
			Paleocene		Muwaqqar	chalky marl, marl, limestone	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 marly 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)
			Cenomanpian		Hummar	limestone, dolomite	30-100	A4 (AQUIFER)
					Fuheis	marl, limestone	30-90	A3 (AQUITARD)
					Naur	limestone, dolomite, marl	90-220	A1/A2 (AQUIFER)
		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	
					Sahl as Suwwan	mudstone, siltstone, sandstone	0-200	
	ORDOVICIAN			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					Unassigned clastic unit	sandstone, argillaceous siltstone, claystone	0-1000	BASEMENT COMPLEX
					Saramuj	conglomerate, sandstone	up to 420	
					Aqaba Igneous			

Figure 23 Stratigraphic chart of Jordan with hydrogeological classifications (after El-Naser, 1991 and Margane et al., 2000)
]

3.2.1 Ram Hydrogeological Unit

The Ram Group (Cambrian to Ordovician) consists mainly of medium- to coarse-grained siliciclastic rocks that unconformably overlie the peneplain crystalline granite basement complex (Barthelemy et al., 2010; Powell et al. 2014). The sediments were deposited at high velocity by a high-discharge system of braided rivers in a near-coastal environment, as evidenced by brief marine intercalations. The source rocks were distant Neoproterozoic granitoids of the Arabian-Nubian shield that were uplifted and eroded (Powell et al., 2014).

Outcrops are located along the lower slopes of the rift escarpment and in the southern desert, where the complete sequence reaches a thickness of up to 1000 meters. Information from boreholes shows that the Ram Group sandstones underlie all of Jordan except for small areas around Aqaba and on the eastern escarpment of Wadi Araba, where the Ram Group units are either eroded or separated from additional eastern occurrences by faults. The thickness increases to the northeast, reaching more than 2000 m in the Wadi Sirhan depression (BGR/ESCWA, 2013).

From a hydrogeological point of view, the Ram Group is an important porous aquifer that dewaters towards the Dead Sea. The name “Disi Sandstone” is sometimes used for this formation, but the Disi Sandstone is just one of the formations that comprise the Ram Group. In western Jordan, the Kurnub aquifer directly overlies the Ram Group aquifer, forming a combined aquifer complex (Margane et al., 2002). In eastern Jordan, low-permeability strata from the Khreim Group separate the two sandstone aquifers.

3.2.2 Khreim Hydrogeological Unit

The Silurian Khreim Group consists of several formations (Sahl as Suwaan, Umm Tarifa, Trebel, and Alna). The unit is composed of fluvial to shallow marine sediments. The main lithologies are fine-grained sandstones and siltstones.

Due to the low permeability of the sandstones and siltstones, the entire unit is considered to be an aquitard (Margane & Hobler, 1994, Barthelemy et al., 2010).

3.2.3 Zarqa

The Permian to Triassic Zarqa Group combines two formations of marine and alluvial origins (Hudayb and Ramtha). The overlying marine Jurassic carbonates of the Azab Formation are usually included in this group, although it was elevated to group status in the 2016 stratigraphic chart of Jordan (Hussein & Moumani, 2016). The Zarqa Group forms a minor aquifer that is hydraulically connected to the Kurnub sandstone in some areas.

3.2.4 Kurnub

The Kurnub Group is composed of sandstones that mark the base of a Lower Cretaceous transgressive event. It lies directly on top of the Ram Group in the western part of Jordan, whereas to the east, the Khreim unit separates these two groups. The thickness increases to the northeast and reaches 30 m-150 m near Azraq (Barthelemy et al., 2010). Outcrops are mainly located south of the Zarqa River and on the lower slopes of the rift escarpment as well as in deeply incised wadis. The Kurnub sandstone is an aquifer.

3.2.5 A1/A6 Hydrogeological Unit

Several formations belonging to the Upper Cretaceous Ajlun Group are usually grouped together as the “A1/A6 aquitard” when working at the countrywide scale. At the local scale, the A1/A2 and A4 aquifers are important for the water supply, especially in areas where the overlying A7/B2 aquifer has nearly dried up. The Naur Formation (A1/A2) is composed of intercalations of limestone and relatively thin layers of marl and marly limestone. The Hummar Formation (A4) mainly consists of thick limestone layers, whereas the Fuhais (A3) and Shuayb (A5/A6) formations are principally composed of marl and marly limestone. Outcrops of the Upper Ajloun Group are mainly located northwest of Amman and are common on the slopes of the rift escarpment and side wadis. The A3, A4 and A5/A6 units cannot be distinguished from each other south of the Siwaqa Fault.

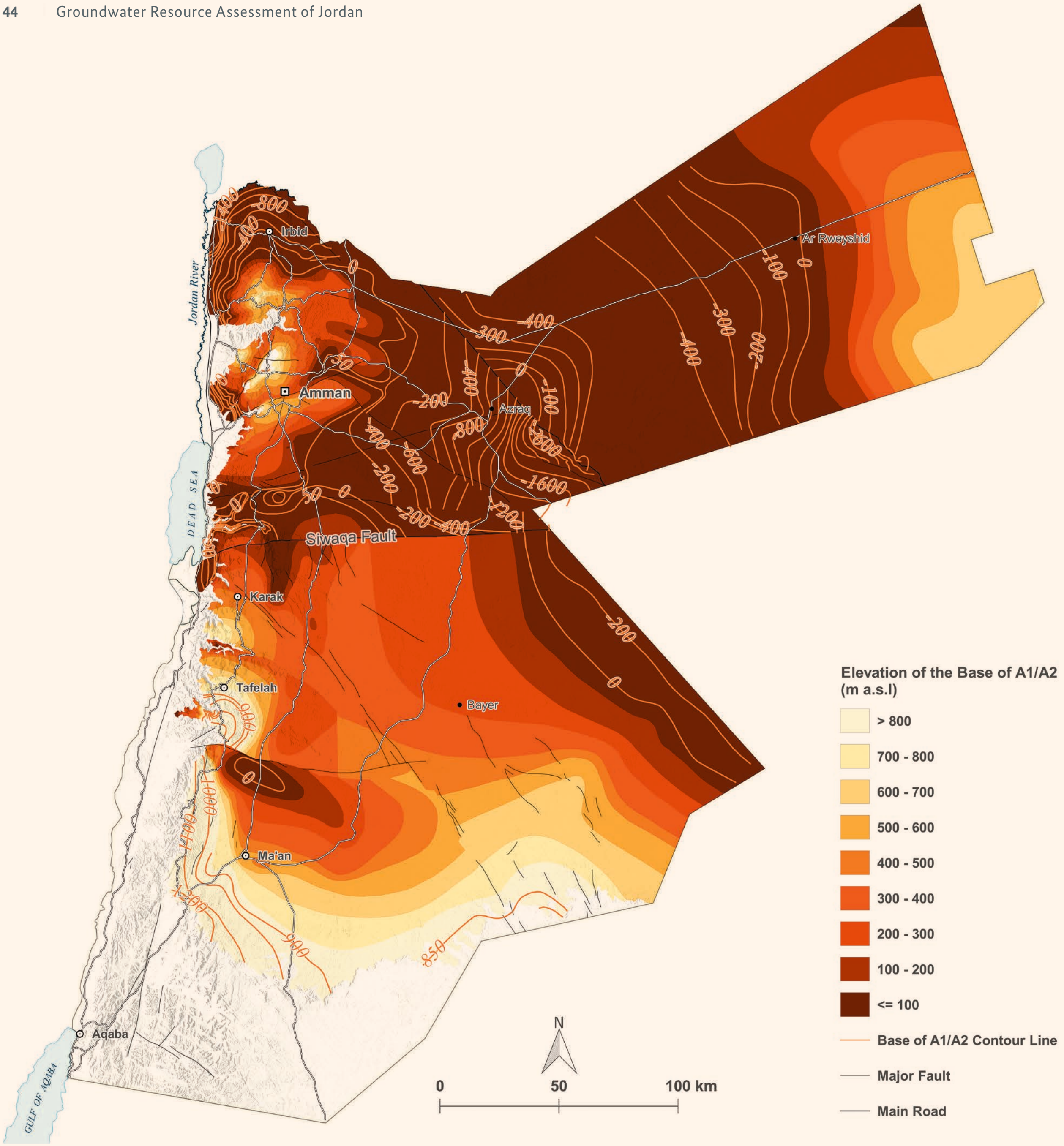


Figure 24 Structure contour map of the A1/A2 aquifer

A1/A2 Aquifer

The Naur Limestone formation (A1/A2) formed during a major marine transgressive event during the early Cenomanian over the alluvial rocks of the Kurnub sandstone (Powell, 1988). The prominent cliff-forming dolomitic limestones can be found across most of Jordan except in the south, in the highlands along the Dead Sea Rift south of the Dead Sea and along the lower reaches of the Zarqa River. The aquifer thins from nearly 300 m in the Irbid area in the north to approximately 150 m in Wadi Mujib to only 25 m at the Ras en Naqb escarpment in the south. Several structural elements can be identified (Figure 24), including the structural high of the Ajloun Dome in northern Jordan, from which the strata dip to the west, north and east; the depression of the Jafer Basin north of Ma'an; the deeply subsided Wadi Sirhan Graben with the bordering Fuluq Fault; and the Siwaqa Fault, an east-west-striking fault south of the Dead Sea with large displacements. In general, the A1/A2 and overlying formations dip gently to the east due to uplift of the graben shoulder of the Dead Sea Rift.

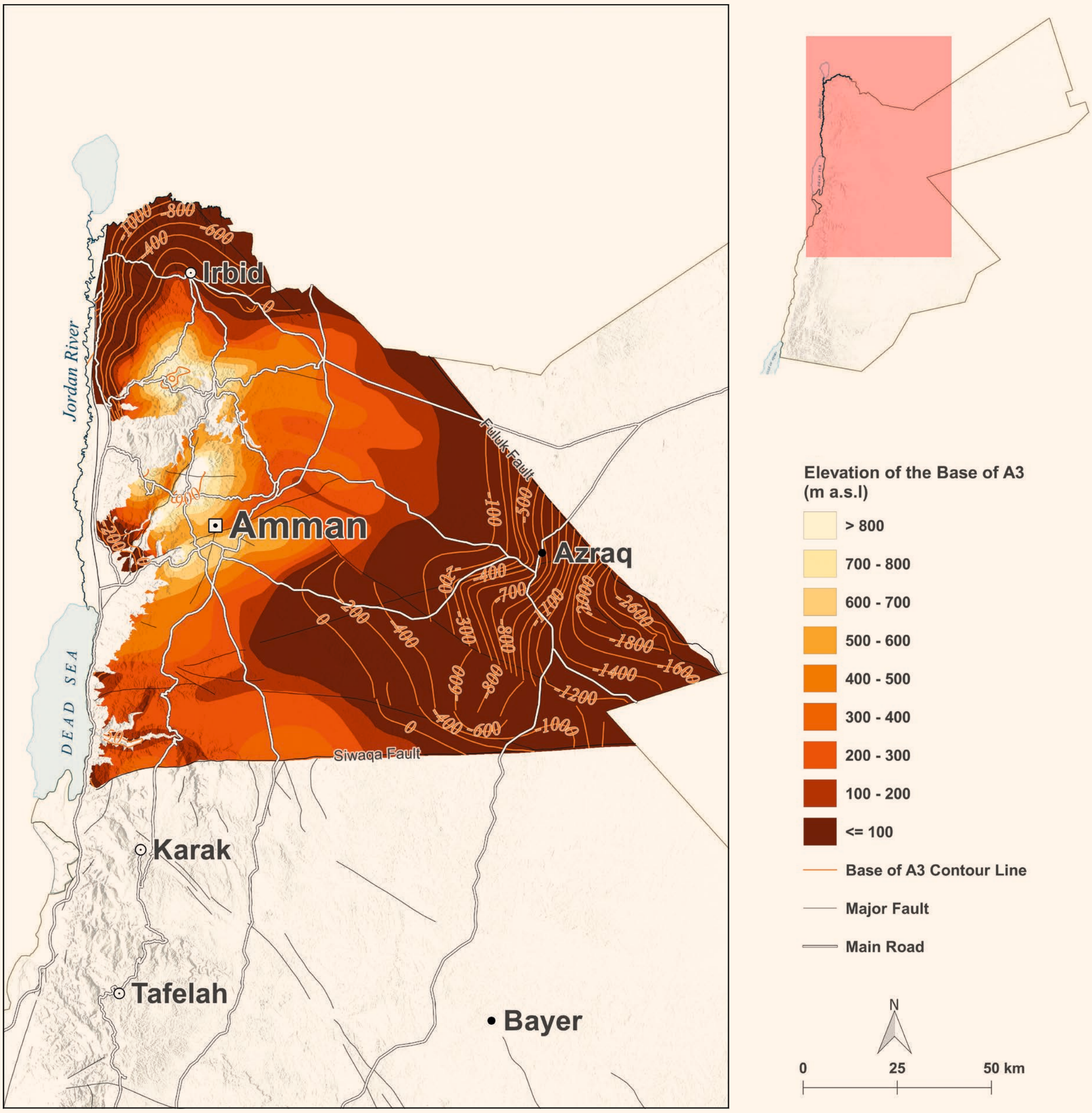


Figure 25 Structure contour map of the A3 aquitard

A3 Aquitard

The A3 aquitard (Fuhais Formation) has an average thickness of approximately 50 m and thins to the south. The structural trends follow that of the underlying A1/A2 Formation (Figure 25). The A3 is not present in the lower Zarqa River, the Baqa'a Valley northwest of Amman and between Amman and the northern Dead Sea. There are no data regarding the presence of the A3 aquitard east of the Fuluq Fault. Due to facies changes, the borders between A3, A4 and A5/A6 are unclear south of the Siwaqa Fault, and these units are mapped as one unit. North of the fault, the formation is characterized by marls and argillaceous and nodular limestones (Schulze et al., 2003)

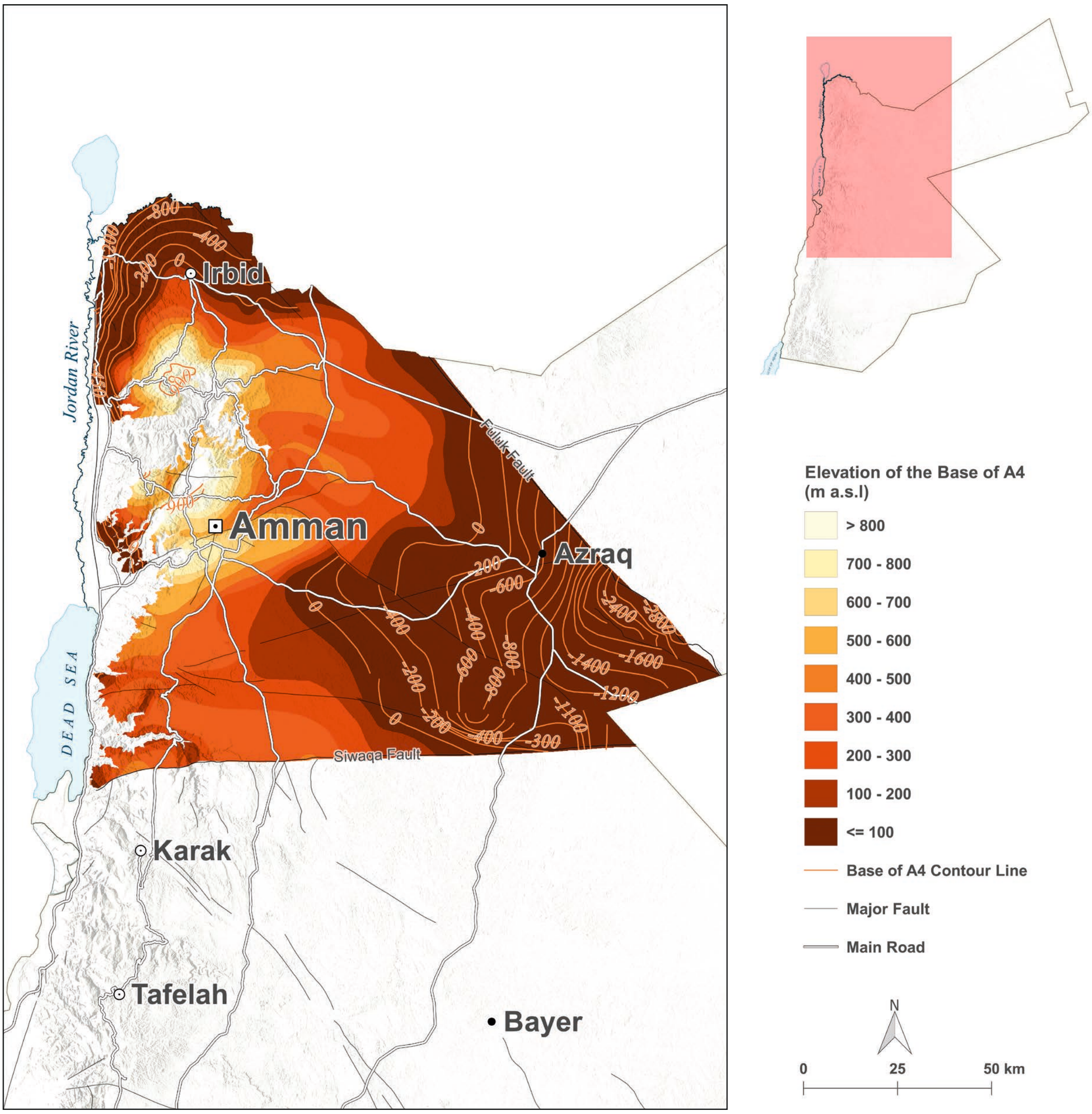


Figure 26 Structure contour map of the A4 aquifer

A4 Aquifer

The thickness of the A4 aquifer (Hummar Formation) is comparable to that of the A3 aquitard. The lithology changes from cliff-forming dolostones and dolomitic limestones in the north to marls and shales intercalated with fossiliferous limestone in central Jordan (Schulze et al., 2003). Several springs emerge from this aquifer (see Chapter 5). The aquifer is hydraulically connected to the underlying A1/A2 aquifer or the overlying A7/B2 aquifer due to faulting and karstification (Brückner et al., 2015; Margane et al., 2009; Subah & Hobler, 2004). The structure of the A4 aquifer is shown in Figure 26.

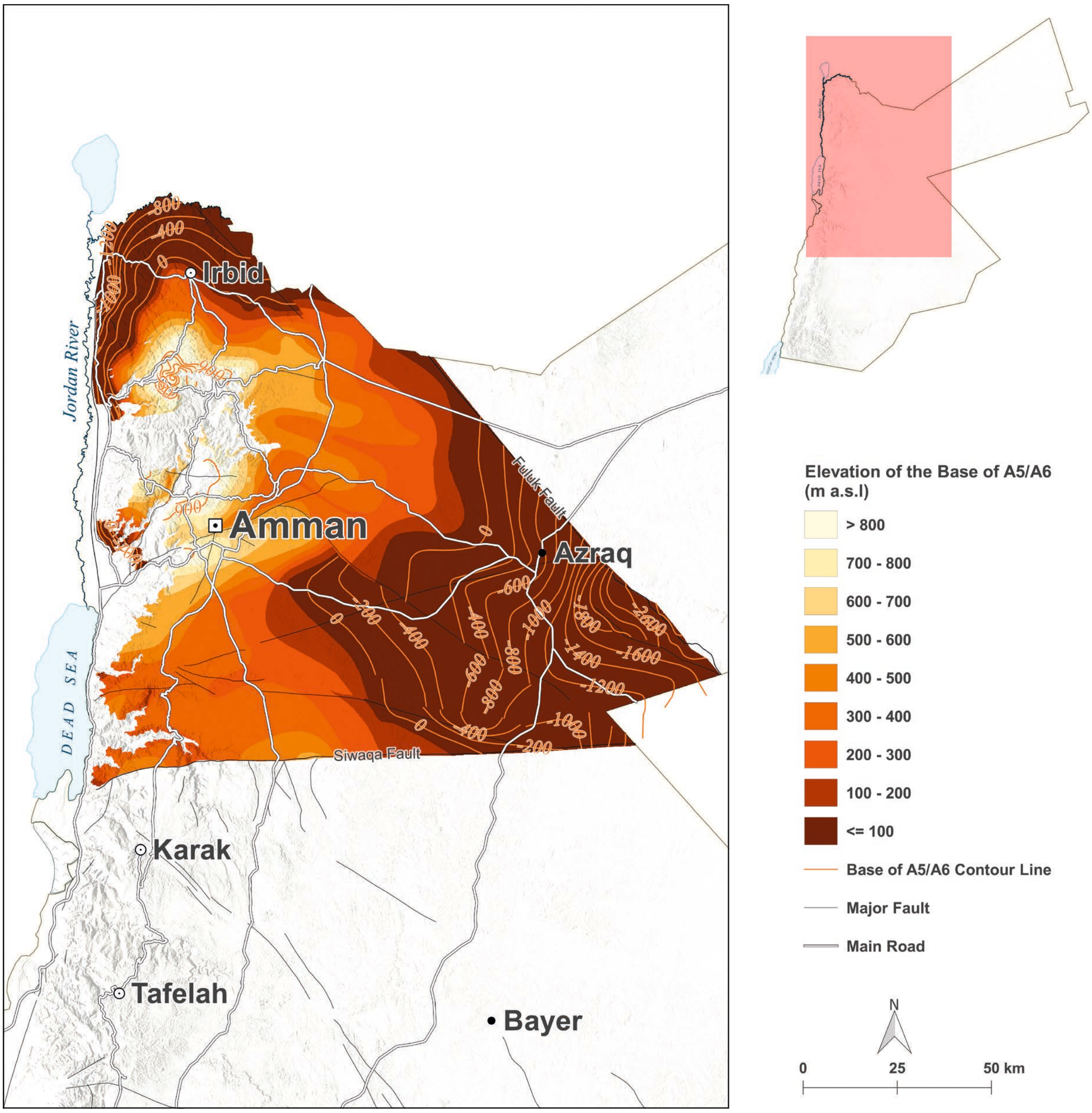


Figure 27 Structure contour map of the A5/A6 aquitard

A5/A6 Aquitard

The A5/A6 aquitard, or Shueyb Formation, has a similar distribution and thickness to the A3 and A4 formations (Figure 27). This aquitard separates the A4 aquifer from the A7/B2 aquifer, although there is some evidence that this separation does not always exist, which is probably due to karstification (Brückner et al., 2015). This aquitard consists of a limestone member in the upper part of the formation and marls and marly limestones in the lower part with occasional claystones and bituminous shales.

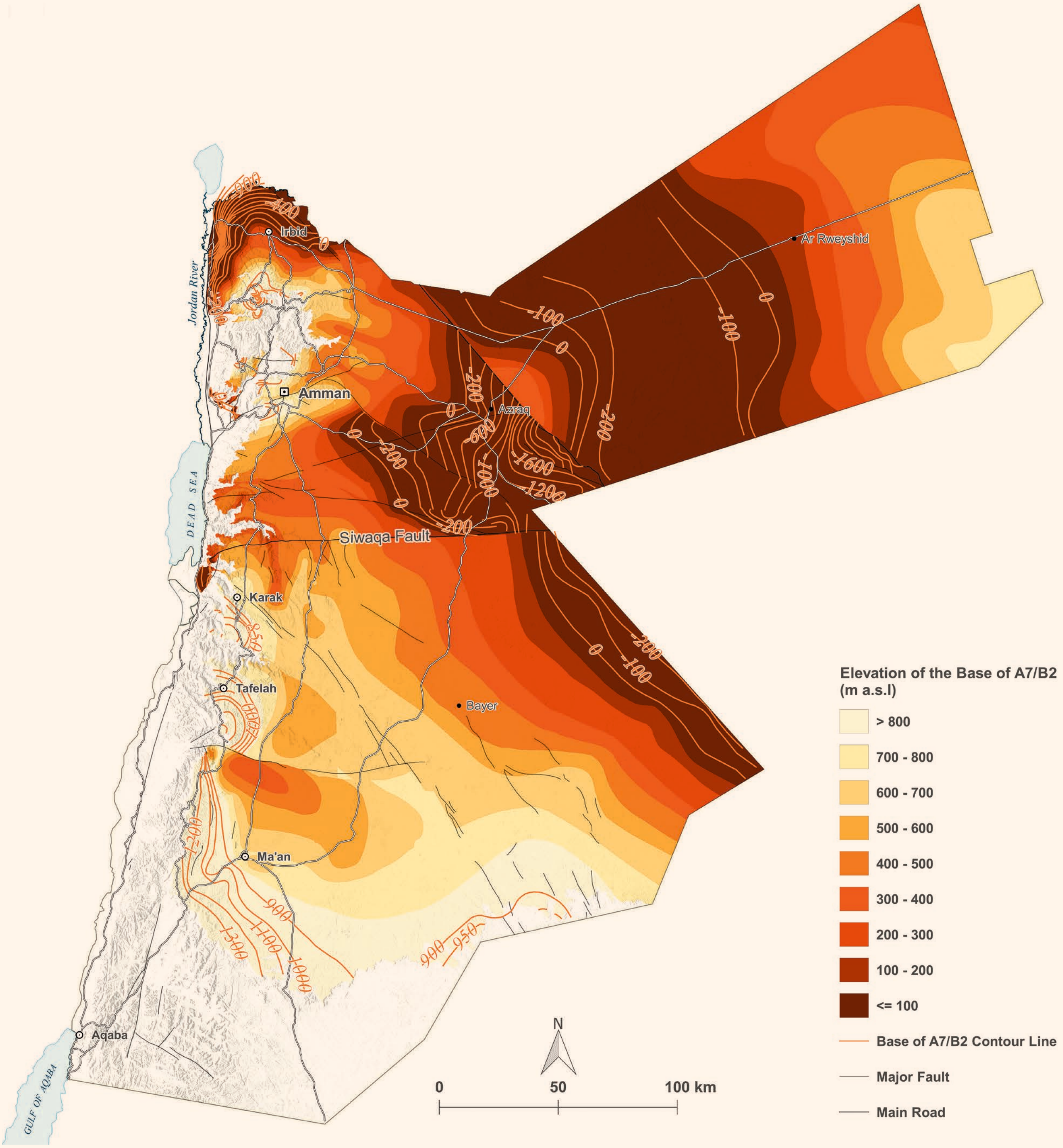


Figure 28 Structure contour map of the A7/B2 aquifer

3.2.6 A7/B2 Aquifer

The A7/B2 aquifer consists of three formations of the Upper Cretaceous Ajloun (Wadi as Sir) and Balqa (Wadi Umm Ghudran and Amman-Al Hisa) groups. The main lithologies are massive limestone, dolomitic limestone, and dolomite with intercalated beds of sandy limestone, chalk, marl, gypsum, chert, and phosphorite (Margane et al., 2002).

The majority of the wells that fully penetrate the A7/B2 aquifer are located in northern Jordan between Amman, Mafraq, and Ajloun. The thickness increases towards the Sirhan Graben, where it can reach 2200 m. The dip is generally towards Wadi Sirhan and away from Ajloun Dome (Figure 28), which is a prominent structural high in northern Jordan.

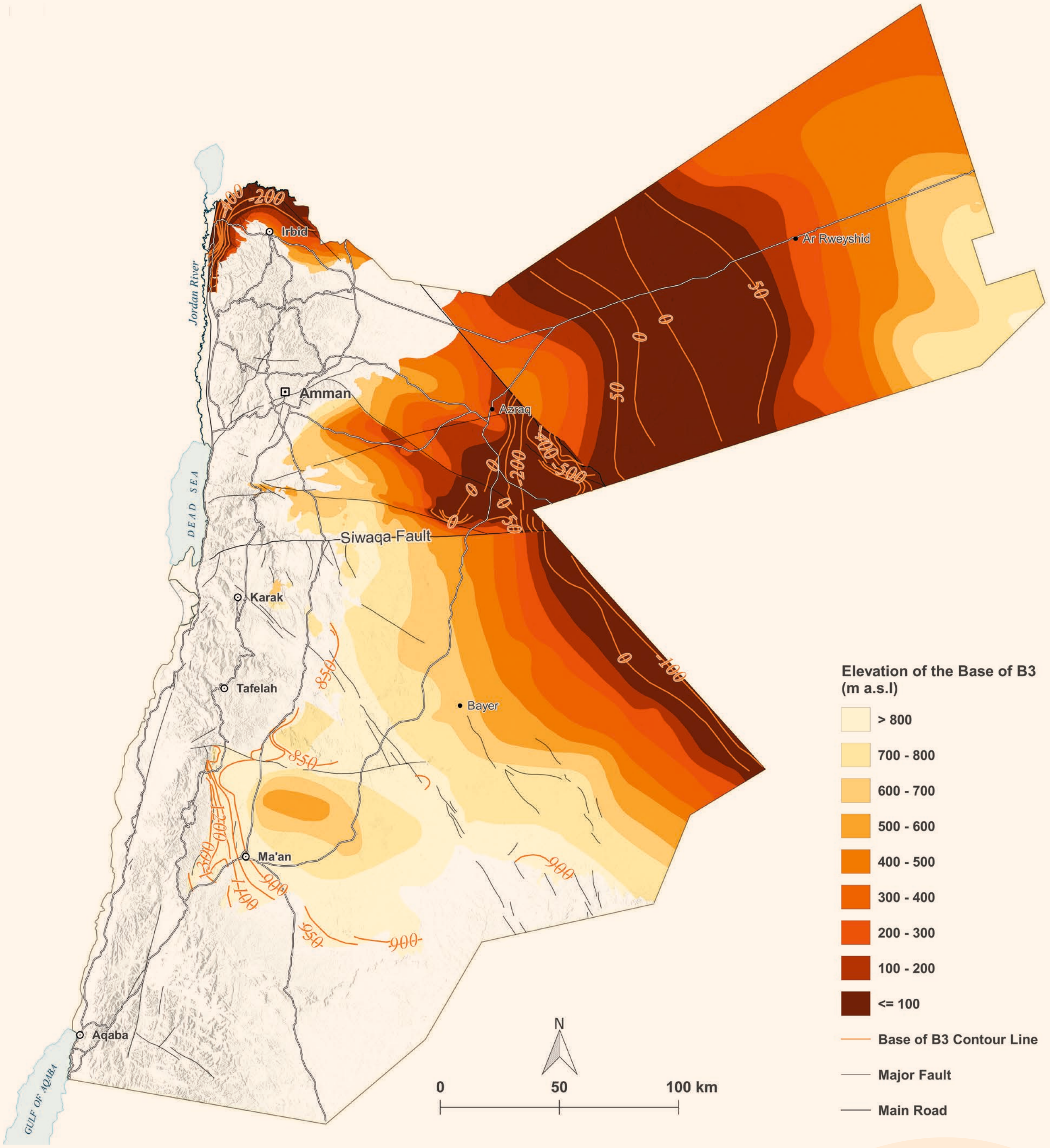


Figure 29 Structure contour map of the B3 aquitard

3.2.7 B3 Aquitard

Chalky to marly Paleogene limestones with minor intercalations of chert comprise this formation, which is the most important aquitard in Jordan. These limestones were deposited in a shallow shelf environment. Most of the proven oil shale reserves in Jordan formed in the lower part of this formation due to locally elevated bitumen contents (Ziegler, 2001).

Because the majority of the water wells in Jordan tap the underlying A7/B2 aquifer, the base of this formation is generally well documented (Figure 29). Additionally, significant amounts of “oil shales” (lithologically: bituminous marls) are present in this formation, and many exploration boreholes have been drilled to investigate the potential for its extraction.

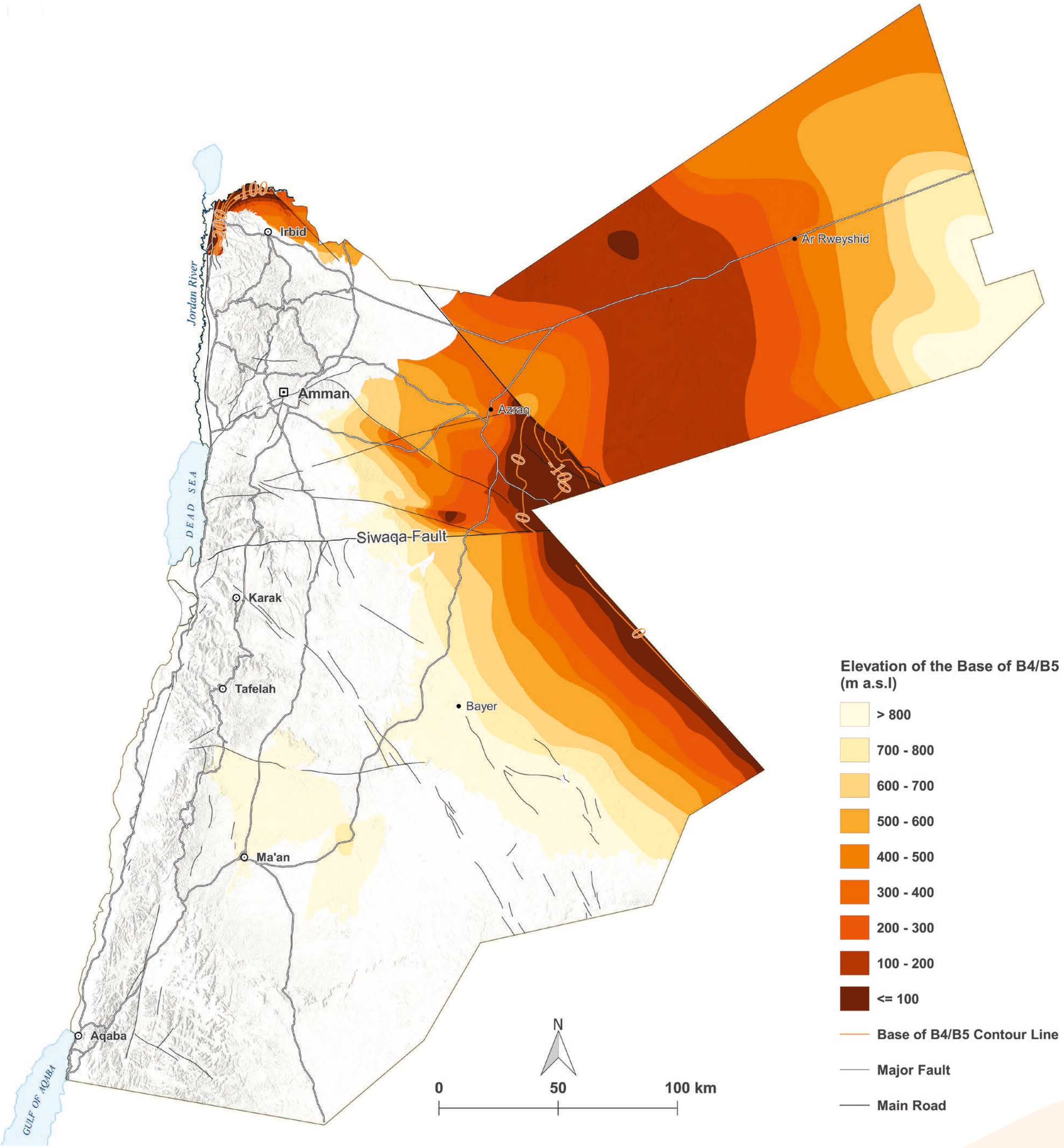


Figure 30 Structure contour map of the B4/B5 aquifer

3.2.8 B4/B5 Aquifer

The Paleogene B4 (Umm Rijjam) and B5 (Wadi Shallala) formations form a combined aquifer at the regional level, although the marls in B4 can act as aquitards in some areas (Margane & Hobler, 1994). Outcrops of the B4/B5 aquifer can be found in eastern Jordan as well as in the north and in the Jafer Basin. In some areas, the outcrops are unclear because of extensive alluvial cover, especially north of Azraq. The average thickness of the B4/B5 aquifer is approximately 230 m, and the maximum thickness of 970 m, including the alluvium, is located in the Sirhan Graben (Figure 30).

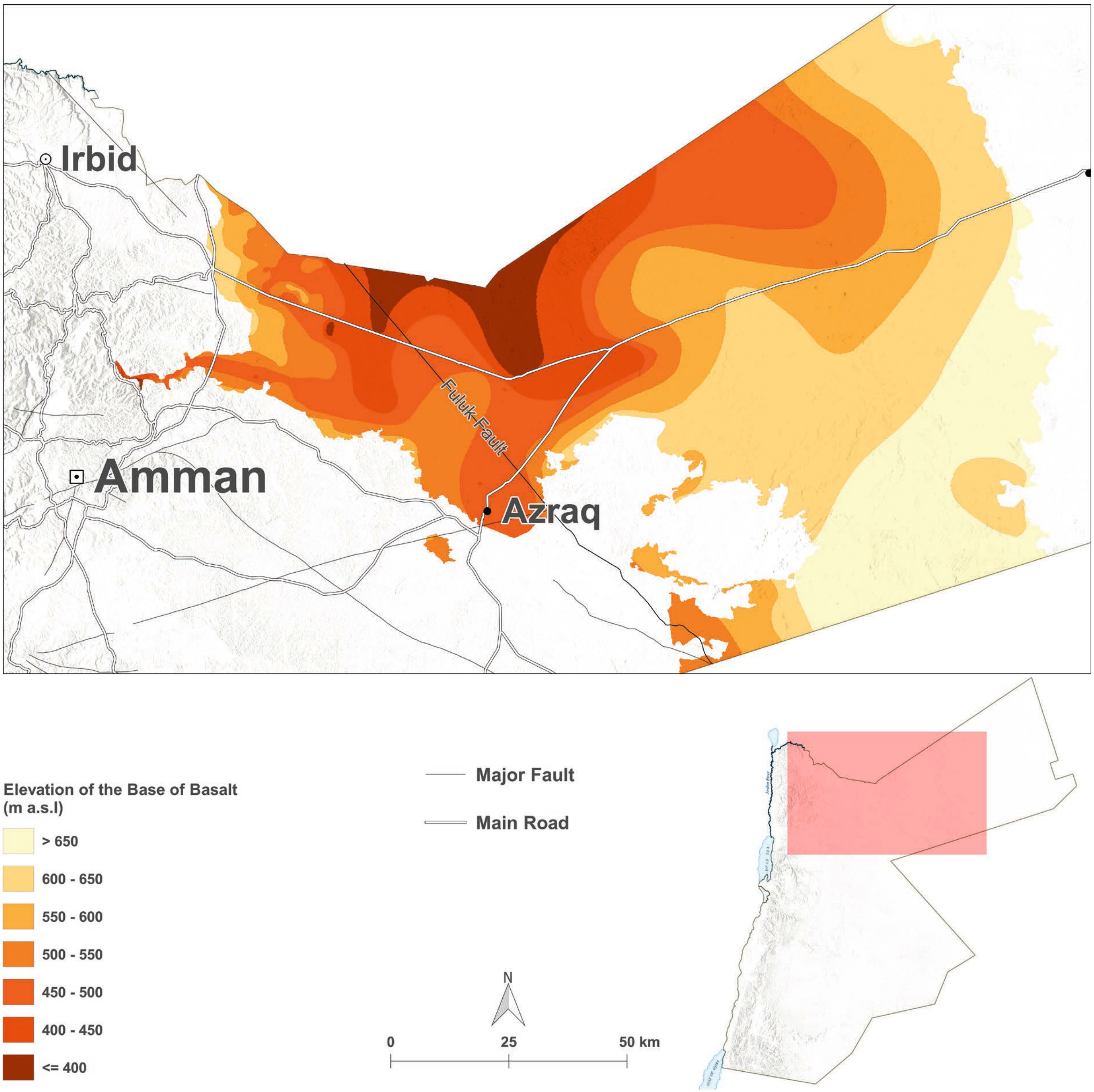


Figure 31 Structure contour map of the Basalt aquifer

3.2.9 Basalt

The Harrat Ash Shams Basalt (Tertiary to Quaternary) is the Jordanian part of the North Arabic Volcanic Province. This region includes the Golan Heights and Harrat Province in Saudi Arabia and is centered on the Jebel al Arab in Southern Syria. The province consists of Neogene plateau basalts as well as Quaternary lava flows and shield volcanoes (Wagner, 2011). The greatest thickness of approximately 1500 m is located at the Jebel al Arab volcano (1803 m asl), and the thickness decreases to the south with a maximum estimated thickness in Jordan of 500 m (Figure 31) (Margane et al. 2002). The Jebel al Arab Mountain is the main recharge area for the Basalt aquifer. Groundwater flow in the Basalt is highly anisotropic, with higher horizontal conductivities between the individual lava flows with thicknesses between 3 m and 25 m (BGR/ESCWA, 1996) and local perched aquifers. In addition, faults and cooling cracks lead to downward leakage. In Jordan, the Basalt aquifer is hydraulically connected in some areas to the underlying formations. The contact between the Basalt and the underlying layers is obscured by alluvium over large areas. Several important wellfields for the water supply of Amman are located in the Basalt area, including the Aqeb and Corridor wellfields (Borgstedt et al., 2007).

Source: BGR

3.3 Recommendations

To improve the accuracy of future SCMs, two issues must be addressed: data quality and data quantity.

The main reason for the low accuracy in some areas is the low quality of some of the data. Several improvements are feasible from the field level to data storage. In the field, it is recommended that an independent site geologist ensures that the geological description is accurate and that the quality of the borehole geophysics allows for later interpretation. Minimum quality standards for borehole descriptions can be formulated in terms of reference (ToR) for well drilling. When entering the data, a data validation step should be mandatory to avoid typing errors and incorrect coordinates. Drilling reports should be stored for future re-interpretation and quality control.

In terms of data quantity, it would be useful to store all borehole information, not only water wells, in a central lithology database. Many high-quality lithological data were produced from gas, oil, oil shale and uranium exploration wells, but the data are scattered and in danger of becoming lost. As a short-term solution, exploration wells could be entered into the WIS database, which is currently the largest lithological database in Jordan. Additionally, it is recommended to not only store the analysis of borehole logs but also the original borehole data in digital form because these data can be used in 3D geological models.

Source: BGR

GROUNDWATER RESOURCE ASSESSMENT

4

4

Groundwater Resource Assessment

Rebecca Bahls

Groundwater resources are the main water supply sources in Jordan, and these resources are used for domestic, industrial, and agricultural purposes. Due to population growth and expanding industrial and agricultural activities, the demand for water is continuously increasing.

Decreasing groundwater levels and dried out production wells and springs are indicators of extremely critical groundwater resource conditions in Jordan. Therefore, it is important to assess and analyze the actual conditions to have a sound base for taking drastic but necessary actions to safeguard Jordan's scarce groundwater resources.

This chapter presents groundwater contour maps of the Ram/Disi, Kurnub, A1/A2, A4, A7/B2, B4/B5 and Basalt aquifers for October 2017. The groundwater contour maps are the basis for other thematic maps, such as maps of the saturated thickness, the depth to water level, and the groundwater level difference between 1995 and 2017. Without the subsurface structure information presented in Chapter 3.2, the thematic maps could not be created.

4.1 Methods and Data

To collect reliable groundwater level data from all available monitoring points in Jordan, a comprehensive field campaign was carried out in October 2017. Additionally, a DGPS survey to record the precise locations and elevations of all sites used in this report was conducted. Because the point data are not homogenously distributed, data from other sources had to be included. The main data sources are as follows:

- Groundwater level measurements by BGR/MWI in October 2017
- “Water Information System” (WIS) database of the MWI
- Yarmouk Water Company
- Hydrometeorological System Support Project (HSSP) performed by the MWI with the consultation of Dornier Consulting International GmbH, Germany
- Energy Efficiency Project, Fichtner
- Water Authority Jordan (archived data and new data obtained during maintenance of abstraction wells)
- Immediate Measures Water Supply North Project (IMWS), Dorsch International Consultants
- UNICEF wells in Azraq
- Drilling reports from various companies

The field data collected by the MWI and BGR as well as the data from the WIS database of the MWI are from groundwater monitoring wells. The measurements from the other sources were mainly recorded from pumping wells during maintenance of the pumps and are likely to represent static water levels.

An area of data certainty was defined for each aquifer based on the available data distribution. All of the thematic maps are limited to this area.

4.1.1 Groundwater Contour Map - October 2017

In addition to the measurements made by the MWI/BGR project in 2017, historical data from 2012-2016 were considered after quality analysis and extrapolation following the long-term water level trends to estimate the October 2017 values (Bahls et al., 2017). Whenever a monitoring well had only a single measurement, the water level trend from the closest well in the same aquifer was used instead.

The different data sources and various degrees of uncertainty were considered in the interpolation and manual drawing of the groundwater contour lines. Given the limited number of groundwater level monitoring wells and their often-inadequate spatial distributions, the drawing of the contour lines for a given aquifer was mainly based on interpretation of the hydrogeological conditions. To identify unsaturated areas, the structure contour map (Chapter 2) of the considered aquifer was subtracted from the corresponding groundwater contour lines.

4.1.2 Depth to Groundwater Map

The depth to groundwater map has economic implications because it shows the minimum drilling depth and required pump lift. The depth to groundwater map in meters below the surface for each aquifer was calculated by subtracting the corresponding October 2017 groundwater contour lines from the SRTM 30 digital elevation raster (Jarvis et al. 2008; Farr et al. 2007; Verdin et al. 2007).

4.1.3 Saturated Thickness Map

The saturated thickness was determined by the difference between the October 2017 groundwater contour lines and the base of the representative aquifer (Chapter 3.2). The entire thickness of the aquifer was plotted in areas where the aquifer is still confined.

4.1.4 Difference Map for 1995-2017

This map presents the difference between the groundwater contour lines from 1995 and those from 2017 and provides an indication of the groundwater level changes over the last 22 years for each aquifer.

4.2 Results

The unsaturated areas are based on calculations and have not been confirmed by field measurements due to the lack of reliable monitoring information (e.g., monitored aquifer, screened depths). Furthermore, these areas depend on interpolations of point data (water level measurements as well as lithological drilling descriptions and interpretations). The results of the individual thematic maps and possible uncertainties are described in the following subchapters. All major maps are included in the attachments.

4.2.1 Deep Sandstone Aquifer System

The deep Sandstone aquifer system is composed of two major aquifers (Rum and Kurnub), the low-permeability Zarqa aquifer and the Khreim aquitard. The aquifer system is a large reservoir of fossil groundwater and plays a crucial role in the water supply of Jordan. The Disi wellfield (Ram/Disi aquifer) in the south of the country makes a major contribution of approximately 100 MCM per year to the domestic water supply. It began operations at the end of 2013, and water is transferred to northern Jordan via the Disi conveyer.

Figure 32 shows the data scarcity for the deep Sandstone aquifer system. The data covers only parts of southern and western Jordan. Additionally, the classification of the tapped sandstone aquifers is neither precise nor reliable. Groundwater contour maps can only be produced for the parts of the country where data are available.

In addition to the data collected in 2017, historical groundwater levels from the exploration wells were compared with the 2019 measurements. Because the levels have remained more or less constant, the 2019 values were used to draw the contour lines.

For the deep Sandstone aquifer system, 63 measurements were used, including 4 springs and 14 measurements obtained before 2017, which were extrapolated.

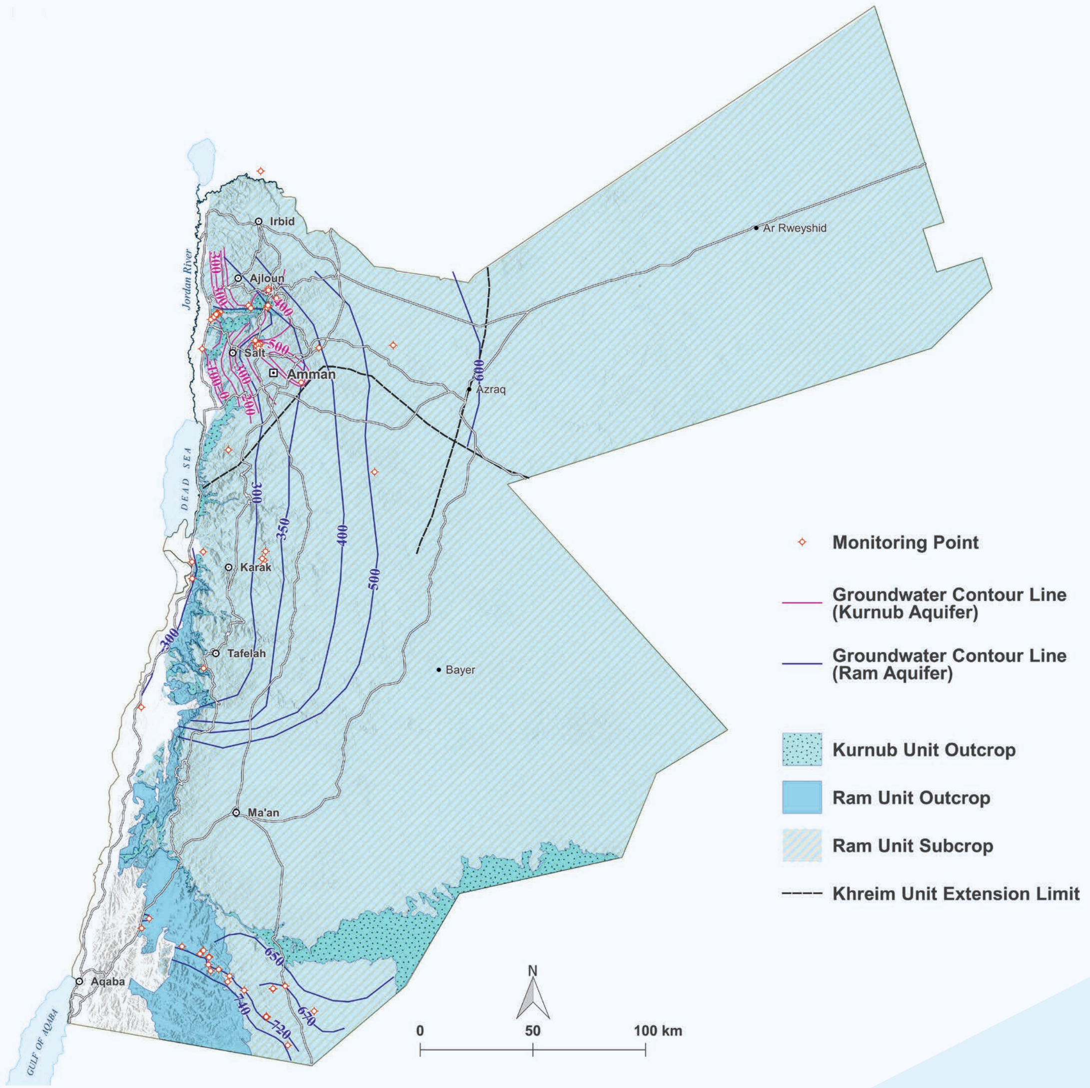


Figure 32 Groundwater level contour lines for the deep Sandstone aquifer system and the Kurnub aquifer, October 2017

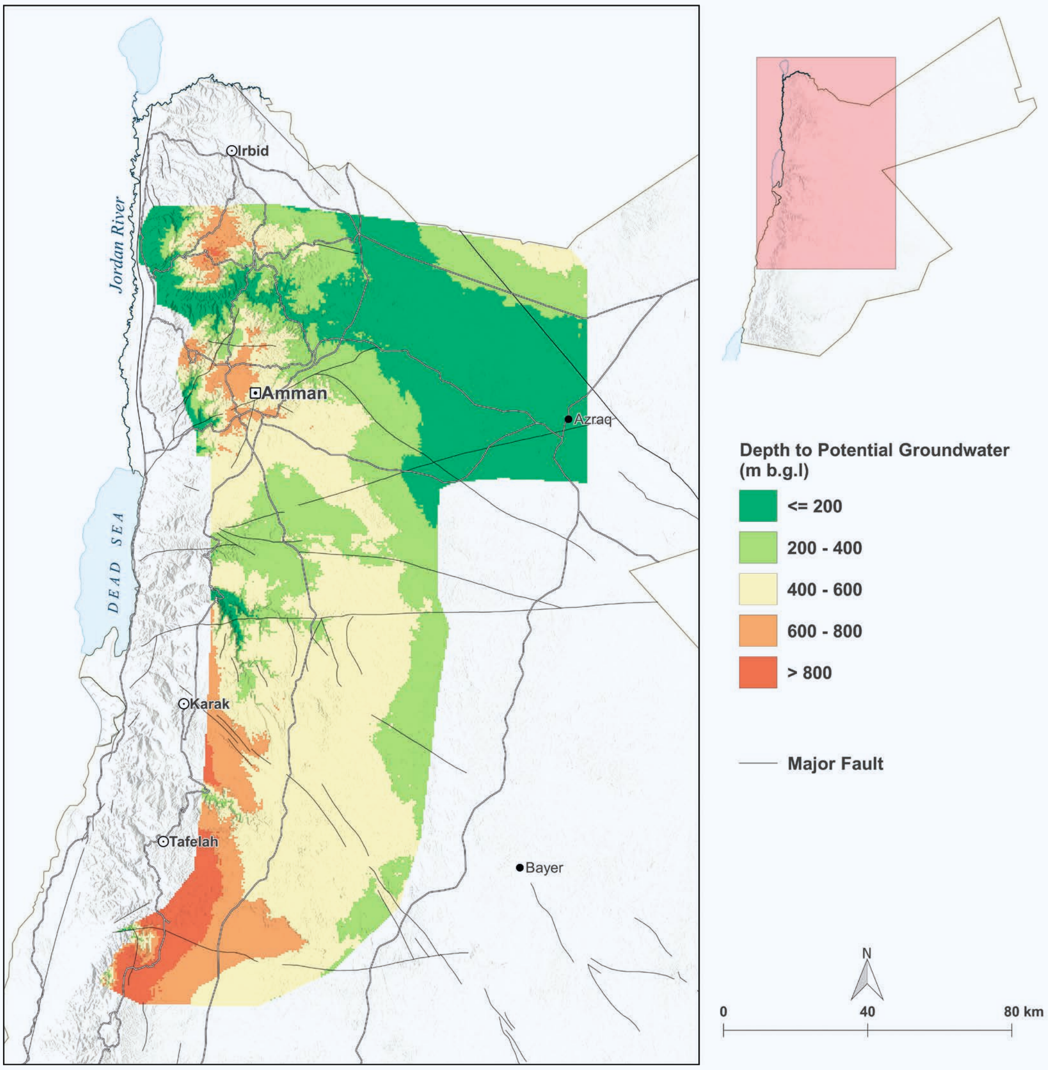


Figure 33 Potential depth to groundwater in the deep Sandstone aquifer system

Groundwater Contour Map – Ram/Disi and Kurnub

In central and southern Jordan, where the Khreim aquitard and Zarqa aquifer are thinned out, the Kurnub and the Ram/Disi Sandstone form one hydraulic unit. Around Amman to the northwest, the Zarqa Group separates the Kurnub aquifer from the Ram/Disi aquifer, which is visible based on a difference in the hydraulic heads of more than 100 meters. Therefore, each group is presented separately in Figure 32 and Annex 3.

In southern Jordan, groundwater in the deep Ram/Disi aquifer first flows from Saudi Arabia to the northeast, turns to the northwest around the Ras en Naqb escarpment and finally discharges into the Dead Sea. Due to data scarcity, contour lines for the Kurnub aquifer can be drawn only for a small region northwest of Amman. The area around Salt and Ajloun, where the Kurnub aquifer outcrops, appears as a dome that indicates a recharge area, from which groundwater flows in all directions but dominantly towards the Jordan Valley.

Depth to Groundwater Map – Deep Sandstone Aquifer System

Figure 33 shows the depth to groundwater (m bgl) for the deep Sandstone aquifer system in central and northern Jordan (Annex 4). Because the aquifer is confined in most of the area, this is the potential depth to groundwater and allows for calculation of possible pump lift. However, the drilling depth is generally much deeper and must be considered for well construction. The interpolated information has to be addressed and requires further verification in the field.

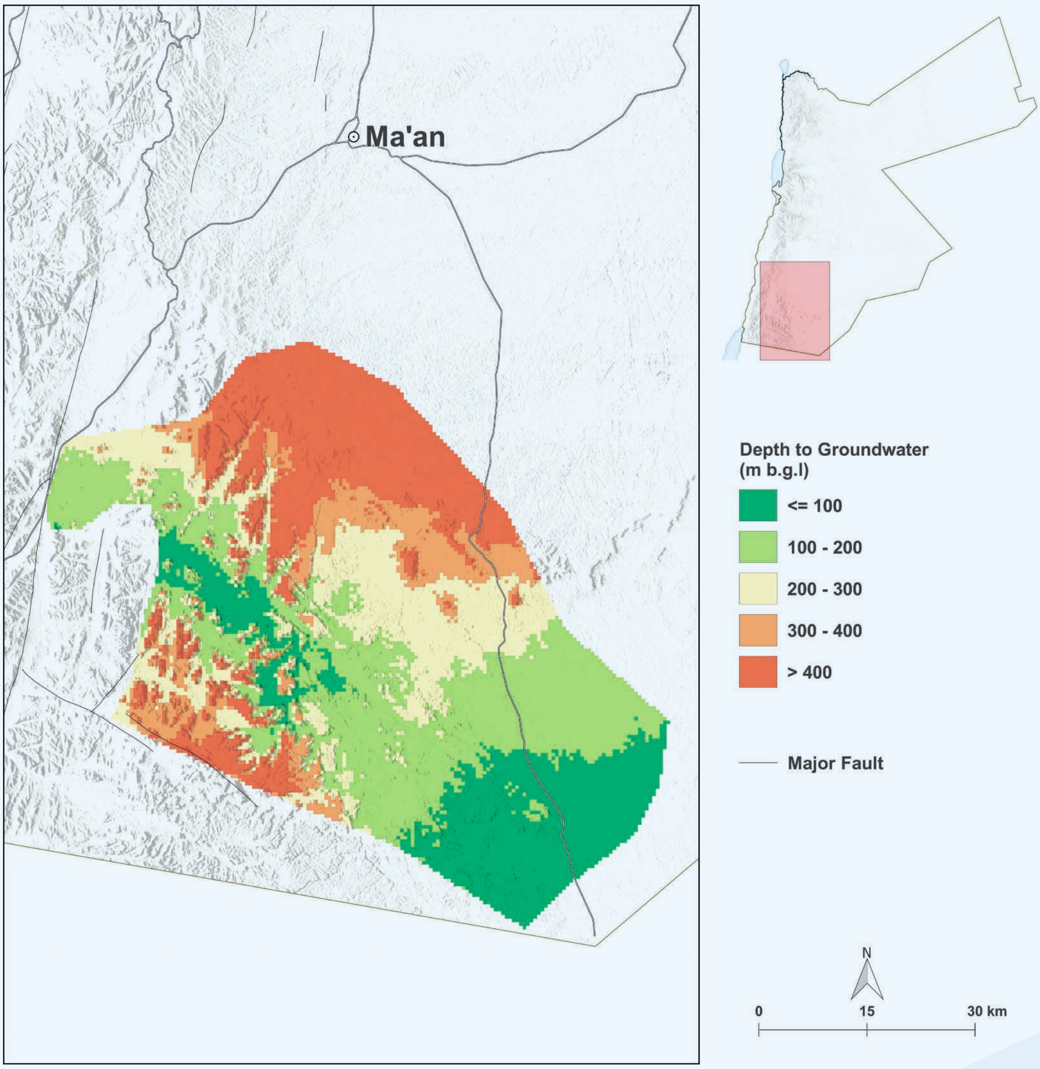


Figure 34 Potential depth to groundwater in the Ram/Disi aquifer

Depth to Groundwater Map – Ram/Disi

Figure 34 shows that the potential depth to groundwater (Annex 4) varies from less than 100 meters to more than 400 meters, which can be used to estimate pump lift. When the Ram/Disi aquifer is confined, especially where the Khreim aquitard outcrops, the drilling depth would be much deeper. There may be a difference of several hundreds of meters between the drilling depth and the potential groundwater level.

Difference in Groundwater Map – Ram/Disi

The difference in groundwater levels between the 1990s and 2017 is generally less than 25 meters (Figure 35), which confirms the long-term decline measured in monitoring well K1000, located 40 km east of Disi. The hydrograph in Figure 36 shows a continuous decline at a rate of 0.6 m/yr until 2013 and a total decrease of 11 meters. The water level appears to have stabilized since 2013, probably due to the ceasing of agricultural activities during that year. A drawdown of more than 50 meters in the far western part of the area is an artifact of the interpolation in the area (Figure 35).

In areas with high abstraction rates, larger drawdowns of up to 50 meters are noticeable (Figure 35). In monitoring well ED1328 (Figure 37), located southeast of K1000, the recorded average decline rate from 1995 to the end of 2013 was 0.55 m/yr, but it increased ten times after the beginning of operations of the Disi conveyer project to approximately 5 m/yr between 2013 and 2017.

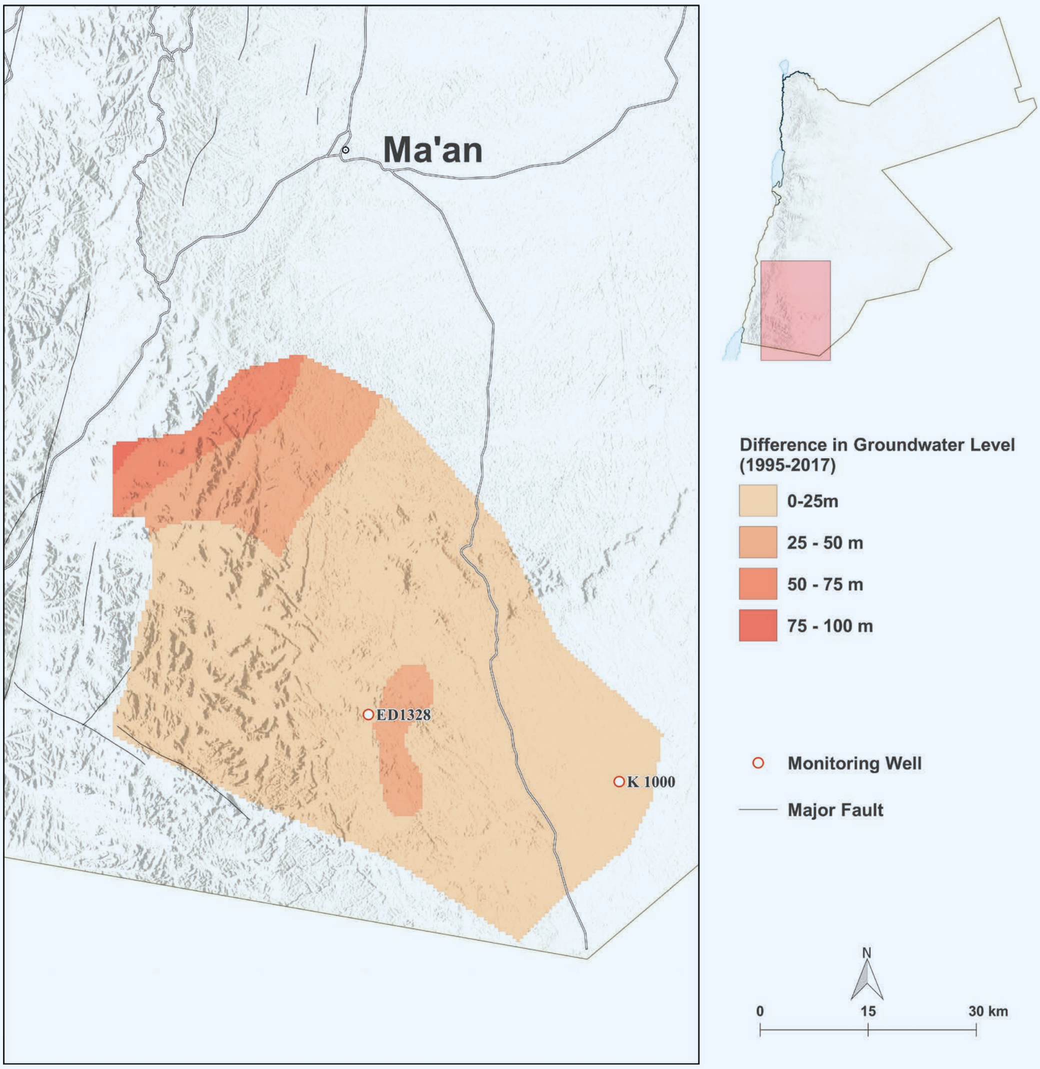


Figure 35 Difference in groundwater levels of the Ram/Disi aquifer between 1995 and 2017

Source: BGR

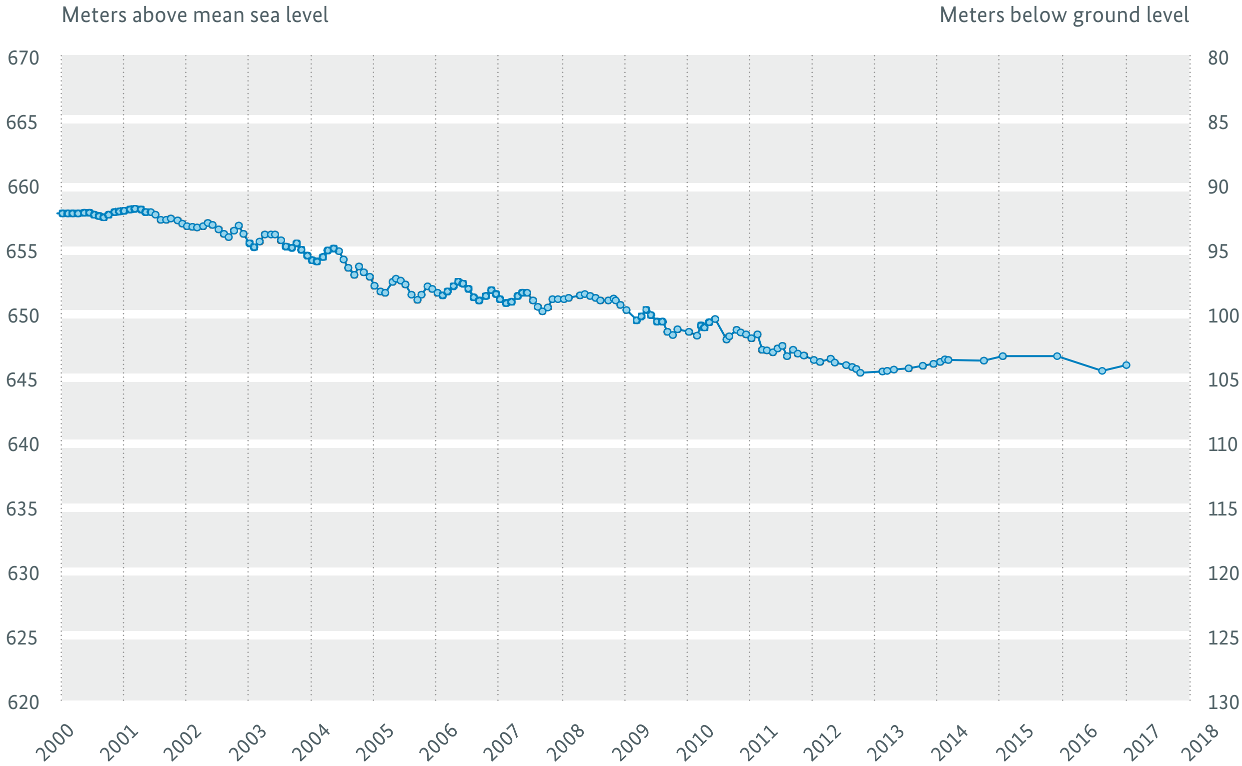


Figure 36 Groundwater levels in the Ram/Disi aquifer recorded from 1995 to 2017 at well K1000

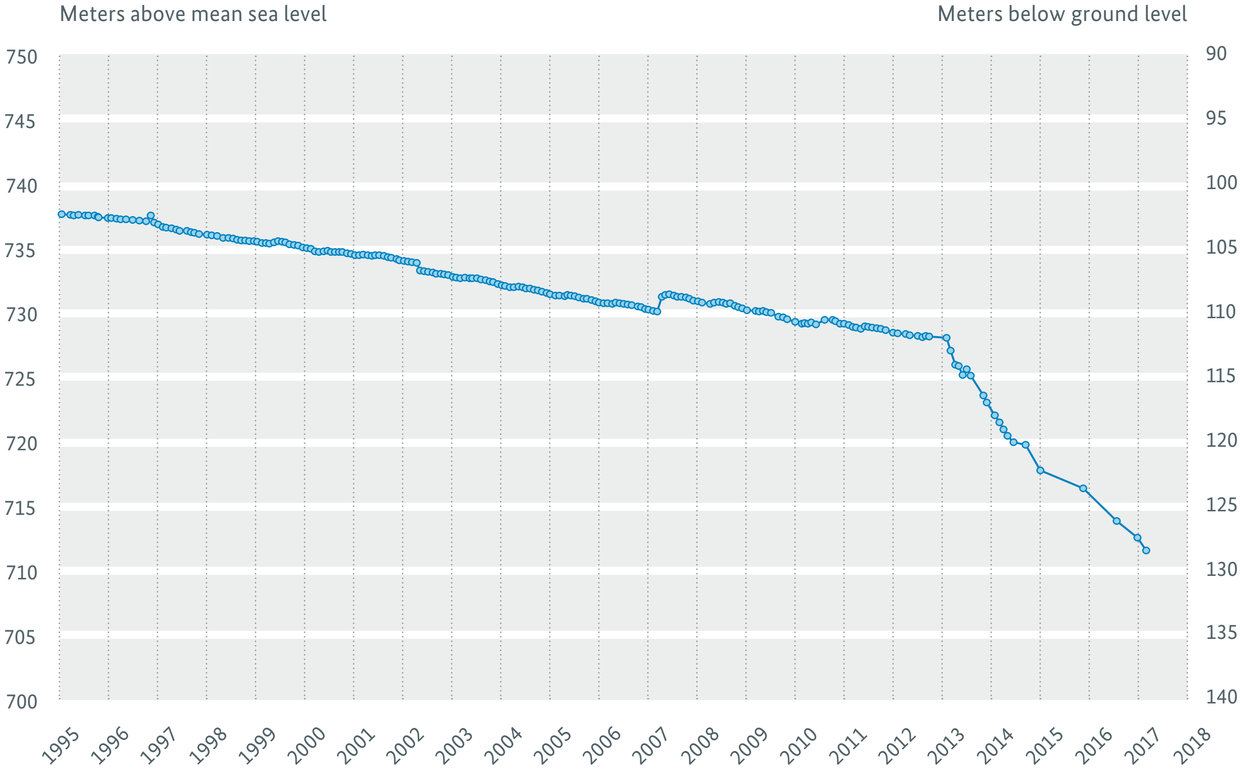


Figure 37 Groundwater levels in the Ram/Disi aquifer recorded from 1995 to 2017 at well ED1328

4.2.2 A1/A2 and A4 Aquifers

The first-ever groundwater contour map produced for the A1/A2 and A4 aquifers reflects the 2017 conditions (Annex 5). These aquifers are of high importance locally, especially in northern Jordan, where the overlying A7/B2 aquifer is partially exhausted. Because both aquifers have similar hydraulic heads, they are analyzed together using 51 groundwater level measurements (27 from 2017) and 28 spring measurements.

The analysis differentiated the aquifer north and south of the Siwaqa Fault. North of the Siwaqa Fault, all individual units, including A1/A2, A3, A4 and A5/A6, are described separately (Chapter 3). South of the Siwaqa Fault, the units are similar and cannot be clearly distinguished from one another (Figure 38).

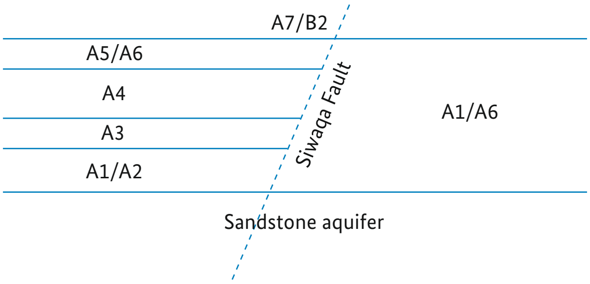


Figure 38 Schematic representation of the A1/A6 units near the Siwaqa Fault

Groundwater Contour Map

All 80 groundwater level measurements from the A4 and A1/A2 aquifers were included in the construction of the groundwater contour lines (Figure 39). Information about the aquifer tapped by each observation well was retrieved from the WIS database. However, a clear distinction between the different formations was not always possible, even north of the Siwaqa Fault, which indicates that the

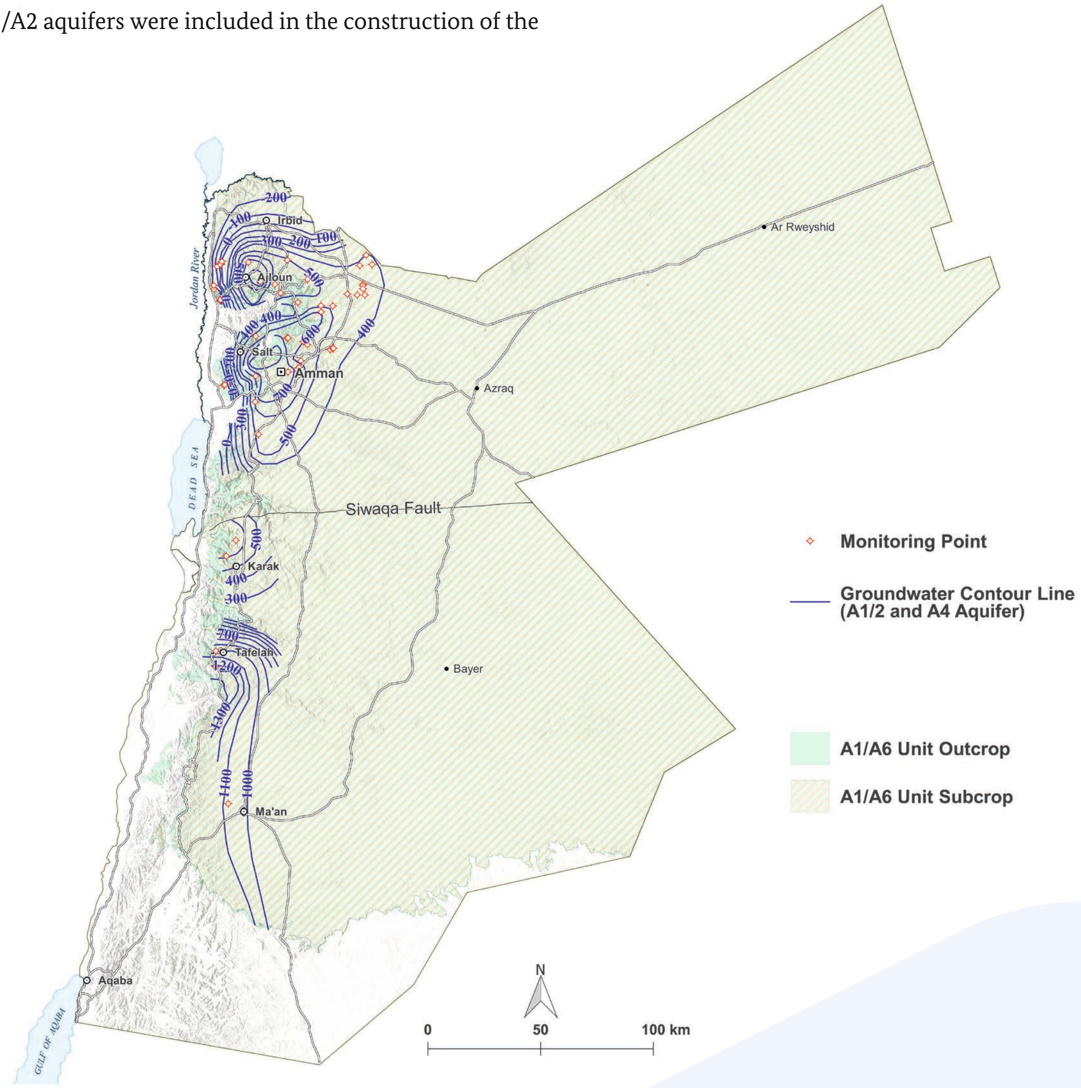


Figure 39 Groundwater level contour lines for the A1/A6 aquifer complex, October 2017

information in the database is not always accurate. Furthermore, in some cases, the upper A4 aquifer is already exhausted, and the wells have been deepened into the lower A1/A2 aquifer, but the information is not available in the database.

Groundwater is recharged in the Ajlun and As-Salt Mountains. The groundwater then flows mainly towards the Jordan Valley, north, and east. Recharge also likely occurs at Jebel al Arab in Syria and enters the country to the south/southwest. The data density decreases greatly to the south, but groundwater recharge in the outcrop areas around Karak can be assumed to flow mainly to the east.

Depth to Groundwater Map

The maps presented in this chapter are based on the groundwater contour lines for October 2017 and show the potential depth to groundwater for the A4 (Figure 40) and A1/A2 (Figure 43) aquifers north of the Siwaqa Fault as well as the depth to potential groundwater for the entire A1/A6 aquifer unit south of the Siwaqa Fault (Figure 45). These maps can be used to estimate the pump lift, but because most of the saturated areas are confined, the depth to the top of the aquifer is shown in separate maps (Figure 41, Figure 44, and Figure 46) to obtain information about the possible drilling depth.

North of the Siwaqa Fault, the depth to groundwater in the A4 aquifer varies from less than 100 to more than 400 meters, which is confirmed by in situ water level measure-

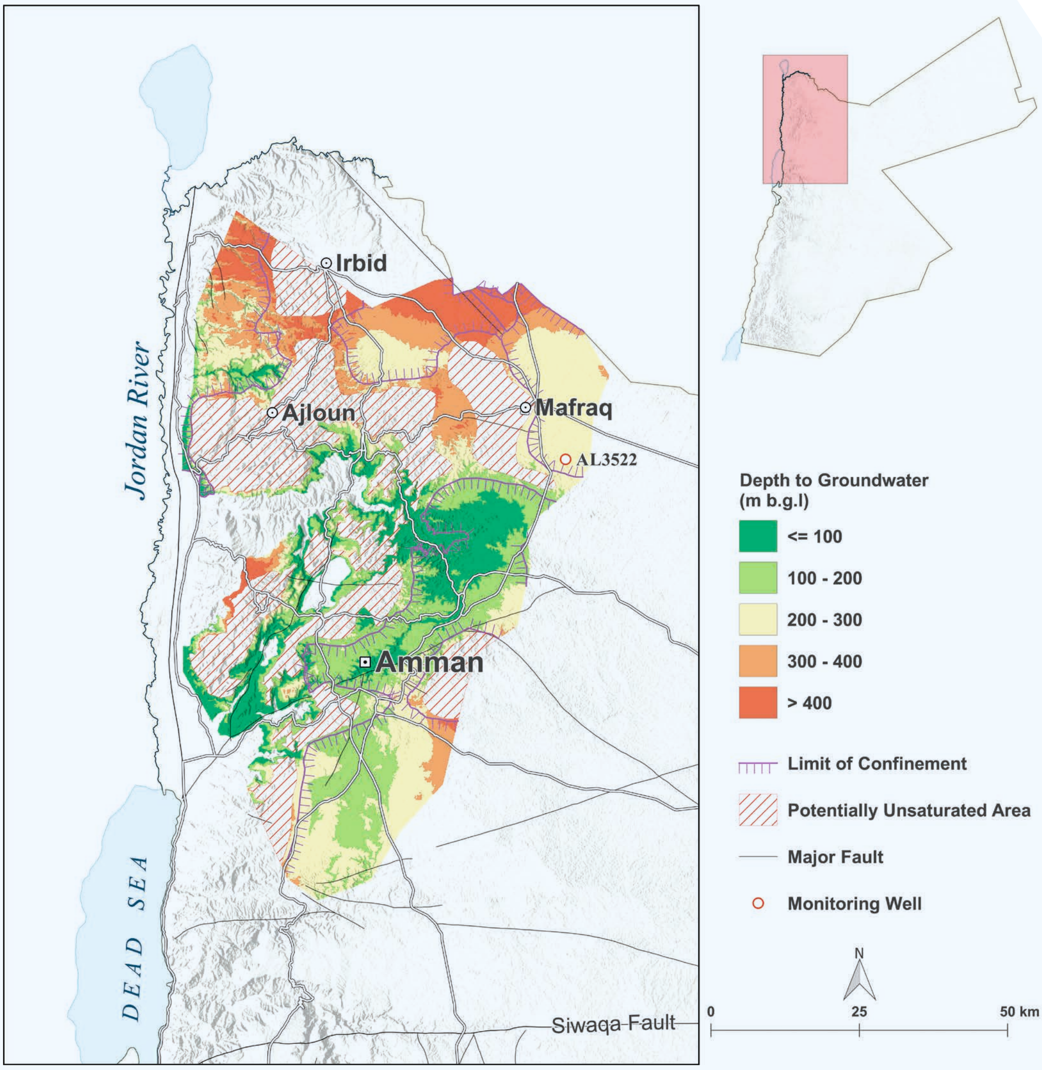


Figure 40 Depth to groundwater in the A4 aquifer

ments at monitoring well AL3522 (Figure 42). A wide area of the aquifer appears to be unsaturated, and groundwater is abstracted from the deeper A1/A2 aquifer.

North of Ajloun, the A4 aquifer appears to be unsaturated. Here, the aquifer dips steeply, and its top is encountered between 200 and 700 m bgl. The exploitation of the overlying A7/B2 aquifer is economically challenging in the area north of Irbid; thus, exploitation of the A4 aquifer appears to be impossible. The area between Mafraq and Irbid requires an on-site investigation of the A4 aquifer to precisely define its depth.

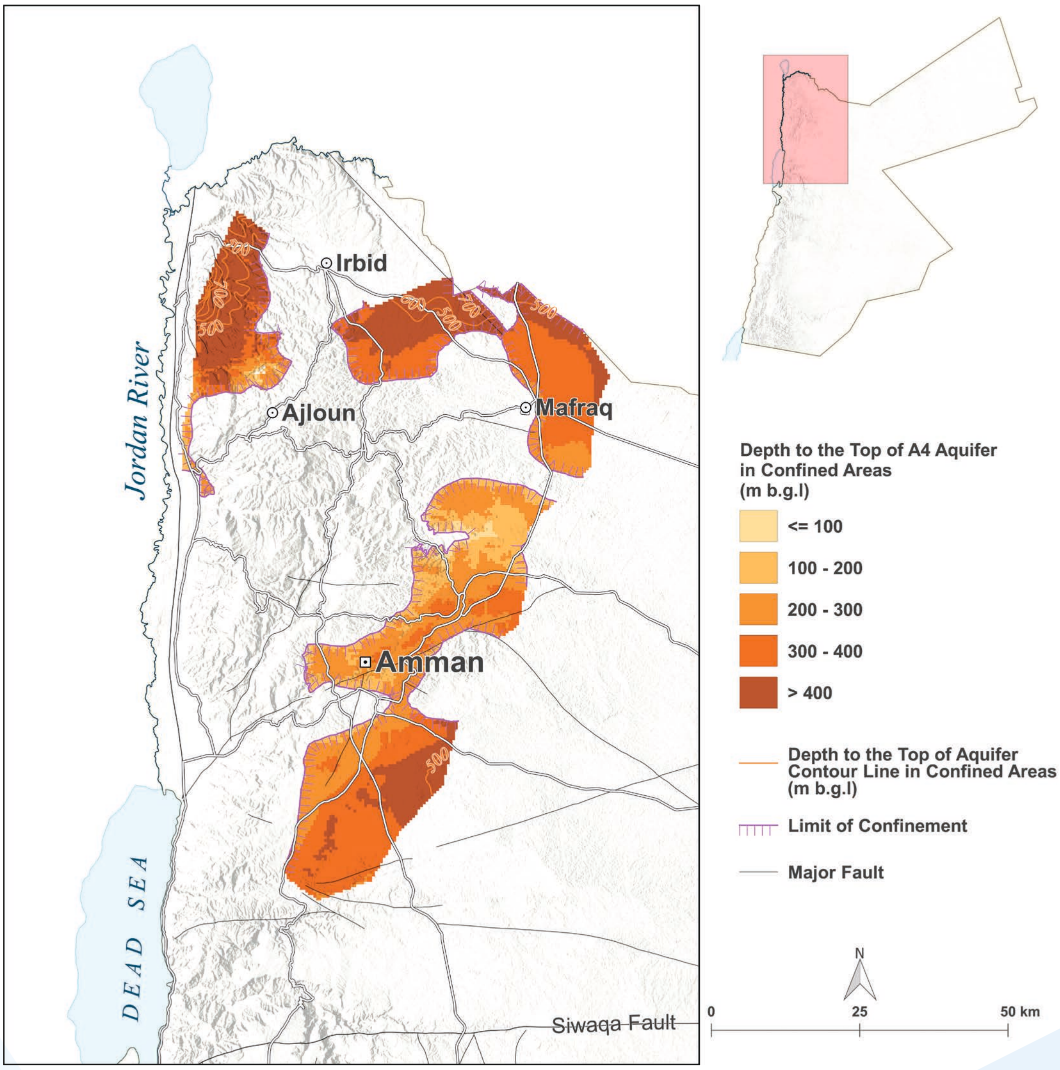


Figure 41 Depth to the top of the A4 aquifer in confined areas

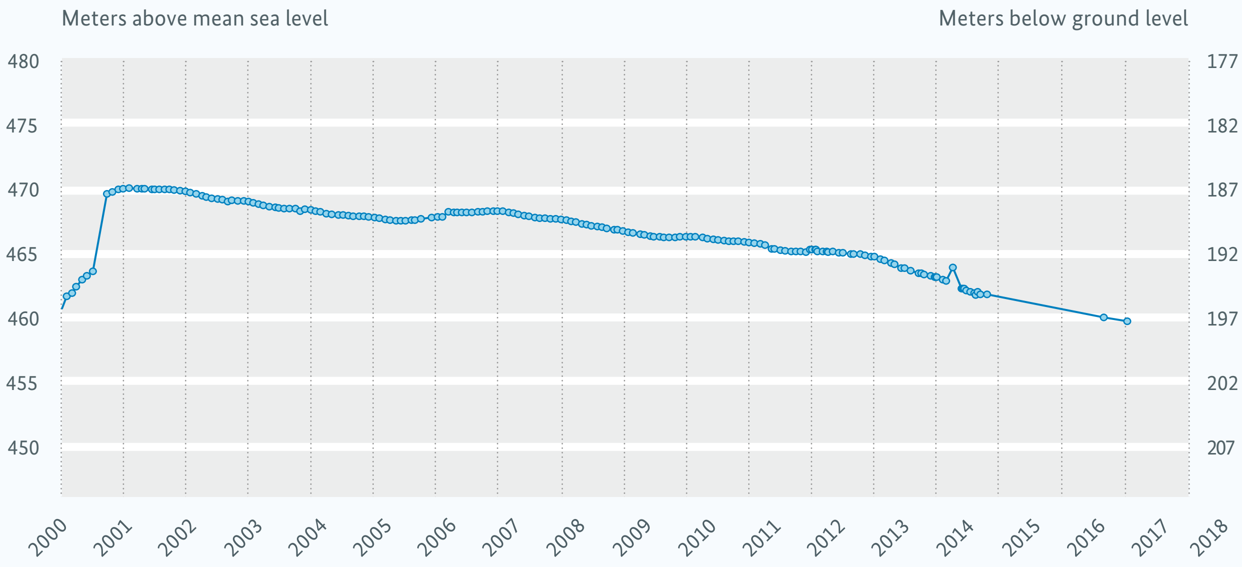


Figure 42 Groundwater levels in the A4 aquifer recorded in 2000-2017 at well AL3522

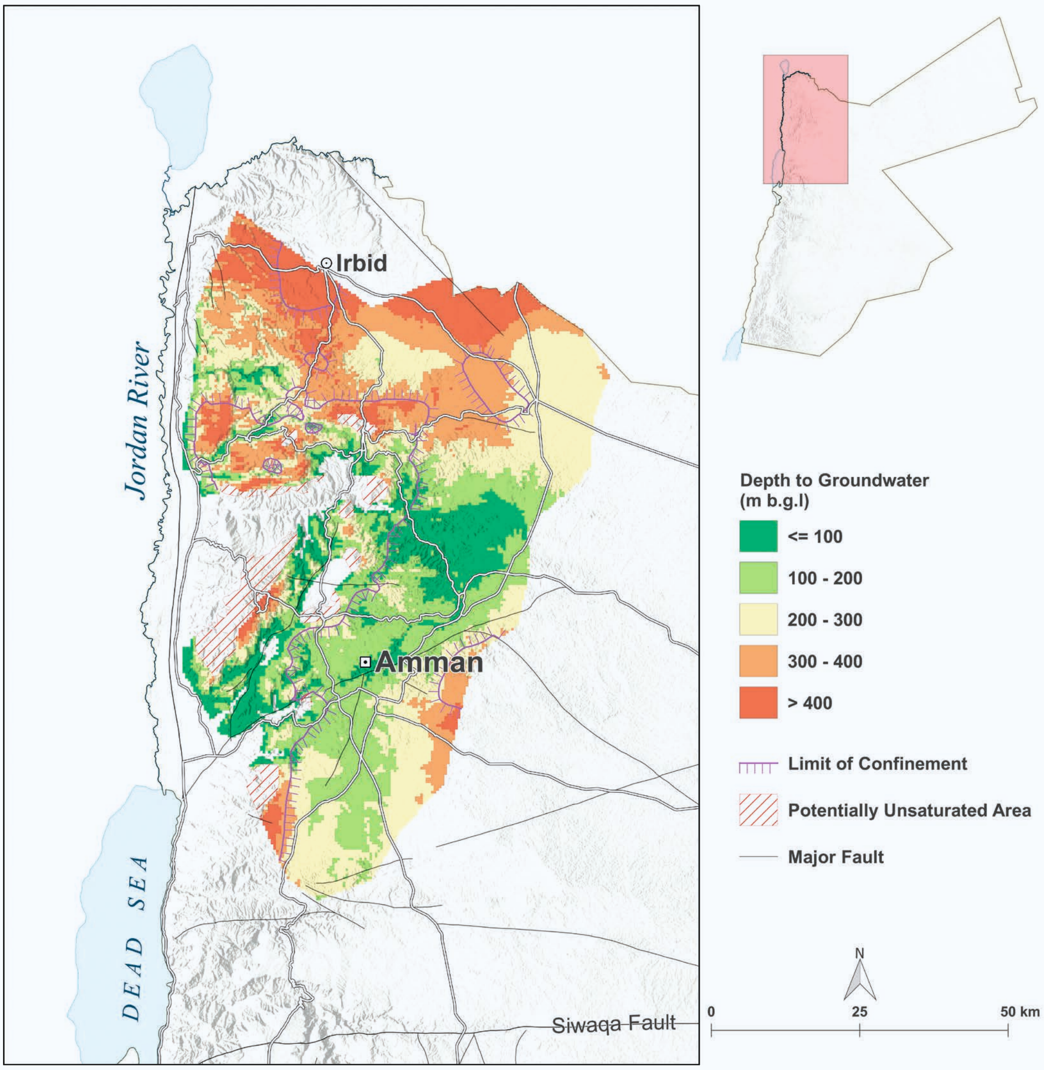


Figure 43 Depth to groundwater in the A1/A2 aquifer

Near Mafraq, the groundwater level in the Za'tari monitoring well shows a continuous decline and no seasonal variations. From 2001 to 2017, the groundwater level decreased by approximately 10 m with an average of more than 0.6 m/yr (Figure 42). This indicates the overexploitation from the A1/A6 aquifer in the northern part of Jordan described above.

The potential depth of groundwater in the A1/A2 aquifer is based on the same groundwater contour lines, but the expansion of the potentially unsaturated zones is much smaller (Figure 43). The depth to the potential groundwater around Amman is less than 100 meters in the western part and increases to the east to more than 300 meters. The widest area is north of Amman, with a potentially shallow depth to groundwater that increases to the north to depths greater than 400 meters. In the area of potentially shallow groundwater, the top of the aquifer is closer to the surface at 200 to 300 m bgl. Otherwise, the depths to the top of the aquifer are from 300 m to 400 m bgl and greater in the A1/A2 aquifer north of the Siwaqa Fault.

South of the Siwaqa Fault, nearly the entire reliable area is under confined conditions (Figure 45, next page). The potential groundwater depth is relatively shallow at less than 200 m bgl. South of Tafelah, the top of the A1/A6 aquifer is between 100 and 300 m bgl. Because of tectonic faulting, the aquifer is much deeper in the area around Petra. Furthermore, the aquifer dips to the east, and the depths vary from 100 m in the westernmost outcrop to 800 meters in the eastern part of the reliable area (Figure 46, next page).

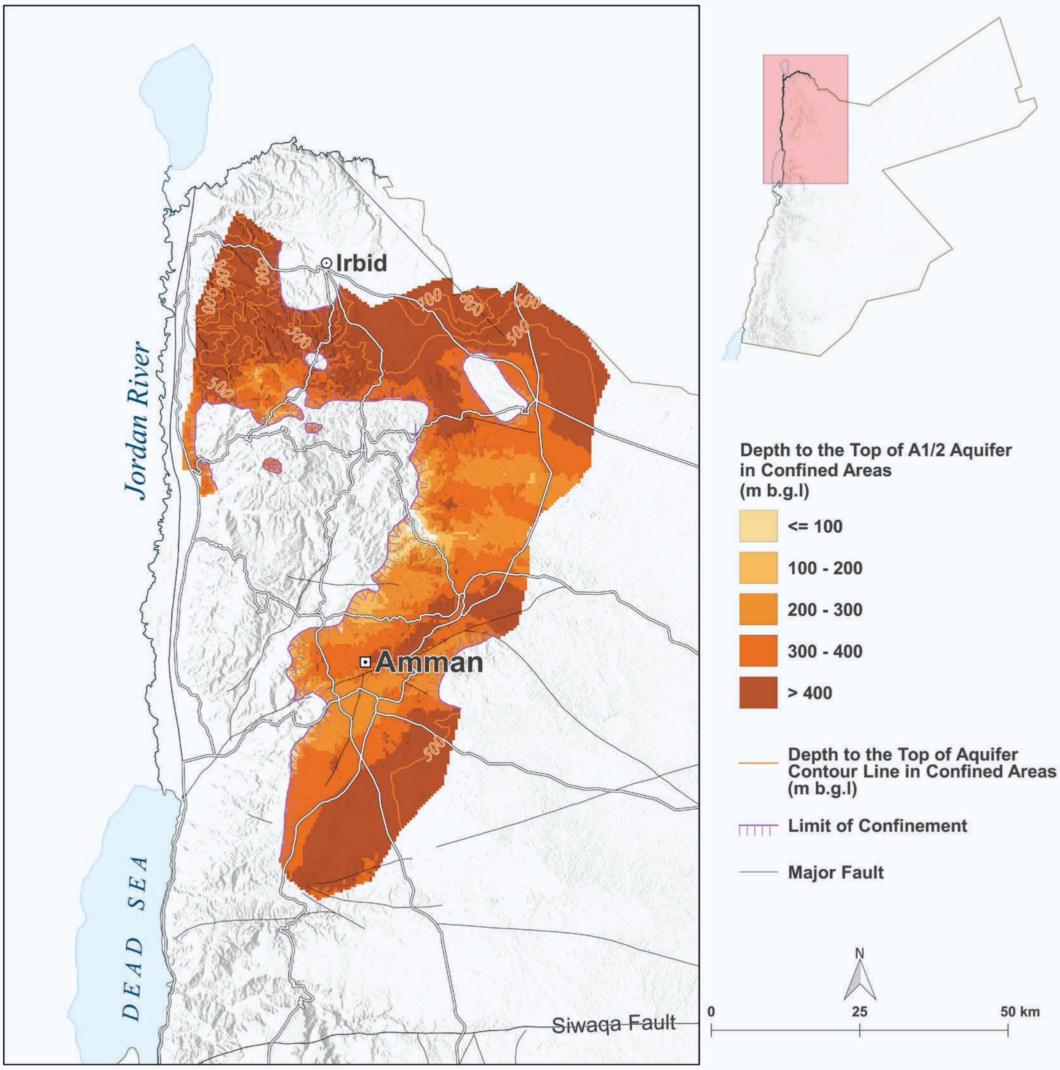


Figure 44 Depth to the top of the A1/A2 aquifer in confined areas

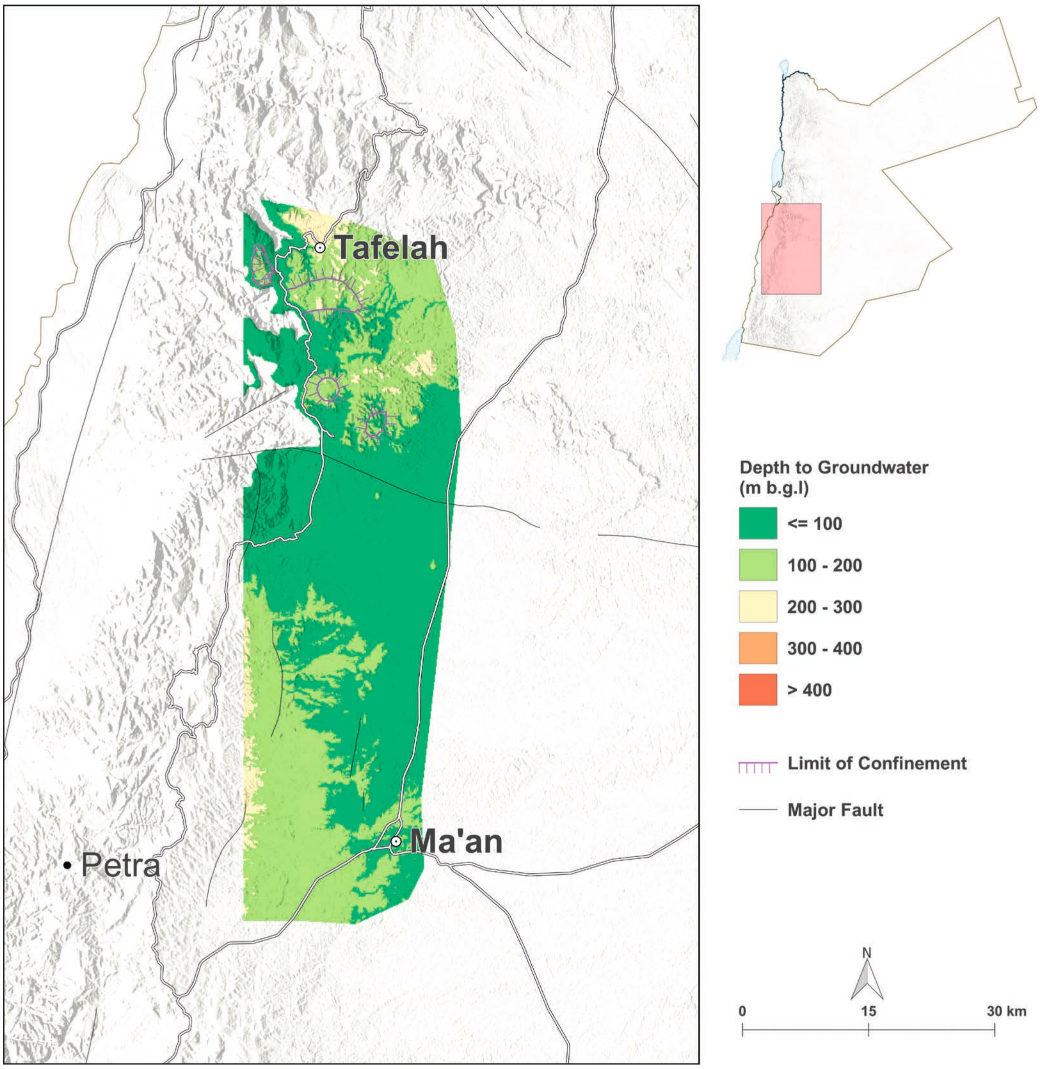


Figure 45 Depth to groundwater in the A1/A6 aquifer

Source: BGR

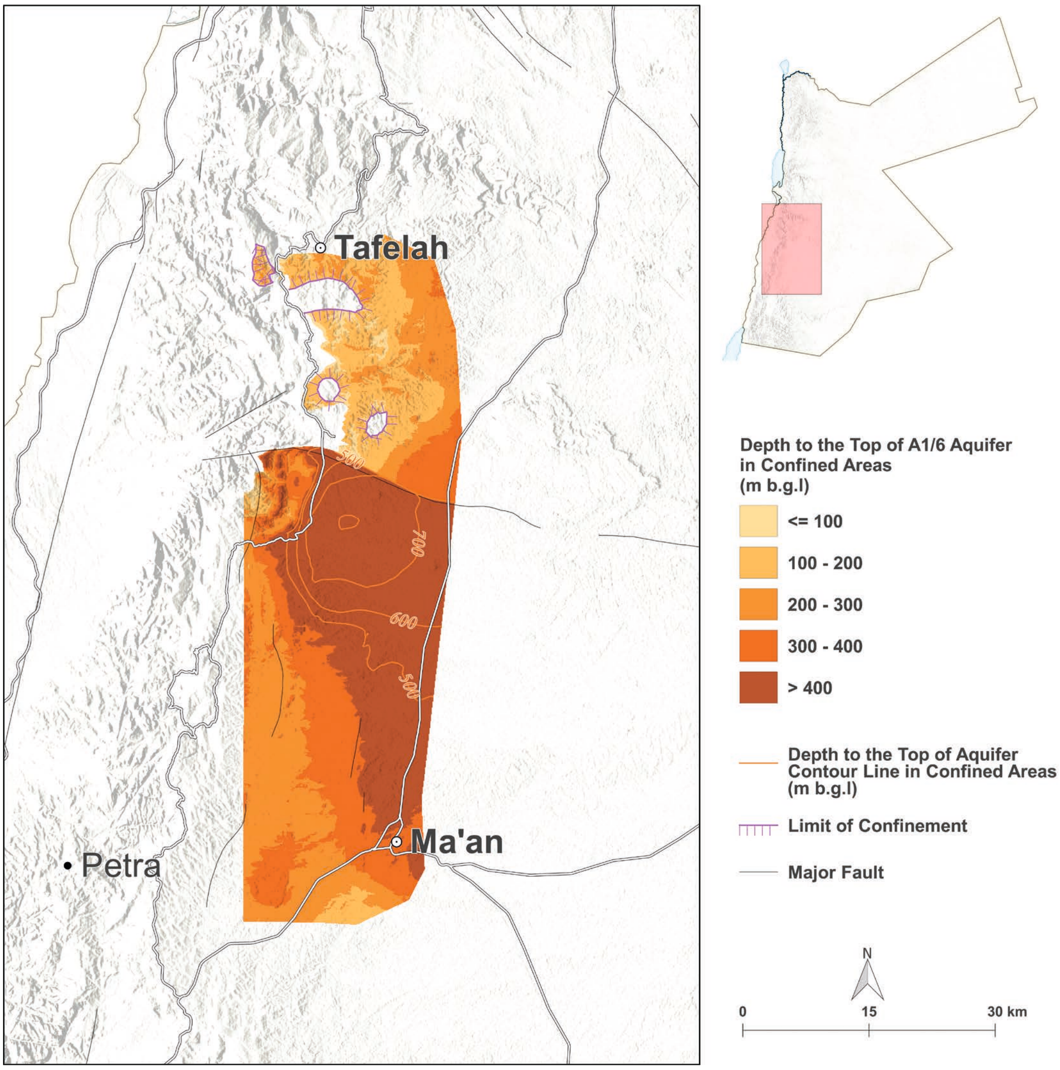


Figure 46 Depth to the top of the A1/A6 aquifer in confined areas

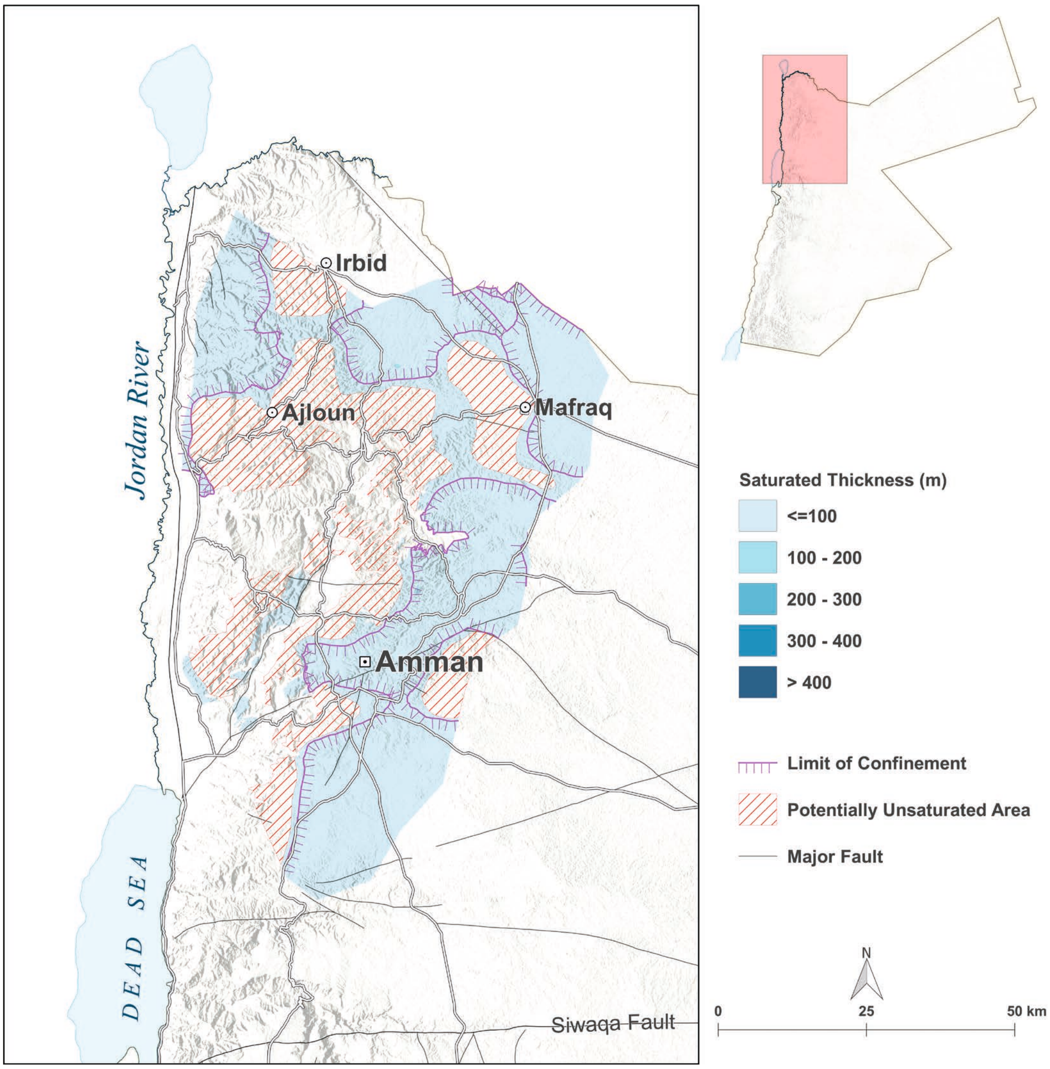


Figure 47 Saturated thickness of the A4 aquifer north of the Siwaqa Fault

Saturated Thickness Map

The individual saturated thicknesses for the A4 and A1/A2 aquifers north of the Siwaqa Fault and for the entire A1/A6 unit south of the Siwaqa Fault were determined based on Brückner (2018) and the groundwater contour lines for October 2017 (Annex 7).

North of the Siwaqa Fault, a considerable area of the A4 aquifer is already under unsaturated conditions (Figure 47), mainly where the overlying A7/B2 aquifer is dry and the wells were deepened into the A4 aquifer. Although most of the still-saturated area is under confined conditions, the saturated thickness is less than 100 meters.

Additionally, the A1/A2 aquifer shows first indications of unsaturated areas north of the Siwaqa Fault, mainly in the outcrops (Figure 48). Elsewhere, the aquifer is under confined conditions. Around Amman, the saturated thickness varies between 100 and 200 meters. Farther north between Mafraq and Irbid, the saturated thicknesses increase to 200 to 300 meters and more. To reach the aquifer, the drilling depth is very deep (more than 400 meters), and it is doubtful that it is economically feasible.

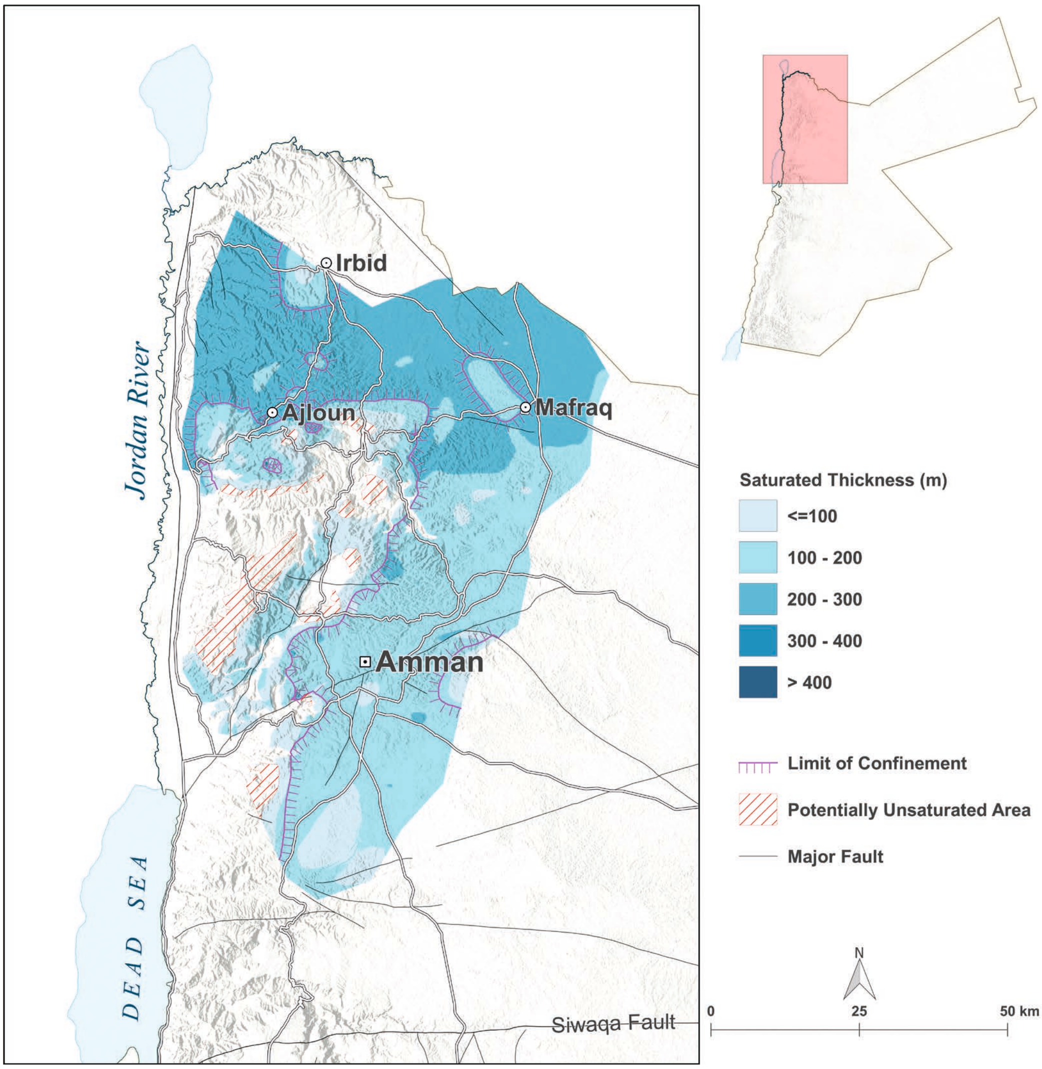


Figure 48 Saturated thickness of the A1/A2 aquifer north of the Siwaqa Fault

The saturated thickness of the entire A1/A6 unit south of the Siwaqa Fault (Figure 49) shows that the aquifer is under confined conditions. Because a clear distinction between the individual units is not possible, less permeable units are also part of the estimated saturated thickness. Therefore, estimated thicknesses between 200 and more than 400 meters cannot be considered a total economically usable thickness. Detailed on-site investigations are needed prior to any further abstraction planning.

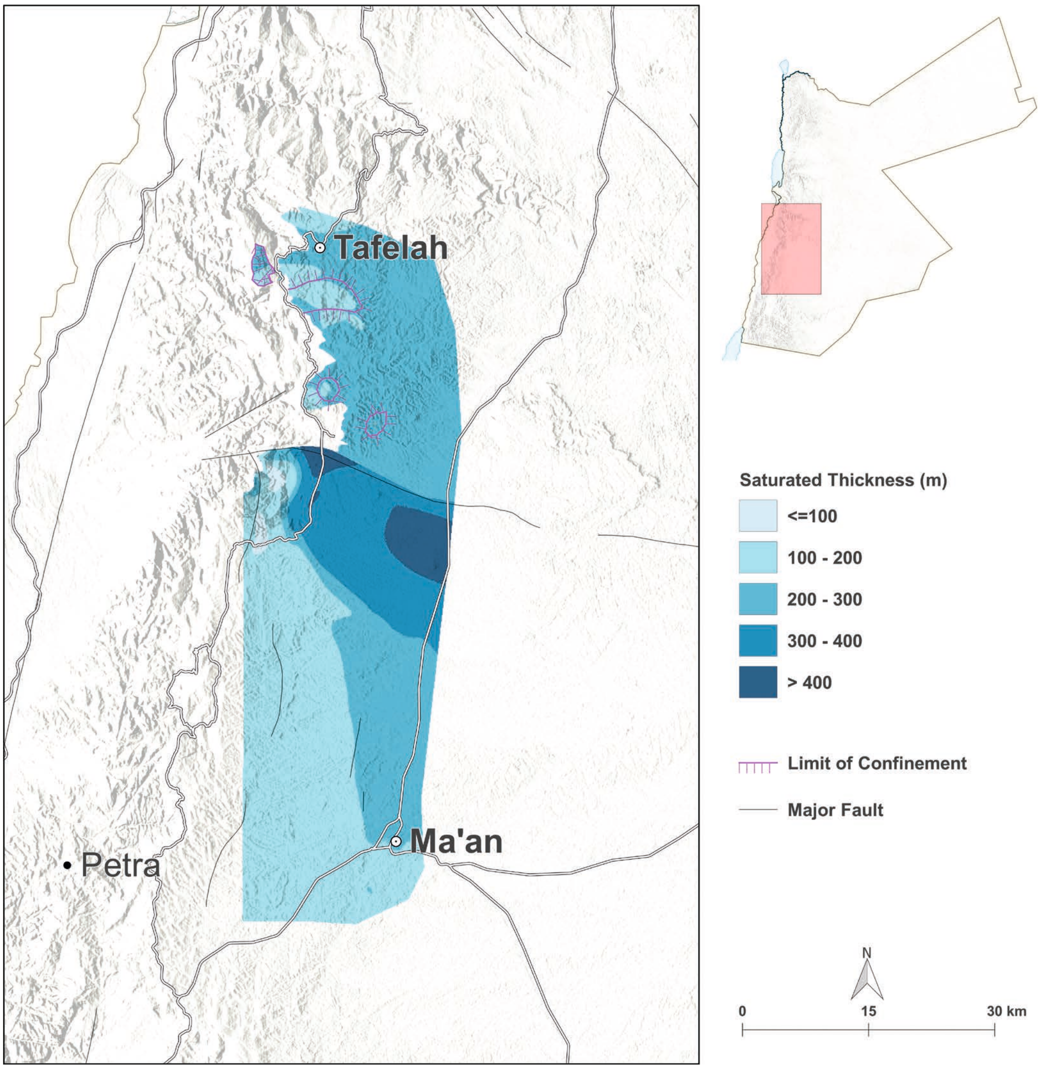


Figure 49 Saturated thickness of the A1/A6 aquifer south of the Siwaqa Fault

4.2.3 A7/B2 Aquifer

The A7/B2 aquifer is the most important aquifer in Jordan and is extensively exploited, especially in the northern and central highlands. The actual conditions of this aquifer and the changes since the last nationwide study conducted in the 1990s are of key importance for groundwater management in Jordan.

The available data for the A7/B2 aquifer comprises 111 groundwater level measurements taken in 2017, 118 measurements extrapolated to 2017 and 14 spring elevations.

Groundwater Contour Map

All 243 groundwater level measurements from the A7/B2 aquifer were used in the construction of the groundwater contour lines. Information about the aquifer tapped by the observation wells was retrieved from the WIS database. However, the aquifer is already exhausted in some areas, and the wells have been deepened into the lower-lying A4 or A1/A2 aquifer. This information was not entered into the database.

A small-scale version of the original A7/B2 groundwater contour map attached to this report (Annex 8) is shown in Figure 50. The southern outcrop areas indicate groundwater recharge with an easterly flow direction, following the dip of the aquifer base (Figure 28). The transmissivity increases and the groundwater level gradient decreases

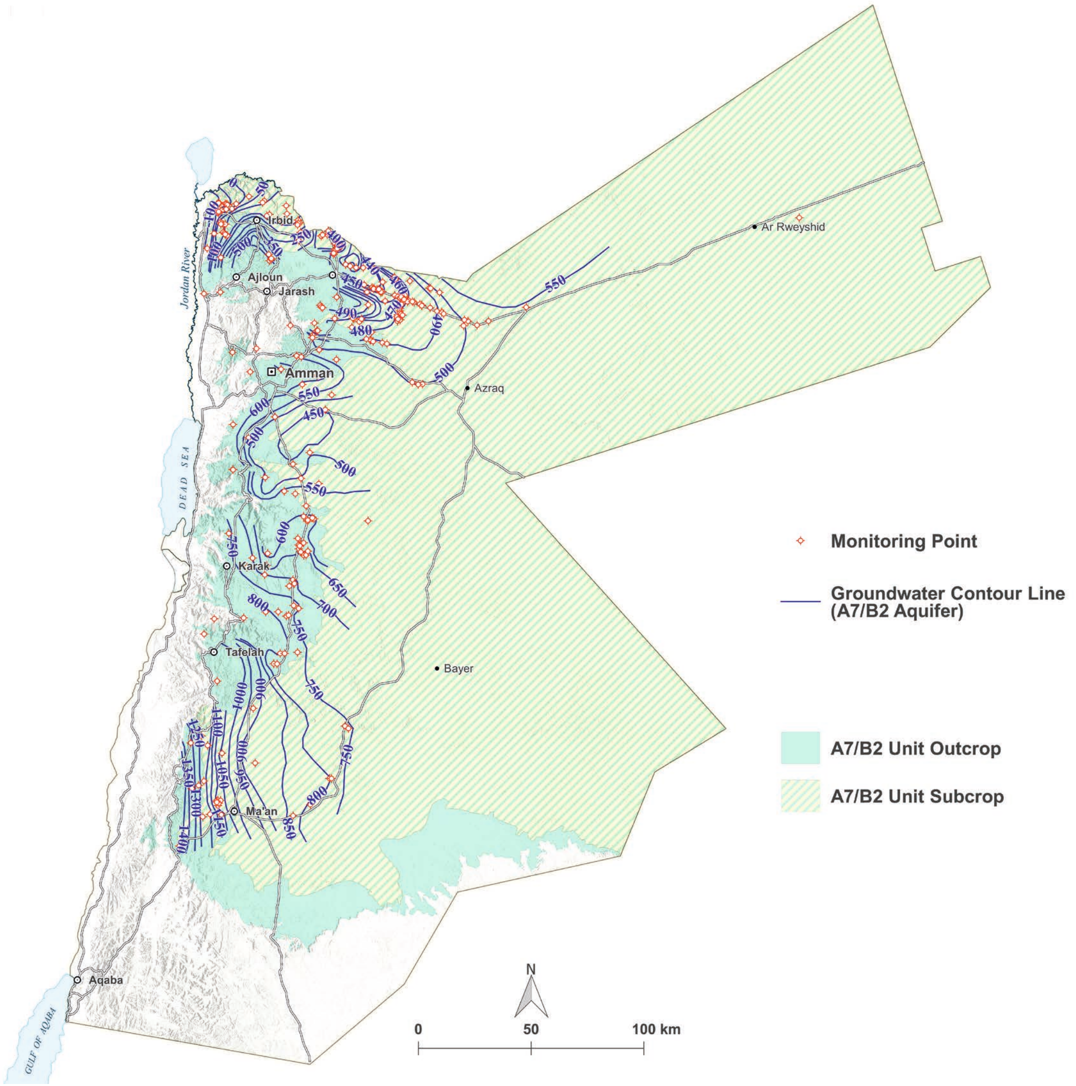


Figure 50 Groundwater level contour lines for the A7/B2 aquifer, October 2017

(contour lines are farther apart) towards the Jafer Basin. The groundwater contour map also shows that northeast of Tafelah, the natural flow direction begins to slowly turn from east to north.

In the northern part of the country, groundwater flows from the recharge areas around Ajlun and Jerash to the northeast and east. Recharge also occurs in the north at Jebel al Arab in Syria and enters Jordan as lateral inflow to the south. In 1995, groundwater inflow from Syria mainly flowed towards the Azraq depression. Due to intense agricultural abstraction east of Mafraq, a large cone of depression has developed. Groundwater now flows towards this cone and the Yarmouk River, even from the Azraq depression.

North of Ajlun, the groundwater flow direction turns from north to northwest towards the Jordan Valley, following the overall dip of the strata (Figure 28).

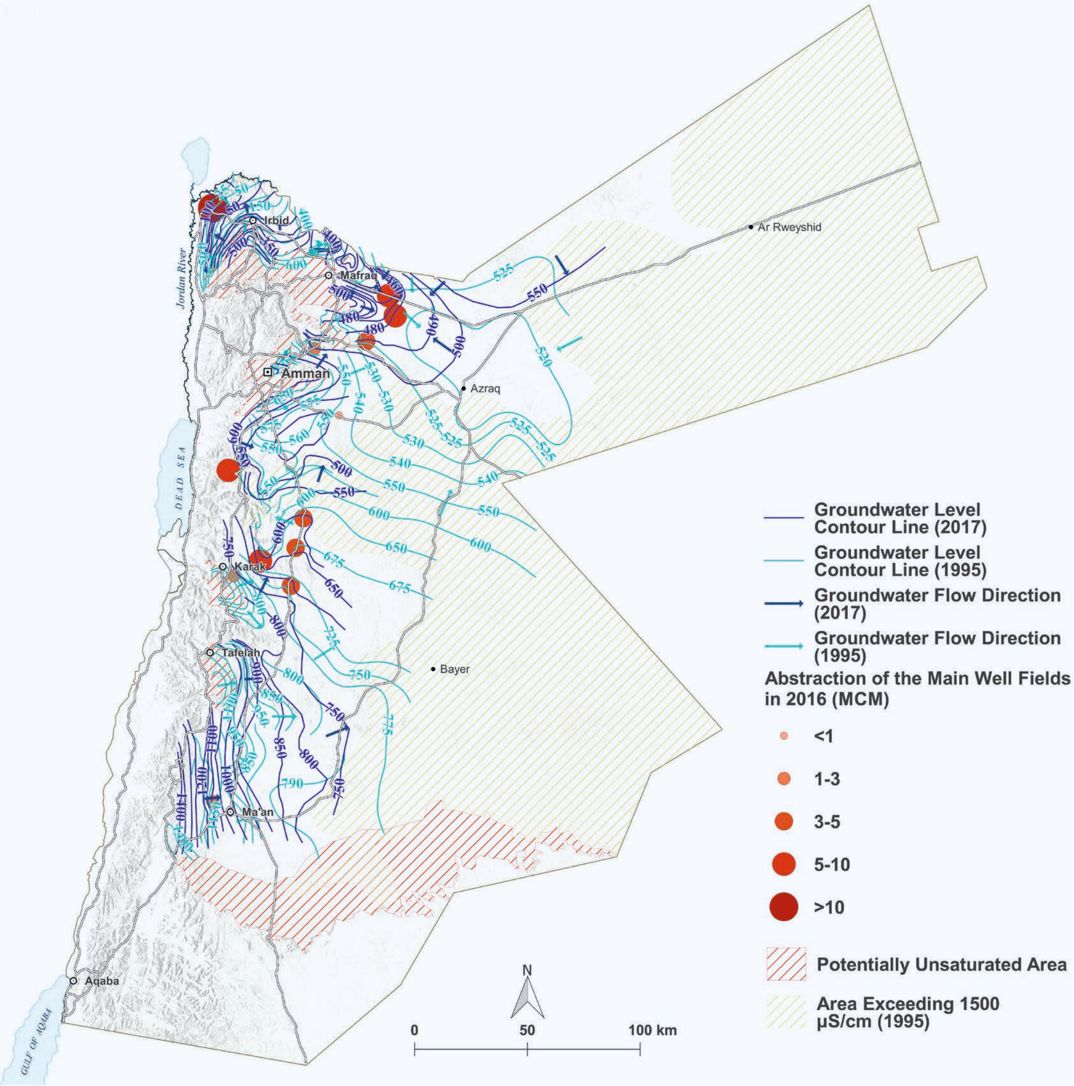


Figure 51 Regional comparison map of the A7/B2 aquifer from 1995 to 2017

Regional Groundwater Comparison Map (1995-2017)

The map shown in Figure 51 was prepared on special request by the management of the MWI to analyze several components in one map (groundwater contour lines, flow direction, area of high salinity, unsaturated areas, and main wellfields) and to compare the changes in flow direction between 1995 and 2017. The 1995 groundwater contour lines were digitized from the available map. In 1995 and 2017, different monitoring wells were used to interpret the groundwater conditions, which means that the areas of detail are also different. The contour lines are very precise and detailed in some areas in 1995 and in other areas in 2017. This fact must be considered when analyzing the differences in groundwater levels and flow directions.

Only minor changes in the regional groundwater flow pattern occurred in southern Jordan between 1995 and 2017. However, the situation in the northern part of the country is very different; in this area, the groundwater flow direction appears to have turned by 180° in the following regions:

→ North of Irbid: The flow direction is now to the west towards the Jordan Valley rather than to the north-west. This change probably results from the intensive groundwater exploitation in the area, which has caused a regional depression cone.

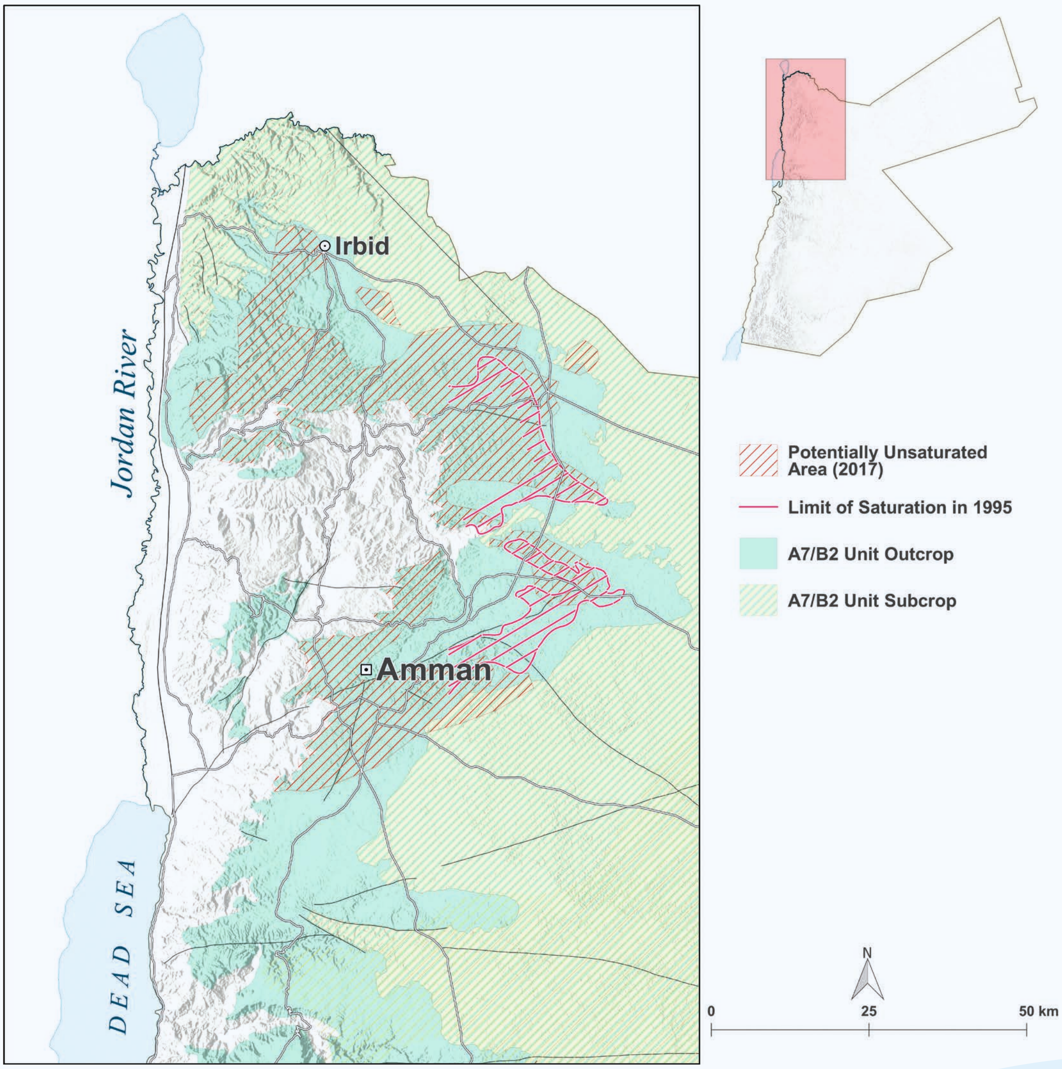


Figure 52 Potentially unsaturated areas in 1995 (pink) and 2017 (brown)

- Northwest of Mafraq: The groundwater flow direction near the border has rotated from E-W to NE-SW. The increasing pumping activities are the only plausible cause for this change.

- Jebel al Arab and east of Mafraq: The radial flow at Jebel al Arab results in a lateral inflow at the border, such as the north-south flow direction turning towards the west near Mafraq. As a result of high abstraction, a regional cone of depression with its center east of Mafraq has developed, which has led to a change in flow direction from dominantly N-S to NW-SE.

- Azraq: In 1995, a wide area around Azraq was mapped as a slight depression with general groundwater flow towards the Azraq region. It was not possible to collect recent (2012 to 2017) water level data for this area, and an assessment of the actual groundwater conditions is difficult. However, the groundwater flow direction NW of Azraq appears to have reversed and is now southeast-northwest rather than northwest-southeast. A similar trend was indicated in the updated groundwater contour map for the area around Mafraq in 2013 (Margane et al., 2014). This would imply that as a result of the intensive groundwater exploitation in northern Jordan, a regional cone of depression that dominates the groundwater flow patterns has developed, which also indicates that the Azraq area no longer receives any groundwater inflow from the west.

Figure 52 (see previous page) shows the limit of saturation in 1995 and the potentially unsaturated areas in 2017. In the areas that are potentially unsaturated, economically feasible abstraction of groundwater for domestic supply is no longer given. In 1995, the unsaturated areas in northern Jordan were estimated to cover approximately 620 km². In 2017, this area had tripled to 1,900 km² for the northern area alone, as shown on the map. Continuous abstraction will lead to an even faster expansion of these areas.

Depth to Groundwater Map

Figure 53 shows the potential depth to the static groundwater level in the A7/B2 aquifer (Annex 9). These values were calculated based on the October 2017 groundwater contour lines and a digital elevation model (SRTM 30). The accuracy of the map is rather low, especially in areas with high elevation gradients near the escarpment. In the areas where the A7/B2 aquifer is confined, the potential depth to groundwater is shown. In these areas, the actual depth to the aquifer is represented by the contour lines of the top of the aquifer. This means that to penetrate the aquifer, drilling must be deeper than the top of the aquifer indicated in the map by the purple contour lines.

This regional map allows for the identification of areas where shallow water levels are encountered and, provided

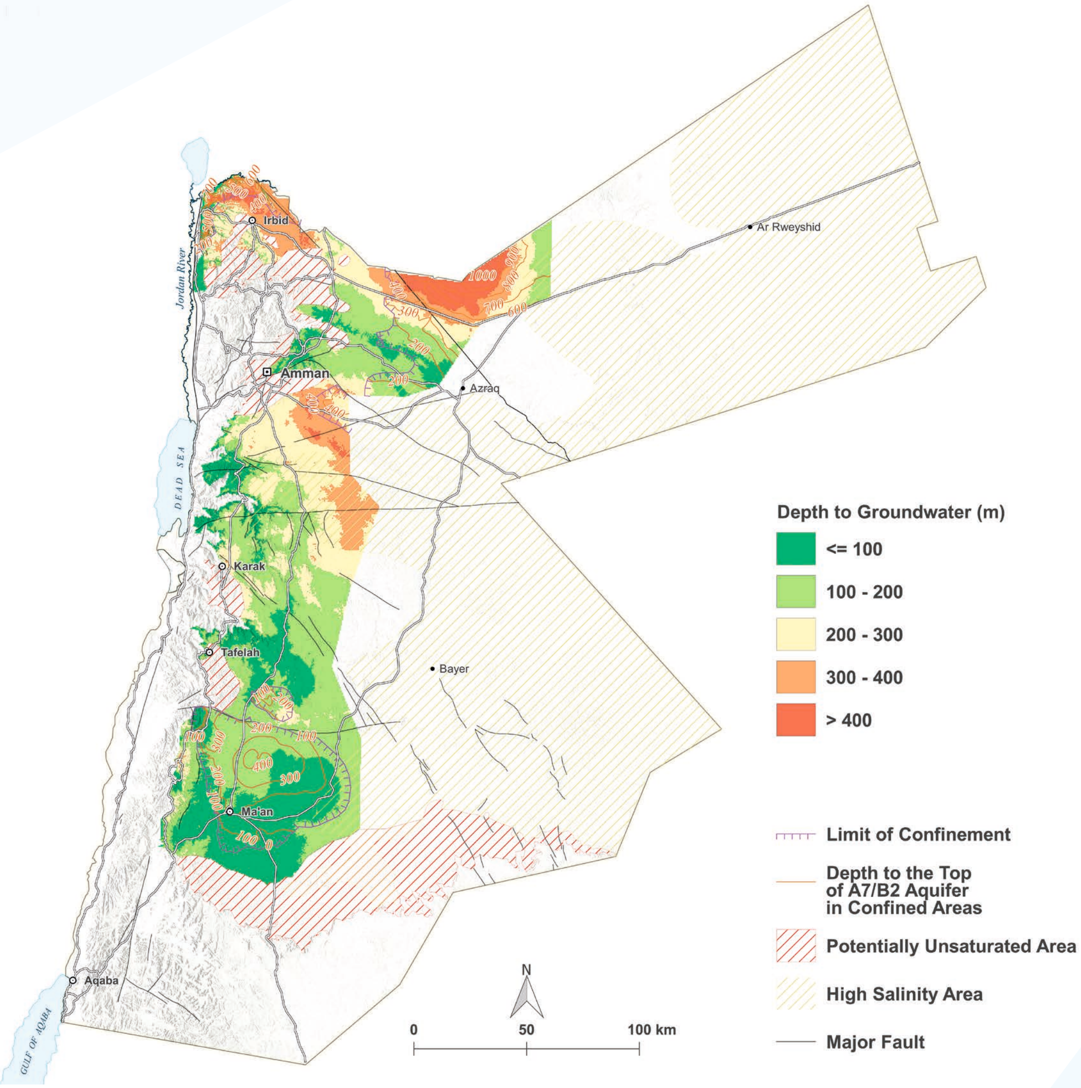


Figure 53 Depth to groundwater in the A7/B2 aquifer

there is sufficient aquifer saturation, where low pump lift allows for an economically feasible use of resources. Shallow groundwater depths are mainly located near the wadis and in the southern part of the aquifer. In the southern area, the depth to groundwater is generally between 50 and 200 m bgl. Because the groundwater is confined, the depth to groundwater shown in the map corresponds mainly to the potential depth. The depth to the aquifer (i.e., the depth required to reach the groundwater in a potential well) varies between 100 m and 400 meters.

In northern Jordan, the depth to groundwater is generally much greater and varies between 200 m and 400 m. South of Jabel al Arab, the groundwater is confined, and the groundwater level potential depth is at least 300 m. The actual depth to the top of the aquifer is between 500 m and 1000 m below the surface.

Saturated Thickness Map

The saturated thickness was estimated based on the groundwater contour lines for October 2017 and the base of the A7/B2 aquifer by Brückner (2018) (Chapter 3.2). In the areas where the A7/B2 aquifer is confined (Annex 10, Figure 54), the entire aquifer thickness is considered to be the saturated thickness. Given the uncertainties in the structural model and the extrapolated groundwater contour map, this map only allows for the regional identification of potential areas for groundwater abstraction. Local on-site investigations are needed to confirm these regional results, especially in the outcrop areas, where the saturated thickness appears to be too optimistic, such as in the highlands between Madaba and Karak.

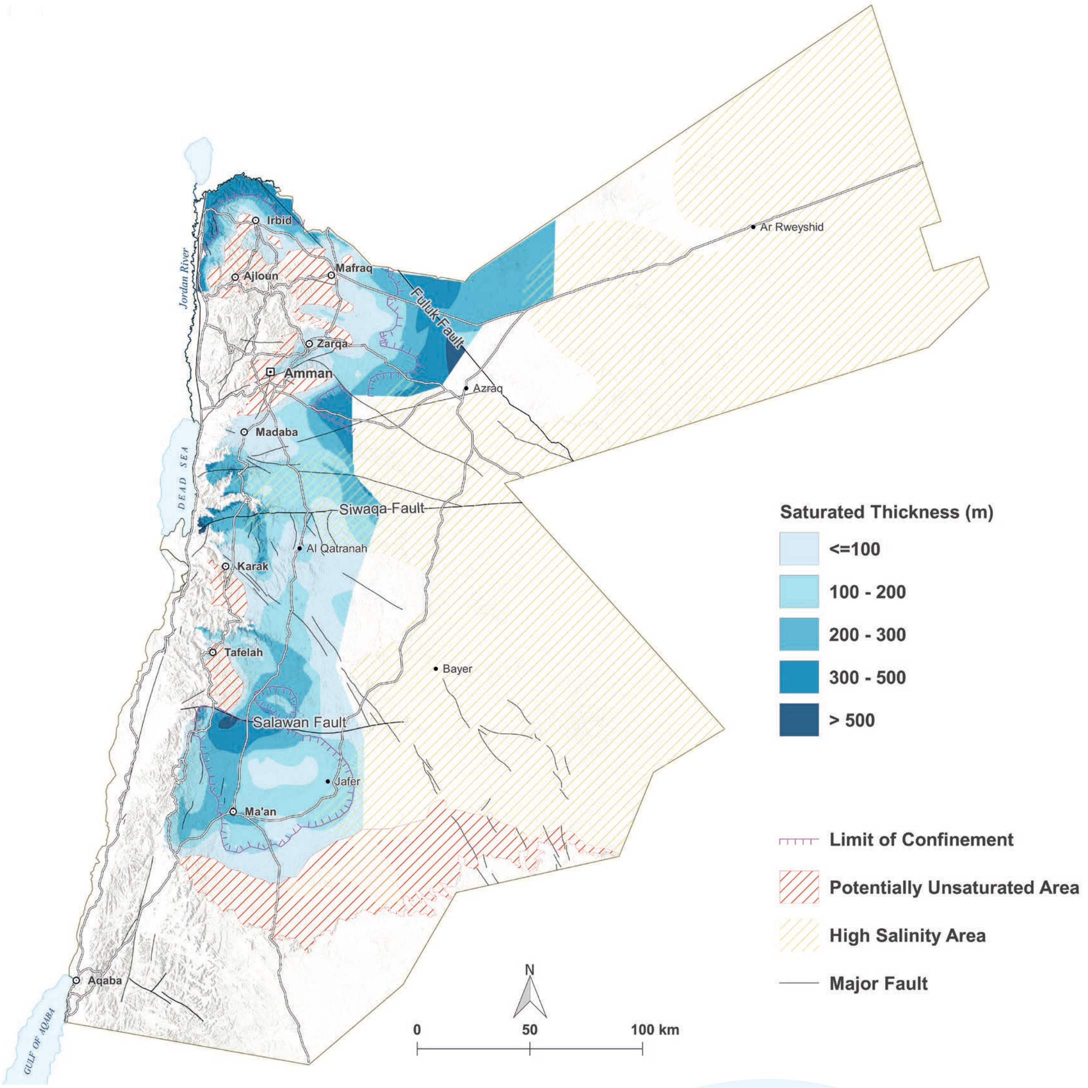


Figure 54 Saturated thickness of the A7/B2 aquifer

Source: BGR

In summary, the map shows the following findings:

- The area between Ajlun and Irbid appears to be unsaturated.
- Previously reported unsaturated areas around Mafraq have expanded slightly to the east.
- Areas west and northwest of Amman, between Zarqa and Mafraq, and between Amman and Madaba are now unsaturated.
- Small areas west and southeast of Al Qatranah appear to be unsaturated.
- The unsaturated area in the southernmost part of the aquifer along the Ras en Naqb escarpments has substantially expanded.

Saturated thicknesses of less than 100 m mainly surround unsaturated areas as well as in the confined area west of Jafer. Only small parts of the aquifer have saturated thicknesses greater than 300 m, such as in the north around Irbid, west of the Fuluq Fault and south of the Salawan Fault. However, groundwater exploitation in these areas should be considered carefully as the A7/B2 aquifer dips steeply, and the aquifer base is more than 2500 m bgl (Figure 28). Groundwater exploitation is not economically feasible at these depths.

In the outcrop areas south of Madaba to Tafelah, the aquifer is at high elevations and generally dips to the east. Recharge occurs in these outcrops. However, as the aquifer experiences significant drawdowns, most of the recharge is assumed to flow east following the general dip towards the low-lying unsaturated areas of the aquifer and does not saturate the outcrop areas. The aquifer is relatively unsuitable for economic abstraction in the outcrops, which is confirmed by the fact that some wells in the Heedan wellfield had to be deepened to reach the deeper A4 aquifer. Due to the lack of monitoring data, the groundwater conditions in the outcrop areas as well as the potentially unsaturated areas are only assumptions. The areas between Madaba and Karak as well as north of Tafelah are not classified as potentially unsaturated, although their natural conditions are similar to the areas south of Karak and south of Tafelah. These areas may also be unsaturated, but some springs near the escarpment still show small but continuous discharges, which indicates groundwater availability in the area. Additional investigations are needed to confirm the results.

The map also shows the eastern limit of aquifer confinement. This limit has a high degree of uncertainty because it is estimated based on the structure contour map and extrapolation of the groundwater level surface because no groundwater level data are available in that area.

Difference in Groundwater Map

The groundwater level difference between 1995 and October 2017 (Annex 11, Figure 55) was estimated based on the contour lines for both years and shows the changes in groundwater level over the last 22 years at a regional scale. The data sources for both maps are very different and have high accuracies in different areas. Some areas are very precise in the 1995 map, whereas they do not have good data distributions in 2017. These differences lead to uncertainties in the map. Therefore, this map only provides a broad regional indication of the drawdown, and the values can differ significantly from those measured at a certain location.

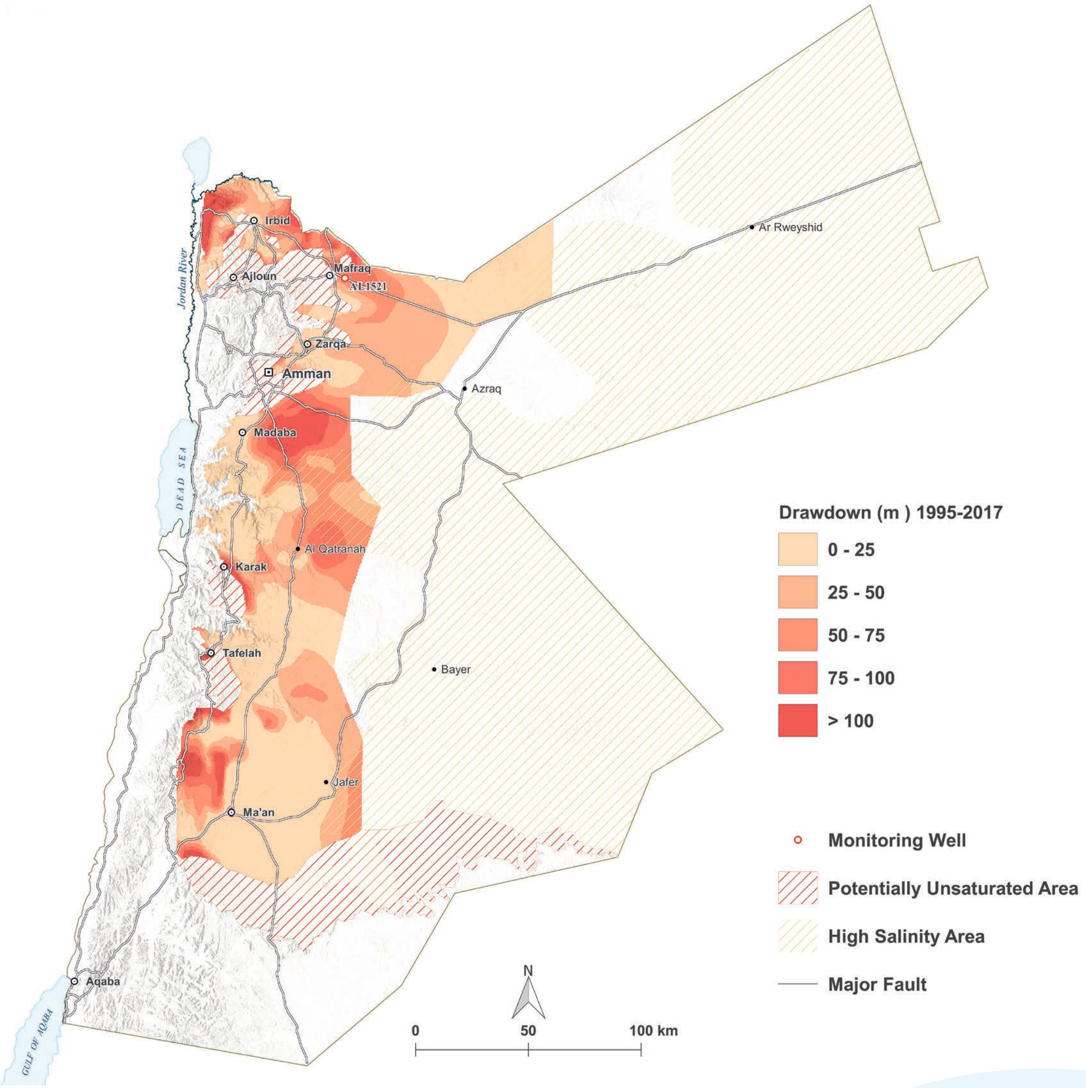


Figure 55 Difference in groundwater levels of the A7/B2 aquifer between 1995 and 2017

The following results can be obtained from the map:

- The groundwater level in the area south of Karak and Tafelah has declined by more than 100 meters, and the aquifer is now unsaturated.
- Around Amman, due to a mapped groundwater drawdown of between 50 and more than 100 meters, the aquifer is now unsaturated.
- Depending on the available saturated thickness between Mafraq, Irbid, and Ajlun, the drawdown varies strongly. However, the entire area appears to now be unsaturated.
- North of Irbid, the water level shows a general drawdown of approximately 50 meters.
- North of Mafraq, the overall drawdown is approximately 60 meters.
- The area between Amman and Zarqa shows a drawdown of approximately 25 meters.
- Between Amman and Madaba, the drawdown generally varies between 50 and 75 meters.
- The area between Madaba and Al Qatranah shows a general drawdown of 50 meters.
- Drawdowns of up to 25 meters can be observed in the area between Al Qatranah and Tafelah.
- The area south of Tafelah shows a large variability in local drawdown from no significant drawdown to 50 meters.

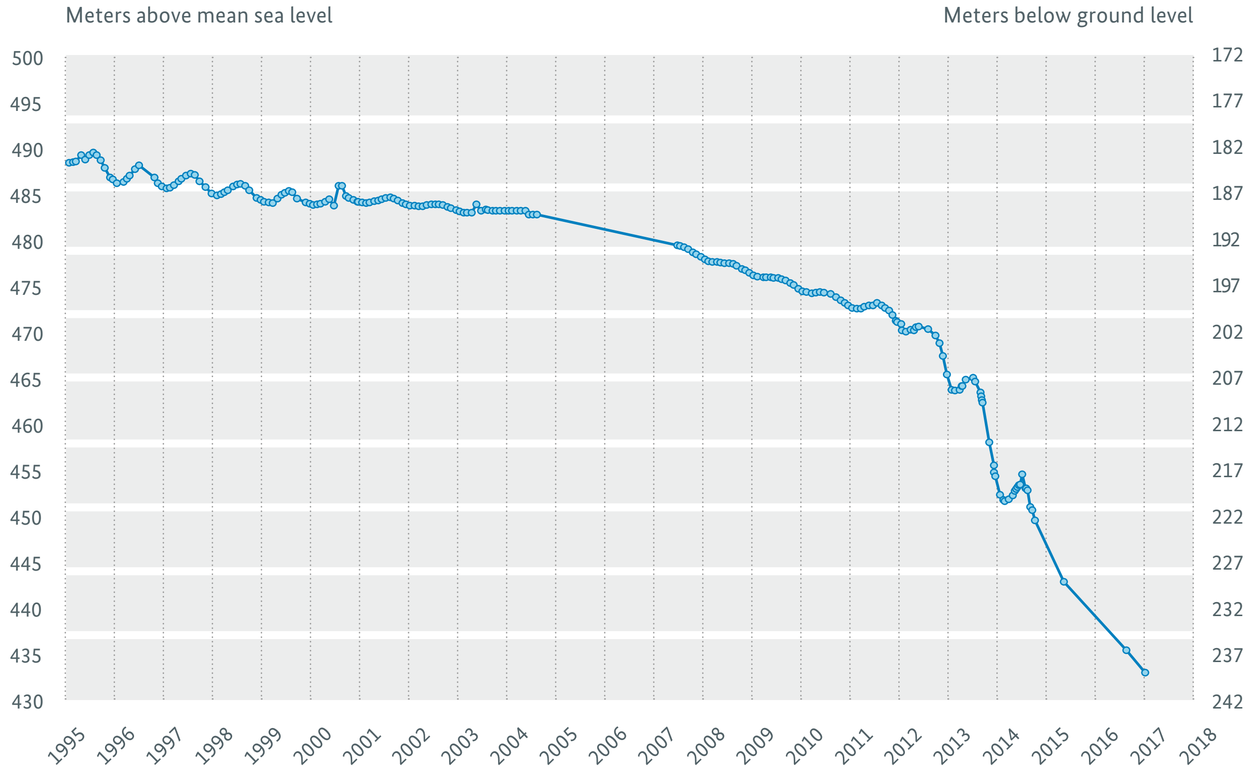


Figure 56 Groundwater levels recorded for 1995-2017 in the A7/B2 aquifer at well AL1521

Strong long-term drawdowns can also be observed in the monitoring wells. Near Mafraq, strongly rates of decline were registered in observation well AL1521 (Figure 56). From 1995 until 2005, the groundwater levels declined at a rate of 1 m/yr. Since 2013, the drawdown rate has increased suddenly to 12 m/yr, which is probably due to the large volume of groundwater abstracted from the area, representing a quarter of all exploited groundwater in Jordan (Margane et al., 2013).

Figure 57 shows the locations and annual production volumes of both private and governmental wells (Figure 57) compared with the groundwater level drawdown (Figure 57, right). The concentrations of wells in certain areas explain the strong measured decline in groundwater. However, it is unclear whether all of the considered wells are in the A7/B2 aquifer, as this information is generally not available. Some wells may penetrate a deeper aquifer, which is a sign that the A7/B2 aquifer is already dry in these areas.

In summary, the drawdown map (Figure 57) shows the following findings:

- The area west of Ma'an is dominated by governmental wells with yearly productions of more than 500000 m³ and drawdowns of 50-100 meters over the last 25 years.
- The area east of Petra is dominated by private wells with productions between 250000 and 500000 m³ in 2016, resulting in drawdowns of 50-100 meters. The area around Petra has experienced a drawdown of more than 100 meters in the last 25 years as a result of the high density of abstraction wells east of Petra.
- The governmental wellfields along the King Hussain desert highway between Ma'an and Al Qatranah have local effects on the aquifer. The drawdowns vary from minor to 100 m just north of Al Qatranah.
- The area between Al Qatranah and Amman is strongly dominated by private pumping wells that produce overall drawdowns of between 50 and 100 meters. The area

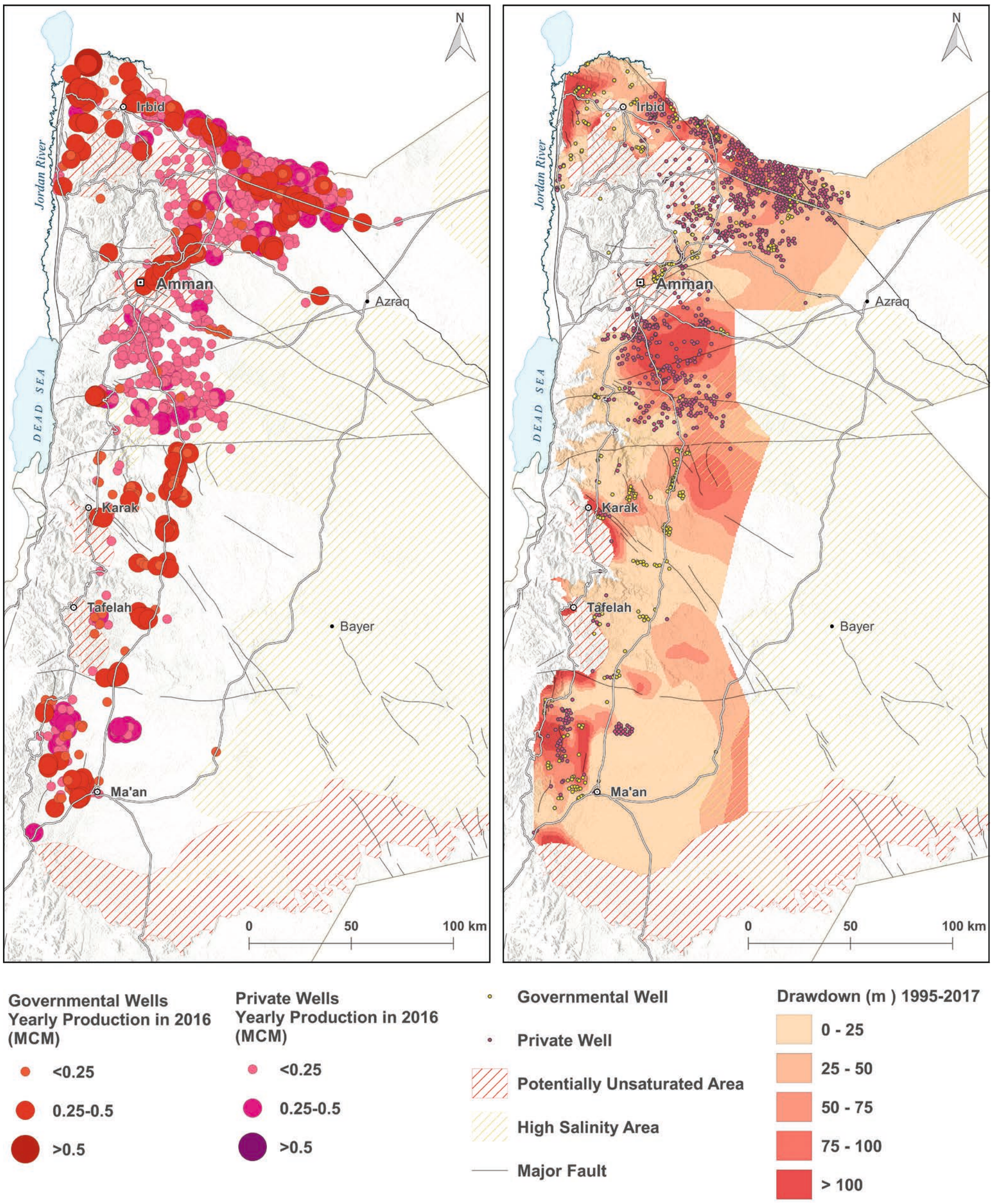


Figure 57 Left: Abstraction wells according to their volume (MCM), right: groundwater drawdowns since 1995 and locations of abstraction wells

east of Madaba has a drawdown of more than 100 meters. In 1995, the salinity in this area was already above 1500 µS/cm. Due to the steady drawdown over the last 25 years, the water quality has most likely continued to deteriorate.

→ Between Amman and Zarqa, governmental wells with annual productions of more than 500000 m³ are dominant, but the overall drawdown is less than 50 meters.

→ East of the Zarqa and Mafraq Road, private wells are dominant. Only a few governmental wellfields exist and have productivities of >500000 m³ for the water supply of Amman. The unsaturated area extends to the east as a result of the high density of abstraction.

→ The area between Mafraq and Ramtha has a high density of private abstraction wells and high drawdowns of more than 100 meters in some areas.

→ The areas around Irbid and the Yarmouk River Valley are of special interest. The number of wells is very small, but the drawdown is extremely high (more than 100 meters). This is an indication of illegal pumping for agriculture in the region, which can be seen in Google Earth images (Figure 58 and Figure 59).

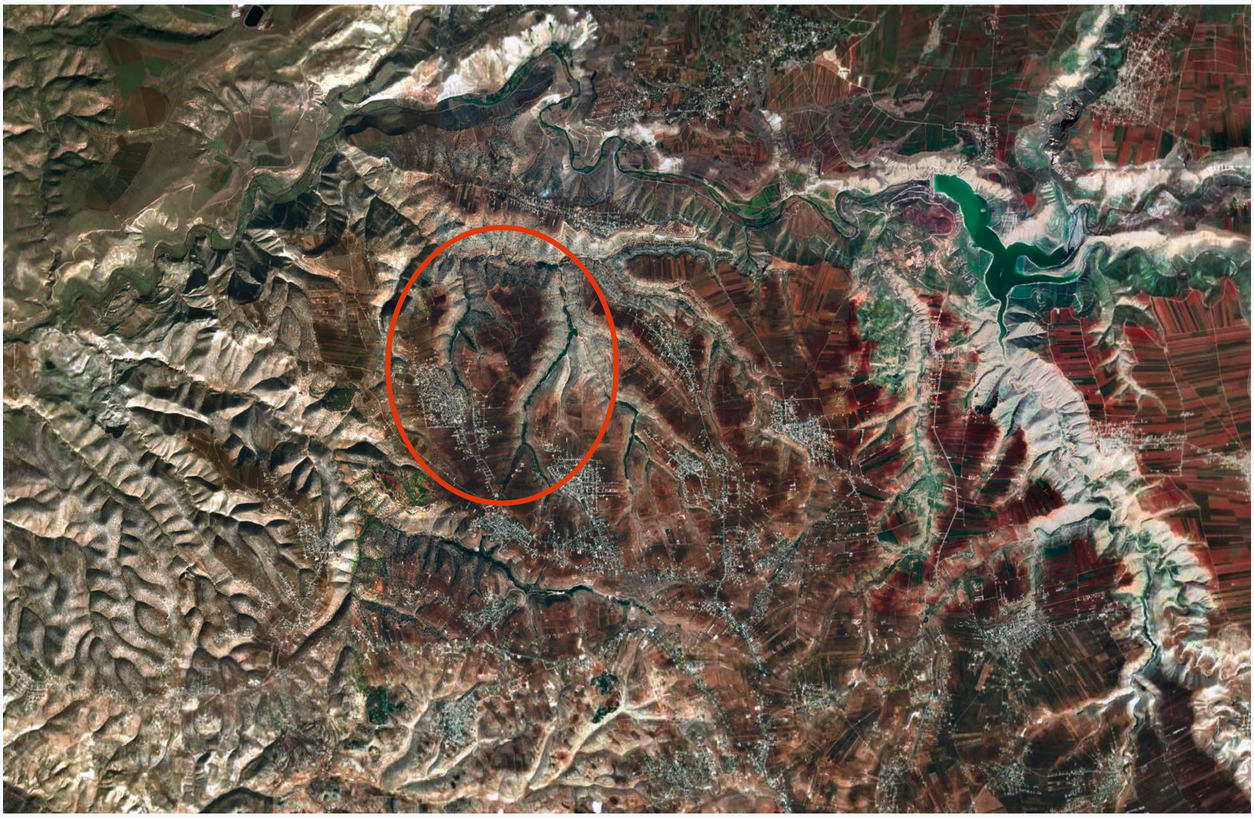


Figure 58 Google Earth image of the area W/NW of Irbid (source: Google Earth V 7.1.8.3036, June 2018, northern Jordan, 32°41‘37.02“ N 35°48‘13.23“ E, Eye alt 23.89 km, Maxar Technologies 2019, CNES/Airbus 2019)

Figure 59 Close up Google Earth image of the red circle indicated in the Figure 58, showing the agricultural activities in this area (source: Google Earth V 7.1.8.3036, June 2018, northern Jordan, 32°42‘23.95“ N 35°47‘21.30“ E, Eye alt 1.95 km, CNES/Airbus 2019)

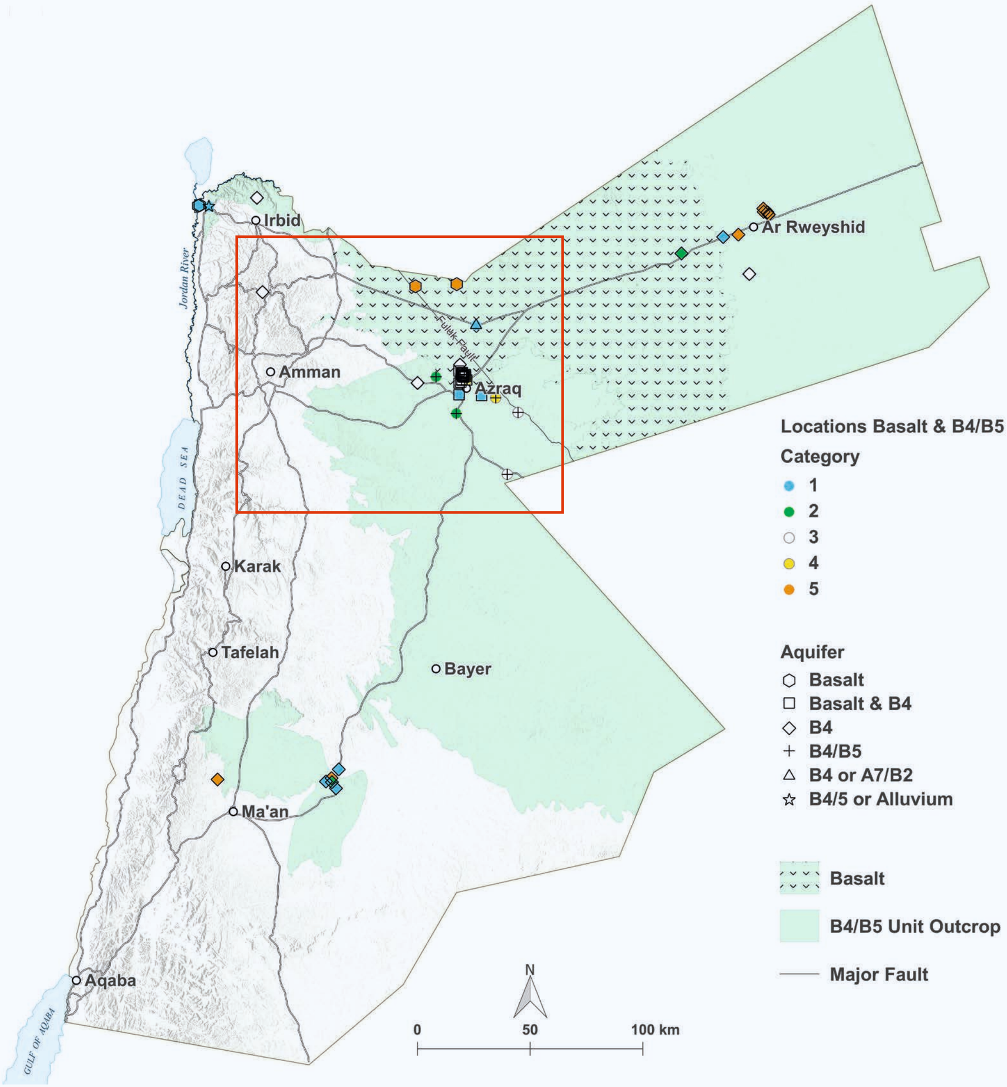


Figure 60

Spatial distribution of monitoring locations with indications of quality measurements. The red rectangle indicates the Azraq area, which is analyzed further

4.2.4 B4/B5 Aquifer

The Basalt and B4/B5 aquifers are only of regional importance, mainly in the area around Azraq, where a wellfield for domestic water supply is located (Figure 60). The wells farther east towards the Iraqi border are military wells.

Only the area around Azraq has an adequate data density for the development of groundwater contour maps (Figure 60). However, the reliability of some of the available data is highly questionable and must be considered during the analysis.

Groundwater Conditions Around Azraq

The groundwater contour lines for the B4/B5 and Basalt aquifers in the Azraq area are presented in Figure 61 (see next page).

The AWSA wellfield is located north-northwest of Azraq, which is indicated by the cone of depression north of Azraq. The hydraulic heads of the A7/B2 aquifer are very similar to those of the B4/B5 and Basalt aquifers (Figure 61, next page), which is an indication of the hydraulic connectivity between B4/B5 and A7/B2. The B3 aquitard usually separates the A7/B2 from the B4/B5 in this area. However, the A7/B2 aquifer is confined in this area, and private wells probably penetrate both aquifers, which could lead to vertical bypass through the boreholes.

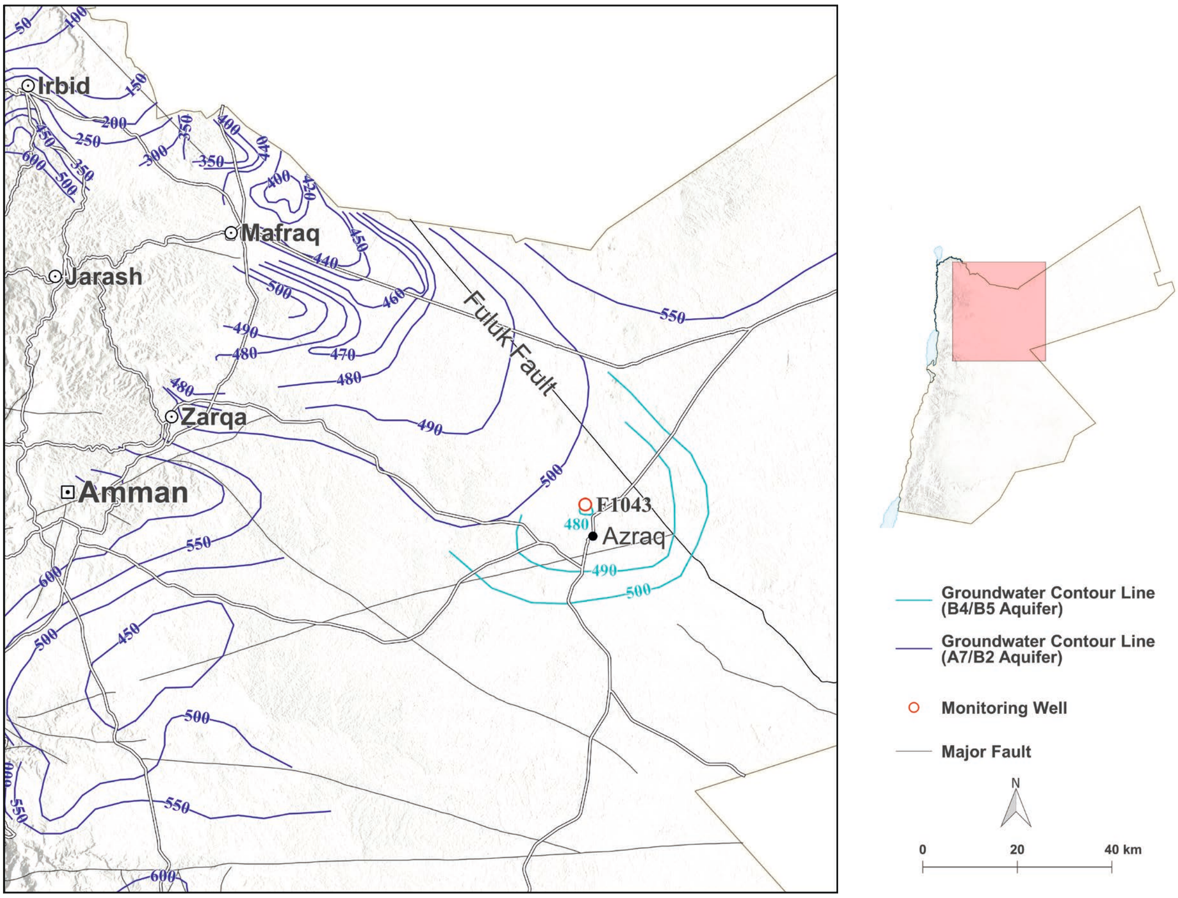


Figure 61 Groundwater level contour lines for the Basalt and B4/B5 (light blue) and the A7/B2 (dark blue) aquifers in the Azraq area, October 2017

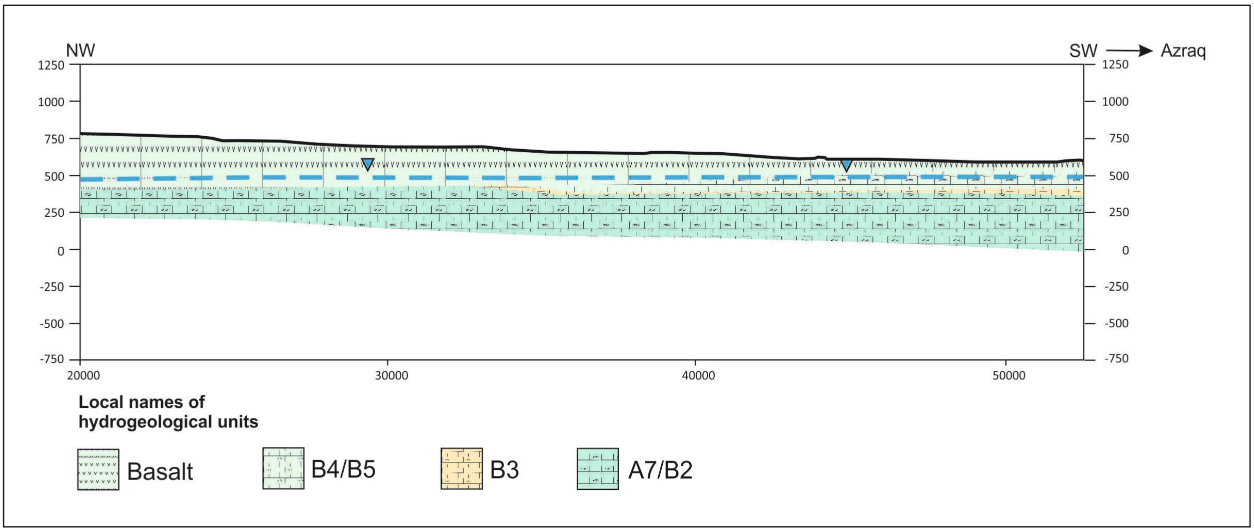


Figure 62 NNW-SSE cross-section

A hydraulic connection between the A7/B2 and B4/B5 aquifers through the overlying Basalt may also be possible. To the NW, the Basalt aquifer is hydraulically connected to the underlying A7/B2 aquifer (Figure 62). Farther to the SSE, the A7/B2 aquifer dips down and the B3 aquitard appears, which is in turn covered by the B4/B5 and Basalt aquifers. The confined A7/B2 aquifer could recharge the Basalt aquifer in the NW by means of vertical leakage. Groundwater would flow in the Basalt to discharge into the B4/B5 aquifer farther to the SE.

A hydraulic contact through the Fuluk Fault is also a possible hydraulic connection between A7/B2 and B4/B5, but the flow direction does not indicate such an effect. A hydraulic connection through the fault south of Azraq is also possible, but this cannot be analyzed further due to the lack of data.

Considering the amount of water abstracted from the B4/B5 aquifer for irrigation purposes, it is questionable whether the recharge from the north (Jebel al Arab) is sufficient to maintain the water level. The contour lines of A7/B2 (Figure 61) bulge towards the east (Azraq), which indicates groundwater abstraction, although B4/B5 is the main aquifer source in this area. Probably, the bulge in the contour lines is due to the effect of the hydraulic connection between the two aquifers.

The overall drawdown since the 1990s in the Azraq area appears to be approximately 10 meters, which is reflected in monitoring well F1043 (Figure 63). The water level declined steadily between 1995 and 2009 before a more irregular drawdown was recorded, likely due to temporarily higher abstraction rates.

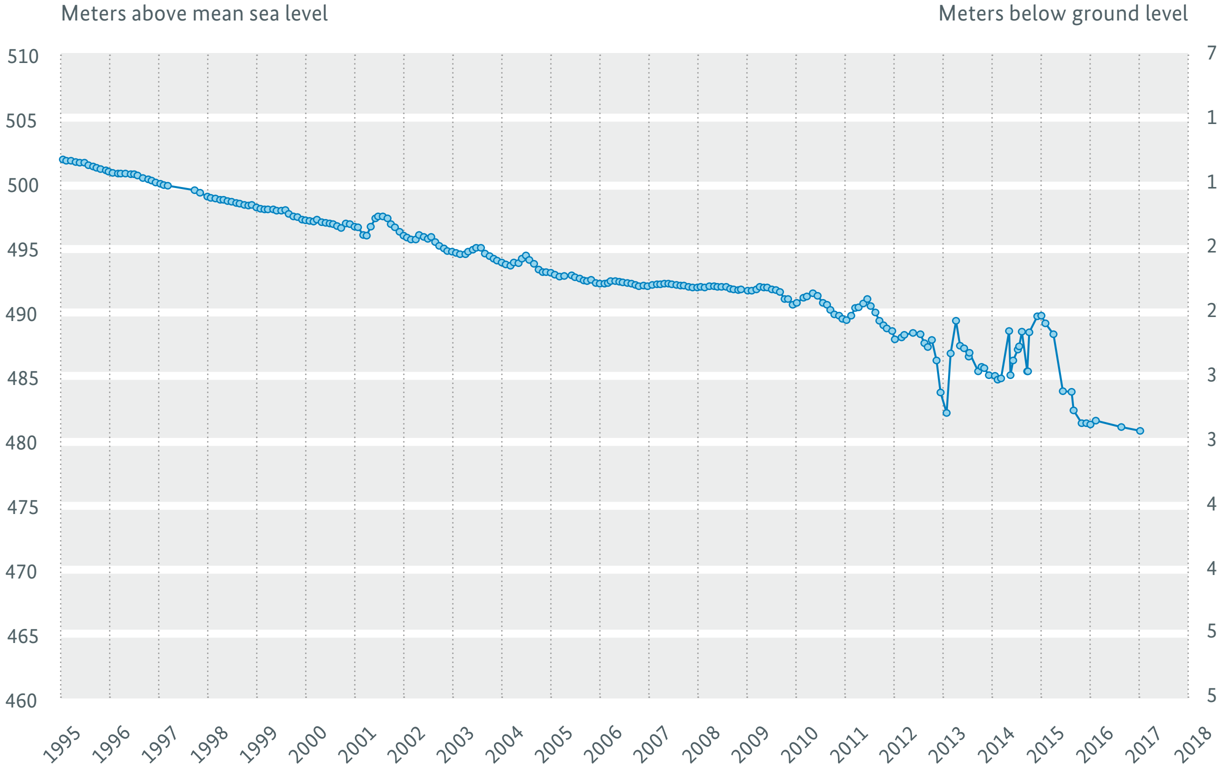


Figure 63 Groundwater levels in the B4/B5 aquifer for 1995-2017 recorded at well F1043

4.3 Recommendations

Generally, decreasing water levels and increasing unsaturated areas will have serious economic and operational consequences for water abstraction for private and public use. The growing drawdown increases energy consumption for lifting the water and consequently increases operational costs. Furthermore, existing wells must be continuously adapted to lower water levels; wells must be deepened, riser lines must be extended, and pumps must be exchanged for more powerful and expensive pumps. In extreme cases, wells have to be replaced. A significant number of wells will become dry in the coming years. Because salinity and mineralization of the abstracted groundwater increase with depth, water quality will become a major cost factor, eventually requiring water treatment by expensive technologies and disposal of brines.

To mitigate these conditions and slow or reverse the continuous increase in the water supply costs as well as to secure the future water supply, decisive measures by the Jordanian government are urgently needed. Possible actions include different water demand and water supply management options. Determining which options are the best and most effective in the context of Jordan is beyond the scope of this study. These decisions must be made by the Jordanian government considering not only the contribution of each option to increasing water security for the population but also its social, economic and environmental implications. Subject to the information presented above, a few potentially effective measures are listed that could contribute to mitigating or overcoming the (ground)water crisis in Jordan.

Development of new wellfields

The development of new wellfields for public water supply has the potential to improve the continuity of the drinking water supply and reduce the costs of groundwater exploitation.

However, new wellfields will not reduce the overexploitation of groundwater, but they may be effective to buy time and sustain the drinking water supply while measures oriented towards a long-term solution for the water crisis are implemented.

The maps in this study can be used to identify feasible areas for the development of new wellfields. These areas should have large saturated thicknesses and low depths to groundwater.

For example, the area east of Mafraq in the Al-Badiah district has favorable characteristics with a groundwater depth of less than 200 m and saturated thicknesses of up to 300 m.

In the south, the area north of Ma’an has a good saturated thickness of more than 300 m. Hardly any drawdown has occurred over the last 20 years, and the depth to groundwater is less than 200 m. However, the B5/B4/B3 formations overlie the A7/B2 aquifer, which can be reached at drilling depths of over 300-400 meters. Here, a risk of contaminating the water, such as by arsenic, nickel and salinity, which are present in the northern and middle parts of Jordan, exists if the groundwater from the B3 or B4 Formation infiltrates through the well. This is likely to occur if the casing and sealing of the annular space is not completely tight.

Large saturated thicknesses can be found in other areas, but the depth to groundwater is already approximately 300 meters below the ground, and exploitation is likely not economically feasible because of the high pumping lift, the resulting high energy cost and the likelihood of high salinity groundwater. For example, in NW Jordan around Irbid, the saturated thickness of the A7/B2 is very high, but the aquifer dips to the N/NW.

The maps in this study can be used to identify potentially favorable wellfield locations. However, the final decision on the siting of a new wellfield must be based on an exhaustive feasibility study, in which the local hydrogeological conditions, the distance to the demand site, required infrastructure, water quality, building and operational costs, land ownership, possible impacts on existing water rights and security issues are evaluated.

Assess illegal groundwater abstraction

This study identified areas with large drawdowns but small numbers of wells. In these areas, installations of many illegal wells should be considered. This is especially the case north and west of Irbid, where records of private wells in the WIS are rare, but satellite images show a wide area used for agriculture.

To restrict the illegal abstraction of groundwater, the importance of the problem must be evaluated. As a first step, it is highly recommended to assess the expansion of irrigated agricultural areas and to compare the needed irrigation water volumes with records of licensed water uses. Using remote sensing technologies and satellite images taken during the dry season, the irrigated agricultural areas can be delimited, and the crops can be identified. By overlaying this spatial information on a map of the licensed wells and the surface water infrastructure used for irrigation, irrigated areas with and without water rights can be identified. The total illegally abstracted volumes can be estimated by multiplying the illegally irrigated areas by the typical crop water demand in arid or semiarid climates.

The same approach can be used to estimate the water volumes used on the licensed irrigated areas, and this can be compared with the volumes declared by the well owners. Therefore, the illegally abstracted water volumes in the licensed agricultural wells can be quantified.

Based on the results of this assessment, additional measures can be taken, such as closure of illegal wells, strict control of abstracted volumes, revocation of licenses, and application of higher water fees.

Identify and reform subsidies for groundwater abstraction

The results of this study show that groundwater in Jordan is extracted at depths of more than 100 meters and up to >300 meters in the northern highlands. Consequently, the pumping lifts and the resulting energy costs are extremely high.

The sector that is most sensitive to the high cost of water is the agriculture sector; it requires large volumes of water and has relatively low profitability. Despite the extremely high pumping lift and energy consumption in the Jordanian highlands, extensive agricultural activities can be observed.

One explanation of this apparent contradiction is subsidies for agriculture in the highlands.

Subsidizing systems exist because they were created with a certain objective, such as to support the rural population or to secure the national food production. The existence of subsidies for agriculture in the highland desert region implies that the Jordanian government or population pays for the overexploitation of scarce groundwater resources, which appears to be paradoxical. However, the negative implications are often not known at the time these subsidies are designed and implemented.

Therefore, it is highly recommended to study the economics of agriculture in the highlands and identify subsidies for groundwater abstraction. The subsidies may be direct payments to farmers, and these subsidies can be easily identified and quantified. However, subsidies can also be indirect or hidden, which create special low tariffs for the energy required for groundwater abstraction (diesel or electricity) and artificially high prices for agricultural products. Artificially high prices are achieved through price regulation, high customs duties on the agricultural products or other situations that lead to a type of monopoly by local farmers.

Only accurate knowledge of the subsidy system and its total cost for the beneficiaries and payers can facilitate a political discussion of the objective of subsidies and their negative impacts. This discussion, with the participation of all involved parties and sectors, can lead to system reform and maintain the objective of the original subsidies while avoiding the negative impacts.

Source: Aerial Photographic Archive for Archaeology in the Middle East

Source: Bashar Tabbah Photography

Increase awareness of the water crisis based on solid information

One of the most effective measures for addressing the water crisis is to increase awareness among national, regional and local decision makers as well as among the most important private water users, such as water companies and farmers. All institutions related to the water sector must be informed about this study.

Knowledge of the water resource conditions, its past development and the possible future impacts strengthens the ability to find a solution to the crisis and fosters the formation of alliances.

Messages to decision makers and the general public must be based on reliable and credible information.

Enhance groundwater monitoring

The results of this study are based on reliable information. In the future, the MWI will need to regularly update the results of this study and develop foundational information about the groundwater conditions. To recollect the necessary reliable data, the following tasks are highly recommended:

- Manually monitor the groundwater levels in all available monitoring wells every 3 months. Automatic systems may also be used for the collection of continuous groundwater data. Because of the failure susceptibility of the telemetric systems observed during the implementation of this project, groundwater monitoring must rely on manual measurements.

- Measure the SWLs in pumping wells during maintenance. There is an urgent need for close and reliable cooperation with the WAJ Well Maintenance Department to collect the additional groundwater level data required for the development of groundwater level contour maps.

- In every transaction regarding any kind of well drilling, maintenance or rehabilitation work, the proper collection of the SWL, including the date, must be explicitly mentioned in the requirement of the ToR. In many cases, an SWL is available, but not the date of the measurement, which renders the value useless.

- Measure the coordinates and elevations of all wells, particularly monitoring wells, with differential GPS technology. The project acquired one type of DGPS equipment and trained the technical staff of the MWI and WAJ in its use. A well can be used to update groundwater level contour maps only if the exact coordinates are available.

Save water

Any potential for saving water should be fully exploited. Water companies should reduce water losses due to leaking pipes to a minimum through continuous maintenance or, where necessary, modernization of the water supply network.

In the agricultural and industrial sectors, water-saving technologies and processes as well as cultivation of low-water demand crops should be promoted. Therefore, positive or negative incentives or a combination of both may be used. The positive incentives include monetary or nonmonetary awards for innovative water-saving technologies, and fees for water abstraction are the most important negative incentives. For Jordan, it is highly recommended to assess whether these fees are sufficiently high to stimulate the investment in water-saving technology or the shift towards low-water demand crops. In addition, the economic sense of a minimum volume that is free of charge should be evaluated.

In cases where private water users severely affect the groundwater abstraction for the drinking water supply, the well licenses should be renewed annually as mentioned in the bylaw. In critical areas, the licensed water volumes should be reduced, or the licenses should not be extended. Purchase of private wells by the water company or the MWI should also be considered. These measures would stop or reduce private groundwater abstraction in areas affected by very high groundwater drawdowns.

Identify alternative water sources

For all of the water supply and demand management options discussed above, it is highly recommended to identify alternative water sources, such as the desalination of seawater or brackish groundwater, and to study their economic feasibility for the domestic water supply by comparing their costs to the continuously increasing costs of groundwater exploitation.

The costs of the use of alternative water sources in the near future could be below the cost of exploiting continuously deeper and more saline groundwater resources. Furthermore, the development of new sources reduces the dependency of the drinking water supply on the shrinking groundwater resources, increases the sustainability of the drinking water supply and improves water security.

ASSESSMENT OF SPRINGS

5

5

Assessment of Springs

Rebecca Bahls

As the scarce groundwater resources in Jordan are continuously decreasing, the surface water resources should be used for the water supply as much as possible. Therefore, springs must be considered in comprehensive groundwater resource management, especially in Jordan, with its many springs along the highlands. A total of 861 springs are listed in the WIS database of the MWI for the different aquifers; however, no recent data were available for many of them. In this project, a nationwide assessment of the springs was conducted to identify their current status for a comprehensive analysis. In 2016/2017, only 23 springs were used for the drinking water supply. Many springs cannot be used because of bacterial pollution, despite large amounts of discharge. The water from important springs is treated to remove the bacterial contamination. In 2017, approximately 20 MCM of water was provided by springs for the drinking water supply.

5.1 Methods and Data

All available data for the 861 springs in Jordan in the WIS database were collected and analyzed. The springs were classified based on their recorded discharge as “perennial flow”, “seasonal dry” or “dry”, although no current information was available for a considerable number of these springs. Therefore, two field surveys were conducted in this project in combination with the MWI to identify the statuses of all of the springs that had not been measured during the last three years but had recorded discharge measurements for the prior 2 years. To evaluate the seasonal variations, the first survey was conducted at the end of the rainy season (March 2018), and the second survey was completed at the end of the dry season (October 2018).

The average discharge over the last five hydrological years (October 2013 to September 2018) for perennial springs was estimated considering all recorded data (Annex 12). Using these values and the natural neighbor interpolation method (Sibson, 1981), hot spot areas of high spring discharge were identified.

Additionally, the average spring discharges of all springs in a single aquifer was analyzed to provide an overview of the changes in discharge per aquifer over time and to identify any correlations with the decrease in groundwater. Because not all springs have a continuous data series, the 5-year average was calculated for each spring.

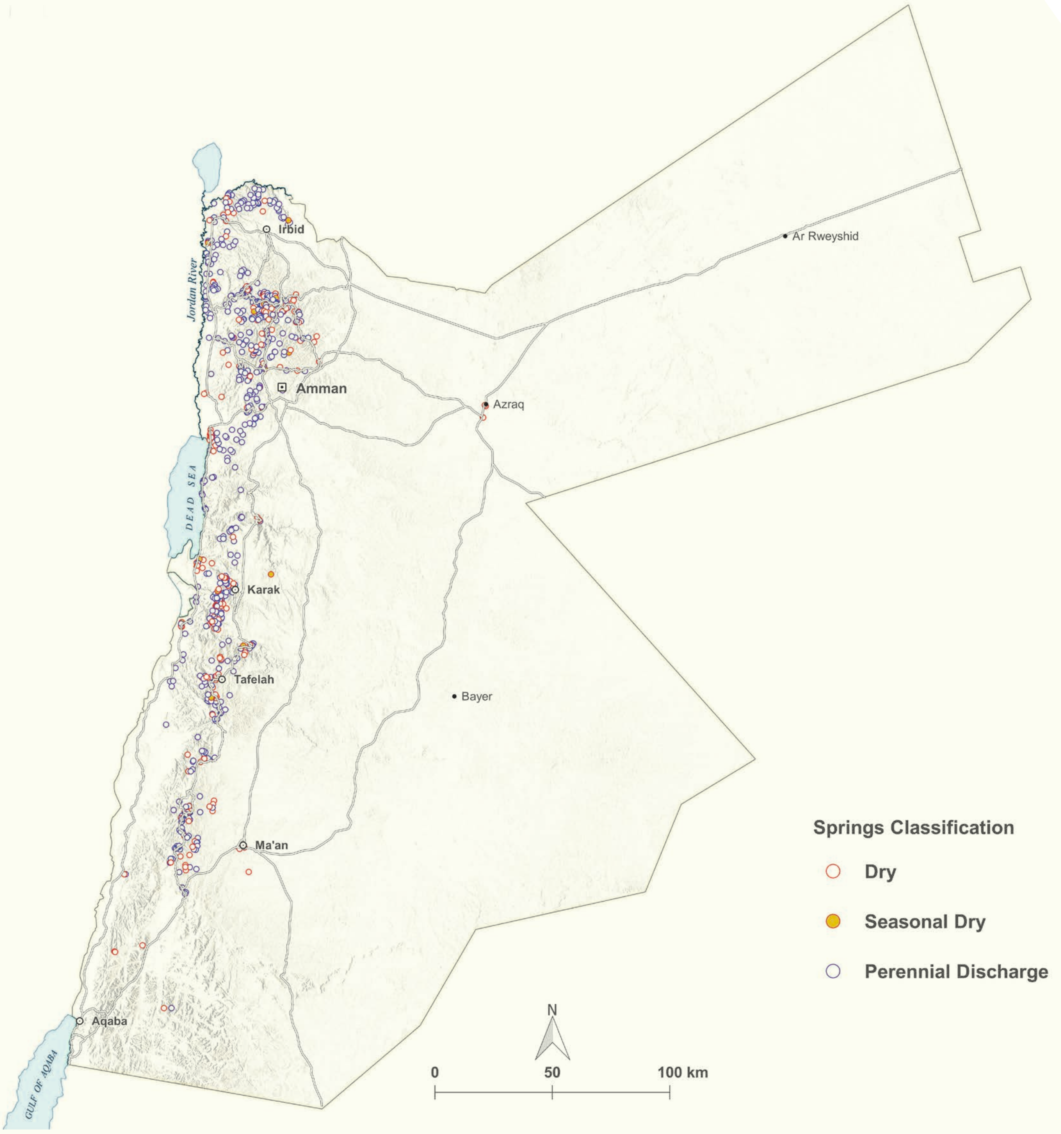


Figure 64 Locations and classification of springs in Jordan

5.2 Results

Figure 64 (previous page) shows a map of all springs in Jordan based on their current status: 361 springs are perennial, 23 are intermittent, and 195 are dry (Annex 12). The flow conditions of the other 12 springs remain unknown because it was impossible to identify these springs in the field.

The map indicates that springs are concentrated in the highlands. Perennial and dry springs are evenly distributed, and there is no specific area where dry springs are more common.

Figure 65 shows the number of springs that dried per year. The number is exceptionally high in 1995. The last nation-wide inventory was conducted in that year, and many of the classified dry springs had likely dried before 1995. The number of dry springs has varied annually, but the overall trend has increased since 1987, with four peaks in 1988, 1995, 1999, and 2014.

According to Figure 66, the number of newly drilled wells per year was already very high in the 1980s (1100) but nearly tripled to 2900 in the 1990s. Because the largest number of springs had dried in the 1990s, it can be concluded that there is a correlation between the number of new wells and the number of dry springs.

Figure 67 shows the distribution of the 5-year average spring discharge of perennial springs. In the high recharge areas in Ajloun, northwest of Amman, areas of large spring discharges (approximately 10 MCM/yr) are located to the south-southwest of Madaba, around Karak, Tafelah and south of Petra.

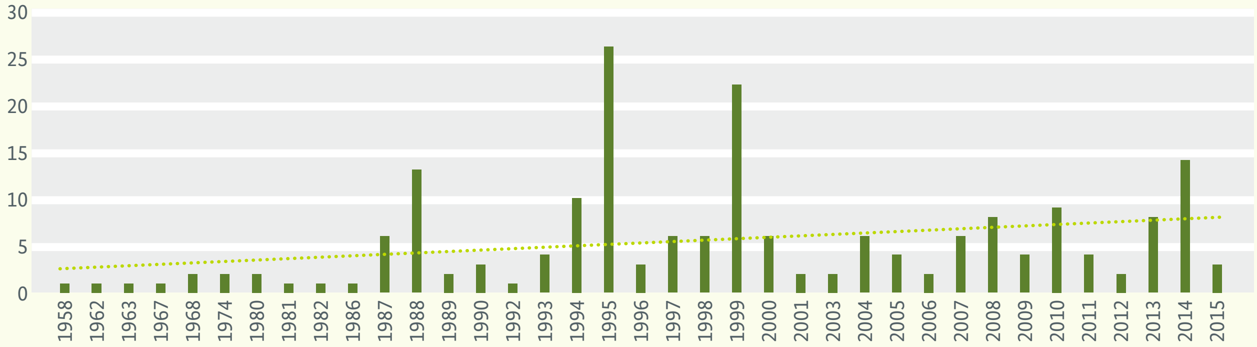


Figure 65 Number of dry springs per year

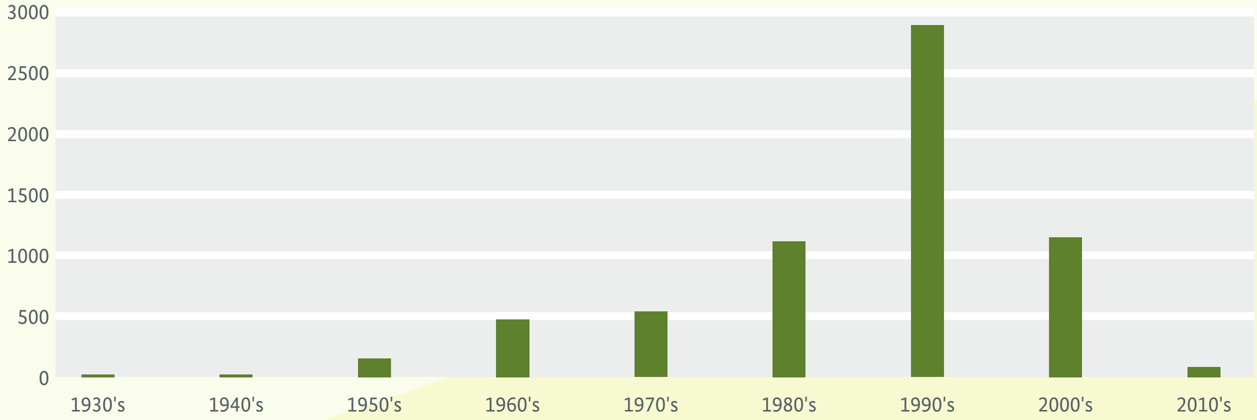


Figure 66 Number of wells drilled per decade according to the WIS. The database contains 8420 wells, but 1966 have no dates and therefore are not considered

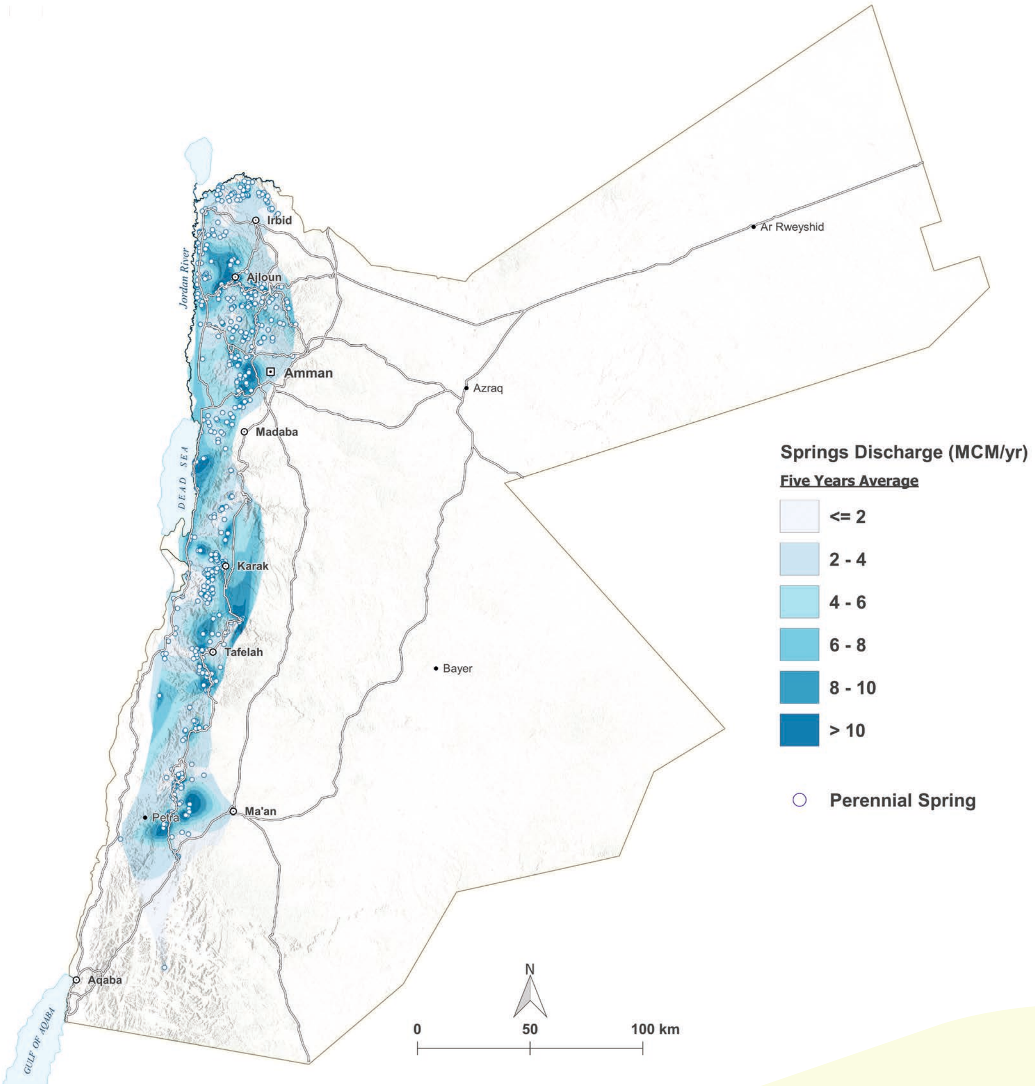


Figure 67 Five-year average discharge of the perennial springs in MCM

Regular collection of discharge data for springs began in the early 1970s and covered a larger number of springs. The total yearly spring discharge had a recorded maximum of 249 MCM/yr in the early 1970s (Figure 68) and has decreased constantly since, except in the early 1990s, when an increase was recorded. The latest discharge values show that the total spring discharge decreased by more than 115 MCM/yr to 136 MCM/yr in the early 2010s.

The same trend is observed for the individual aquifers. The average yearly spring discharge for the A7/B2 aquifer (Figure 68) was approximately 120 MCM in the early 1970s but decreased to 90 MCM/yr in the early 1980s, probably as a result of water abstraction from the aquifer when the number of drilled wells began to increase (Figure 66). In the late 1980s, the discharge decreased to less than 80 MCM/yr due to the large increase in the number of drilled wells, which more than doubled since the years prior to being recorded. However, the discharge recovered to 90 MCM/yr in the early 1990s. Since then, the average spring discharge has continuously decreased to 68 MCM/yr. The second largest source of spring discharge is the A4 aquifer at more than 50 MCM/yr in the early 1970s. Except for a small increase in the early 1990s, groundwater extraction from this aquifer caused a continuous decrease in spring discharge to 23 MCM/yr. The average spring discharge from the Alluvium remained approximately constant from the early 1970s (29 MCM/yr) to the end of the last millennium (23 MCM/yr). Since then, the discharge has declined to 12 MCM/yr.

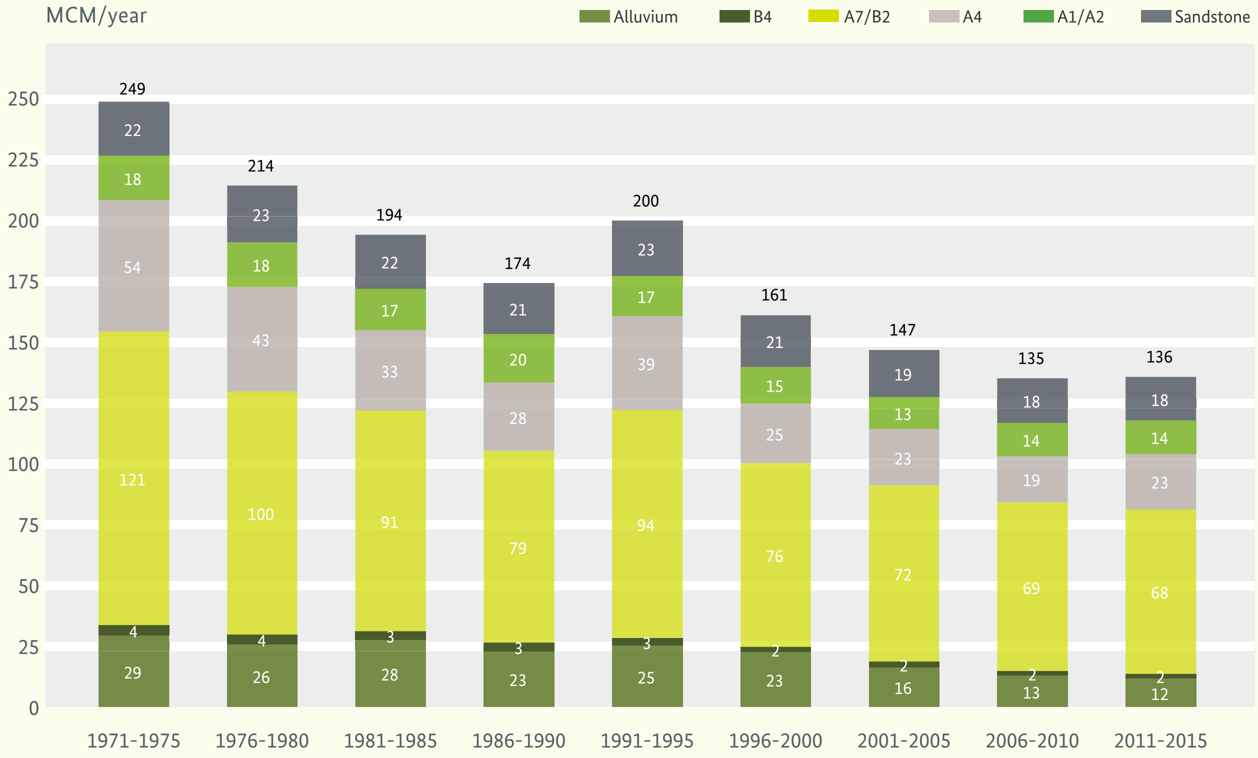


Figure 68 Average spring discharges per aquifer in MCM/yr

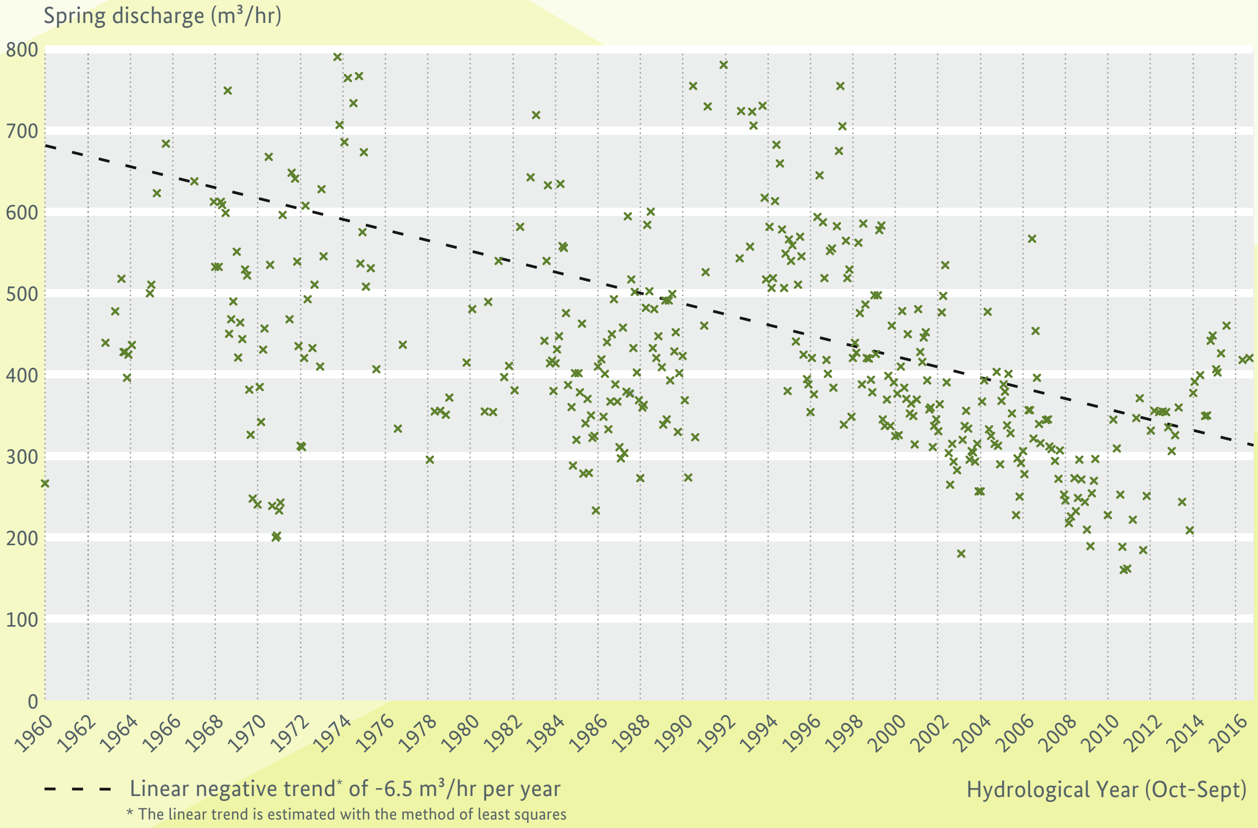


Figure 69 Discharge measurements from 1960 to 2017 at Sarah spring

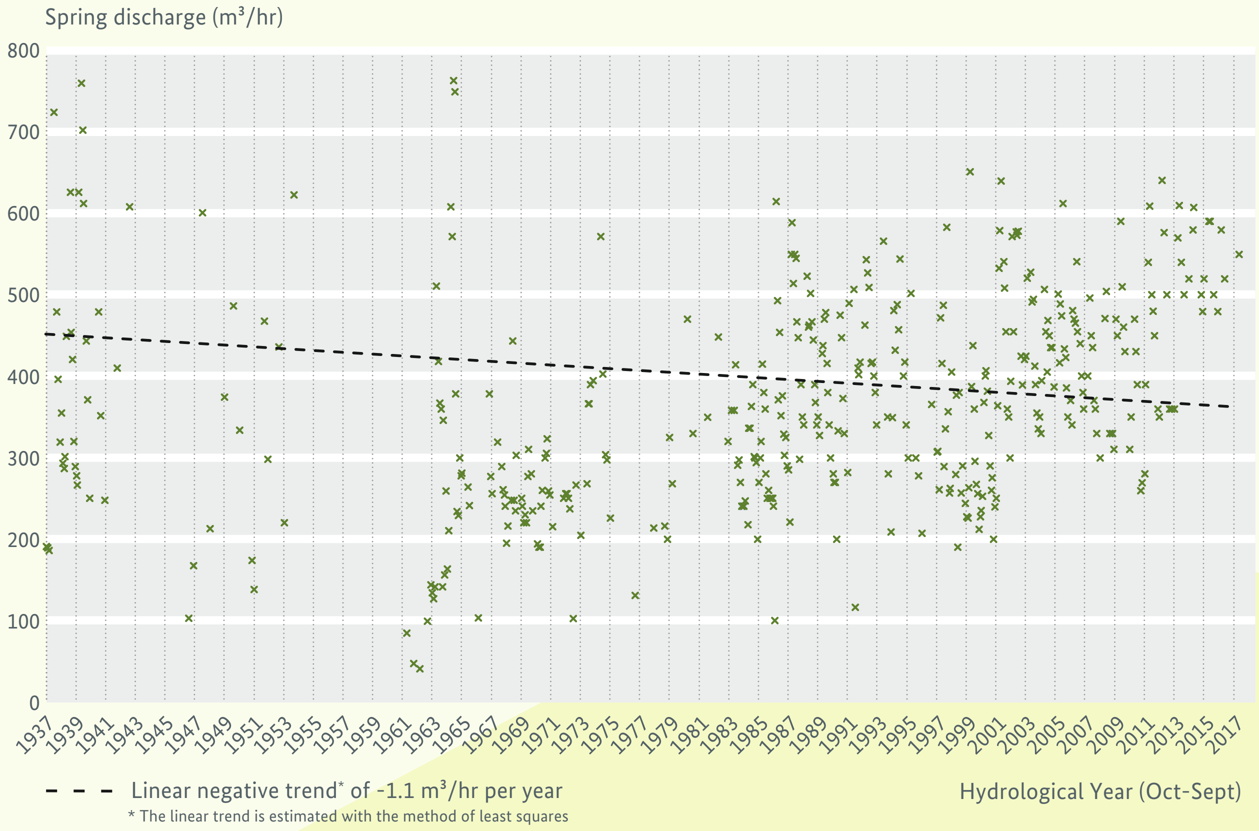


Figure 70 Discharge measurements from 1937 to 2017 at the ‘WADI ES SIR’ spring

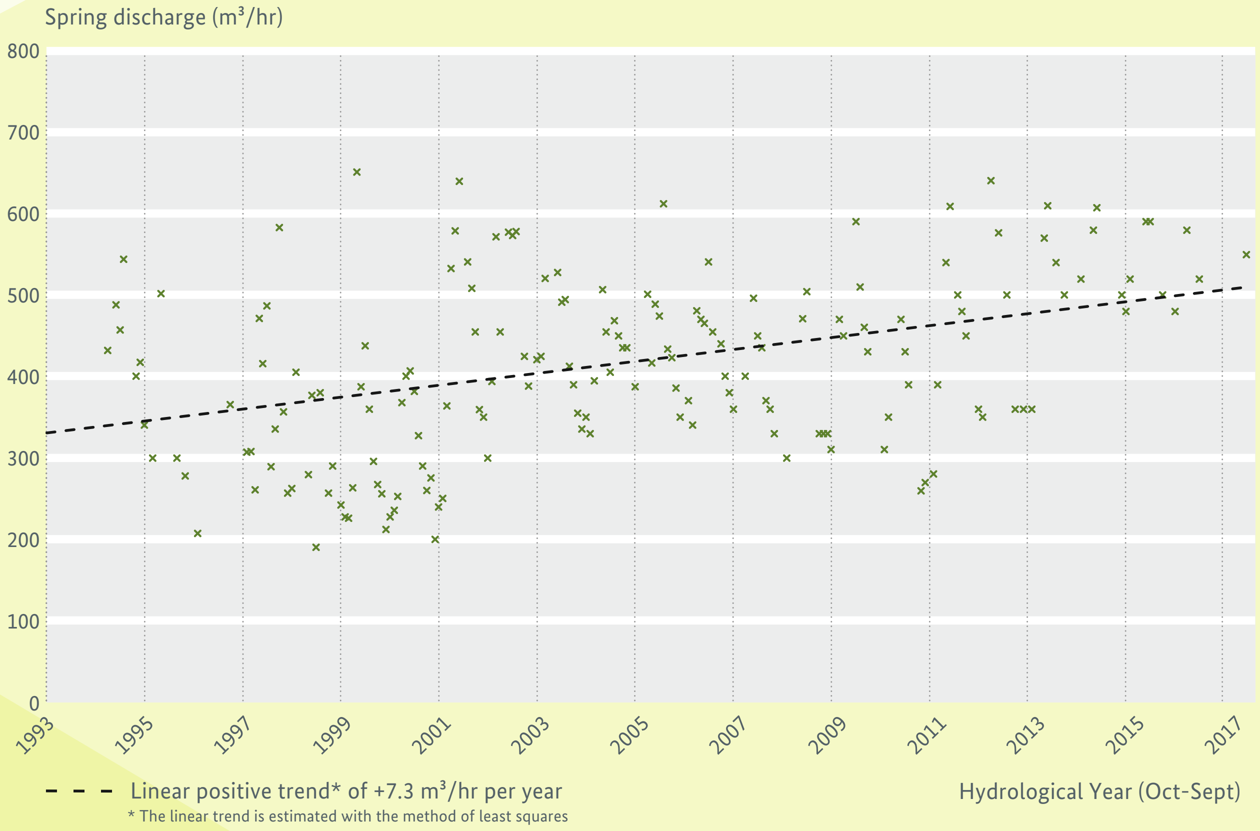


Figure 71 Discharge measurements from 1995 to 2017 at the ‘WADI ES SIR’ spring

The discharges of the springs dewatering the Sandstone aquifer and the A1/A2 aquifer remained generally constant at approximately 20 MCM/yr and 16 MCM/yr, respectively, over the described time period.

This decreasing trend can also be observed in individual springs. One example is the Sarah spring (Figure 69) in Karak, which dewaters the A7/B2 aquifer. Here, the long-term analysis shows a negative trend of -6.5 m^3/hr per year. However, the negative trend is even more severe at -12.1 m^3/hr per year since 1995, when the last nationwide study was completed.

In springs located near larger cities, such as the Wadi Es Sir spring west of Amman (dewatering the A4 aquifer), the trend is not as severe (Figure 70) as other springs dewatering the same aquifer. The long-term decrease in discharge at this spring is -1.1 m^3/hr per year. Interestingly, a positive trend is observed since the last nationwide study in 1995 (Figure 71). This effect is most likely due to the leaking water supply network of the city of Amman.

5.3 Recommendations

The critical water conditions in Jordan are also reflected in the decreasing spring discharge and increasing number of dry springs. Groundwater resources are limited in Jordan, which makes the available surface water even more precious. These resources need to be protected from any type of contamination. The treatment of already contaminated springs with high discharges and the connection of additional springs to the water supply system must be evaluated.

Source: Bashar Tabbah Photography

Source: BGR

GROUNDWATER MODEL OF JORDAN

6

6

Groundwater Model of Jordan

Mark Gropius

Comprehensive water resource management requires previously described information about the subsurface, the current groundwater level conditions and past developments. Based on this important information, decision makers can take suitable actions, such as the installation of a new wellfield. The possible effects of this new wellfield on the groundwater conditions can be simulated in a groundwater model.

A groundwater model is a simplified approximation of an aquifer based on subsurface information and uses numerical methods to calculate the hydraulic flow processes. The model simulates hydraulic heads and water table elevations, calculates groundwater flow rates and directions, and estimates the water balance. Once these models have been calibrated to reasonably reproduce past groundwater behavior, they can be used to analyze the present conditions of groundwater resources and to forecast future groundwater development. Presently, the MWI uses a WEAP model for the nationwide assessment and planning of water allocation. The possibilities of the WEAP model to account for groundwater resources are very limited because aquifers are considered to be homogeneous and infinite reservoirs, which do not represent the local natural hydrogeological conditions. Therefore, a nationwide numerical groundwater flow model (using the finite difference code MODFLOW) was developed to spatially assess and quantify all relevant hydraulic processes and to provide detailed information about the groundwater levels of all relevant aquifers.

Furthermore, the numerical groundwater flow model can be applied as a stand-alone tool for assessing the effects of management strategies on groundwater resources, such as to predict the impacts of

- **decreasing groundwater levels on existing wellfields,**
- **new or currently unaccounted for groundwater abstractions, and**
- **water use reductions in different sectors and/or locations.**
- **By coupling the groundwater model with the existing WEAP model, a decision support system is created (WEAP-MODFLOW-DSS) that assesses groundwater-related processes as well as the spatial and volumetric limitations of available water resources in detail. With this tool, the MWI is capable of improved strategic management of the groundwater resources and the water supply infrastructure within the MWI.**

6.1 Methods and Data

6.1.1 Groundwater Modeling

Previous Studies

Several numerical models have been established in Jordan in the past. The most important modeling studies covering the majority of the Jordan territory are as follows:

- BGR, 2005 (Schmidt) in the framework of the National Water Master Plan (MWI, 2005)
- WAWI, 2006 (Mull & Holländer)
- BRGM, 2010 (Barthelemy et al.)

Each of the models includes different assumptions or limitations. BGR (2005) conducted numerical flow modeling in the framework of the National Water Master Plan, which covers all of the hydrogeological units from the Ram/Disi aquifer to the basalt. However, this model excludes the Jordan Valley and some areas to the east and south of the country and neglects any vertical exchanges among hydrogeological units. Mull & Holländer (2006) simulated only the Ram/Disi aquifer as a transboundary aquifer. The BRGM numerical groundwater model included the deeper hydrogeological units ranging from the Ram/Disi to the A7/B2 aquifers, although the latter was only considered to investigate the impact of vertical leakage processes.

6.1.2 Hydrological data

The quality of a model depends on the quality of the considered data. In the following section, all of the relevant data used and their sources are described.

Precipitation

The rainfall distribution is based on the WorldClim Version 1.4 (release 3) dataset created by Hijmans et al. (2005). The rainfall distribution roughly follows the topology. The largest amounts of rainfall occur in the highlands of Jordan (540 mm/a) and the Syrian Arab Republic (975 mm/a). The rainfall amount decreases rapidly to the southeast and the Wadi Araba (Jordan Valley).

Groundwater Recharge

Groundwater recharge was estimated by considering that the recharge in areas with precipitation more than 75 mm/a is approximately 3.3% of the total rainfall (Margane et al. 2002). This assumption leads to an annual recharge volume of approximately 280 MCM within Jordan.

The groundwater recharge in the model was distributed as follows:

- 20% where the annual precipitation exceeds 300 mm/a
- 2% where the annual precipitation is from 75 mm/a to 300 mm/a
- 0% where the annual precipitation is less than 75 mm/a

The recharge was not differentiated based on the outcropping rocks except for the B3 outcrops, where the recharge was set to zero because the B3 Formation is considered to be impermeable. The distribution used in the steady state calculations is shown in Figure 72. As expected, the largest recharge occurs in the highlands east of the Jordan Rift Valley. An additional important area is the Jebel Arab (Jebel al Arab) in southern Syria, which adds significant recharge to the basalt aquifer.

For the transient simulations, the groundwater recharge varied according to the deviation in annual mean precipitation from the long-term average.

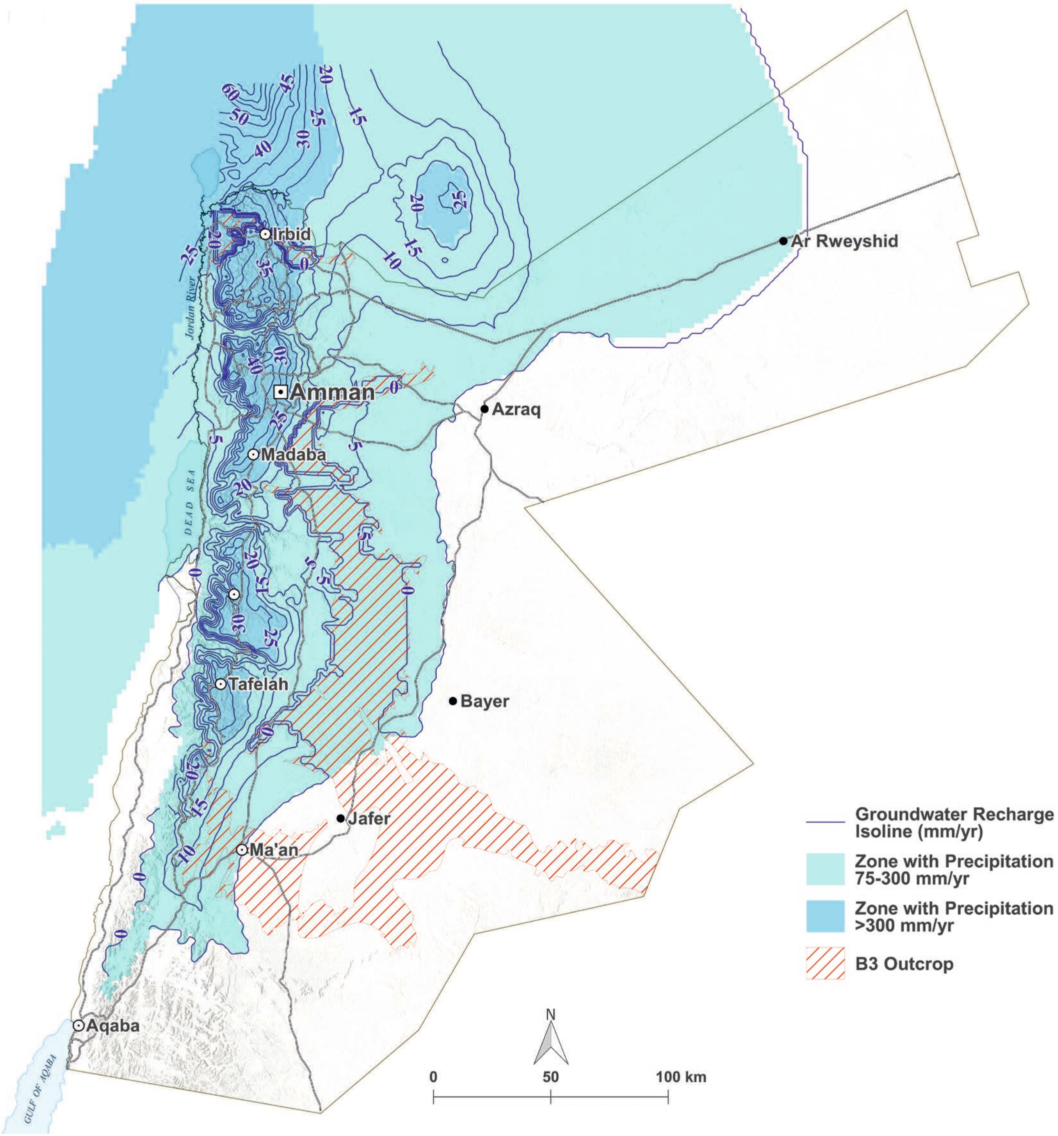


Figure 72 Groundwater recharge distribution for the steady state calibration

Groundwater Level Data

Groundwater level data were taken from the WIS, which stores groundwater level measurements collected since the 1960s. The data availability for each well varies from single observations to long-term time series. For the steady state calibration, an average of the available groundwater level data between 1960 and 1990 was calculated for each monitoring well, irrespective of the amount of data. This average was assumed to represent groundwater levels under predevelopment conditions (Figure 73). For the Ram/Disi aquifer, the static water levels measured after completion of the deep wells were also used.

Because the A7/B2, B4/B5 and Basalt aquifers are hydraulically connected, their predevelopment conditions were compiled using selected observation wells that correspond to either of the aquifer units, and only one hydraulic head distribution was applied as a target for the steady state calibration. The coordinates and elevations were taken from the groundwater resource assessment study (Chapter 4). Time series available in the WIS database were used to calibrate the transient model

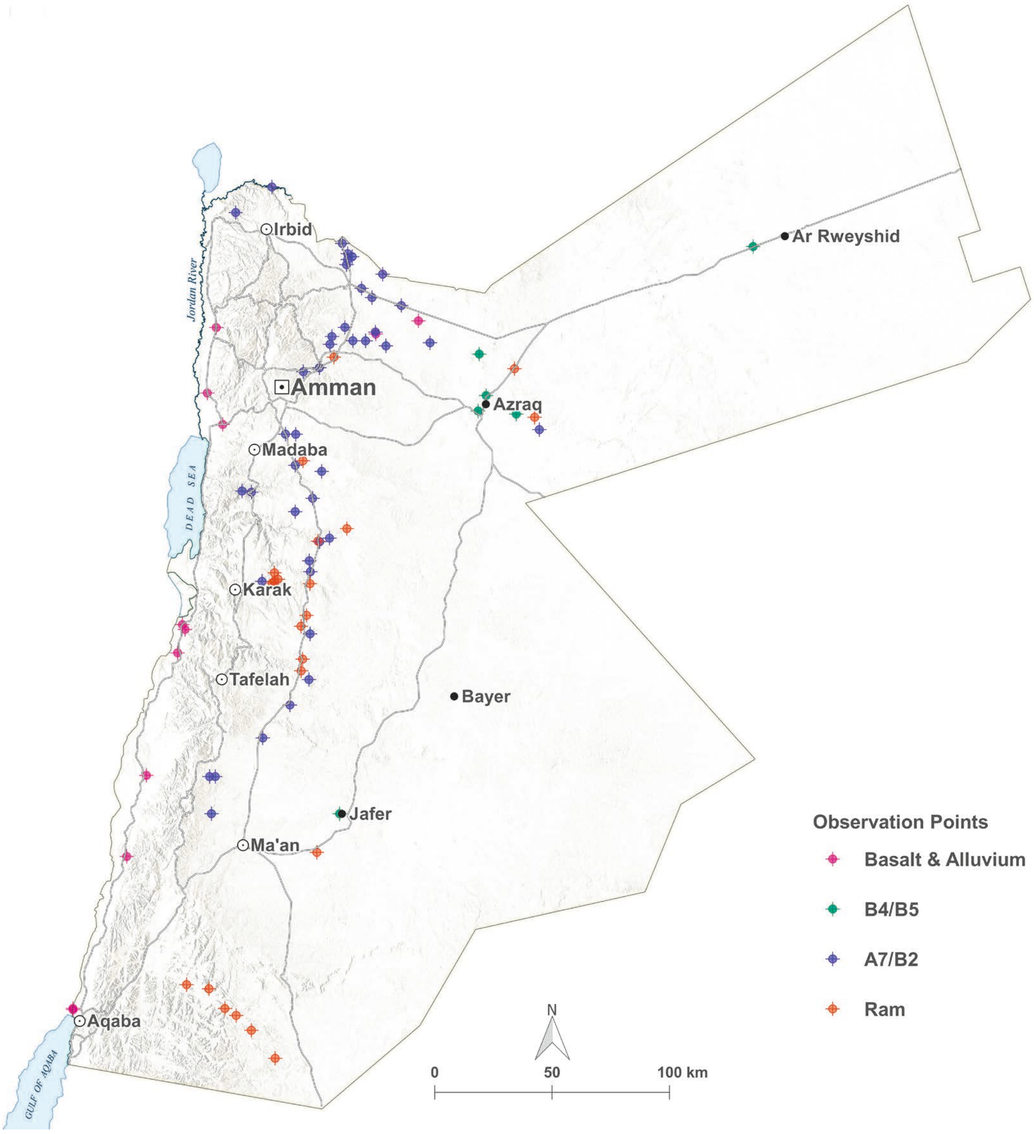


Figure 73 Structure contour map of the A3 aquitard

Spring Discharge Data

Springs with discharges greater than 150 m^3/h and the locally well-known springs were considered in the model (Figure 74, next page). The outflow elevations were taken either from the results presented in Chapter 5 or from Google Earth.

Figure 74 Locations of springs assigned in the groundwater model

6.1.3 Conceptual Hydrogeological Model

The aquifer systems described in Chapter 3 were implemented in the groundwater flow model, as shown in Table 1

Table 1:

HYDROGEOLOGICAL UNITS AND THEIR CLASSIFICATION IN THE GROUNDWATER FLOW MODEL

Hydrogeological unit	Classification
Harrat Basalt	Aquifer
Alluvium (Jordan Valley)	Aquifer
B4/B5	Aquifer
B3	Aquitard
A7/B2 Group	Aquifer
A1/A6 Group	Aquitard
Kurnub	Aquifer
Zarqa Group	Aquitard
Khreim Group	Aquitard
Ram/Disi	Aquifer

Geological Structure Model

The geological structure model was adopted from the regional model by the BRGM, which was provided to the BGR without any information corresponding to Saudi Arabia. Units younger than the A7/B2 Formation, which were not included in the BRGM model, were derived from previous BGR studies (Margane et al., 1995, MWI, 2005).

The most important tectonic features are the Jordan Valley and the Fuluq Fault, which delimit the Sirhan depression to the east. These features cause vertical displacements of more than 2000 m. In the Disi area in southern Jordan, the Karawi basaltic dike extends from Mudawwara to the northwest to the Jordan Valley escarpment and acts as a hydraulic barrier. All three tectonic structures are included in the model.

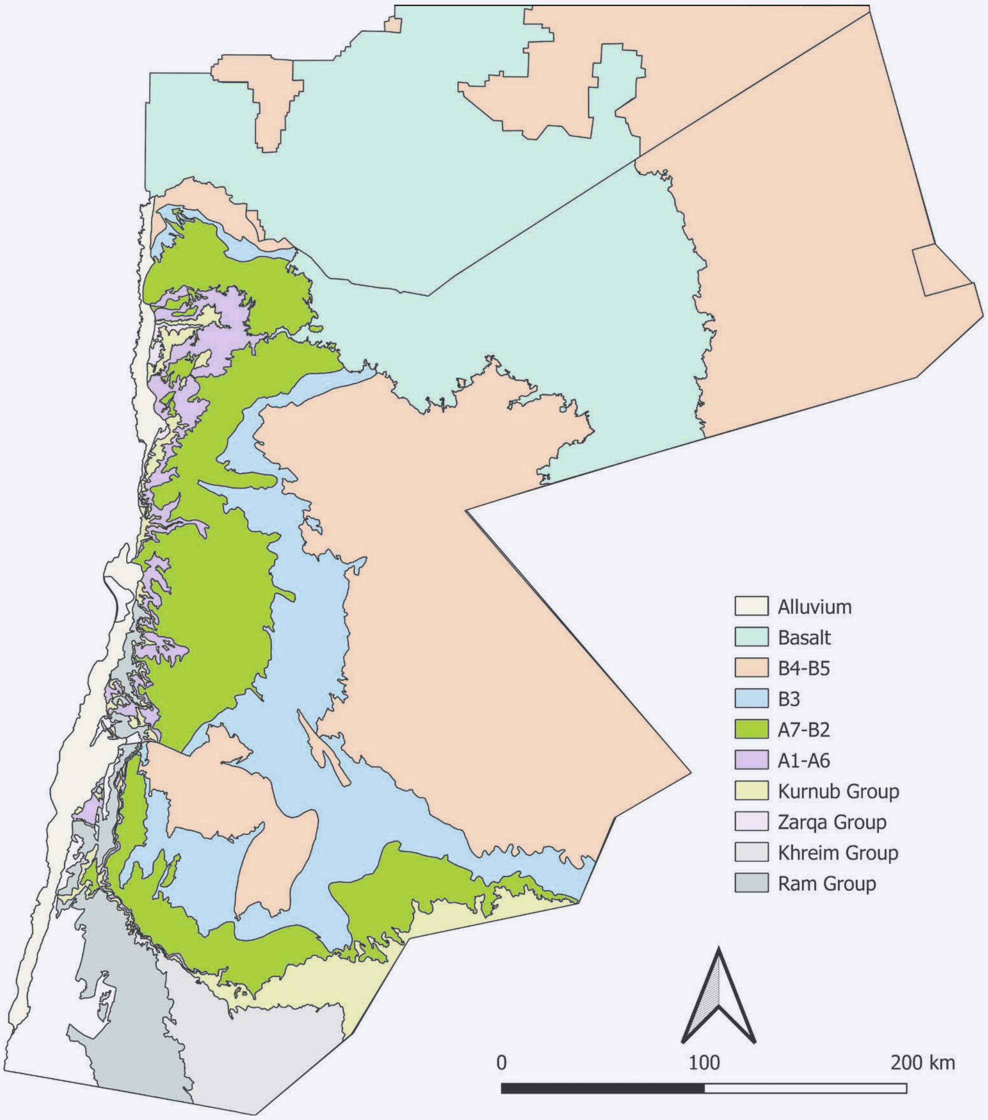


Figure 75 Extent of the numerical model. The grid cell size is 2,000 m x 2,000 m. The colors indicate the geological units of the model in layer 1 (land surface). The white areas are not modeled

6.1.4 Numerical Groundwater Flow Model

The numerical model is based on the MODFLOW-NWT source code (Niswonger et al., 2011), which applies the finite difference method to solve the groundwater flow equations. The commercial software package Groundwater Modeling System (GMS) from Aquaveo LLC was used to set up the model.

2D Model Grid

The political borders with Saudi Arabia to the south and southeast and with Iraq to the east delimit the groundwater flow model. The model extends to the north into Syria, including the area of Jebel al Arab, which is an important recharge zone for the Basalt aquifer.

The model covers a total area of 109,564 km2 with 27,391 active cells with a cell size of 2,000 m x 2,000 m (Figure 75).

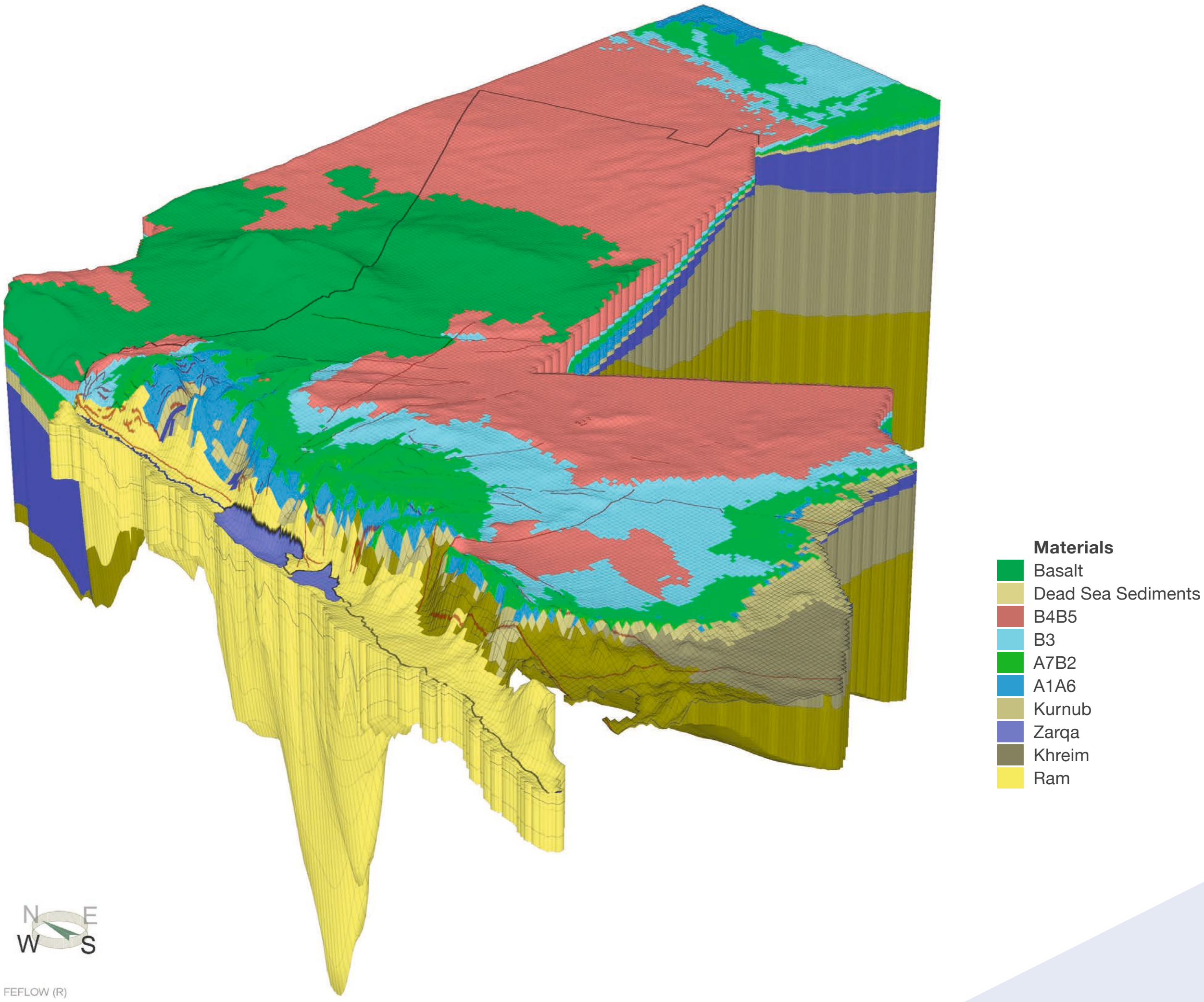


Figure 76 3D groundwater model

3D Model

The 3D model is composed of 9 layers and has a total of 246519 active cells. All of the model layers have the same lateral extent (Figure 76). The top of the model (land surface) varies from approximately 1803 m asl in the highlands to -750 m asl in the Dead Sea. At the bottom, the model has elevations from approximately 1500 m asl to -6500 m asl. The layer elevations derived from the BRGM structural model were manually smoothed to avoid numerical instabilities.

Parameter Settings

Relevant hydraulic parameters were obtained by calibrating the numerical model (Table 2 and Table 3). Changes in the hydraulic conductivity were applied regionally and do not reflect local variations.

A horizontal hydraulic conductivity of 1.0E-05 m/s was initially assigned to A7/B2 but was altered during the transient simulation. Values of 1.0E-06 m/s and 2.0E-04 m/s were needed in the recharge areas south of Al Shubak and in Jafer, respectively, to achieve a better fit of the calculated hydraulic heads. The lateral hydraulic conductivities of B3 and A1/A6 were also altered in the areas south of Al Shubak. The B3 layer was altered marginally in Yarmouk. The hydraulic conductivity of the Ram aquifer was set to 1.8 m/s but had to be changed to 2.5 m/s in the Disi area.

Additionally, the vertical hydraulic conductivities of the A1/A6 layer varied regionally to reproduce the hydraulic head differences between the overlying limestone and the underlying sandstone formations.

Table 2

HYDRAULIC CONDUCTIVITIES CONSIDERED FOR THE HYDROGEOLOGICAL UNITS IN THE MODEL						
Hydrogeological unit	**Kh [m/s]**			**Kv [m/s]**		
Basalt	1.0E-04			1.0E-04		
B4/B5	8.0E-05			8.0E-06	-	8.0E-05
Alluvium (Jordan Valley)	1.0E-05	-	1.0E-04	1.0E-05	-	1.0E-04
B3	1.0E-07	-	2.0E-07	5.0E-09	-	1.0E-08
A7/B2	1.0E-06	-	2.0E-04	1.0E-07	-	2.0E-05
A1/A6	5.0E-07	-	2.5E-06	2.0E-11	-	2.5E-08
Kurnub	5.0E-06			5.0E-07		
Zarqa Group	2.5E-06			2.5E-08		
Khreim Group	5.0E-07			5.0E-09		
Ram/Disi aquifer	1.8E-05	-	2.5E-05	1.8E-05	-	2.5E-05

Table 3

SPECIFIC STORAGE AND POROSITY VALUES USED FOR THE HYDROGEOLOGICAL UNITS IN THE MODEL									
Hydrogeological unit	**Spec. storage [1/m]**			**Spec. yield [-]**			**Porosity [%]**		
Basalt	1.0E-07			0,05			5%		
B4/B5	1.0E-07	-	1.0E-05	0,03	-	0,1	2%	-	5%
Alluvium (Jordan Valley)	1.0E-06			0,1			10%	-	15%
B3	1.0E-06			0.001			0.1%	-	1.0%
A7/B2	1.0E-06	-	1.0E-05	0.025	-	0,1	4%		
A1/A6	1.0E-06			0,01	-	0,04	2%		
Kurnub	1.0E-06			0.025			2%		
Zarqa Group	7.0E-07			0,01			1%		
Khreim Group	7.0E-07			0,01			1%		
Ram/Disi aquifer	7.0E-07			0,05	-	0,1	2%	-	10%

Table 4

LATERAL BOUNDARY CONDITIONS ALONG THE MODEL BORDERS			
Border	**Hydrogeological unit**	**Type (steady state)**	**Type (transient)**
Southern border with Saudi Arabia	Ram/Disi	Constant head	Fixed flux (wells)
Eastern border with Iraq/Saudi Arabia	Ram/Disi	Constant head	Fixed flux (wells)
Northwestern border (Jebel Sheikh)	Basalt - B4/B5	Constant head	Fixed flux (wells)
Jordan River	Alluvium	Constant head	Constant head
Dead Sea	Alluvium	Constant head	Transient head
Red Sea	Alluvium	Constant head	Constant head

Boundary Conditions

Bottom of the Model

The bottom of the model is represented by the top of the Precambrian Basement complex of crystalline rocks that are considered impermeable and is thus assumed to be a no-flow boundary.

Lateral Boundary Conditions

For the steady state model, constant head boundaries were applied along the borders. The head values were derived from the results of BRGM (2010). The fluxes calculated along the respective boundary sections were then converted to fixed flux boundaries for the transient groundwater flow model (Table 4). The western boundary of the model was set as a no-flow boundary because no information about groundwater flow to or from the west is available.

Table 5

DISTRIBUTION OF PUMPING WELLS (THROUGH 2017)

	Domestic	Irrigation	Industry	Total
Basalt	50	217	3	**367**
Alluvium		-	-	**13**
B4/B5	180	1771	53	**2044**
A7/B2	646	1158	178	**2143**
A1/A6	131	73	13	**220**
Kurnub	68	74	10	**168**
Zarqa	6	4	1	**11**
Ram/Disi	42	103	4	**194**
Sum	**1123**	**3400**	**262**	**5160**

Source: BGR

Pumping Wells

The abstraction from approximately 5160 pumping wells was included in the model. The data through 2017 were retrieved from the WIS. The information includes the use type (domestic, industrial, irrigation) as well as from which aquifer the groundwater was withdrawn (Table 5). However, it is unclear when well operations began, and the pumping rates are not always reliable due to noncontinuous monitoring.

For irrigation wells, the start of operation in the WIS does not coincide with the start of irrigation development in the country. In such cases, the pumping rates were linearly extrapolated to zero at the time that irrigation development reportedly began in a specific area. The simulation results show that this approximation is more appropriate than neglecting the initial pumping activities.

The significant increase in the number of abstraction wells at the turn of 1994/1995 is noticeable. This coincides with the decision of the Jordanian government to equip all private wells with flow meters in 1993 (Margane & Almomany, 1995). However, significant uncertainties about extraction by wells remain, mainly due to illegal wells, unlicensed deepening, relocation of existing wells and broken flow meters.

Beginning in 1995, the licensed wells were found to be 23% governmental and 77% private, whereas the total abstraction was 51% governmental and 49% private. However, recent studies of the Azraq and Ramtha areas using remote sensing (Al-Bakri, 2016) and a classic comparison using water level declines and specific yields (Margane et al., 2015) revealed large discrepancies between the metered abstractions for private wells and the estimated real abstraction rates, which are 2.5 to 3 times higher than the official values. Pumping wells outside Jordan were not considered due to a lack of data.

Springs

Springs are modeled as drain boundary conditions. The Azraq wetlands, also referred to as the Azraq Oasis, discharged approximately 14 MCM per year (Margane et al., 1995) in 1963/64. The irrigation development in the area and the start of the AWSA wellfield operation in 1982 led to the disappearance of springs in 1993. Two springs with an outflow elevation at 515 m asl are assigned in the model as drain boundary conditions. Additional drain boundary conditions are applied to seven cells within the wetland area at 508 m asl.

Wadis/Rivers

Major rivers (Yarmouk and Zarqa) and wadis (Kafrein, Mujib, and Hasa) are considered to be drain boundary conditions. The Jordan River is modeled as a constant head in both the steady state and transient models. The river water levels were estimated based on a digital elevation model and Google Earth.

Dead Sea

The Dead Sea is assumed to be a constant head at -395 m asl (head in 1960) with the present-day extension in the steady state model. For the transient model, a transient head boundary condition reflecting the observed decline in the Dead Sea water level is assigned (Figure 77).

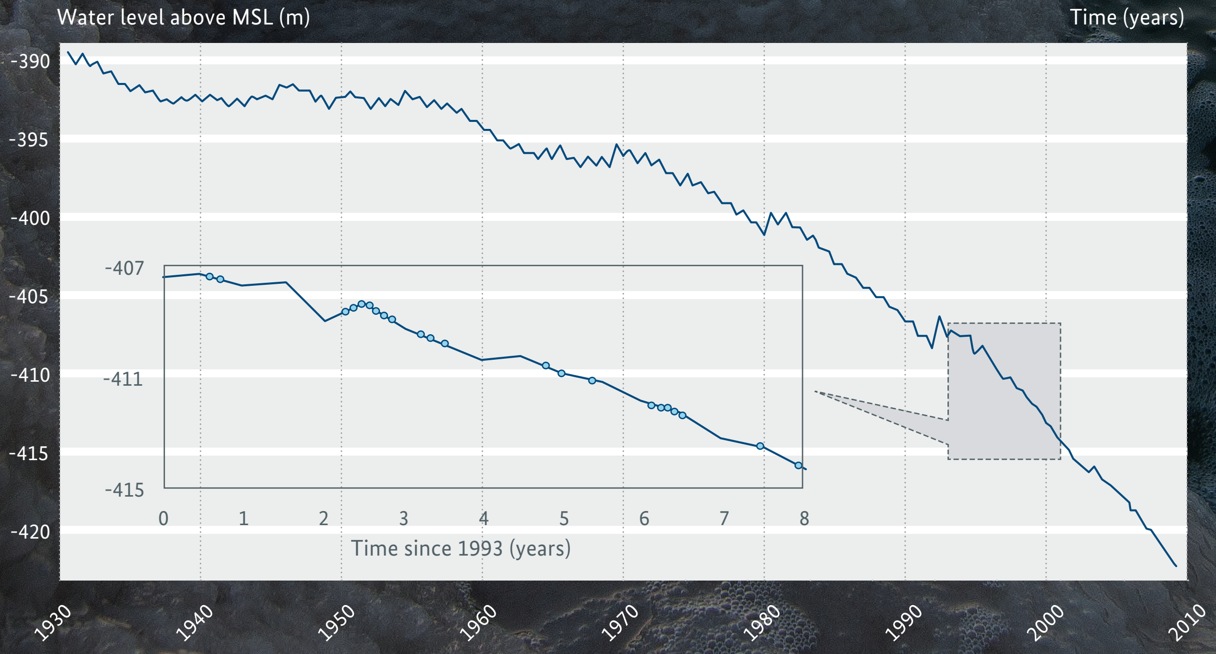


Figure 77 Water level of the Dead Sea (Nof, 2012)

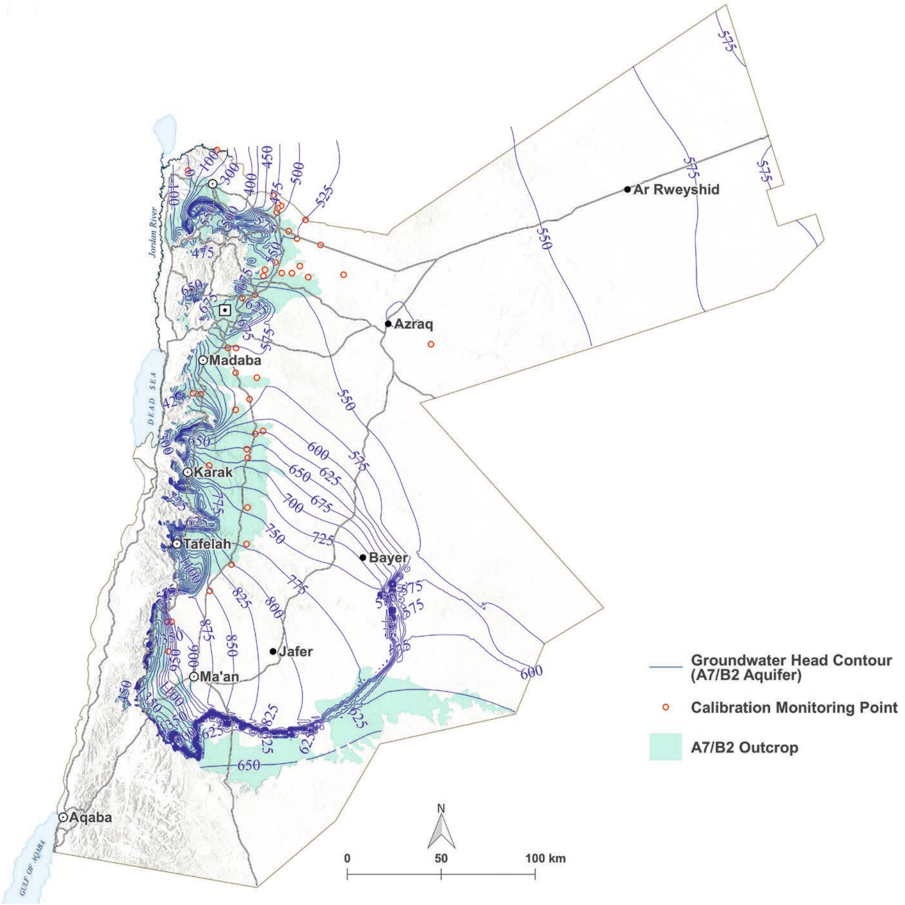


Figure 78 Groundwater contours for the predevelopment conditions in the A7/B2 aquifer

Figure 79 Groundwater contours for the predevelopment conditions in the Ram/Disi aquifer

6.2 Results

6.2.1 Calibration

The model was calibrated for steady state conditions and validated under transient conditions.

Steady State Hydraulic Heads

The steady state calibration provides results under predevelopment conditions. The modeled groundwater contours for the A7/B2 and Ram/Disi aquifers are shown in Figure 78 and Figure 79, respectively. The hydraulic heads and flow directions are consistent with the results of BRGM (2010) and MWI (2005).

Steady State Water Balance

The water balance of the calibrated steady state conditions is presented in Table 6. The overall model has a total inflow of 797.47 MCM and a total outflow of 797.51 MCM. The difference between the total outflow and inflow is -0.04 MCM or 0.4%, which is acceptable for the size of the model area.

A more detailed water balance analysis (Table 7) reveals that most of the inflow is lateral inflow from Saudi Arabia (269 MCM) through the Ram/Disi aquifer followed by groundwater recharge (260 MCM).

The highest discharge occurs in the Dead Sea (216 MCM), followed by discharge into the Yarmouk River (120 MCM). In addition, a significant outflow from Jordan to Saudi Arabia of 82 MCM occurs along the no-flow barrier that represents the Karawi dike.

Table 6

WATER BALANCE FOR STEADY STATE CONDITIONS

	Inflow [MCM]	Outflow [MCM]
Constant head	433.01	445.58
Wells	0	23.61
Drains	0	328.32
Recharge	364.46	0
Total	797.47	797.51
Total Inflow – Outflow	**-0.04 MCM (≈ 0.4%)**	

Table 7

DETAILED WATER BUDGET ANALYSIS FOR STEADY STATE CONDITIONS [MCM]

	Inflow [MCM]	Outflow [MCM]	Literature [MCM]	Source
Inflow from the south (Ram/Disi)	269	82	300 (inflow)	BGR (2005) Mull & Holländer (2010)
Inflow from the east (Kurnub - Ram/Disi)	78	43,5	90 (inflow)	BGR (2005)
Outflow to the Azraq Oasis/wetland		19,9	Dez 18	Margane (1995)
Wadi Zarqa River		15,2	60	Margane (2002)
Wadi Kafrein and Shuayb		33	28	
Wadi Mujib		53	57	
Wadi Hasa		8,5	25,5	
Yarmouk River		122	120	
Outflow to the Dead Sea		216	210	BGR (2005)
			300	Mull & Holländer (2010)
Inflow from the north (Jebel Sheikh)	79		114	Recharge estimation BGR
Recharge in Jordan	260		280	Margane (2002)
Pumping wells		23,5		Active wells 1960

6.2.2 Transient Modeling

The hydraulic heads and parameters of the steady state calibration were used as initial conditions for the transient modeling that simulates the 1960-2017 period with annual stress periods subdivided into 12 equal time steps. The transient data applied to the transient model comprise the water level of the Dead Sea, groundwater recharge, and pumping rates of abstraction wells.

The results of the transient simulation were verified using the observed historical groundwater level measurements in monitoring wells, the discharge rate at the Azraq springs, and the groundwater contour maps (Chapter 4).

Transient Hydraulic Heads at Monitoring Wells

The calculated and observed hydraulic heads for selected monitoring wells and aquifers are discussed below.

Alluvium

The calculated heads correlate appropriately with the long-term trend at well AB1164 (Figure 80) in the northern part of the Jordan Valley. However, near the Dead Sea, the calculated heads follow the trend of the Dead Sea water level, which is not shown by the observed levels (Figure 80, right). Thus, the model is unreliable in the vicinity of the Dead Sea, most likely due to density-dependent flow processes that are not considered in this model.

Basalt

The calculated groundwater levels at well AL3361 (Figure 81, next page) follow the measured decline of approximately 30 m from 1988 to 2012. However, the sudden decline that increased in the 3 years before 2015 was not reproduced. The observed water levels at monitoring well F1014 near Azraq (Figure 81) show a decline of approximately 15 m from 1996 to 2011, and this decline is not mirrored by the model.

B4/B5

Monitoring well F1022 (Figure 82, next page) in Azraq shows a water level decline of approximately 20 m between 1995 and 2015, which is not followed by the calculated heads. However, the decline of approximately 12 m from 1998 to 2015 at monitoring well G3081 (Figure 82) in the Jafer area is matched by the model results.

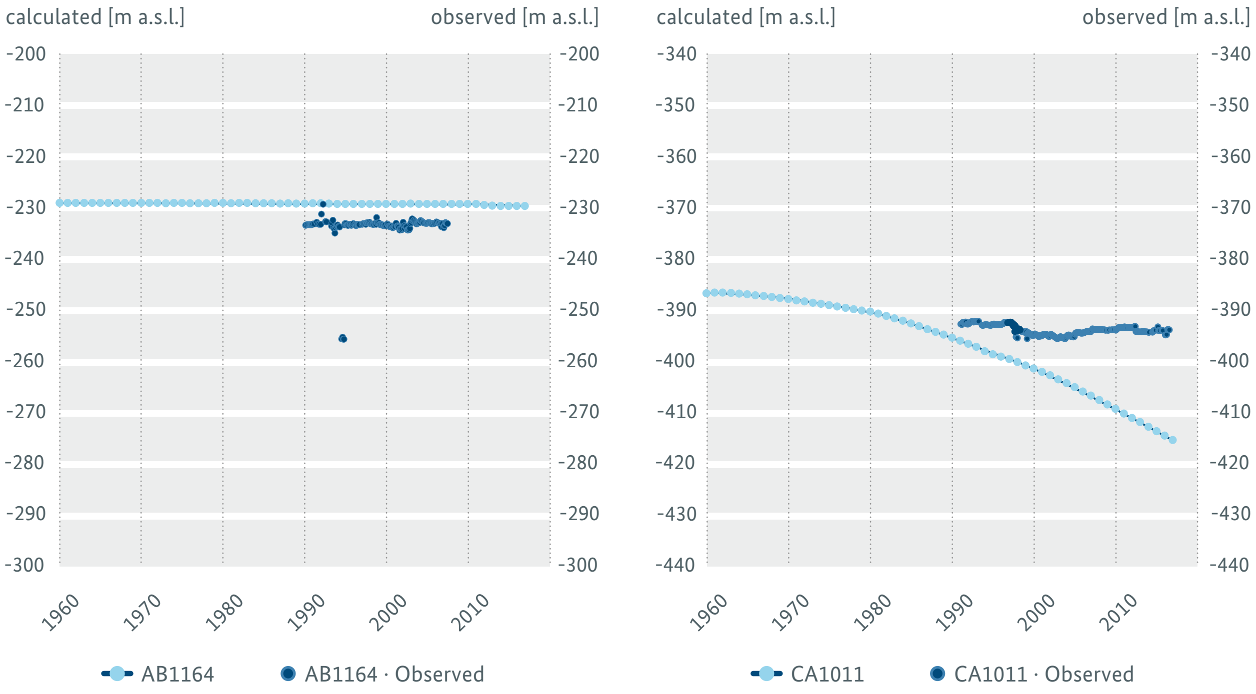


Figure 80 Simulated and observed hydraulic heads for selected monitoring wells associated with the Alluvium in the Jordan Valley

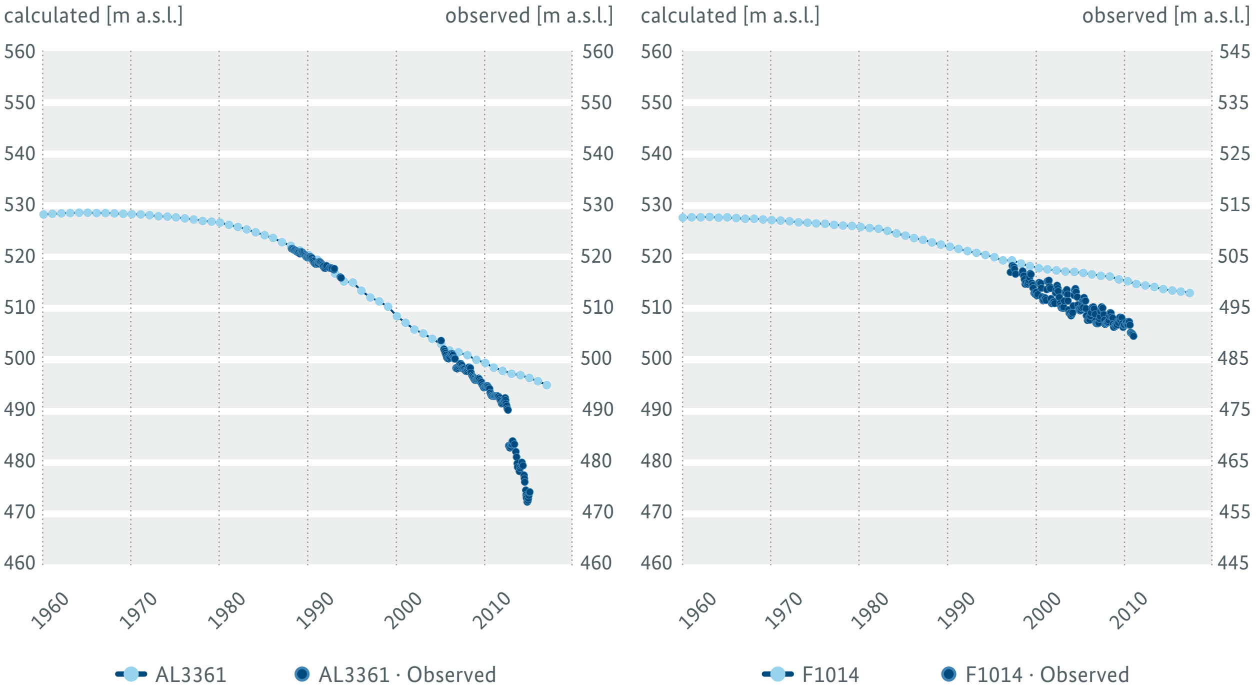


Figure 81 Simulated and observed hydraulic heads for selected monitoring wells associated with the Basalt aquifer

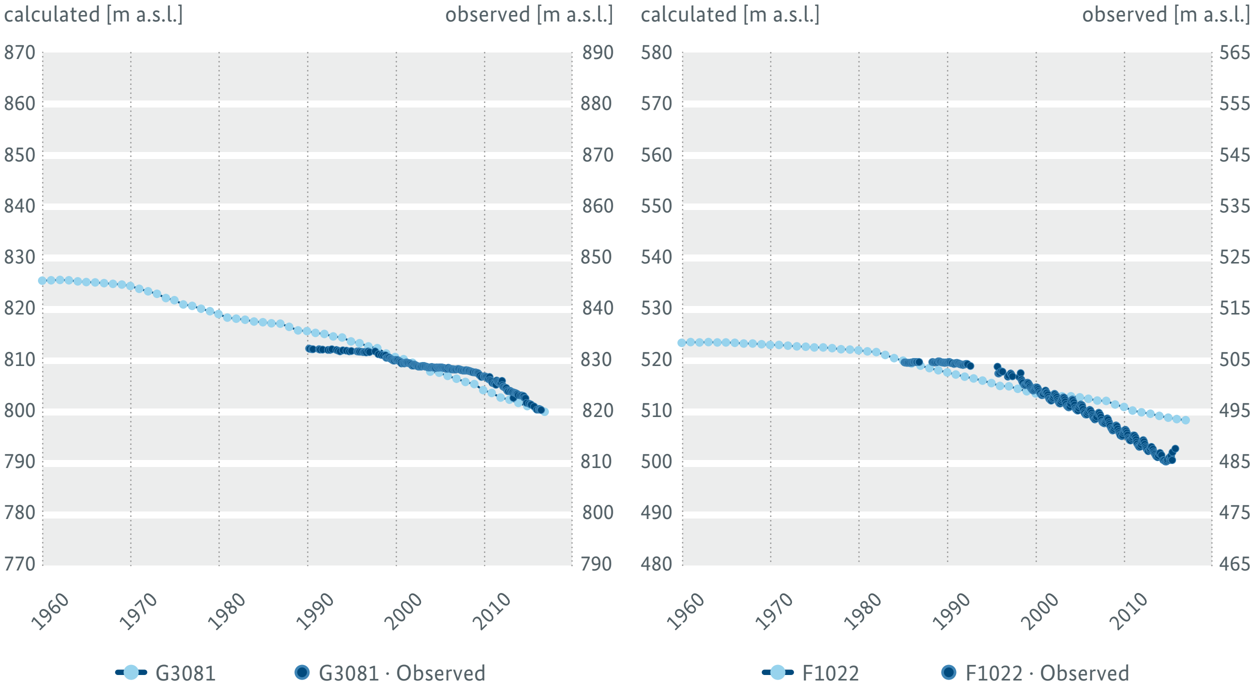


Figure 82 Simulated and observed hydraulic heads for selected monitoring wells associated with the B4/B5 aquifer

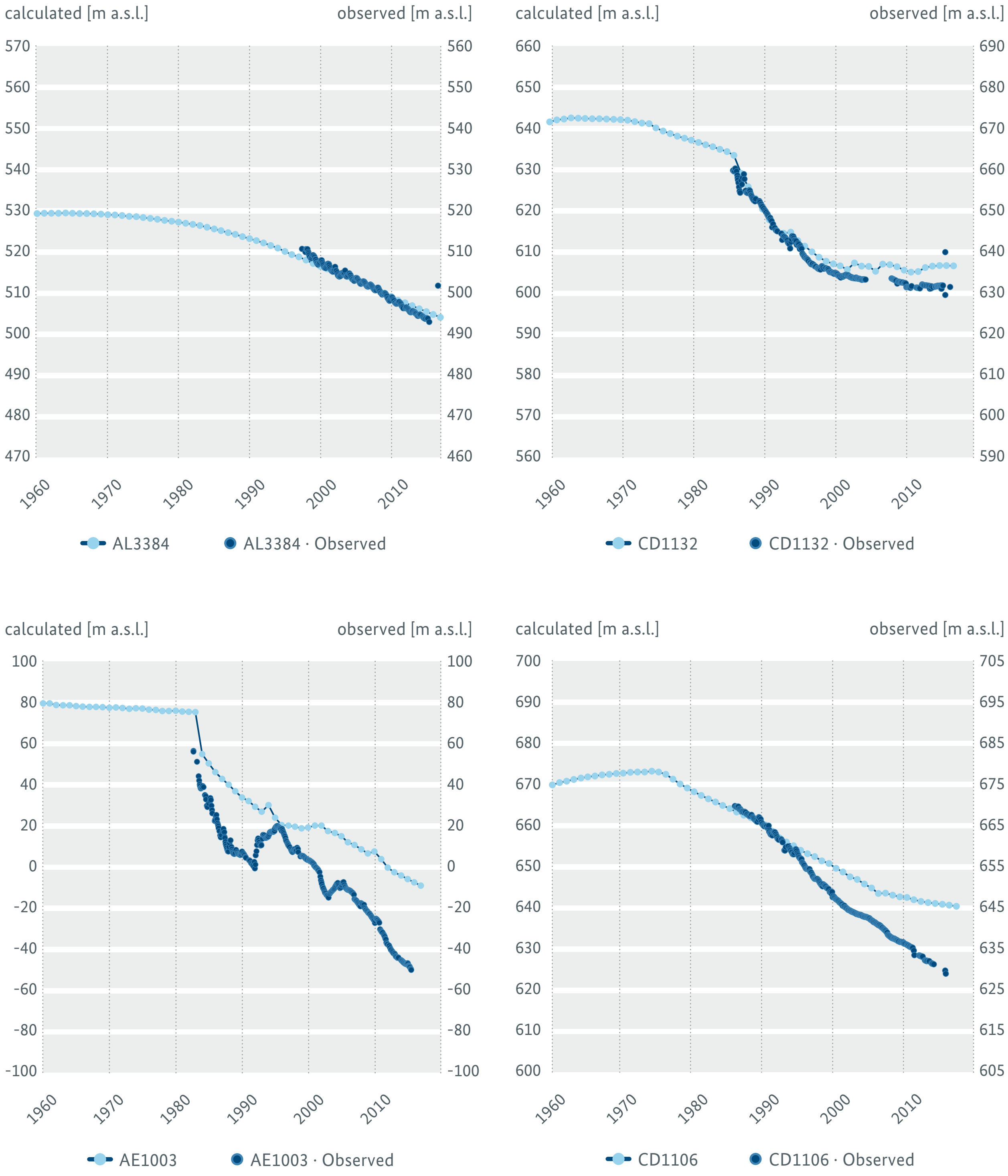


Figure 83 Simulated and observed hydraulic heads for selected monitoring wells in the A7/B2 aquifer

A7/B2

The observed groundwater levels show large decline ranges (5 m to 100 m) from 1980/1990 to 2015 because of the heterogeneous drawdown throughout the A7/B2 aquifer. Furthermore, the steady increase in the extraction rate leads to changes in the trends, which are observed in the measured groundwater levels.

In general, the simulated hydraulic heads reproduce the observed groundwater levels, such as in AL3384, but they fail to reproduce the observed increased drawdown since 2000 caused by the rising extraction rates, such as in wells CD1132, AE1003, and CD1106 (Figure 83).

Local effects that are not yet understood lead to calculated heads that are approximately 225 m lower than the observed values in well G3147 (Figure 84).

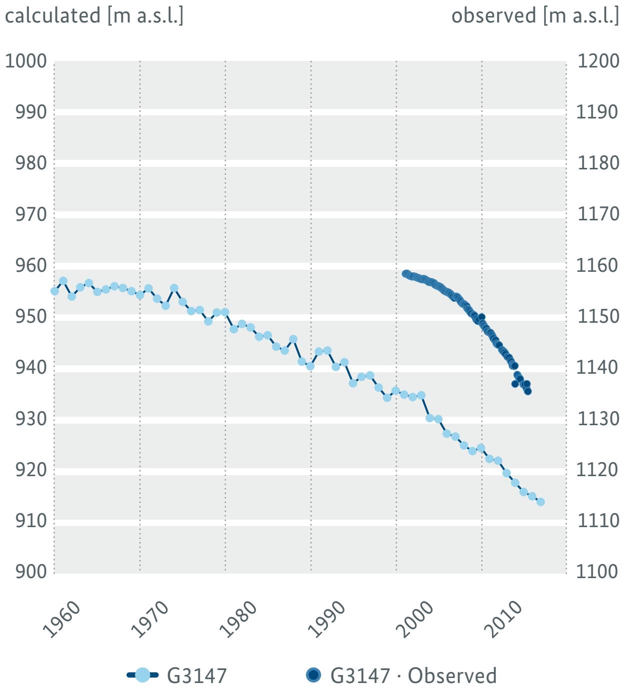


Figure 84 Simulated and observed hydraulic heads in well G3147

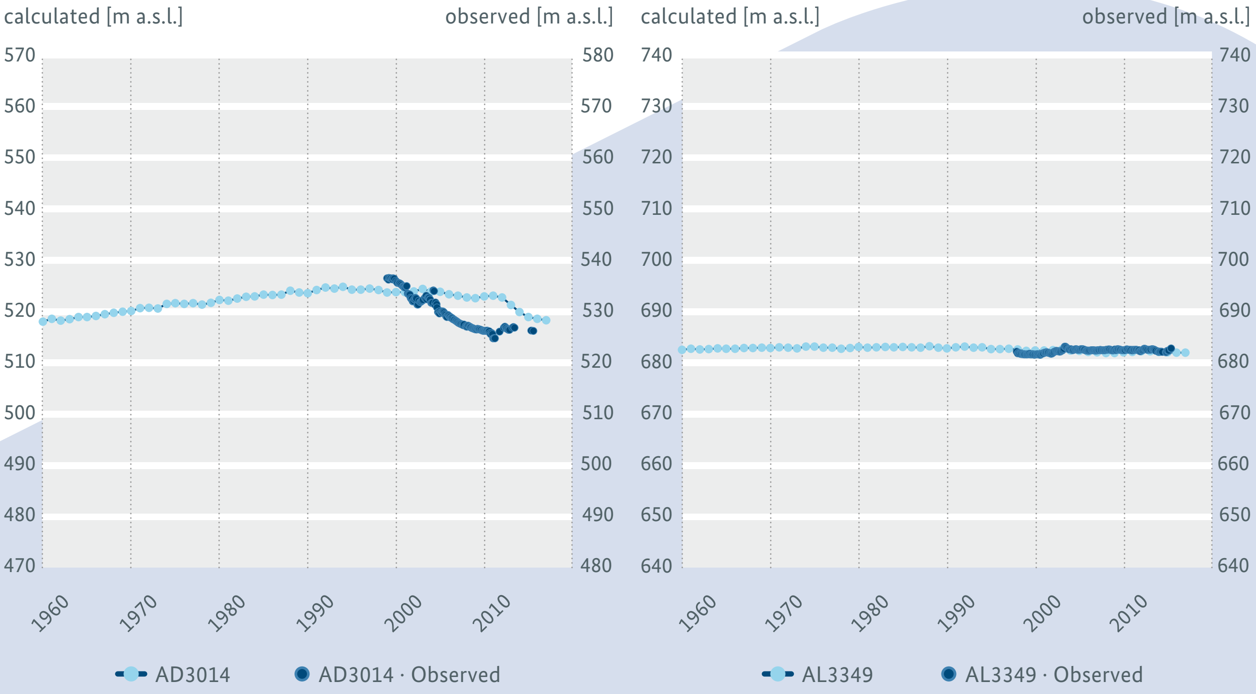
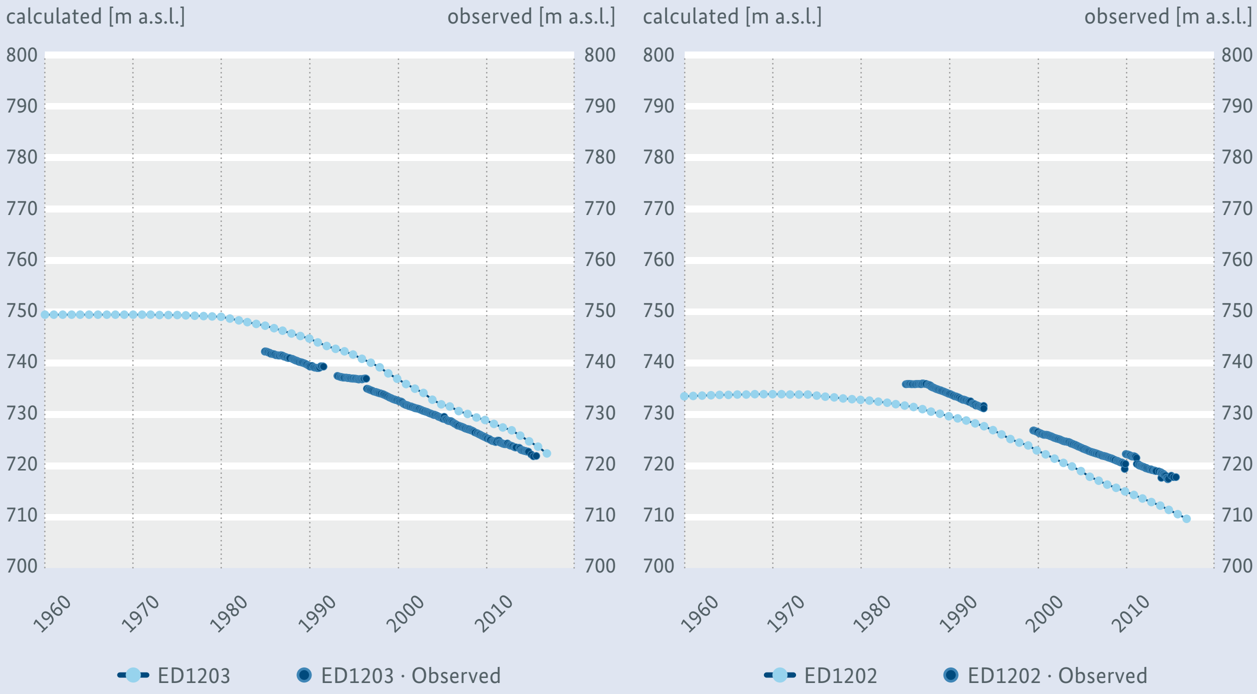


Figure 85 Simulated and observed hydraulic heads for selected monitoring wells associated with the A1/A6 Formation

A1/A6

Figure 85 shows the calculated and observed hydraulic heads for selected monitoring wells associated with the A1/A6 Formation. The calculated hydraulic heads reproduce the small level variation observed at well AL3349, but a decline of only 5 m is simulated at well AD3014 instead of the 10 m that was measured.



Source: BGR

Figure 86 Simulated and observed hydraulic heads for selected monitoring wells associated with the Ram/Disi aquifer

Ram/Disi Aquifer
The observed water level declines at the selected monitoring wells associated with the Ram Group in the Disi area range from 7 m to 20 m during the modeled period. The calculated hydraulic heads adequately reproduce the observed trends (Figure 86).

The results demonstrate that the model is able to adequately reproduce the groundwater development in Jordan, especially considering its size and the data availability.

Water Balance for 2017

The water balance of the transient simulation for 2017 is presented in Table 8. The overall model has a total inflow of 1754 MCM and a total outflow of 1783 MCM. The difference between the total outflow and inflow is -28 MCM or 1.6%, which is acceptable for the size of the model area.

A more detailed water balance analysis (Table 9) reveals that the inflow is mostly lateral inflow from Saudi Arabia (266 MCM) through the Ram/Disi aquifer and groundwater recharge from precipitation (267 MCM).

Groundwater discharge to Wadi Zarqa ceased in 2017, which is consistent with reality because only treated wastewater is currently discharged in this area.

Table 8

WATER BALANCE FOR THE TRANSIENT SIMULATION IN 2017

	Inflow [MCM]	Outflow [MCM]
Constant head	95	909
Wells	464	722
Drains	0	148
Recharge	481	0
Storage	715	4
Total Inflow – Outflow	**-28 MCM (≈ 1.6%)**	

Table 9

DETAILED WATER BUDGET ANALYSIS FOR 2017 [MCM]

	Inflow [MCM]	Outflow [MCM]
Inflow from the south (Ram/Disi)	266	69
Inflow from the east (Kurnub - Ram/Disi)	77	0
Wadi Zarqa River		0
Wadi Kafrein and Shuayb		1
Wadi Mujib		20.5
Wadi Hasa		5
Yarmouk River		120
Outflow to the Dead Sea		601
Springs		3
Recharge in Jordan	267	
Pumping wells		651

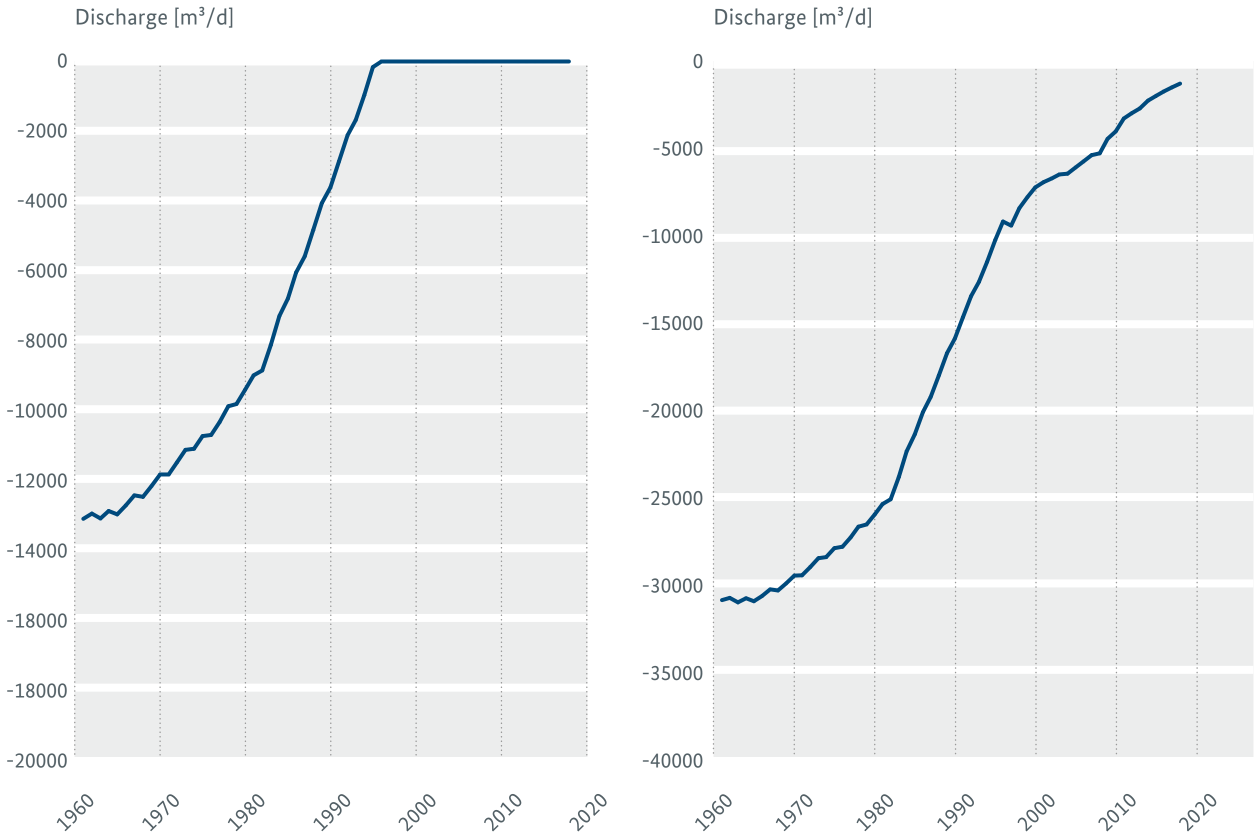


Figure 87 Simulated discharge [m^3/d] of the Azraq springs (left) and wetland outflow (right)

Azraq Springs and Wetlands

The discharge of the Azraq springs declined continuously from 13000 m^3/d (approx. 5 MCM/a) in 1960 to zero in 1995 (Figure 87, left). The real conditions are accurately represented, although the springs dried two years before in 1993.

The total simulated groundwater outflow for the Azraq wetland declined from 31000 m^3/d (approximately 11.5 MCM) before development to 900˚m^3/d (0.3 MCM/a) in 2016 (Figure 87).

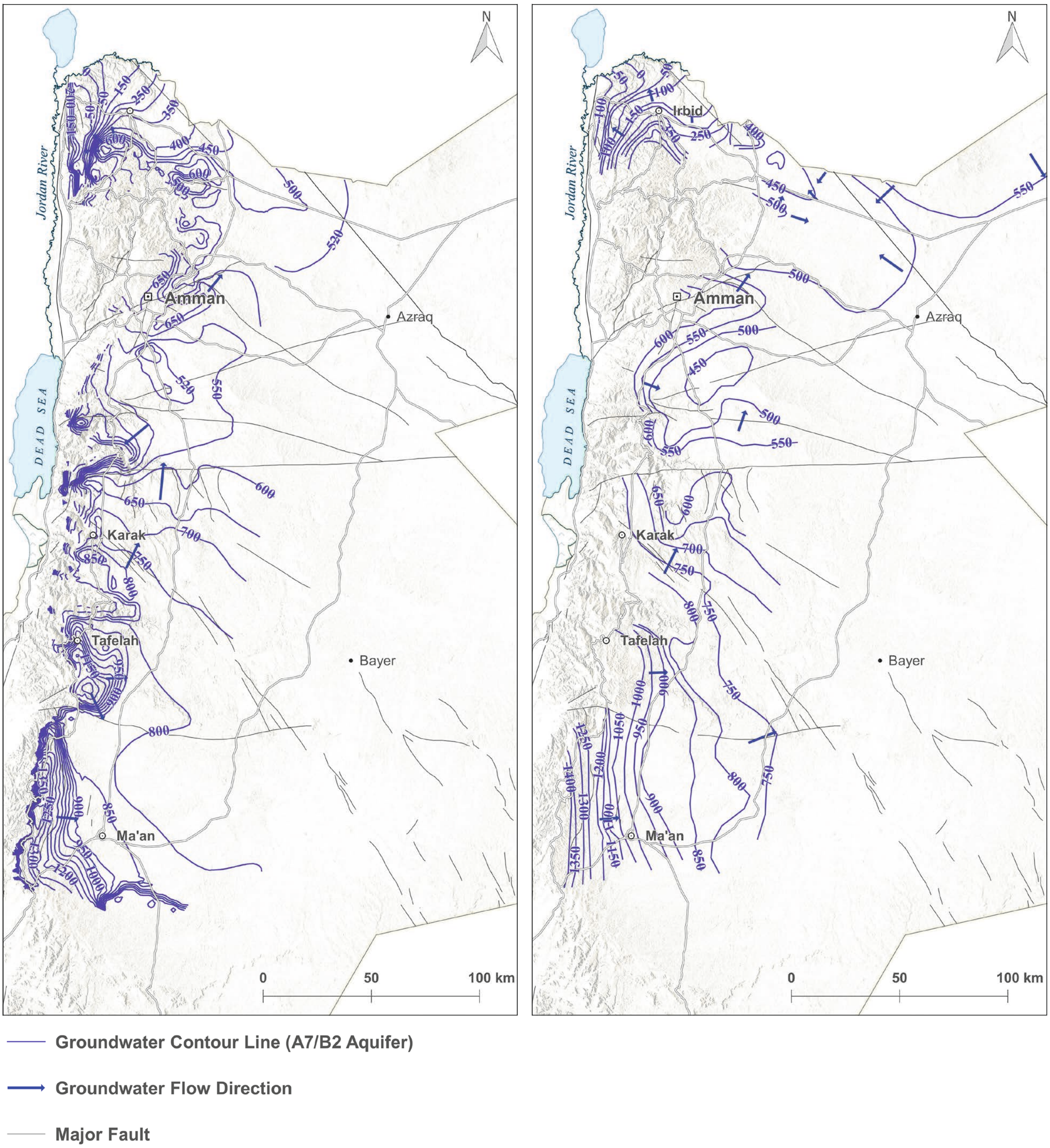


Figure 88 Comparison of groundwater contour maps and flow directions (model results on the left, groundwater resource assessment on the right)

Comparison of Transient Model Results with the Groundwater Resource Assessment Study

The modeled groundwater levels for A7/B2 in 2017 were compared with the corresponding contour map from the groundwater resources assessment (Figure 88). The groundwater levels agree relatively well in both studies. The most significant differences occur in the highlands west of Maan, where the calculated groundwater levels are significantly low. Furthermore, the general flow direction is comparable in both maps, although local differences are visible.

The drawdown during 1995-2017 was compared with the corresponding map from the groundwater resource assessment (Chapter 4.2.3.5). In general, the areas with significant drawdowns coincide, but the modeled total drawdown is significantly less than the groundwater resource assessment results (Chapter 4). The difference occurs because illegally abstracted groundwater for irrigation was not considered in the model; thus, the abstraction was underestimated.

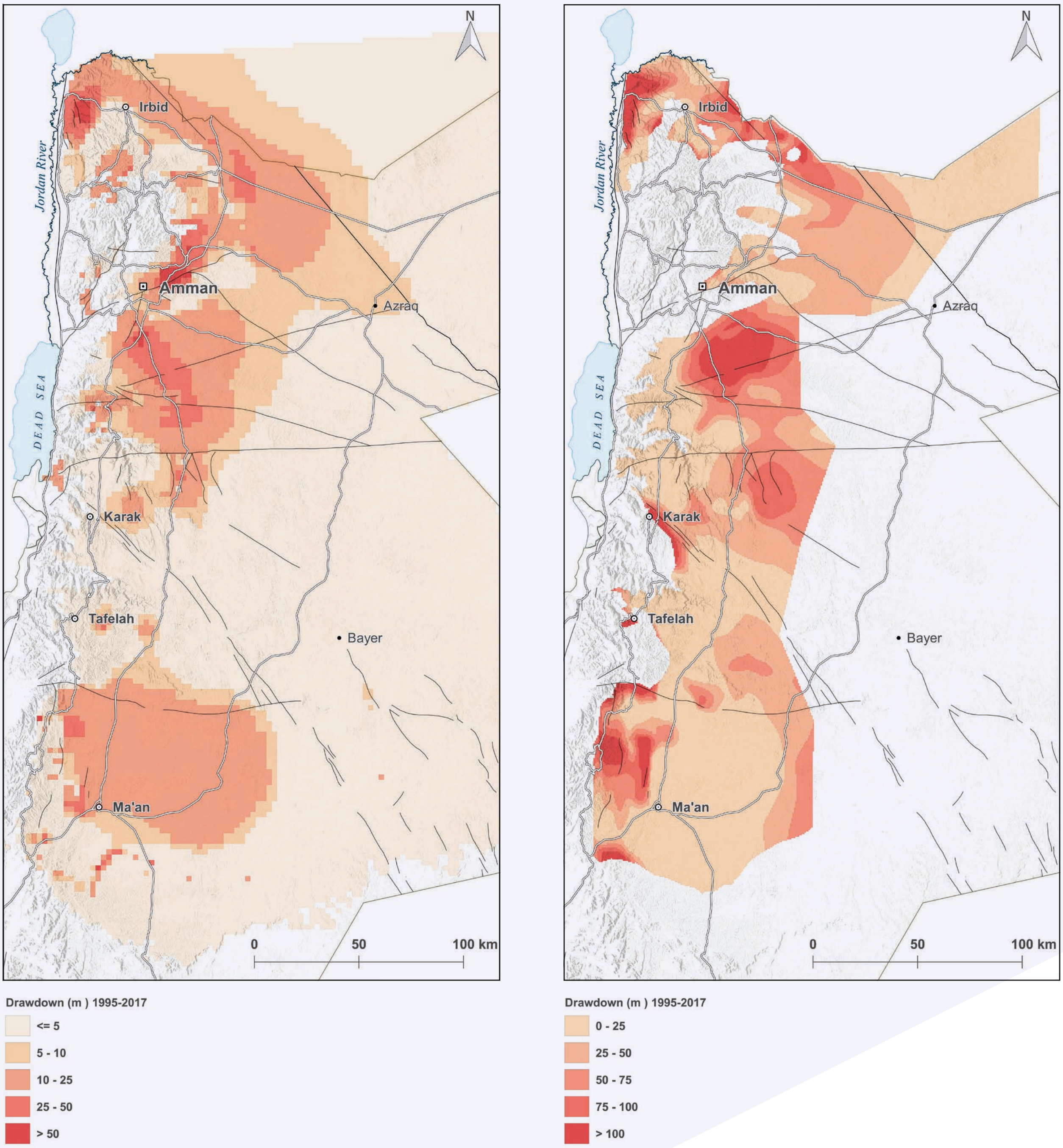


Figure 89 Comparison of groundwater drawdown maps from 1995 to 2017 (model results on the left, groundwater assessment results on the right)

6.2.3 Predictive Modeling

After the transient validation, the model was used to forecast the drawdown for 2000-2050 based on different management assumptions. Two groundwater abstraction options were considered:

1. Baseline scenario: abstraction from the WIS for domestic and industrial uses. The groundwater abstractions for irrigation were taken from the WEAP model, which are based on mapped irrigated areas for 2015 and 2017 using remote sensing data and crop water demand calculations (Al-Bakri, 2016) (Table 10, Figure 90).

2. Enforcement of the groundwater bylaw scenario: abstraction from the WIS for domestic and industrial uses. The groundwater abstraction volumes were based on current abstraction rates documented in the WIS (Table 10).

Table 10

COMPARISON OF IRRIGATION WATER DEMANDS ACCORDING TO THE RESPECTIVE SOURCES

	Baseline scenario	Groundwater-by-law scenario
	Data from WEAP [MCM/yr	Data from WIS [MCM/yr]
MF_Agriculture	103.7	60.8
ZA_Agriculture	33.5	9.1
ZA_Agriculture_Azraq	33.5	25.8
AJ_Agriculture	5.4	0.7
AM_Agriculture	120.8	68.5
IR_Agriculture	17.6	3.2
JA_Agriculture	2.9	2.2
KA_Agriculture	23.7	7.7
MA_Agriculture	63.6	49.2
MD_Agriculture	6.3	2.9
TA_Agriculture	5.1	3.2
AQ_Agriculture	32.4	23.6
Sum	**448.5**	**256.9**

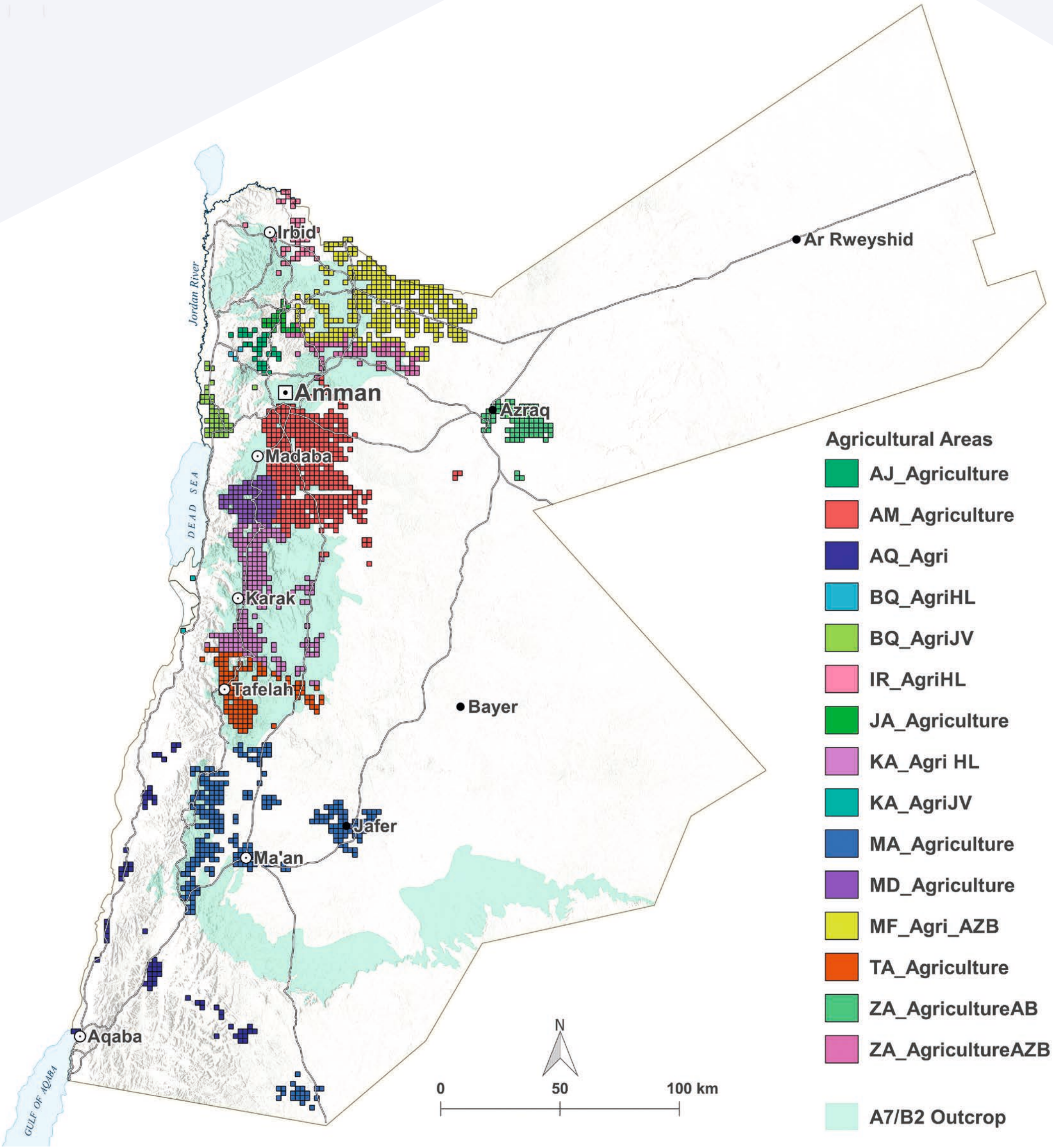


Figure 90 Irrigated areas according to the WEAP model

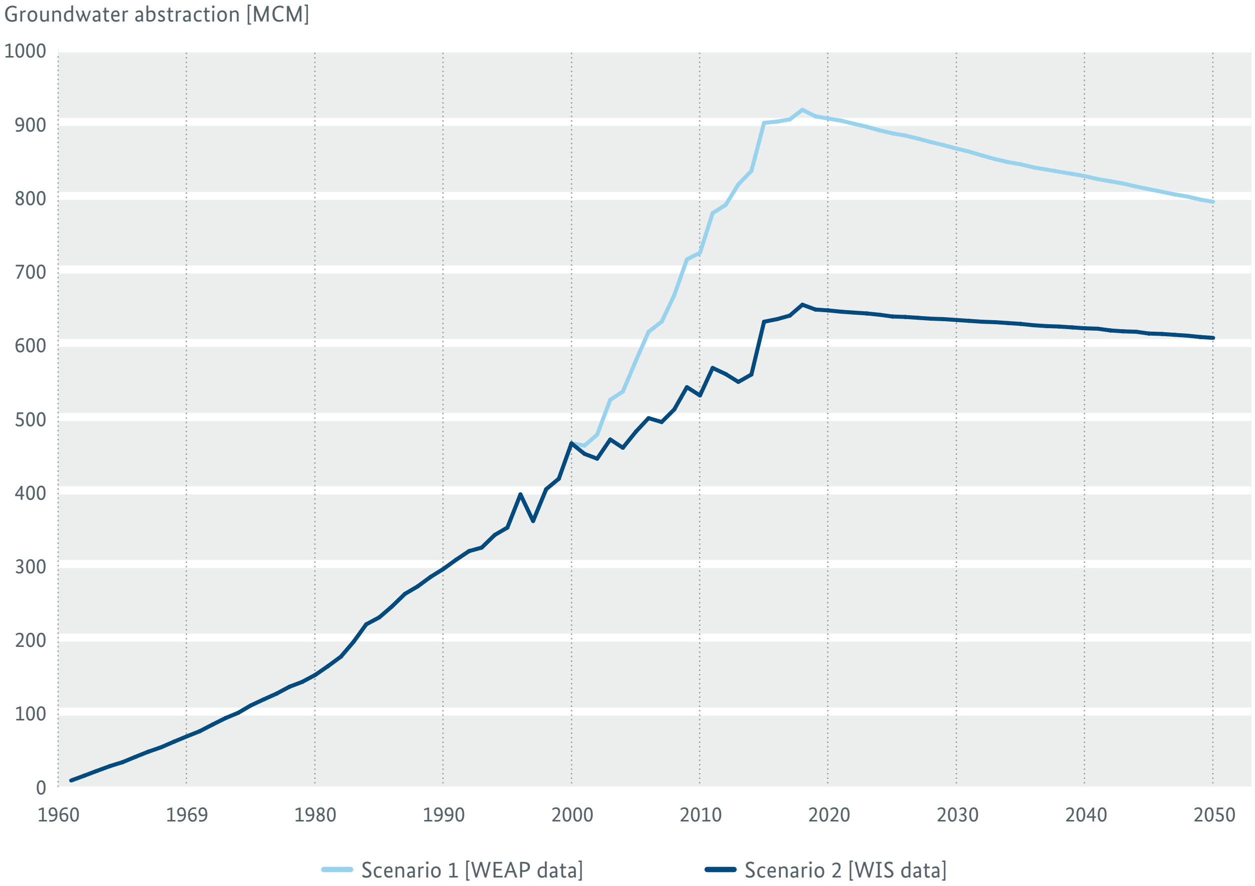


Figure 91 Simulated groundwater abstractions from 1960 to 2050 for all wells

Total Groundwater Abstraction

The difference between the irrigation abstractions in the WEAP model and the data from the WIS in 2014 is 270 MCM, and it was stipulated that additional irrigation abstraction began in 2000.

For scenario 1, the abstraction rates are consistent with the WIS data until 2000. Subsequently, the irrigation rate from WIS increased linearly to reach the WEAP values in 2014.

The total annual groundwater abstraction in 2017 was 920 MCM. Subsequently, the abstractions decreased by 13% to 800 MCM/year in 2050 (Figure 91). For scenario 2, the abstraction rates correspond to the WIS data, increased continuously to 653 MCM/year in 2017 (Figure 91) and then decreased to 600 MCM/year in 2050. This decrease in abstraction rates after 2017 is caused by the decreasing groundwater levels. The model reduces the abstraction relative to the saturated thickness in the well. With decreasing groundwater levels, the saturated thickness decreases until the well becomes dry and the abstraction is zero. The simulated reduction in the abstraction rates corresponds to a reduction in groundwater availability.

Predicted groundwater abstractions decrease by 13% in 2050 if abstraction rates remain unchanged. This decrease in abstraction rates after 2017 is caused by the decreasing groundwater levels and corresponds to a reduction in groundwater availability.

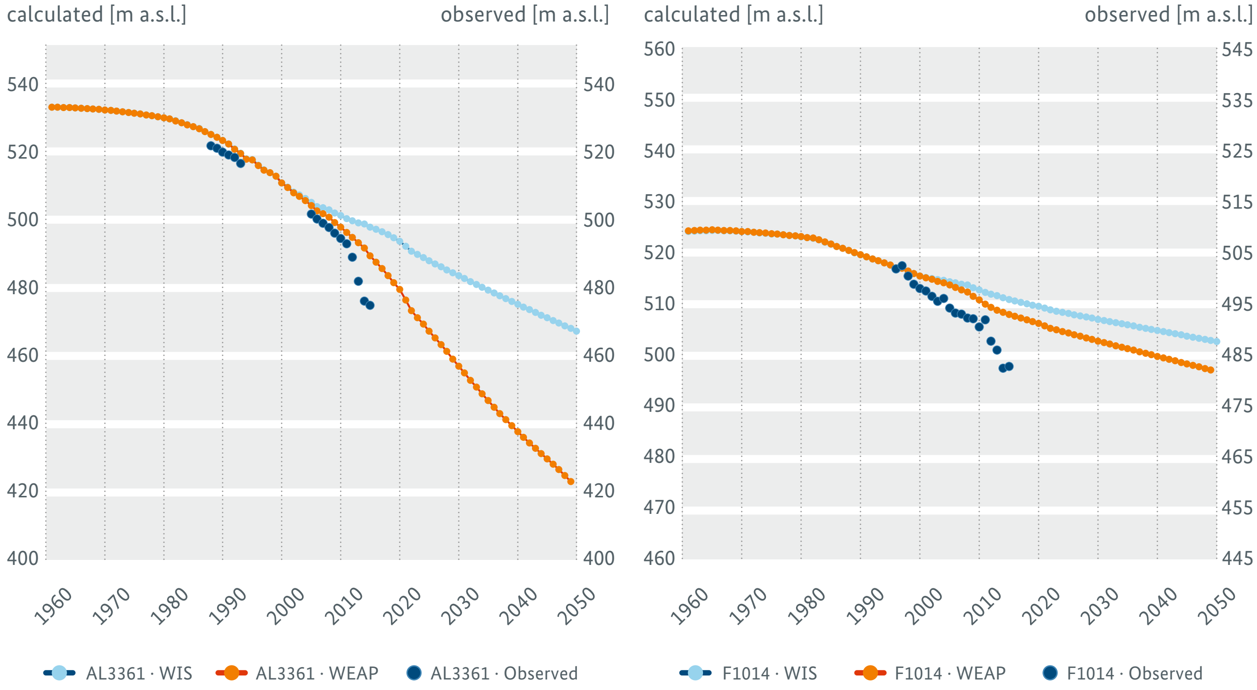


Figure 92 Simulated and observed hydraulic heads for selected monitoring wells associated with the Basalt aquifer

Transient Hydraulic Heads at Monitoring Wells

Basalt

At well AL3361 (Figure 92), the calculated heads for scenario 1 with higher irrigation abstraction from the WEAP model show a drawdown of 63 m for 2017-2050, and the curve follows the currently observed trend. For scenario 2, assuming the lower irrigation abstractions from the WIS, a drawdown of only 29 m is predicted until 2050. This indicates that the future conditions in the Basalt aquifer could potentially improve if the abstraction rates for irrigation are set to the WIS values and enforced by law.

At monitoring well F1014, a water level decline of approximately 10 m is calculated in scenario 1, and a decline of approximately 7.5 m is calculated in scenario 2. The predicted groundwater levels do not follow the steep decreasing trend observed after 2011, likely because of local effects that are not considered in the model.


Source: BGR

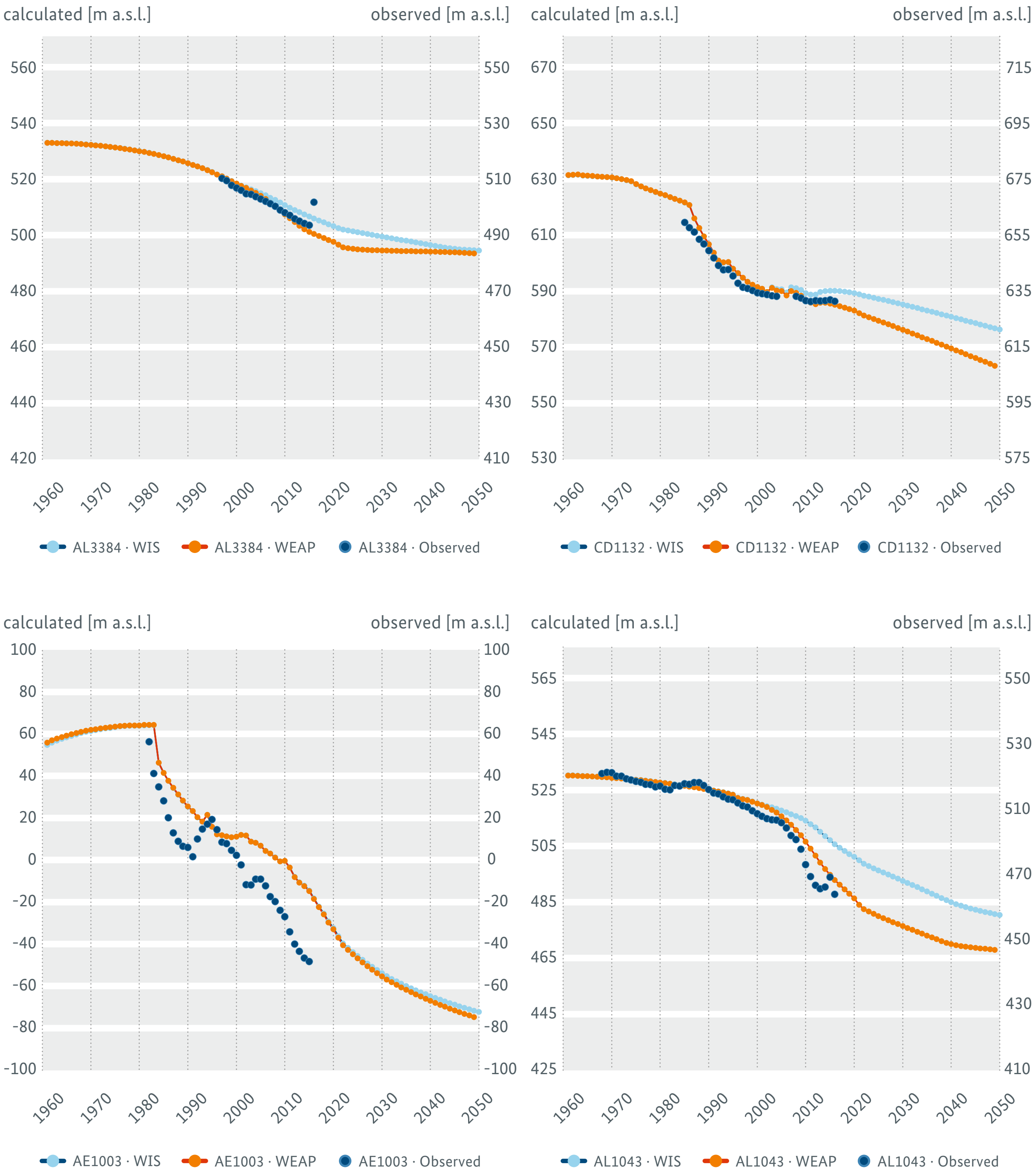


Figure 93 Part 1: Simulated and observed hydraulic heads for selected monitoring wells associated with the A7/B2 aquifer

A7/B2

In general, scenario 1 shows a better fit between the calculated and observed values than scenario 2 (Figure 93), especially in the observation wells close to irrigation areas. The scenario results do not differ at monitoring well AE1003 because there are no agricultural activities nearby.

A better agreement between the calculated and observed values is achieved when higher abstraction rates are applied according to the calculated crop water demand (scenario 1) than for scenario 2 (enforcement of groundwater bylaw), especially close to irrigation areas.

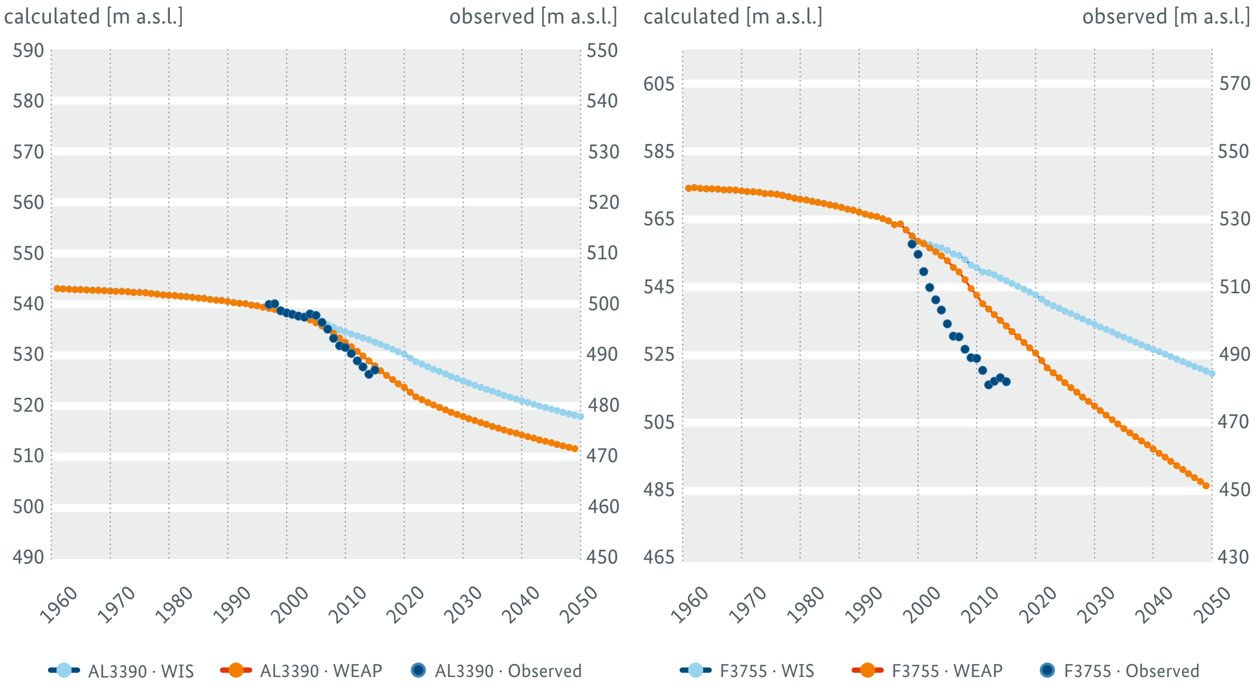


Figure 93 Part 2: Simulated and observed hydraulic heads for selected monitoring wells associated with the A7/B2 aquifer

Ram/Disi aquifer

The calculated decline in groundwater levels is similar in both scenarios (Figure 94) because this aquifer is not used for major irrigation activities. The dominant groundwater abstraction in the area is the Disi wellfield, which is used for the drinking water supply.

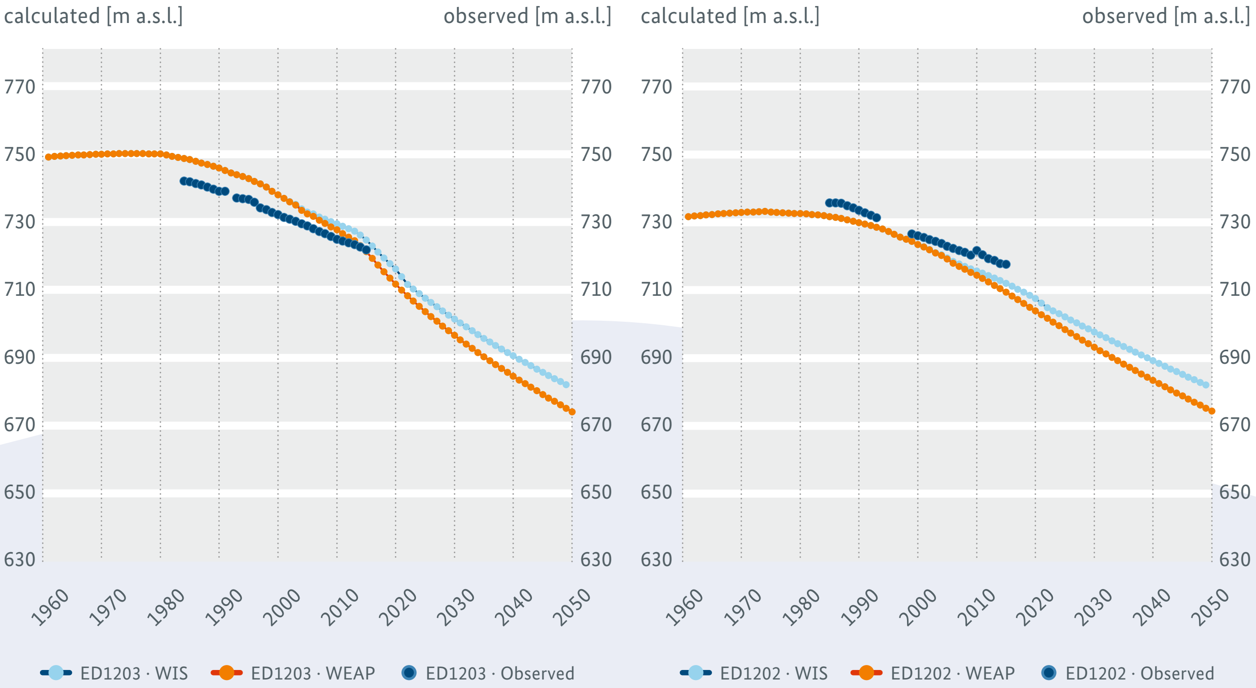


Figure 94 Simulated and observed hydraulic heads for selected monitoring wells associated with the Ram/Disi aquifer

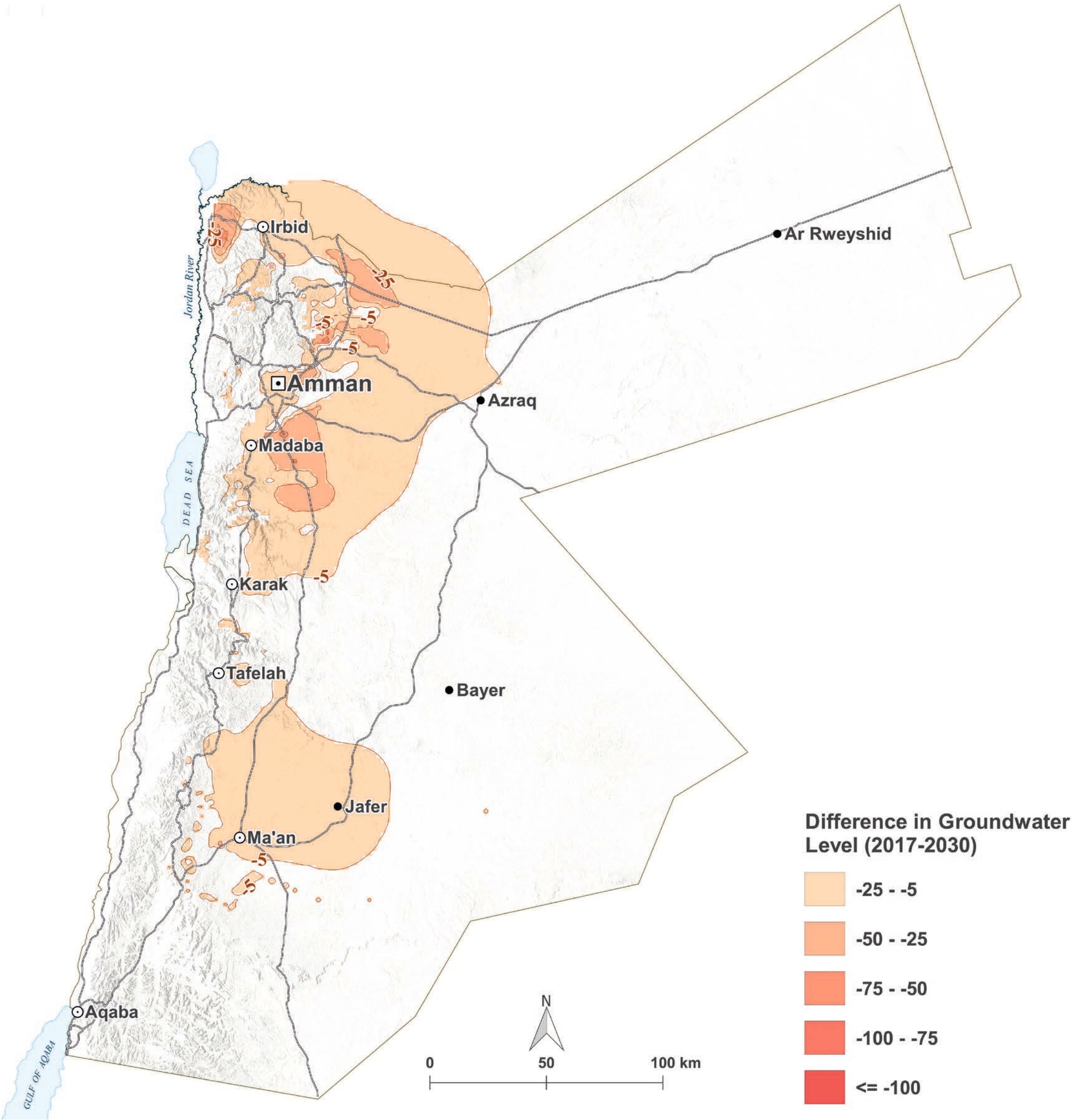


Figure 95 Simulated drawdown in the A7/B2 aquifer for 2017-2030 under scenario 1

Groundwater Drawdown

Scenario 1: Baseline scenario
The predicted drawdown in the A7/B2 aquifer under scenario 1 (Figure 95) reaches 55 m for 2017-2030 and up to approximately 100 m for 2017-2050 (Figure 96).

Scenario 1 results in irrigation abstraction rates from the WEAP model that forecast major drawdowns in Wadi Al Arab, Ramtha/Mafraq, northeast Amman and east Madaba that vary between 25 m and 55 m in 2030 and from approximately 50 m to 100 m in 2050. Predicted drawdowns of 20 m (2030) and 50 m (2050) are calculated for the areas around Maan and Jafer, respectively.

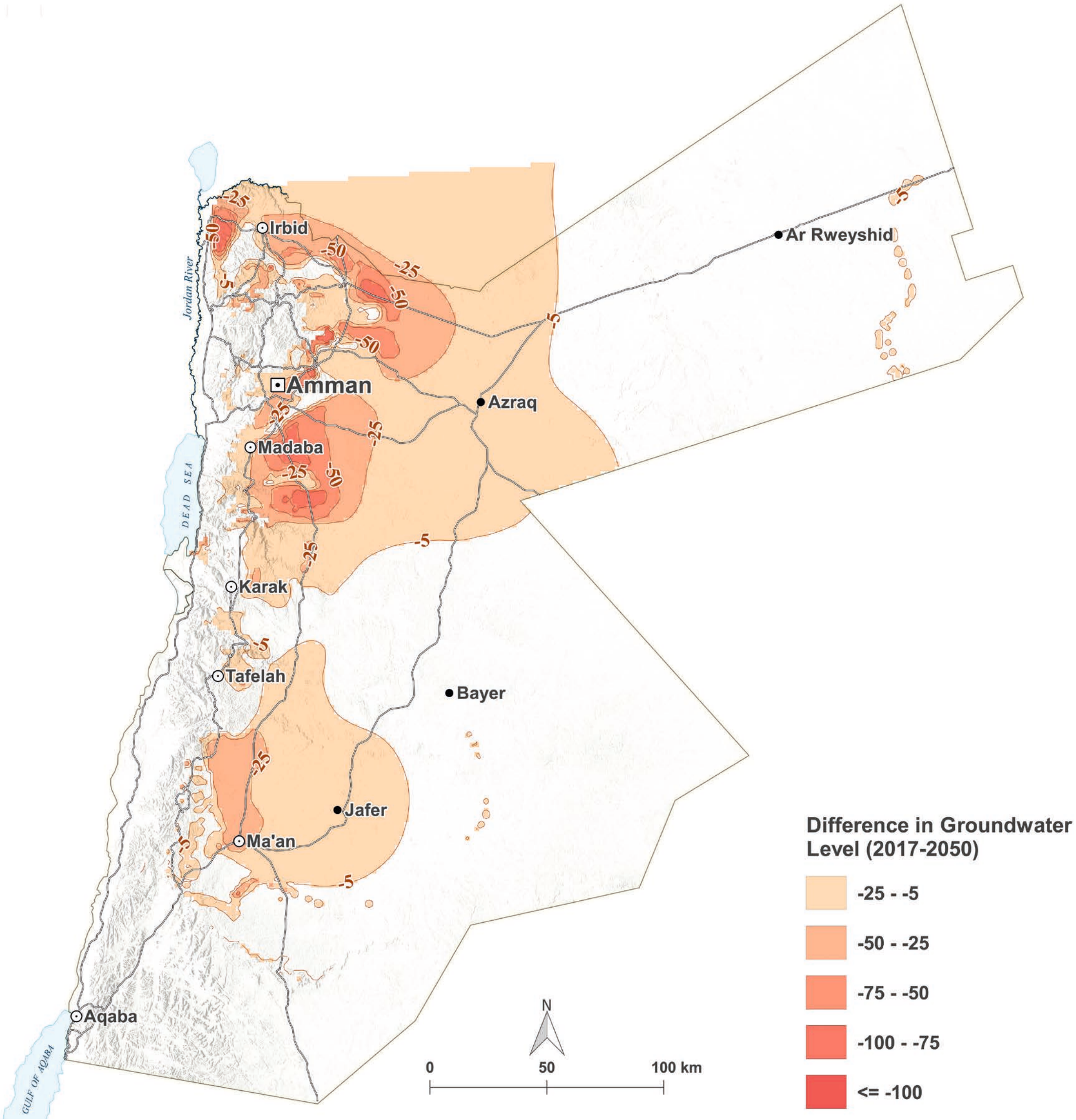


Figure 97 Simulated drawdown in the A7/B2 aquifer for 2017-2050 under scenario 1

Scenario 2: Enforcement of the groundwater bylaw
Under scenario 2 with abstraction rates due to irrigation from the WIS, the model predicts drawdowns of 55 m from 2017 to 2030 (Figure 97) and up to approximately 95 m for 2017-2050 (Figure 98). For scenario 1, the areas with major drawdowns are Wadi Al Arab, Ramtha/Mafraq, northeast Amman, east Madaba and the areas around Maan and Jafer.

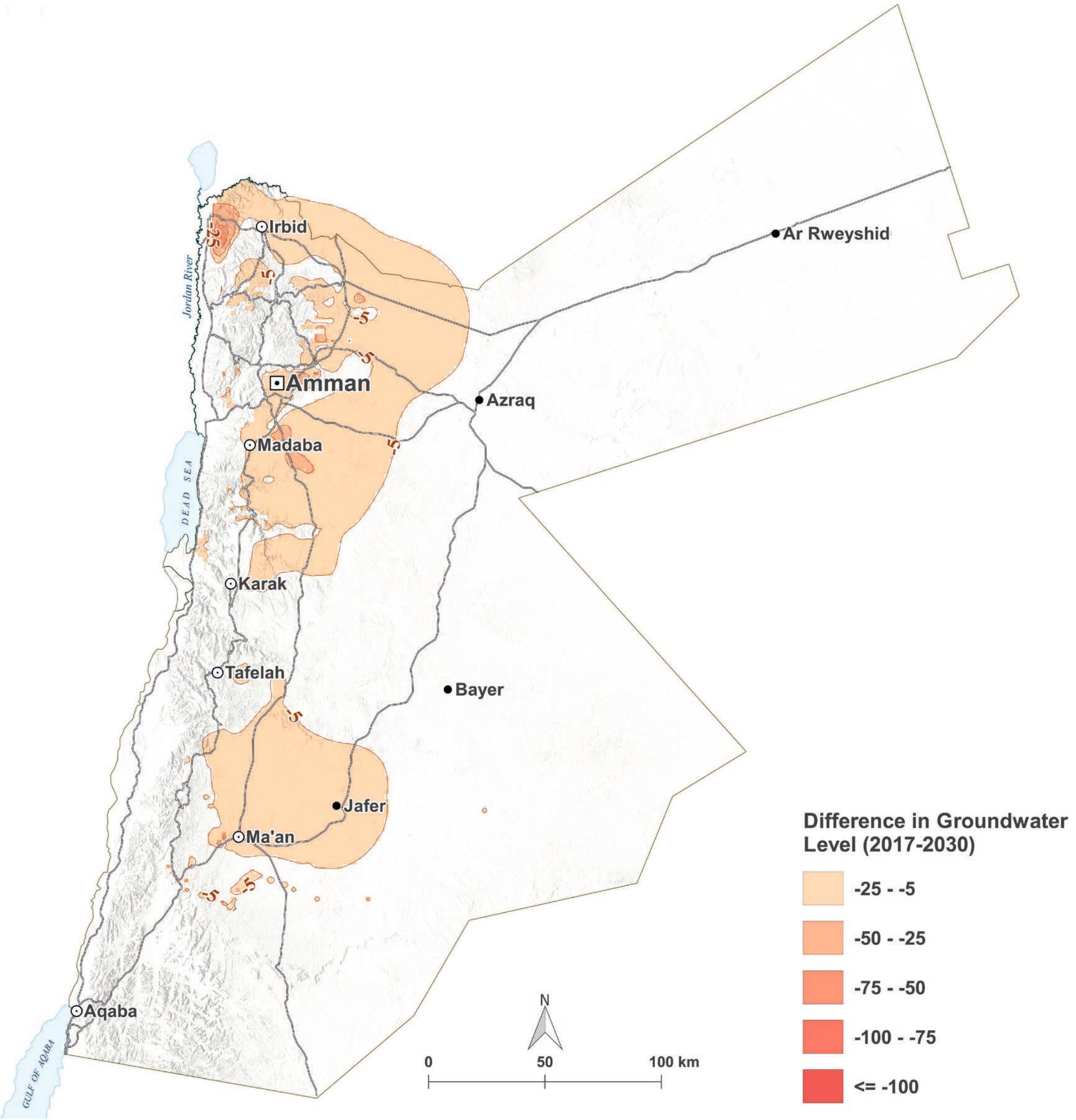


Figure 97 Simulated drawdown in the A7/B2 aquifer for 2017-2030 under scenario 2

6.3 Recommendations

The groundwater model underlines certain restrictions that refer to the model concept and data availability, leading to the following recommendations:

- Reassessment of groundwater recharge. The implemented approach does not reflect the topography, soil and underground parameters.
- Consideration of groundwater abstractions in Syria and northern Saudi Arabia (Tabouk area), which are likely to impact the groundwater resources in southern Jordan.
- Consideration of density-dependent processes in the interaction between the Dead Sea and the groundwater. The impact of the decline in the Dead Sea water level on the adjacent groundwater resources is overestimated in the model and should be revised to increase the reliability of the model predictions in the Jordan Valley.

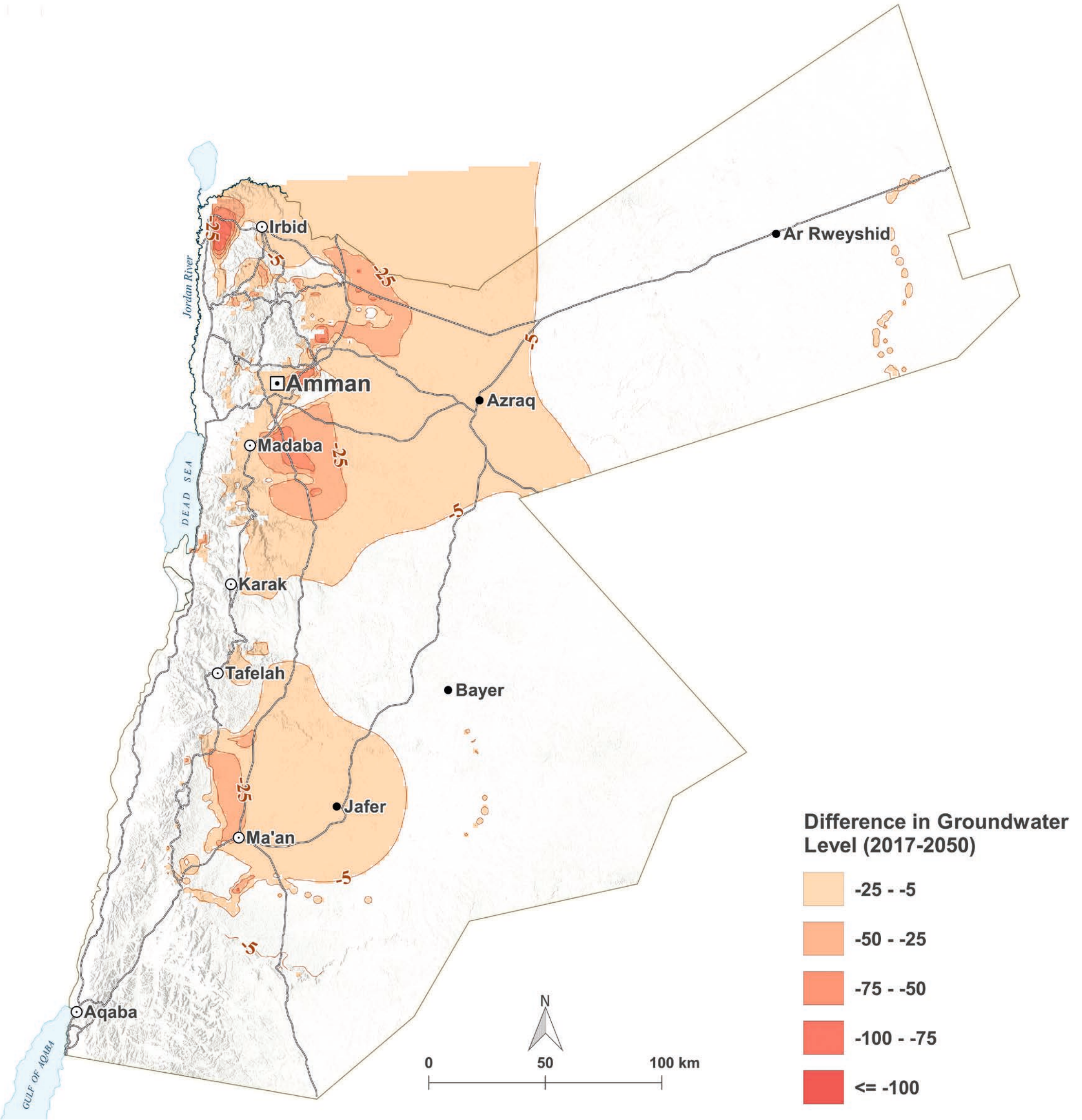


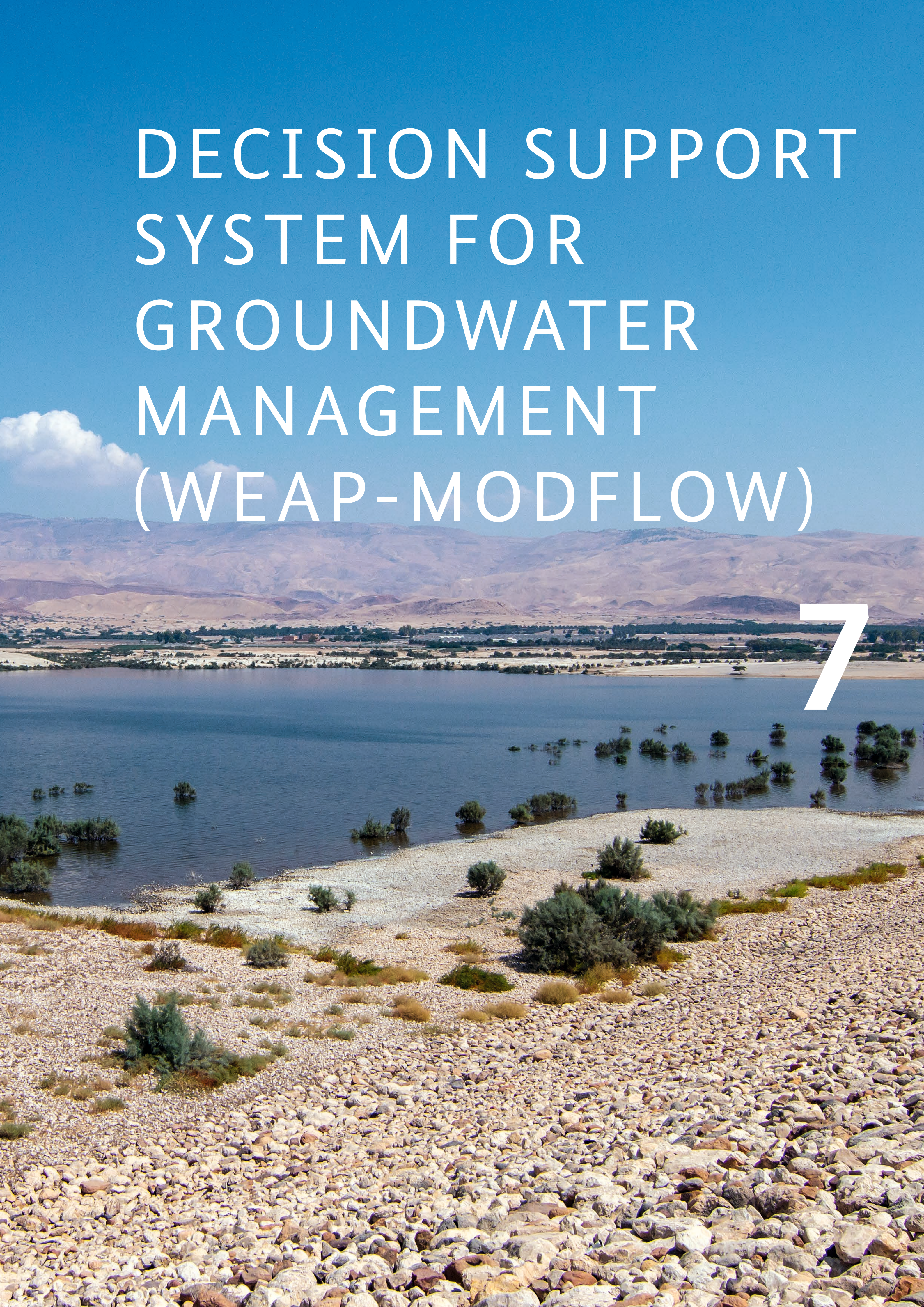
Figure 98 Simulated drawdown in the A7/B2 aquifer for 2017-2050 under scenario 2

The scenario analysis shows that a partial reduction in groundwater abstraction (enforcement of the groundwater bylaw) will improve the groundwater availability compared to the business-as-usual (baseline) scenario. However, the continuous negative development of groundwater resources is not reversible.

Source: BGR

Disclaimer

In evaluating the model results, the countrywide groundwater model is based on a regular grid with a cell size of 2,000 m x 2,000 m and very general assumptions of the hydraulic parameters. While this grid size ensures reasonable simulation times for the numerical model and a manageable effort for coupling with the WEAP model, it implies that local variations in the geological structures and hydrogeological or hydraulic processes are not resolved to a finer degree than the given cell size. Closely grouped pumping wells are not resolved individually but are hydraulically represented as a lump sum within the respective model cell. This is a clear limitation to its use as a wellfield management tool.



DECISION SUPPORT SYSTEM FOR GROUNDWATER MANAGEMENT (WEAP-MODFLOW)

7

7

Decision Support System for Groundwater Management (WEAP-MODFLOW)

Mark Gropius & Markus Huber

The water supply network in Jordan is extremely complex. To improve strategic water resource planning, the MWI applied a nationwide WEAP model that simulates water allocation throughout the water supply network and identifies water supply deficits. The model allows for the evaluation of various water planning options and future scenarios and thus supports decision-making processes for strategic water management. Coupled with the nationwide groundwater flow model (Chapter 6), a reliable decision support system (DSS) for groundwater management purposes is available to the MWI.

Source: Matthew Dalton, courtesy of APAAME

7.1 Methods and Data

7.1.1 WEAP

Since 2009, the MWI has developed and applied a nationwide WEAP model that represents the water supply network at the district scale (Figure 99). In this model, each wellfield is represented by a transmission link whose physical capacities control the amount of water abstracted. Such a design requires high sensitivity when setting up scenarios to avoid underestimation of water shortages due to groundwater resource limitations.

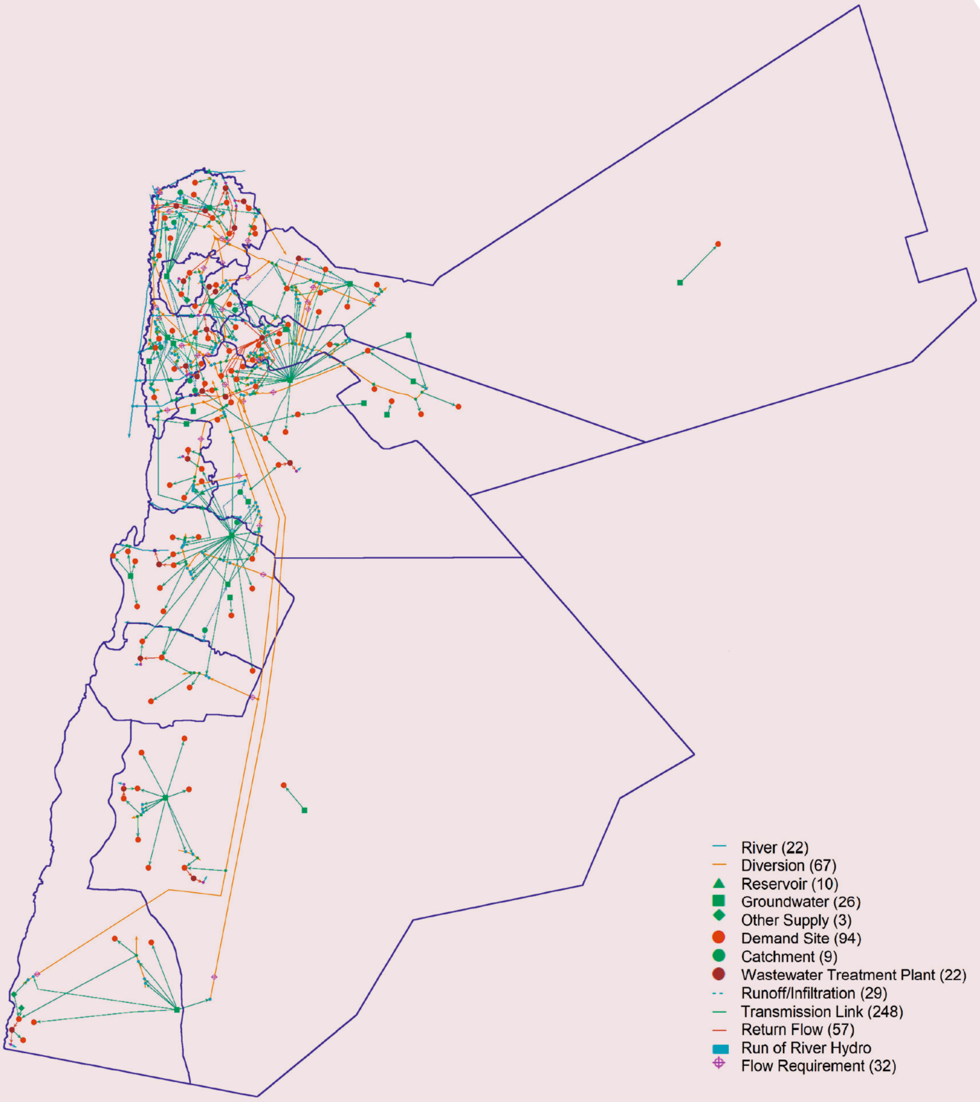


Figure 99 Schematic of the countrywide WEAP model

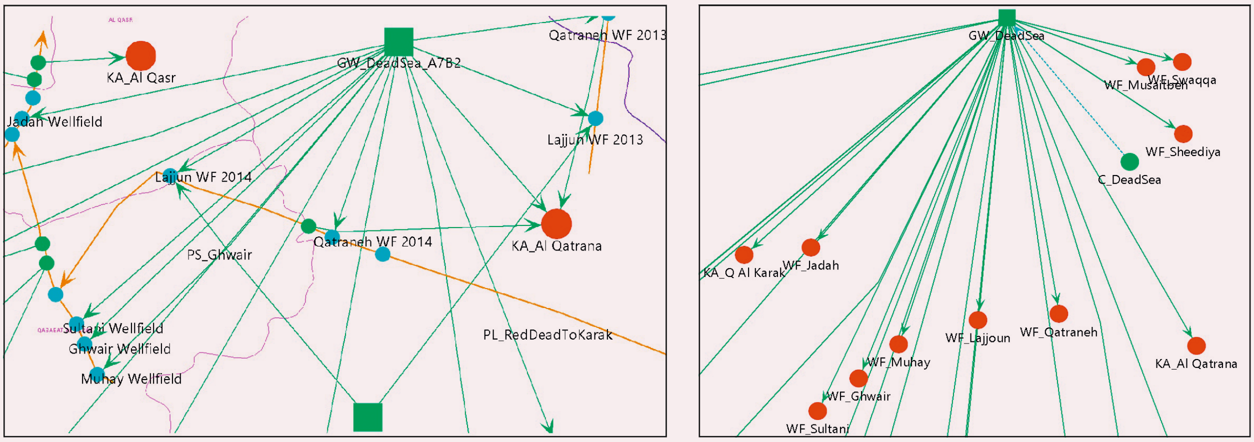


Figure 100 Implementation of wellfields as transmission links in the master model (left) and as demand sites in the slave model (right)

7.1.2 WEAP-MODFLOW Linkage

Setting up a dynamic link between the nationwide WEAP model and the nationwide MODFLOW groundwater flow model (Chapter 6) to develop a comprehensive DSS for groundwater management required a special approach, not only because of the peculiarities of WEAP but also because of the performance. Both models (WEAP and MODFLOW) require a significantly long time to calculate. Whenever scenarios are likely to show no effect on groundwater, such as when dealing with costs, it is not necessary to calculate all of the groundwater processes. Similarly, if abstraction changes are the focus, it is not necessary to integrate every water allocation option into the calculation of the groundwater processes.

The new WEAP-MODFLOW linkage approach uses a simplified WEAP model (slave model) as a surrogate for the nationwide model (master model) without losing any of its detailed information and planning options (Figure 100).

The spatial relationship between the WEAP elements and MODFLOW grid cells was established using a GIS shapefile generated by the tool LinkKitchen (Huber, 2013).

7.2 Results

The continuous declines in groundwater levels in Jordan have led to less groundwater availability for pumping and thus to reduced pumping rates (Chapter 6). The “supply delivered” option in WEAP allows for a comparison of the total abstracted volumes with the supply requirements (Figure 101). Under scenario 1, the amount of groundwater supplied by the aquifer does not cover the requirements assessed by the uncoupled WEAP master model. The calculated supply requirement varies between 1450 MCM and 1550 MCM, but the supply delivered only reaches 1320 in 2015 and approximately 1200 MCM in 2040. The “pumping reduction” option delivers the absolute amount by which the groundwater abstraction at a wellfield or demand site is reduced due to the decline in groundwater level. Figure 102 shows the calculated pumping reductions for all demand sites. A reduction of approximately 40 MCM is estimated in 2015, but it increases to approximately 155 MCM by 2040.

Due to the decline in groundwater levels a reduction of pumping rates of approximately 40 MCM is estimated in 2015, but it increases to approximately 155 MCM by 2040.

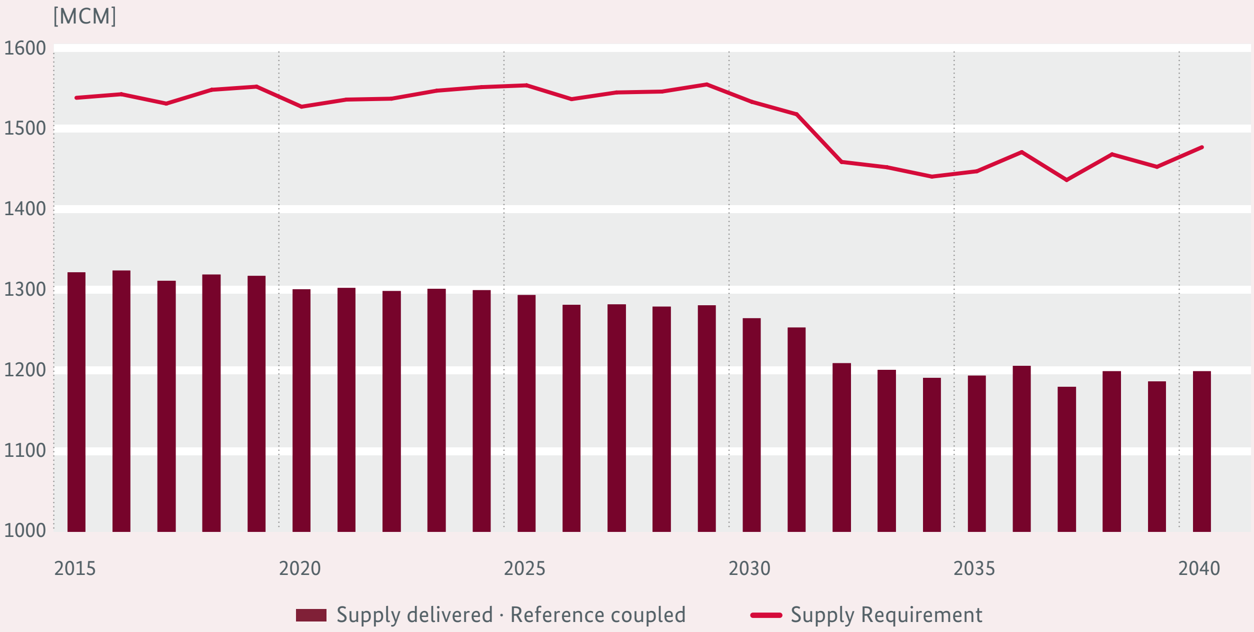


Figure 101 Supply requirements for all groundwater-related demand sites in Jordan and calculated supply delivered by scenario 1

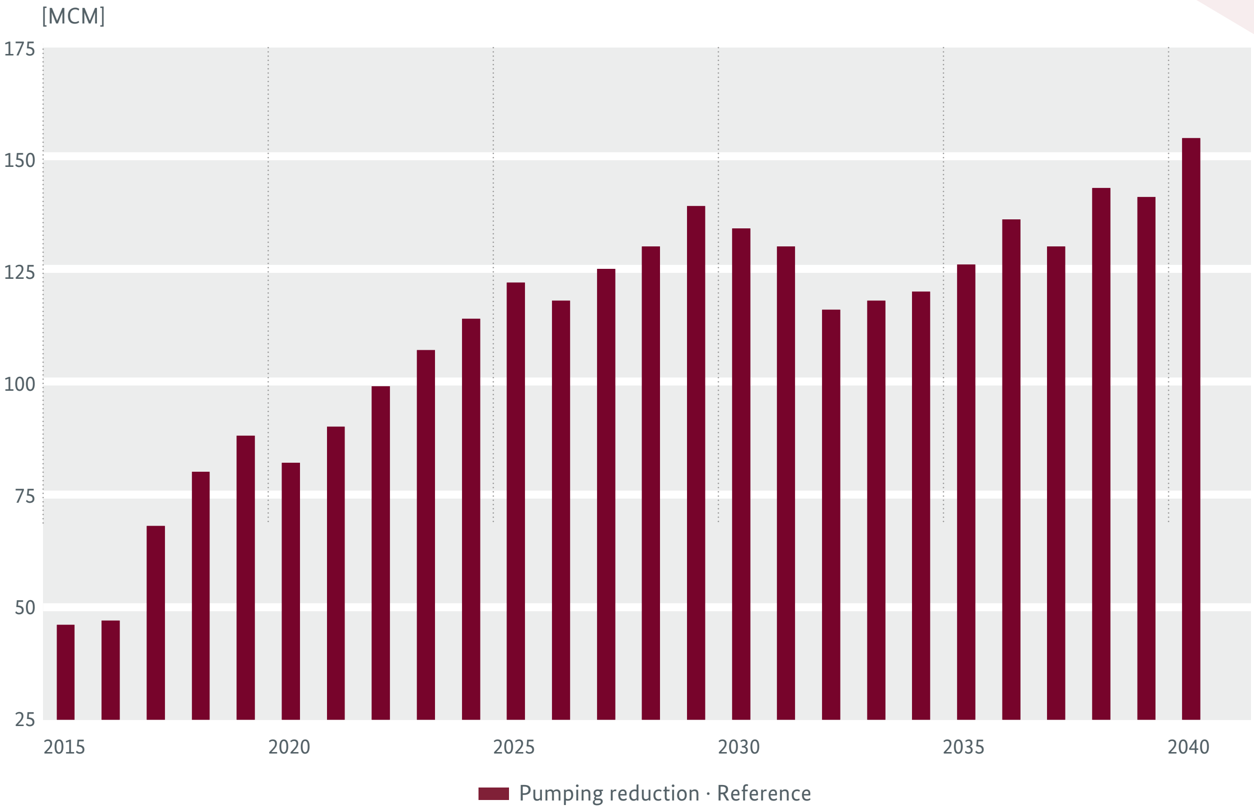


Figure 102 Pumping reductions for all demand sites in Jordan under scenario 1

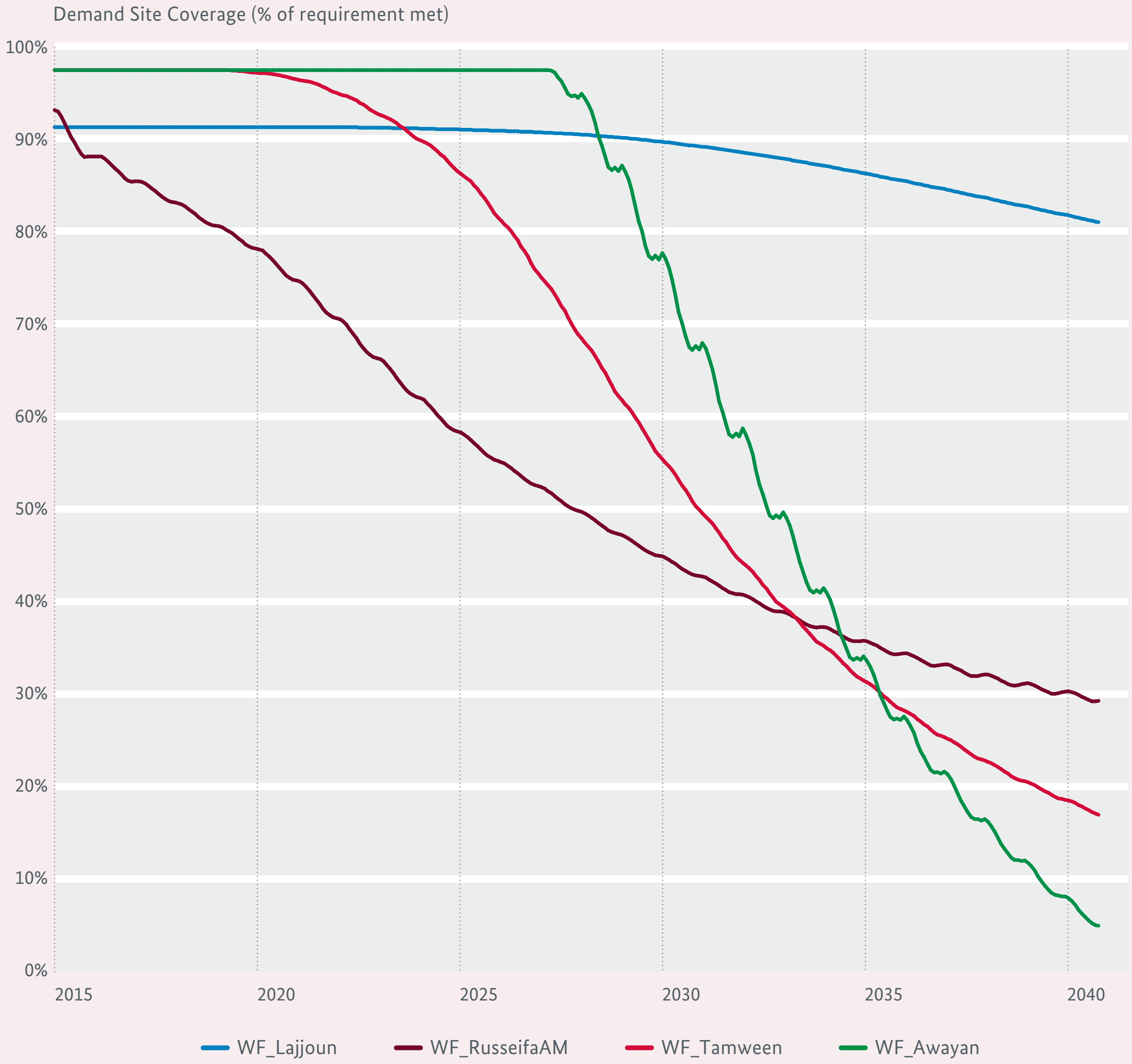


Figure 103 Pumping reductions for selected demand sites under scenario 1

The coverages of the requirements for individual wellfields are quite variable (Figure 103). According to the coupled WEAP slave model, the Lajjoun, Russeifa, Tamween, and Awayan wellfields cover 95% to 100% of the demand under scenario 1 in 2015. By 2040, these individual coverages decrease substantially; Lajjoun reaches 85%, Russeifa is 35%, Tamween is 20%, and Awayan is only 10%.

The “Coupled” WEAP Master Model

The results of the coupled WEAP slave model show that groundwater production is lower than required in the uncoupled WEAP master model. To illustrate the improvement in forecasting of the WEAP-MODFLOW coupled model towards the WEAP master model, the latter was rerun with the reduced abstraction rates provided by the slave model.

Figure 104 illustrates the unmet demand, which is the difference between the supply requirement and the supply delivered. As expected, the unmet demand is higher for the coupled model because of the lower groundwater production. Based on the simulation results, the coupled simulation leads to an unmet demand that increases from 400 MCM in 2015 to approximately 630 MCM in 2040, which demonstrates the increasing water supply deficits in Jordan and the importance of more accurately assessing the groundwater availability.

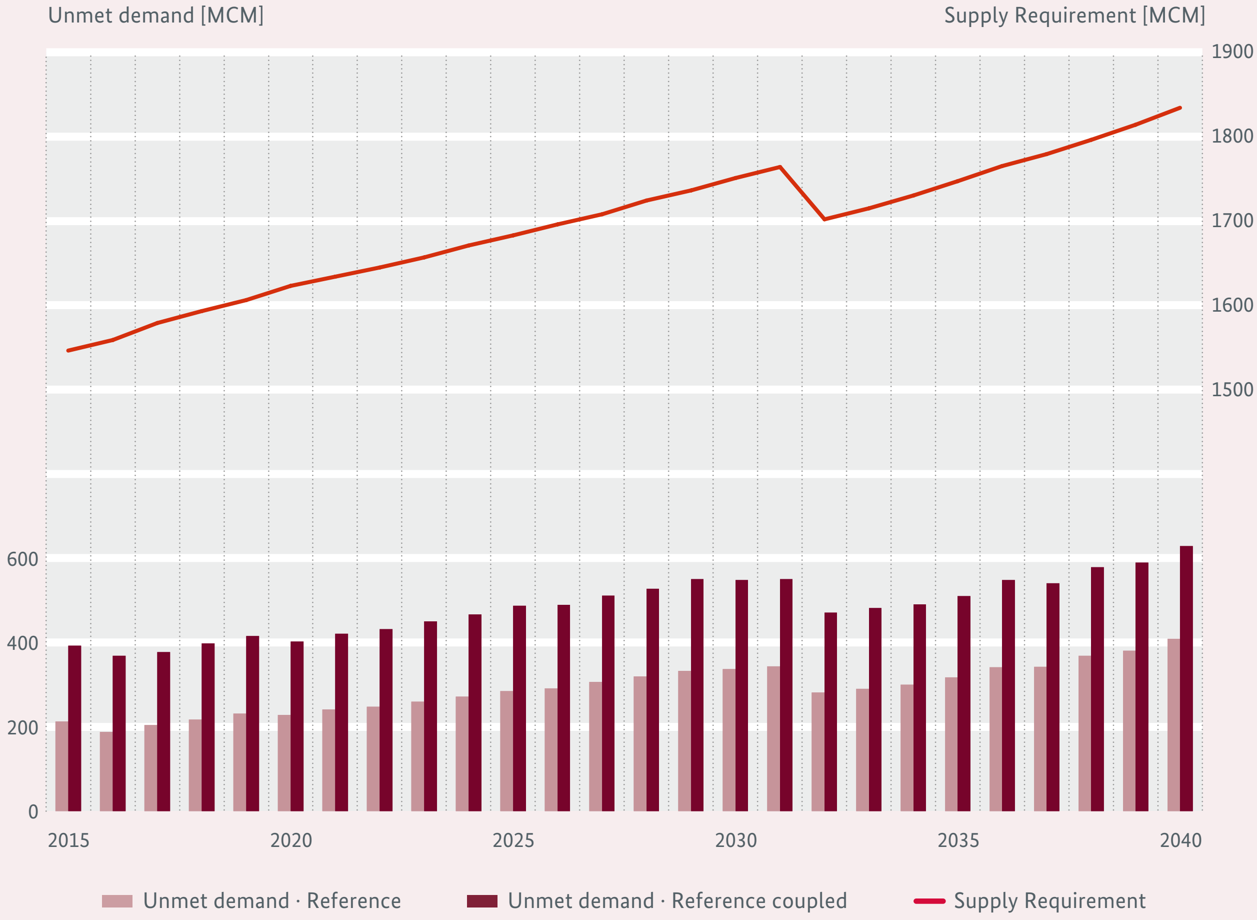


Figure 104 Calculated unmet demands with and without coupling for scenario 1 and the supply requirements for all demand sites in Jordan

The analysis of all irrigation demand sites in Jordan reveals that as expected, the unmet demand is considerably higher for the coupled model (Figure 105). However, neither the coupled model nor the uncoupled model shows any trend in unmet demand because this scenario does not consider an increase in agricultural demand.

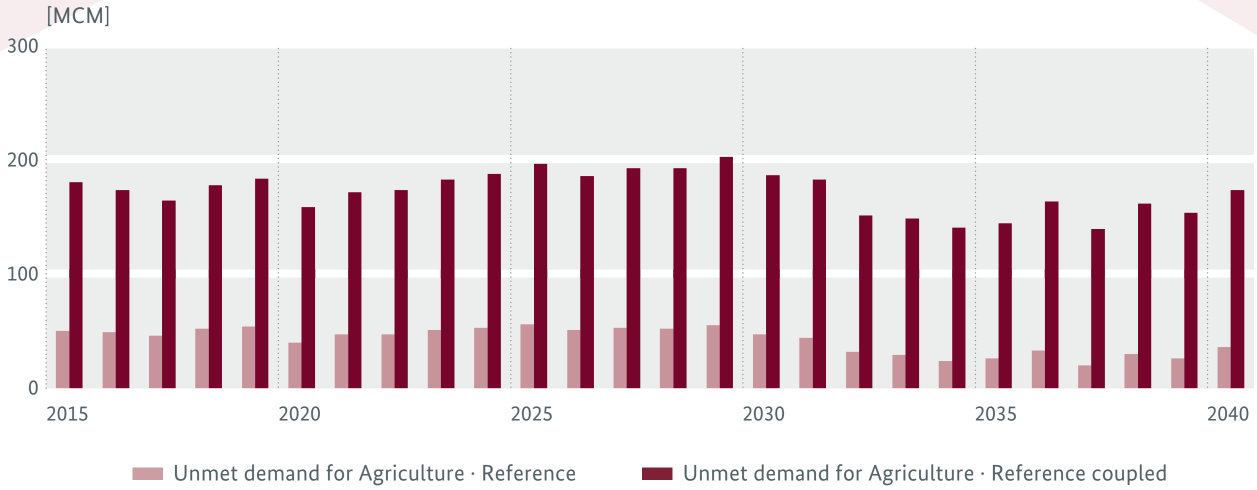
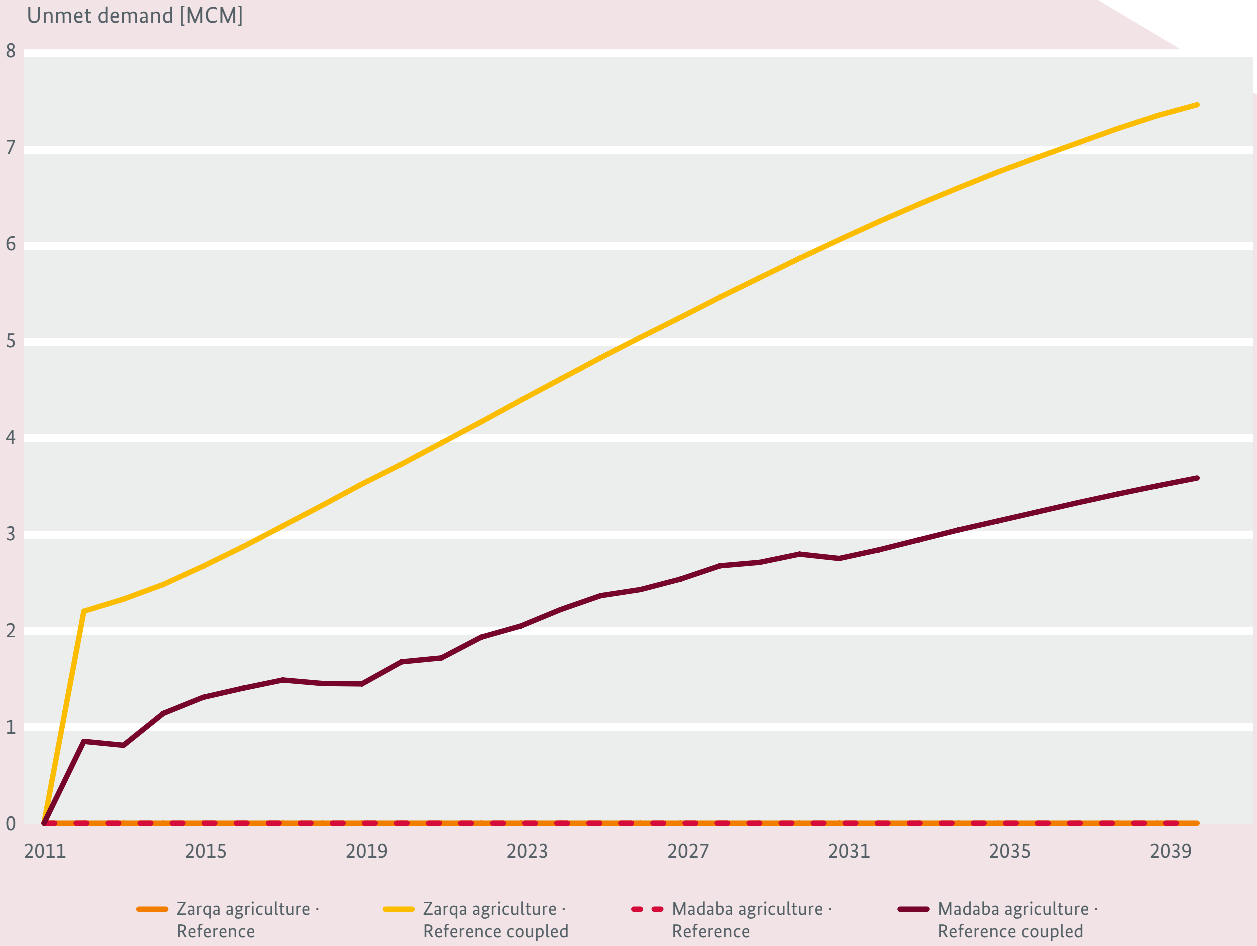


Figure 105 Unmet demands for all irrigation demand sites in Jordan with and without coupling under scenario 1

The impacts of limited groundwater availability can also be visualized at individual demand sites. Figure 106 presents the Zarqa and Madaba irrigation demand sites for 2015-2040 under scenario 1. While the uncoupled model calculated the permanent coverage of supply for both demand sites, the coupled model estimated unmet demands that steadily increase during the period to approximately 7.5 MCM in year 2040 for Zarqa and 3.7 MCM for Madaba.



Source: BGR

Figure 106 Unmet irrigation demands at Zarqa and Madaba with and without coupling under scenario 1

7.3 Recommendations

The coupled WEAP-MODFLOW model improves the ability to forecast future developments. The model allows for the quantification of wellfield productivity and identifies the origin of supply deficits. Although still under development, the countrywide WEAP-MODFLOW-DSS is a valuable tool and must be used for water supply management and planning in Jordan.

GROUNDWATER VULNERABILITY MAP

8

8

Groundwater Vulnerability Map

Florian Brückner

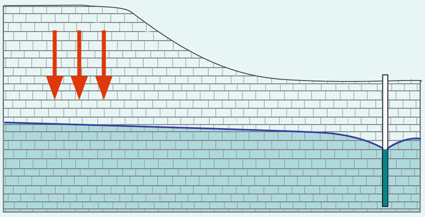
In view of the increasing water scarcity in Jordan, it is important to maintain the quality of existing groundwater resources. The concept of water protection zones was introduced in Jordan with the development of the water protection guideline (MWI, 2002). The aim of these protection zones is to protect existing water sources from pollution by implementing land-use restrictions.

A well-established tool for mapping the susceptibility of an aquifer to pollution is the vulnerability map. Groundwater vulnerability maps indicate how fast potential contaminating substances can reach groundwater resources. They are also a communication tool between water experts and decision makers such as land-use planners; complex hydrogeological settings are translated into simple classes of high to low vulnerabilities. Groundwater vulnerability maps can be used to designate zones for industrial and urban development, prioritize areas to be connected to the sewer network, assess the need for detailed environmental impact assessments and as inputs for the delineation of groundwater protection zones.

Several vulnerability maps have been produced for Jordan [Al-Adamat et al. (2003), Al-Hanbali & Kondoh (2008), Awawdeh & Obeidat (2015), Borgstedt et al. (2007), Brosig et al. (2008), CDM International (2004), El-Naqa (2004); Hamdan et al. (2016); Hijazi et al. (1999), Kuisi et al. (2014), Margane et al. (1997, 1999, 2009, 2010), Talozi (2013), Werz & Hötzl (2007), and Xanke et al. (2017)]. However, these maps were produced using different methods, and they may not be comparable. Therefore, a nationwide vulnerability map was prepared using the COP method (Vías et al., 2006). The method was chosen because it considers the rapid flow through karst features, which are present in northern Jordan (Brückner et al., 2018). Three types of information are required for the application of the method: overlying layers (O), concentration of flow (C) and precipitation (P).

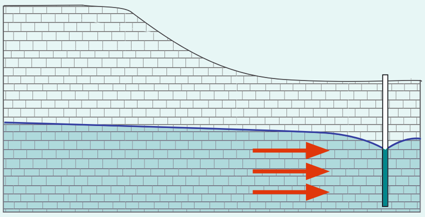
Two Concepts for Groundwater Protection - Groundwater Vulnerability Maps and Groundwater Protection Zones

Groundwater Vulnerability



Target: Groundwater Resource
Pathway: Unsaturated Zone

Groundwater Protection Zones



Target: Groundwater Resource
Pathway: Unsaturated Zone
Modified from Daly et al. (2002)

The aim of both concepts is to prevent groundwater pollution. Groundwater vulnerability describes the transport of contaminants in the unsaturated zone, whereas transport in the saturated zone is used for groundwater protection zones. Groundwater vulnerability looks at the groundwater resource as a whole, whereas only the groundwater catchments of wells or springs are considered for protection zones. Both concepts use land use restrictions in certain areas to achieve that aim.

8.1 Methods and Data

All of the input data were interpolated and classified in GIS. The needed factors were assigned following indexing from the COP method. The different input layers were then combined into a single map to describe the vulnerability of groundwater to pollution.

8.1.1 O Factor (Overlying Factor)

The O factor evaluates the thickness of the unsaturated zone (distance from the surface to the groundwater) and its composition. The farther seeping contaminants need to travel to reach the groundwater table and the more they are degraded and diluted, the less harmful they are.

The method first evaluates the thickness and texture of the soil, both of which depend largely on the soil formation processes and parent rocks. Soils that originate from the sandstone in Wadi Rum are usually quite deep, but water can flow rapidly through the sand. In the highlands, erosion is important because of the steep topography and rainfall. The soils in these areas are often deep and contain large amounts of clay that hinders water percolation. However, if the topography is too steep, soils are washed away by water and accumulate in the valleys.

Subsequently, the thickness and lithology of the geological layers are evaluated. Impermeable rocks such as clay and marl have a high protective function (low vulnerability), whereas the protective ability of sand, gravel or fissured rock is low. Furthermore, groundwater under confined conditions offers more protection than unconfined groundwater. However, deep groundwater levels, as is the case in Jordan, increase the natural protection of unconfined groundwater against pollution. The thickness of the unsaturated zone can only be calculated if enough information on the structure and water levels is available. Because this is not the case for the Kurnub and Disi sandstone aquifers or the alluvial aquifer in the Jordan Valley, these aquifers were omitted from this study.

The vulnerability was always calculated for the upper aquifer, which is the aquifer closest to the surface. The Basalt and underlying aquifers (A7/B2, B4/B5) are assumed to form a combined aquifer system, which is considered in the calculation of the O factor. For this system, the protection is low where the water level is shallow (e.g., incised wadis, Azraq Oasis) and high in areas where the B3 aquitard covers the A7/B2 aquifer (Figure 107).

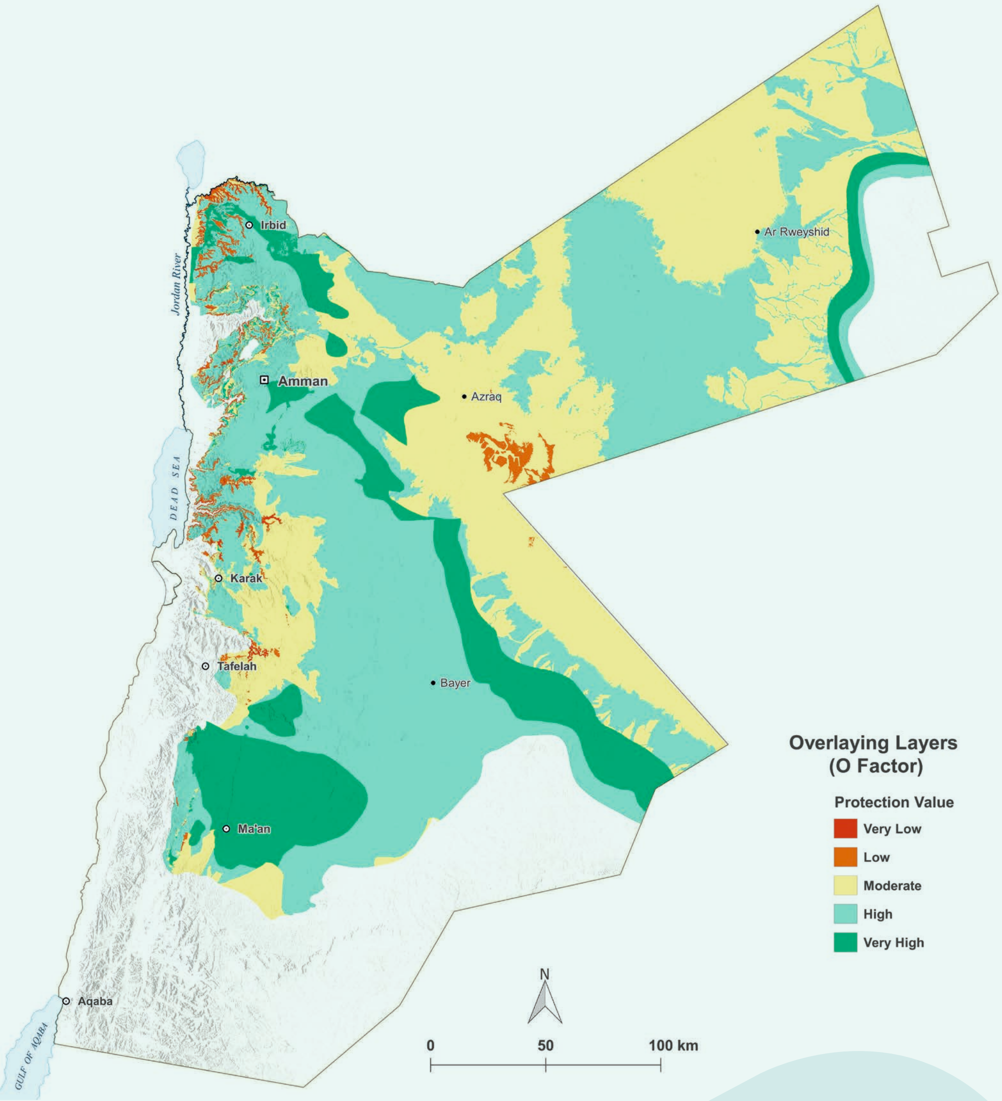


Figure 107 O factor classifications for the different aquifers

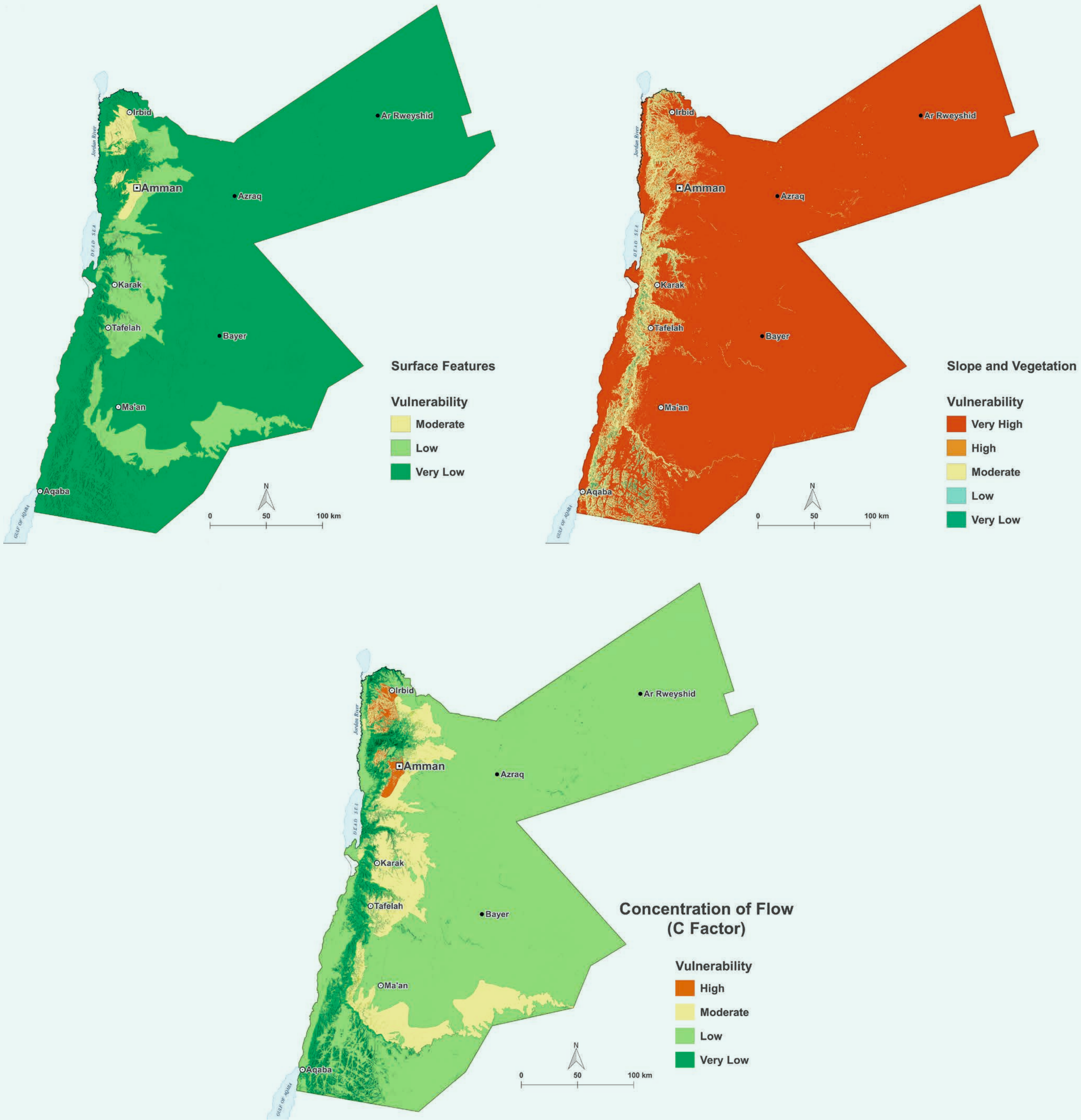


Figure 108 Effects of surface features (top left) and vegetation (top right) on the concentration of flow (bottom).

8.1.2 C Factor (Concentration of Flow)

Water bypasses impermeable layers wherever fissures or karst features are present. This effect is considered in the C factor (concentration of flow). The vulnerability increases with the degree of karstification (Figure 108, top left).

The slope and vegetation also play a role in infiltration. When the vegetation is high and the slope is low, water can accumulate and percolate into the ground, whereas in steep topography, the water will mainly run off along the surface (Figure 108, top right).

The contribution of the flow concentration to the groundwater vulnerability is generally low (Figure 108, bottom). It is very low in the steep slopes of the Dead Sea Rift and moderate to high in the highlands, where karstified limestones crop out.

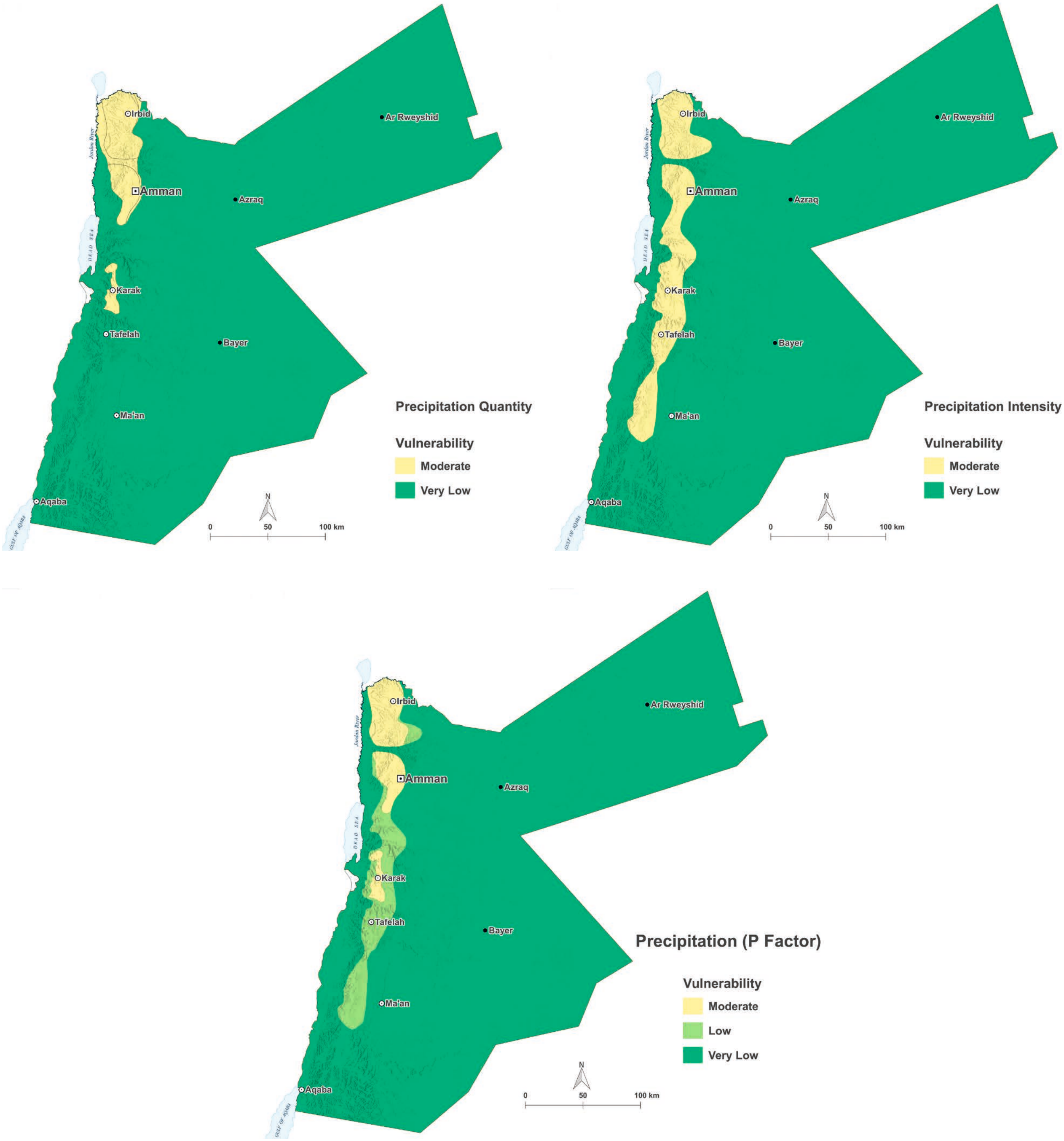


Figure 109 Effects of precipitation quantity (top left) and intensity (top right) on the precipitation factor (bottom left).

8.1.3 P Factor (Precipitation)

Most contaminants reach the groundwater with infiltrating rainwater, which is accounted for by the P factor. The vulnerability increases somewhat with higher rainfall (Figure 109, top left). However, if the rainfall is very high, dilution occurs, and the vulnerability decreases.

The rainfall intensity is also important, especially in arid and semiarid environments. Rainfall from small precipitation events is mostly lost by evaporation. The rainfall is simply calculated as the average annual rainfall divided by the number of rainy days. The resulting precipitation (mm/day) was then classified according to parameters given by the method of Vias et al. (2006) (Figure 109, top right). Rainfall affects the vulnerability only in the highlands, especially in the north between Amman and Irbid (Figure 109, bottom).

8.2 Results

The final vulnerability map was obtained by combining the mapped concentrations of flow, overlying layers and precipitation (Figure 110). The vulnerabilities are highest in areas where the aquifers outcrop, mainly because there is little or no protective cover. This is especially the case in the deeply incised wadis flowing from the highlands towards the Dead Sea Rift basin. However, the vulnerability along the outcrops of B3 is very low because of its large thickness and low permeability.

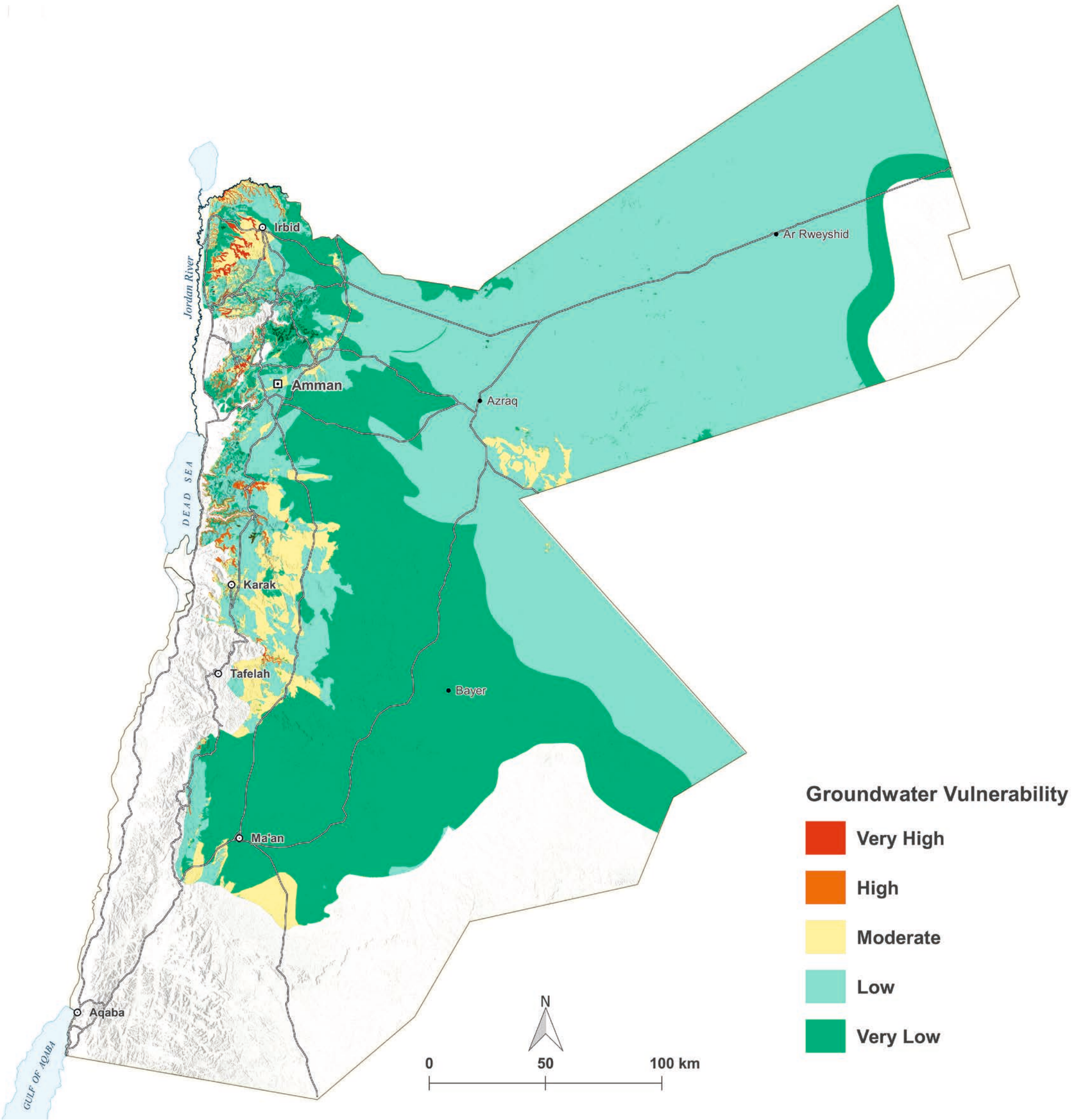


Figure 110 Groundwater vulnerability map

8.3 Recommendations

Groundwater must be protected from any kind of contamination that could additionally impair the available resources and exacerbate the water crisis. The groundwater vulnerability map depicts areas where contamination can rapidly reach the groundwater. Therefore, this map must be considered in land-use planning because many types of human activities can have negative effects on the groundwater quality. Furthermore, several land-use types, such as mining, underground fuel tanks and cesspits, remove the natural protective cover. Thus, the vulnerability is higher than indicated in the map in these areas.

Sources: BGR

APPENDIX

9

9

Appendix

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List of acronyms and units of measurement

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BRGM	Bureau de Recherches Géologiques et Minières (French Geological Survey)
d	day
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DSS	Decision Support System
Kh	horizontal hydraulic conductivity (x- and y-directions)
Kv	vertical hydraulic conductivity (z-direction)
m	meter
m3	cubic meter
m asl	meters above sea level
m bgl	meters below ground level
MCM	million cubic meters
MODFLOW	Modeling Groundwater Flow
MWI	Ministry of Water and Irrigation
NRA	Natural Resource Authority
SCM	Structure Contour Map
SRTM	Shuttle Radar Topography Mission
SWL	static water level
WAJ	Water Authority of Jordan
WEAP	Water Evaluation And Planning system
WIS	Water Information System
yr	year

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The inventory of the Groundwater Resources of Jordan is the first nationwide study since the 1990s. The Ministry of Water and Irrigation (MWI) and the Federal Institute for Geosciences and Natural Resources (BGR) jointly conducted this study, including fieldwork, data analysis, modeling and interpretation. Jordan is one of the most water-scarce countries in the world. The Jordanian government and the international donor community are aware of the critical situation; however, to date, data that cover the entire Hashemite Kingdom of Jordan were missing, making management decisions difficult. Based on all available data, the results of this study show the current conditions in the aquifers and describe different groundwater model scenarios for the future. These tools will support decision makers in the Jordanian water sector to take the best possible actions to secure a continuous water supply in Jordan.

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