Data scarce modelling the impact of present and future groundwater abstraction on national multiaquifer groundwater resources

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Abstract

Rapidly growing demands and climate change stresses water resources worldwide and leads to highly competitive situations between the environment and socio-economic development of a region or nation, calling for a smart and modelling driven water resources management. However, data scarcity often prevents the realisation of a comprehensive, nation-wide resources model, which provides reliable and spatially discretized results of water resources development.

We here present a workflow approach to set up a large-scale multi-aquifer model, overcoming data shortage by stepwise calibration and integrating hydrological and numerical groundwater flow modelling into a coupled system. The study aims to develop such a system to assess how groundwater resources react on anthropogenic impacts on a large, national scale and furthermore, how these resources develop in future under climate change. The exercise was undertaken on the example of the Kingdom of Jordan, one of the water poorest countries on globe.

Simulated heads reliably resembled the monitored ones in more than 70% of the observation wells. That makes us confident, the model represents all the states well from 1970, prior to the intense development of the country until 2015. Regional drawdowns of more than 250 m are observable in both observed large aquifer complexes. Most severe areas in the upper calcareous aquifer are located in the north of Amman and practically in all urban and agricultural agglomerations across the country. Groundwater tables in the deeper sandstone aquifer are particularly affected in the south, at the world heritage of Petra and Wadi Rum as well as in the wider vicinity of the Dead Sea as consequence of its continuous dropping. Simulations of the future development of the groundwater tables indicate a severe deterioration of the situation, whatever RCP-scenarios apply. Since these predictions do not consider population growth the results mark the lowest boundary of all possible future realisations that may occur.

Keywords: Jordan, Groundwater exploration, Arid regions, Groundwater recharge/water budget, Cone of depression, Overdraft, pilot point calibration, discharge Dead Sea

1. Introduction

The Kingdom of Jordan is one of the driest countries worldwide and its water supply relies predominantly on groundwater. The backbones of Jordan's water supply from groundwater are (i) the deep Disi Aquifer, which is part of the Saq-Ram mega aquifer system (Margat and van der Gun, 2013) and (ii) the Upper Cretaceous A7/B2 aquifer complex.

Since the 1970s, it has become clear that sustainable exploration of water resources in Jordan is threatened with many problems. Population growth, intensification of inefficient irrigation and illegal abstractions have increased the stress on the available groundwater resources. The situation even sharpened with the Syrian crisis and refugee streams from Syria and other places, which increased the water demand of the country by 20% on average (Hussein et al. 2020).

The overdraft can be noticed by changing groundwater flow regimes and the rapid depletion of groundwater resources, observable at dry-falling production wells and springs and rising groundwater salinity (Burdon 1982; Dottridge and Abu Jaber 1999; Salameh 2008; Ta'any et al. 2009; Margane et al., 2015; Rödiger et al. 2017).

Pressure on water resources is increasing in many areas worldwide, calling for sustainable groundwater management practices more than ever before. To successfully do so, a profound understanding of the hydrogeological systems including the development and dynamics of water tables is fundamental. An efficient tool to gain such understanding is the joint application of hydrological and numerical models (Sophocleous and Perkins 2000; Rödiger et al., 2017). Over the last 30 years, a lot of groundwater models have been developed to estimate recent and to predict future groundwater resources behaviour in Jordan. These models were either very large-scale, designed to determine the degree of non-equilibrium and time response of the whole groundwater resources (e.g. BGR 1991, BRGM 2010, MWI and BGR 2019, Gropius et al., 2022) or local-scale flow models designed for a very restricted area, i.e. Azraq Basin (Abdulla et al., 2000); Mujib area (Abdulla and Al-Assa'd 2006; Alraggad 2009); Kafrein area (Wu et al., 2011); Zarqa Main (Odeh 2013); Jordan Desert (Al-Zyoud et al., 2015); southern Jordan Valley (Alfaro et al., 2017); Disi (Muller et al., 2017); Al Arab (Rödiger et al., 2017) and Amman-Zarqa (Abdulla et al., 2020). However, all these models have significant weaknesses, which are either unreliable numbers for groundwater recharge (GWR), inappropriate spatial and temporal distribution of GWR or wrong abstraction rates, the consequence of lacking metering and unknown (illegal) pumping.

This study aims to assess, how groundwater resources of Jordan will react on (i) climate change and associated changes in groundwater recharge rates and (ii) on increasing anthropogenic water demand and associated increasing abstraction and further dropping Dead Sea water level.

We realize that aim by setting up and forcing a transient 3D numerical groundwater model of both hard rock aquifer systems (Disi and A7/B2) on the national scale with spatial-temporal patterns of GWR that were derived from a uniform hydrological model (Rödiger et al., 2020) and meaningful groundwater abstraction rates based on calculations derived from changes in the aquifer- and basin-specific groundwater volumes (Rödiger et al., 2020).

In that national groundwater model, the flow system was calibrated by comparing the computed and observed potentiometric heads at the available observation wells. The resulting model improved the spatial distribution data of poorly constrained controlling parameters like recharge rates, thereby providing a first estimation of groundwater outflow to the Dead Sea and the effects of growing abstraction rates on the available water resources. The model successfully reproduced water level drawdown due to abstraction over the last 45 years; therefore, it can be used to forecast changes of groundwater recharge and levels under varying climatic conditions and anthropogenic activities.

In a final step, groundwater recharge based on a previous hydrological model (Rödiger et al. 2020) which using climate scenarios of the representative concentration path (RCP) (RICCAR, 2020) were used to predict changes in the groundwater level over the next few decades.

By pursuing a retrospective of a forward-looking perception of the development of groundwater resources at the national level, the present study is intended to give analyses of such essential and thus strategic resources an additional dimension. Apart from promoting a profound understanding of the complex hydrogeological and structural setting of the investigated area, the present numerical results additionally comprise an example of modelling transboundary aquifer systems under structural ambiguity, potential physical heterogeneities and restricted field accessibility and hence limited investigation. Beyond being important for the Kingdom of Jordan, this case study provides an example of a methodology that integrates hydrological data into a groundwater model to gain insights into water resources in an arid area where data is scarce too.

2. Study area

The Hashemite Kingdom of Jordan is an about 90,000 km^2 large (semi-) arid country with a population of about 10 million. The country is divided into three main physiographic provinces: i) the Jordan-Dead Sea Rift Valley (JDSR), ii) the Western Mountain Highland (WMH) and iii) the Eastern Desert, which covers ca. 70% of the territory (Figure 1A) and is an arid plateau with few ephemeral streams. The Western Mountain Highland is characterized by arable land and Mediterranean evergreen forestry that drops suddenly into the JDSR. While the Eastern Desert and the WMH are on average 600 to 900 m above mean sea level (msl), the JDSR is a deeply incised and narrow valley, which reaches from the Red Sea to the Hermon Mountains. It hosts the Lake Tiberias (-210 m msl), the Lower

Jordan River that connects the lake with the Dead Sea at recently -430 m msl and the dry Arava Valley.

The climate in Jordan is semiarid with precipitation being restricted to hibernal months and average temperatures of 16°C (WMH) to 30°C in the Eastern Desert and JDSR. Aridity poses a strong geographic gradient: while the NW and the WMH receives moderate rainfall of 200–600 mm/yr, aridity increases quickly E- and S-ward to less than 200 mm/yr precipitation in about 90% of the remaining country. The long-term average groundwater recharge in Jordan is indicated between 454 to 533 MCM/yr (NWMP, 2004; Rödiger et al., 2020). The Ministry of Water and Irrigation divides Jordan's groundwater bodies into 15 basins (A-O in Fig. 1B).

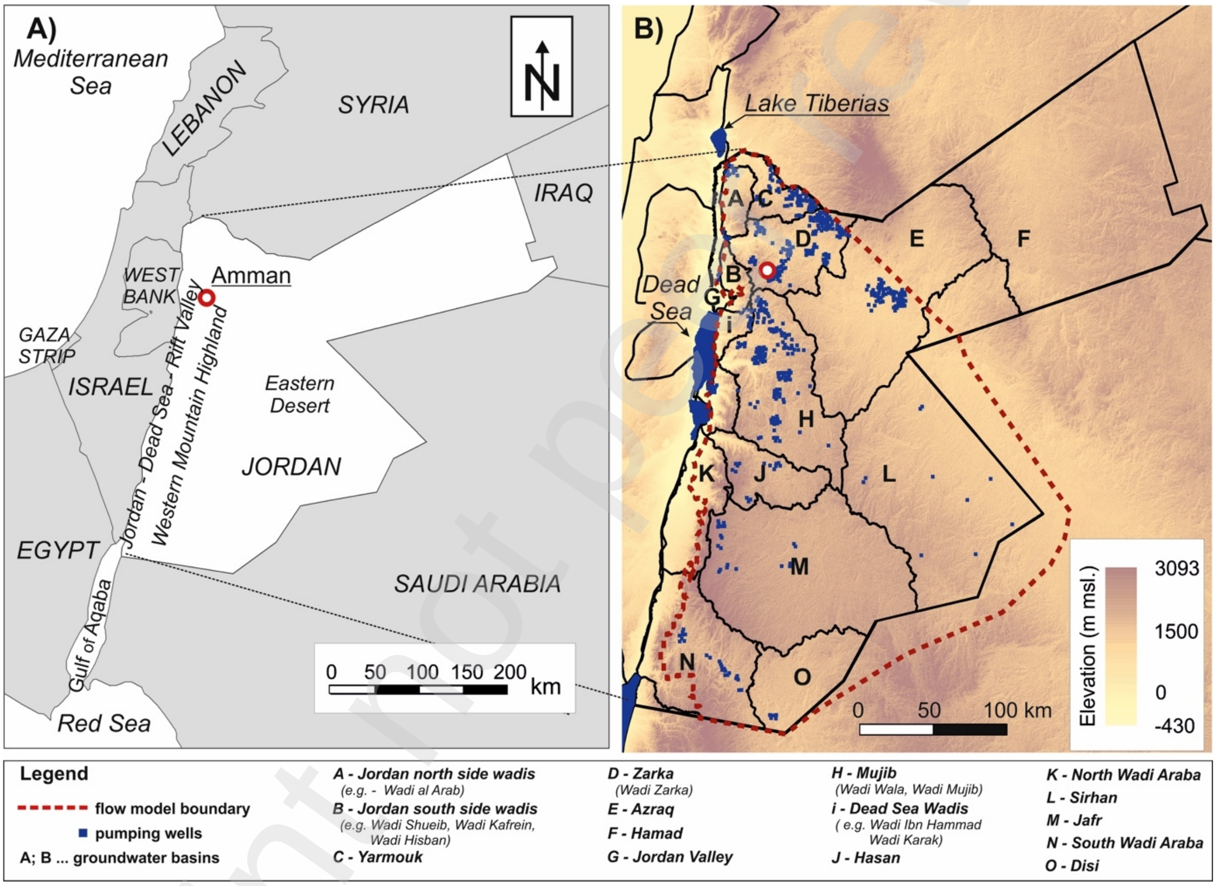


Fig. 1: A) Location map of the study area and B) groundwater basins in Jordan. Boundaries of the 15 groundwater basins (A–O) are taken from MWI (2015).

2.1. Hydrogeology

The groundwater for Jordan's water supply is mainly derived from a roughly 4,000 m thick multi-layered sedimentary rock sequence which is separated into the (I) Palaeozoic-Lower Cretaceous deep sandstone aquifer (DSA), (II) Upper Cretaceous carbonate aquifer (UCA) and (III) the locally occurring Tertiary and Quaternary shallow aquifer complex (SAC). While SAC and UCA are considered as renewable, climatic conditions permit very low to negligible natural recharge in major parts of the predominantly sandy DSA. The total annual groundwater recharge all over Jordan ranges between 454 and 533 MCM/yr (NWMP 2004, Rödiger et al., 2020).

The Deep Sandstone Aquifer belongs to the large Saq-Disi (Ram) groundwater basin, an aquifer complex that extends over 308.000 km² in Saudi Arabia and Jordan, where the DSA is widely exposed in the southern desert and present in the subsurface throughout most of the country.

In most of Jordan, the DSA is divided into two sandy sub-aquifers namely the 1,000-2,500 m thick Lower Palaeozoic Ram Group and the 40-600 m thick Kurnub / Zarqa Group of Jurassic to Lower Cretaceous Period (Lipchin et al., 2007). However, the separating 600-800 m thick Ordovician to Silurian shales and marls of the Khreim aquitard are fully eroded in the WMH and the SW of the country. There the Ram and Kurnub Groups forms a joint sandstone aquifer (Andrews 1991, Andrews 1992a, b; Wagner 2011). Where the subsequent Ajloun Group covers the DSA, groundwater in the deep aquifer gets confined.

The Upper Cretaceous Aquifer complex comprises the Ajloun and the lower part of the Belqa Groups, both deposited as a sequence of lime- and dolostones intercalated with marly strata. The UCA reaches 350-700m of thickness in the Northern Highlands and central Jordan, but is rapidly thinning out south of the Siwaqa Fault (S1). The calcareous oldest portion of the UCA (A1/2) is regionally a highly permeable aquifer is followed by 80m of marls and shales (A3), the karstic A4 limestone aquifer and another aquitard (A5/6). On top of the Ajloun sequence, a thick limestone package extends into the Cenozoic Lower Belqa group, forming the most important drinking water aquifer A7-B2. Again, that aquifer is followed by massive marls (B3), which confine the below hosted groundwater, wherever the B3 covers the A7/B2. The following predominantly chalky parts of the upper Belqa Group (B4/5) (Maastrichtian to Palaeogene) form aquifers of about 20 m thickness in SE Jordan to more than 450 m thickness in the Al Jafr Basin (Bender, 1968).

The **SAC** comprises individual basaltic and sedimentary aquifers of Quaternary age. The basaltic forms a significant good aquifer in the north of Jordan, while the sedimentary rocks and alluvial deposits form local and more or less separated aquifers.

Structurally, the most important features are the S-N directed Dead Sea Transform fault system in the west, the Azraq Graben and Sirhan Basin in the east, which form a hydraulic barrier and the E-W striking Siwaqa Fault (S1). These major geological structures limit the extent of the subsurface Dead Sea basin of the DSA, which forms the model base (Fig. 2).

In the west, the model space is bordered by the Dead Sea Transform fault system and the Dead Sea. In the south and southeast, the underground catchment area extends into Saudi Arabia due to the outcropping of the Ram formation. This expansion results in a subsurface catchment size of 66,950 km^2 for Jordan. Geological sub-structures favoured the formation of regionally important groundwater basins.

The regional groundwater contour maps of the DSA and UCA in Figures 3A and 3B were produced by NRA & GTZ (1977) and MWI & BGR (2017a; b). Jordan's groundwater system is extending into the neighbouring countries Syria, Iraq and Saudi Arabia. Hydraulic heads in the DSA of Saudi Arabia (800 m msl) and Iraq (500 m msl) indicate a groundwater flow towards Jordan, where the water passes westward and eventually discharges into the Dead Sea, whose water level (head) dropped from 1977 (-398 m msl) to 2020 (-430 m msl) (Fig. 3A). Flow patterns in the UCA, which appears in the NW part of Jordan only are remarkably different. They follow the northwards dipping of the strata in general and are locally controlled by structural features. Accordingly, highest hydraulic heads with more than 1,000 m msl occur in the central WHM, decrease northward to 800 m msl in the Ajloun and to less than 500 m msl in the Azraq depression to the east, before them reach -100 m msl in the Yarmouk Gorge (Fig. 3B).

3. Numerical flow model

FEFLOW (DHI, WASY) was applied to solve the partial differential equations governing groundwater flow in porous media. Applying FEPEST, calibration was carried out according to the PEST algorithm (Doherty 1994). The model layers were developed from point data using the Akima (1970) bivariate interpolation method. The grid was built using the TRIANGLE mesh generator by Shewchuk (2003). Mesh refinements were done along important structural features and at locations with reliable hydrogeological information (i.e. monitoring, pumping wells).

As mentioned above, the Dead Sea Transform fault system to the west, the Azraq Graben, and the Sirhan Basin (both hydraulic barriers) to the east limit the model area. As a result, the model space extends across the land border in the southeast (see Fig. 1B). This must be taken into account in the later water balance of the model. The resulting mesh resolution varies between 50 and 400 m in the model domain of 66,950 km^2, containing 316,521 prismatic elements, and 187,800 mesh nodes that ensure network convergence. Figure 2 gives an overview about the structural model and the used boundary conditions for the model set-up.

The 3D geological model contains the major hydrogeological units (Ram, Khreim, Zarqa, Kurnub, A1/4, A5/6, A7/B2, B3 and B4/5) and was developed applying ca. 1,850 well-logs (Jordan Ministry of Energy and Mineral Resources, MEMR), stratigraphic information, cross-sections derived from 1:50,000 geological maps (Royal Jordanian Geographic Centre), and geological reports (MEMR; Geological Mapping Division). Per hydrogeological unit, about

1,500 virtual boreholes were digitized tracing outcrops in geological maps and contour lines from contour line maps of top surfaces of the considered hydrogeological units (MWI-BRGM 2010), respectively. All these spatial information on strata, thickness variations, and faults were pre-processed applying GIS. Plausibility tests were done to remove inconsistencies due to errors in bore logs or misinterpreted geological maps. The approx. 3,500 points data of each individual layer were then interpolated using the Akima (1974) bivariate interpolation method to create xyz-ascii data sets of each layer's basal plane Koch (2016). The Precambrian crystalline basement is considered as impermeable and represents the model's base. The topography was derived from SRTM-DEM data with a resolution of 30 m × 30 m (ERSDAC 2009). The final 3D hydrostratigraphic model consists of 9 layers and has a total of 316.521 active cells.

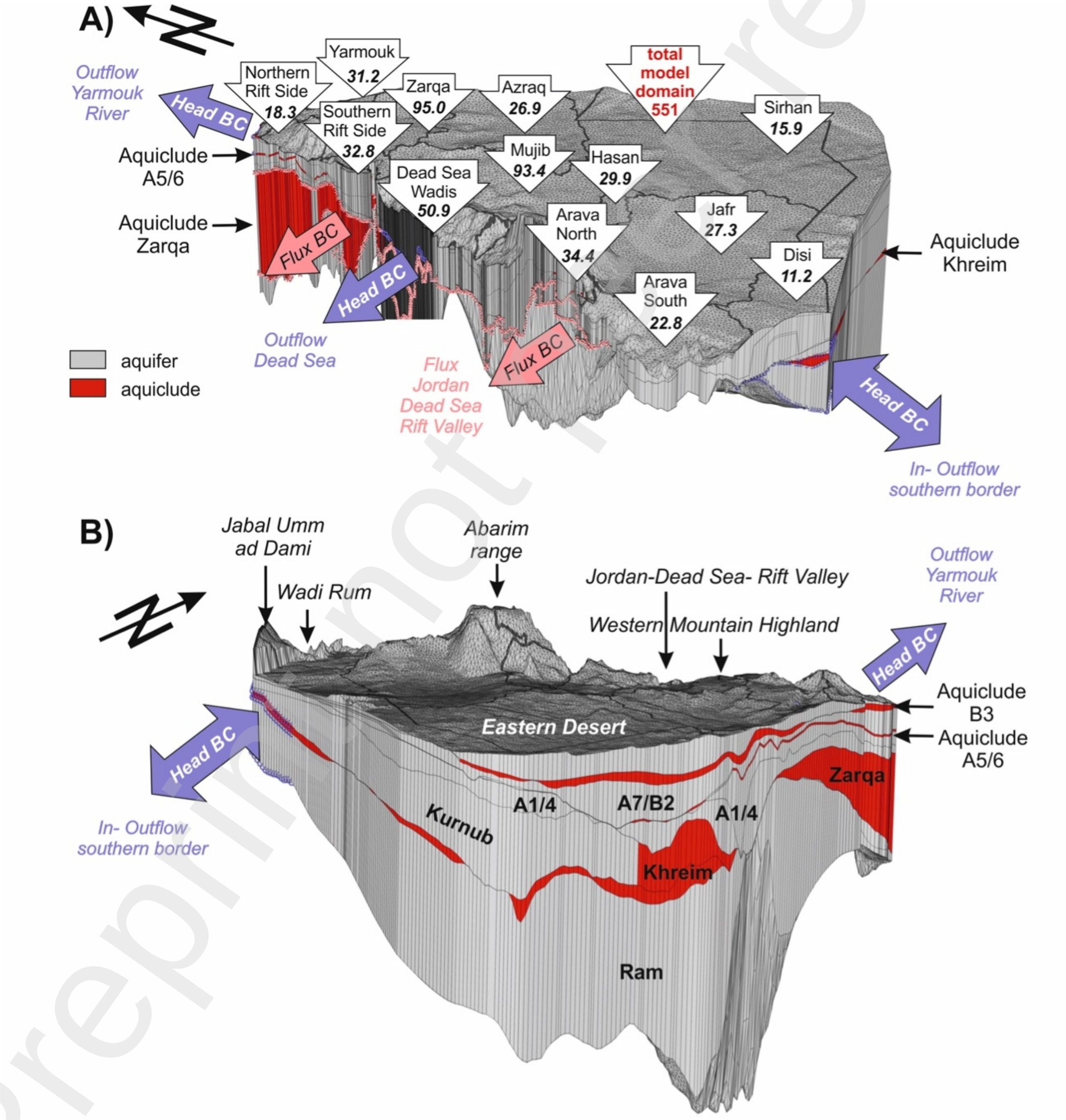


Fig. 2: View of the structural model and applied boundary conditions of the groundwater from A) the south-west perspective and B) north-east perspective

3.1. Parameters and boundary conditions

Due to missing groundwater level data outside the model domain and to allow exchange of groundwater with the outside world, the model front in the N (Yarmouk) and SW is predominantly defined as a head BC (1st kind, Dirichlet BC) (Fig. 2). As described above, the groundwater contour map from NRA & GTZ (1977) was taken to define hydraulic heads as close as possible to natural conditions. Accordingly, in UCA (layers 3, 4), hydraulic heads are interpolated between -100 m (W) and -20 m msl (E) at the Yarmouk. For DSA (layers 8-9), heads were set between 800 m (W) and 650 m msl (E) in the south. Along the Dead Sea however, a time-depend density corrected hydraulic head BC was set for layer 7, which gradually changed from 1970: -399 m msl (density corrected: -328 m msl) to -425 m msl (density corrected: -380 m msl) in 2015. The interface to the JDSR is a fluid-flux boundary (2nd kind). It allows an outflow from 0.0015 (S) to 0.0006 m/day per unit area (at the height of the south basin Dead Sea) from the DSA (layers 7-9) along Arava Valley. In the northern part of the JDSR an outflow between 0.005 (At the height of the north basin Dead Sea) and 0.0006 m/day (N) was set for the UCA (layers 7-9) along the Jordan Valley Graben. All other remaining model edges were treated as no flow BC (1st kind, Neumann BC).

Since the Dead Sea represents an important head boundary condition (BC) of the model, its hydrograph was required and compiled using data of Klein (1985) for the period 1930-1976 and of monthly data for 1976-2015, provided by the Israel Hydrological Service (2017).

Due to aquifer complexity and missing data of groundwater density in the investigation area, we decided to set up the groundwater model without density dependencies. Therefore, the hydraulic head of the Dead Sea had to be density corrected according to Freeze and Cherry (1979) and Domenico and Schwartz (1998) following Eq. (1):

$$H_i - z_i = h_i = P_i / (\rho_i * g) \quad (1)$$

with piezometric head H_I as the sum of elevation head z_i at the piezometer bottom and the pressure head h_i, which is the result from the pressure at the measurement point; ρ_i is the density of the fluid at the measurement point, and g is the gravitational acceleration. The level of the Dead Sea H_{DS} was converted into the hydraulic head h_{DS} following Eq. (2) under the assumption that the Dead Sea bottom z_{DS} is at -715 m msl (Niemi et al. 1997):

$$H_{DS} - z_{DS} = h_{DS} \quad (2)$$

The resulting hydraulic had h_{DS} must be converted into hydraulic pressure h_{gw} of the surrounding groundwater, under the assumptions that the pressure P_i in Eq. (1) corresponded to the atmospheric pressure P_{atm} (Eq. 3):

$$h_{DS} * \rho_{DS} * g = h_{gw} * \rho_{gw} * g \qquad (3)$$

Where ρ_{DS} is the density of Dead Sea brine, h_{gw} is the corrected groundwater hydraulic pressure and ρ_{gw} is the density of the almost fresh groundwater (1 g/cm^3). After the mathematical simplification Eq. 3 results in Eq. 4:

$$h_{gw} = \rho_{DS} / \rho_{gw} * h_{DS} \qquad (4)$$

To realize the correction, the density of the Dead Sea was derived for the modelling period 1977-presence from Steinhorn (1985) and Gavrieli et al. (2011): 1.19 g/cm³ (1950), 1.231 g/cm³ (1979) and 1.24 g/cm³ (today). The density adjustment resulted in the water level at the Dead Sea used as a boundary condition in the model being approx. 50-60 m higher than the observed water level of the Dead Sea.

3.1.1. Groundwater recharge

To force the model, monthly groundwater recharge (GWR) data was taken from the hydrological model of Rödiger et al. (2020) for the period 1970-2015 and implemented as source term. Due to the spatial limitations of the groundwater model (see above), the model domain includes 13 groundwater basins. Thus, GWR could be derived for each of the 13-groundwater basins (Table 1, Fig. 2), which was summed up to an average annual GWR of 490 MCM/yr that was used to establish and calibrate steady-state conditions.

To asses, how groundwater level will react on predicted climate changes, two scenarios for GWR: (i) the moderate RCP 4.5 and (ii) the extreme RCP 8.5 (RICCAR, 2020) were taken from Rödiger et al. (2020).

3.1.2. Groundwater abstraction

The intensive exploitation of groundwater resources started in Jordan in the 1970s (Courcier et al., 2005) with about 170 MCM/yr in total. Over the years, the high abstraction rates led to skewed flow fields, widely dropped groundwater heads, huge depression cones particularly in the northern and the entire western part of Jordan and a negative water balance for the entire nation (BGR & MWI, 2001; MWI 2005 Rödiger et al., 2017; MWI, 2018; MWI & BGR, 2019). However, groundwater contour maps from 1977 to 2017 reveal, these effects were not observable from the very beginning but since the intensification of abstraction at the begin of the 1980s. However, the database is fragmentary, due to illegal abstraction, missing data about starting date and rates of pumping for a large number of operational wells (BGR & MWI, 2001; Al-Bakri, 2016; Moller et al., 2017). The MWI published rough total numbers for specific years only: 440 MCM/yr in 1985, 500 MCM/yr in 1993, 494 MCM/yr in 1999 and a demand of > 650 MCM/yr in 2019 (MWI 2016; MWI and BGR 2019). Therefore, estimations of total withdrawal rates per groundwater basin based on changes of water level were taken from a previous study of Rödiger et al. (2020).

For the year 1985 the MWI (2005) provides annual abstraction rates for 1,500 pumping wells. Therefrom, mean annual abstraction rate A_N for a production well within a certain groundwater basin could be derived. The spatial allocation of the production wells was based on the known well fields according to Moller et al. (2017) (Fig. 1). The number of model nodes used for an initial implementation of the borehole boundary conditions was calculated from the total annual abstraction rate per groundwater basin A_T divided by the mean annual abstraction rate A_N. To derive monthly datasets, the annual A_N was divided equally by 12 months. The resulting monthly abstraction rates were implemented as time-dependent well boundary conditions (4^{th} kind). During the calibration process, abstraction rates have been partly modified manually to minimise the discrepancy between the modelled and the observed hydraulic heads. In Table 1 the abstraction rates present the abstraction in front the calibration process.

Table 1: The assumed model abstraction rates base on known pumping rates from MWI (2005 and 2018) and are additionally taken from Rödiger et al. (2020). The extraction rates were implemented in the model by extraction time series applied per model node. The mean abstraction rates are used as starting conditions and where changed during the calibration process. The last column contains the dimension of groundwater recharge in each of the groundwater basins, derived from Rödiger et al. (2020).

Groundwater basin (productive aquifer)	**Total abstraction A_T***	**Total abstraction A_T#**	**Mean A_N abstraction rate per model node**		**Groundwater recharge#**
	MCM/yr	MCM/yr	No of node / A_N [m^3/d]	mean abstraction MCM/yr ##	MCM/yr
Yarmouk A7/B2	54.16 - 62.8	37.51	22 / 5800	46.57	31.2
Zarqa (total) B4/B5 A7/B2 A1/4 - Kurnub	166.11 N/A 83.4 N/A	N/A 18 118.41 30	N/A 22 / 2550 49 / 4875 16 / 6000	N/A 20.48 87.19 35.04	95.0
Northern Rift Side Wadis (A7/B2) W. al Arab (A7/B2)	46.73 20.8	N/A 19.19	N/A 7 / 10050	N/A 25.67	18.3
Southern Rift Side Wadis	N/A	N/A	N/A	N/A	32.78
Surface Dead Sea basin (Dead Sea Side Wadis; Mujib, Hasan) (A7/B2)	89.98	116.78	38 / 4950	68.65	174.2

Azraq (total) B4/B5 A7/B2	52.54 43.1 N/A	46.87 N/A N/A	N/A 31 / 4100 1 / 4000	N/A 46.39 1.46	26.9
Wadi Araba North (RAM)	6.3	5.67			34.4
Wadi Araba South (RAM)	8.48	4.84	11 / 4167	16.73	22.8
Sirhan (total) B4/B5	1.71 N/A	N/A N/A	N/A 10 / 6000	N/A 21.9	15.9
Jafr (total) B4/B5	32.85 N/A	40.47 N/A	21 / 4510 N/A	34.57 N/A	27.3
Disi (Disi)	90 - 146.96	61.50	17 / 6500	40.33	11.2
total	**569.66 – 635.26**	**499.24**		**444.98**	**489.98**

* MWI (2005; 2018); # Rödiger et al. (2020); N/A unknown; ## mean abstraction rates used as starting conditions

3.2. Model calibration and validation

The model was calibrated for steady state conditions and validated under transient conditions. Steady-state simulations are carried out using best guess initial pre-pumping conditions, assumed to be presented in the 1977 groundwater contour maps (NRA & GTZ, 1977). They most probably reflect nearly undisturbed groundwater heads, applied to reproduce the character and heterogeneity of the natural system at its best. A basic dataset containing hydraulic conductivities and storage coefficients of all model layers was obtained from pumping tests and reports (BGR 1991; El-Naser 1991; CES and ACE 1993; BGR 1994; 1995; 1997; BGR & MWI 2001), allowing narrowing the limits of the automatic parameter estimation process in FE-PEST (Doherty et al. 2010). In FE-PEST the pilot point technique including Tikhonov regularization were applied (S2) to calibrate the complex fractured and large hydrogeological system. The advantage of that regularization is the possibility to incorporate geological knowledge as of the range of hydraulic conductivities for hydrogeological units as starting information during the parameter estimation. In total 2500 pilot points with regular 5 km spacing were distributed over the 9 computational layers, following the groundwater contours of NRA & GTZ (1977). Hydraulic conductivities of aquicluds (Khreim, Zarqa, A5/6, B3) where generally set to 1×10^{-9} m/s. An exception is the A5/6 formation, which is rather a poor aquifer than an aquiclude. Wherever the aquicludes have been fully eroded, pilot points were only applied within the model layer since the aquifers below and above merge.

In each layer, calibration was carried out from bottom to top, resulting in k-values, which are well within the natural ranges of the Jordanian geology (BGR 1997). The achieved threshold error of mean head residual is less than 12 m, as indicated by the correlation coefficient of R^2 = 0.98 (S3). The simulated hydraulic heads lie inside the prediction interval of 95% and absolute deviation between simulated and measured heads over all real monitoring wells ranges from +80 to -75 m, while it is in the range of ±40 m for the majority (70 %) of wells (S3). The largest deviations (outliers) occur where measured water levels were either extremely low or high, most probably referring to monitoring errors.

4. Results

Comparing the simulated hydraulic heads and flow directions for both mega aquifers (Fig. 3) with the groundwater contour maps from 1977 (NRA & GTZ; 1977) indicate a strong concordance between the results.

The calibrated steady-state model was then used as initial condition for the transient model, which was forced to simulate the period 1970-2015 on a monthly base. Storage coefficients derived from available pumping tests were adjusted as initial conditions.

To validate the transient run, from 23 available time series, characteristic well hydrographs have been selected for each groundwater basin. The comparison shows, the transient simulated groundwater levels reproduce the decrease of measured levels (Fig. 4) within the early 1980s very much. The mean variances of observed and calculated heads range between 0.4 and 25 m, while larger discrepancies of >30m (e.g. Fig. 6f; i) may refer to local effects. However, the limited available data for abstraction prevent the simulations from fully reproducing real head fluctuations, as for example for well CD1100 in the Mujib groundwater basin (Fig. 6h).

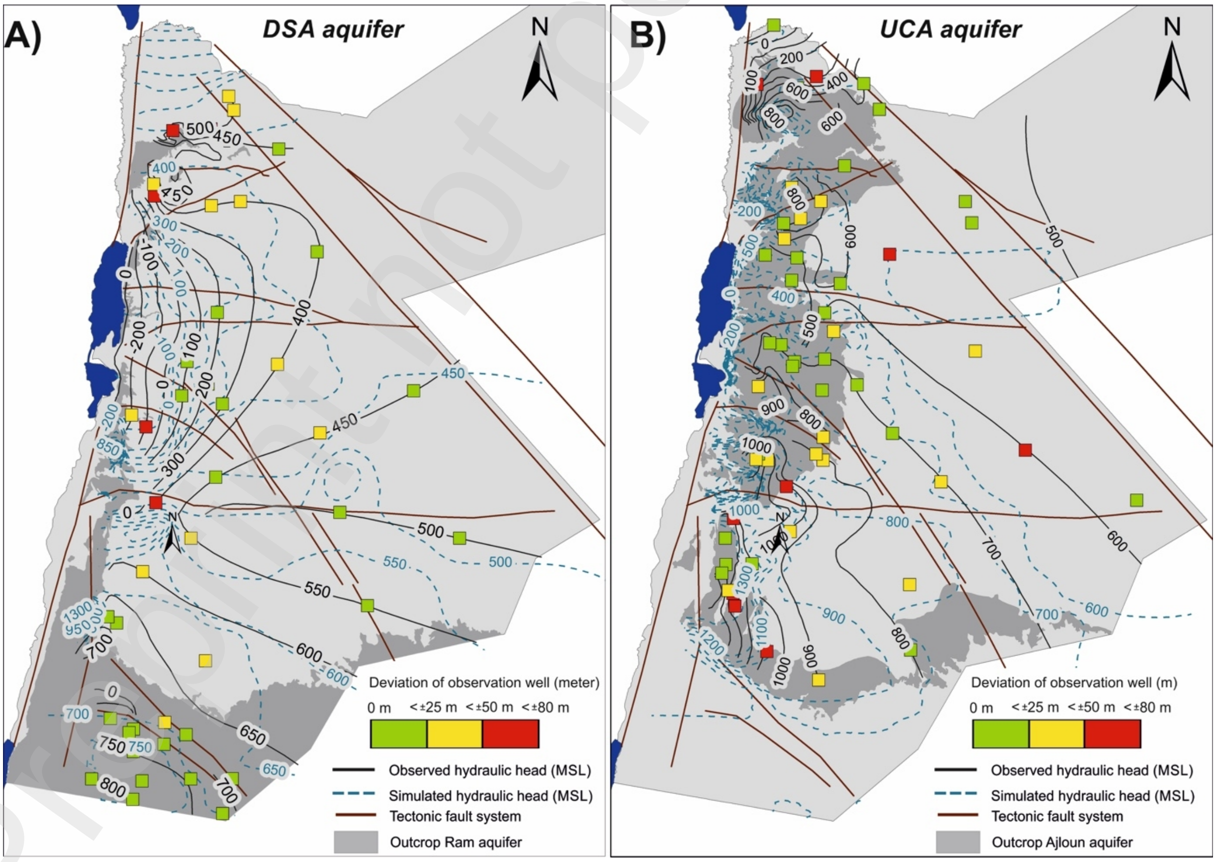


Fig. 3: Steady-state hydraulic heads for A) DSA and B) UCA. Colours of observation wells indicate the degree of deviation between the observed (black solid lines) and simulated water

levels (blue dashed lines).

The transient model was performed applying time series of groundwater recharge for each subarea and corrected Dead Sea level and two different scenarios: (i) under natural condition without pumping and (ii) under stressed condition with time-varying pumping rates.

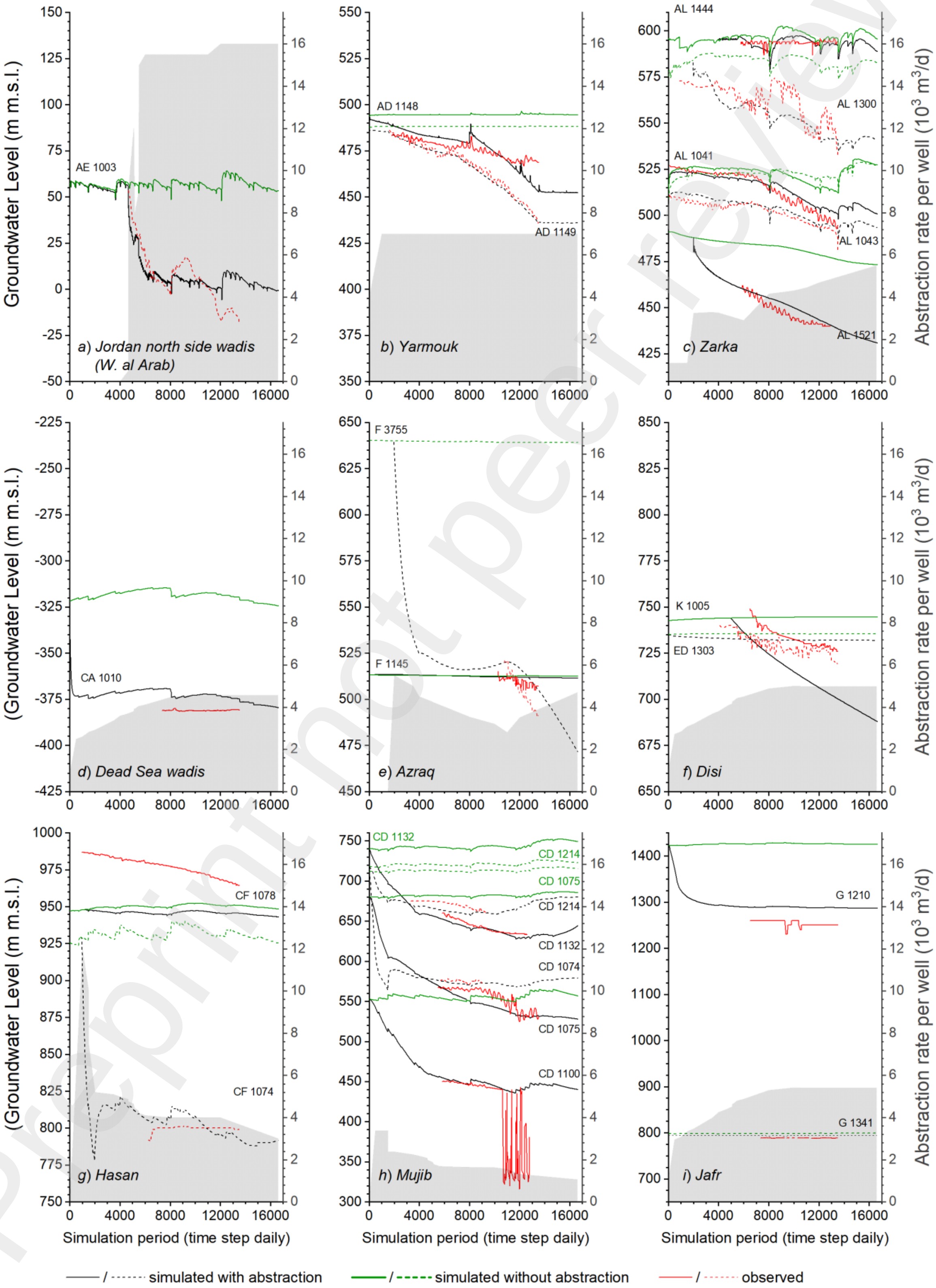


Fig. 4: Simulation results of the transient model showing measured and simulated groundwater levels under two scenarios: with abstraction (grey line) and without abstraction (green line) for 9 different basins and the mean abstraction rate per well (grey filled curve).

The model runs without abstraction (scenario i) show, that the observed dropping groundwater tables (Fig. 4 red dashed and solid lines) cannot be explained by varying recharge conditions due to climate change over the last 45 years. The simulation shows that groundwater tables (Fig. 4 green dashed and solid lines) significantly fluctuate over the year in groundwater basins, which receive > 30 MCM/yr (moderate to high) groundwater recharge. Contrastingly, no seasonal groundwater fluctuations can be observed in basins in the south (Disi, Jafr, Azraq) with low annual recharge amounts (< 30 MCM/yr), indicating a draining strong limited groundwater reservoir.

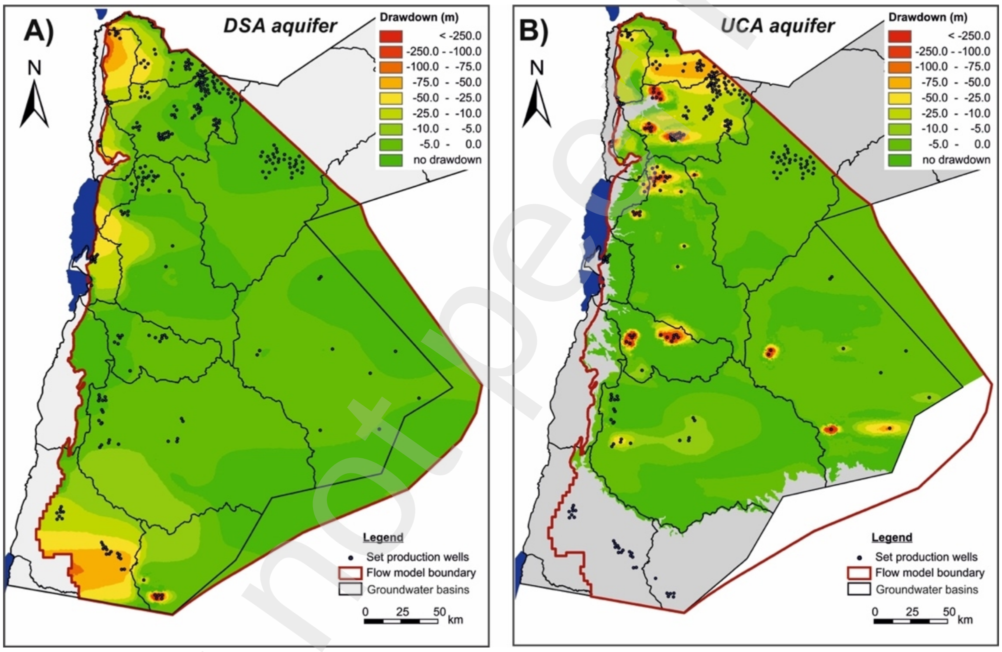


Fig. 5: shows the development of groundwater tables at the end of the simulation period in 2015, compared to 1970 for the DSA complex (A) and the UCA (B).

The figures strikingly indicate areas of heavy impacts of pumping in both aquiver complexes, though there are differences in hotpots observable. The areas of heaviest overdraft in the lower DSA are almost restricted to the JDSR and the wider area of Wadi Rum. These areas are large and characterized by relatively smooth gradients. In addition, concentrated spots are located in the Jordanian Dessert and particularly in the Mafraq area close to Syria, supplying irrigated agricultural areas and other purposes (Fig. 7A). The patterns in the UCA differ in shape. While the locations and reasons are likewise, areas in the UCA, which are affected from pumping, are less extensive, but usually show steeper gradients (Fig. 7B). The strongest depression cones are developed under urban areas in the Jordanian Dessert and the northern highland.

4.1. Water budget

For the similar modelling period of 45 years, the water balance was estimated and shows an annual deficit of 1.16 MCM (S4 and S5; Figs. 6; 7). Though the head and flux BCs at the model's margins may wrongly influence the balance and may cause numerical oscillation artefacts (over- and undershoot) is observable in Figure 6. The oscillation leads to an intense numerical change between inflow and outflow along the boundary conditions, which affects the volume of the water budget (S5 constant head and flux). Therefore, the water balance data can be taken as an approximate order of magnitude and were hence compared with published data (S4). The simulated groundwater hydrographs (Fig. 4) show that the missing numerical instability does not seriously affect the simulations.

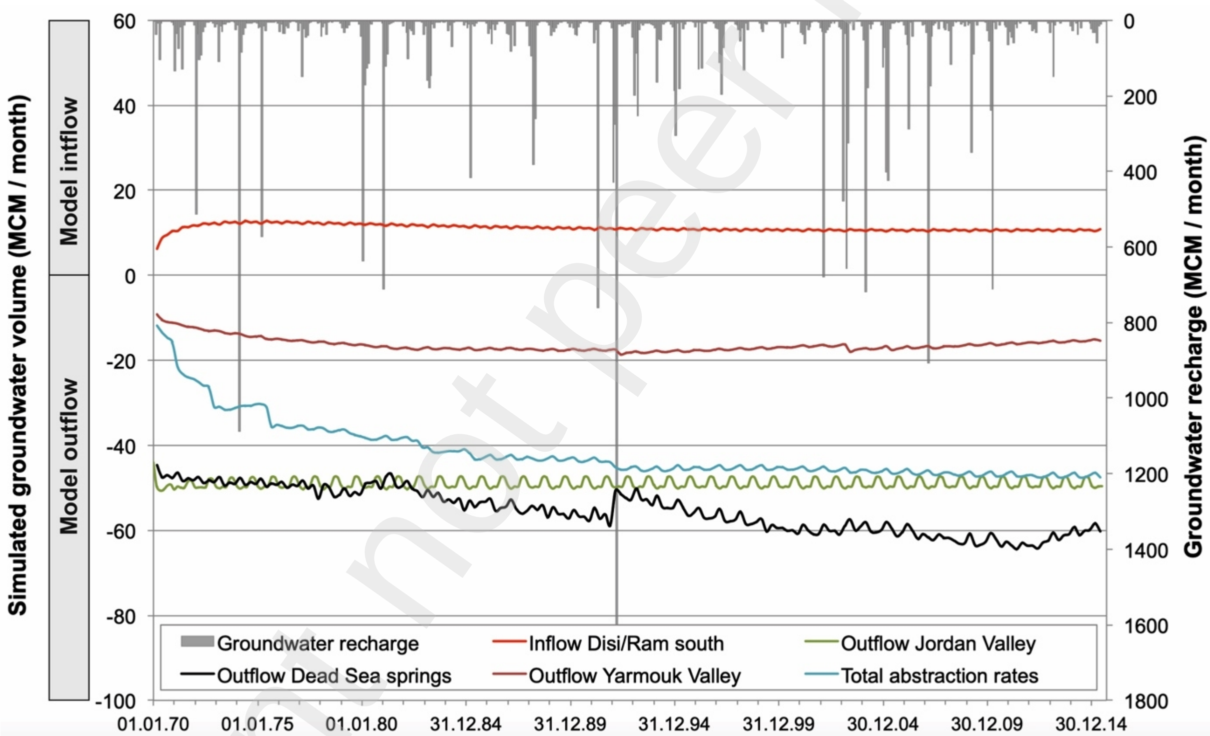


Fig. 6 shows time series of monthly groundwater recharge, total monthly abstraction rates and simulated fluxes through the model margins for the period 1970-2015.

It is visible that the discharge to the Dead Sea has increased significantly over the time period, due to the continuous decline of sea- water table. Remarkably, the outflow along the Dead Sea's rim seem to react considerably on lake level changes, which are on average continuously dropping since decades. It may induce changes in the brackish - saline water interface thus creating the increasing groundwater discharge. The detailed water balance shows that the abstraction rates and the falling Dead Sea water level leads to a clear imbalance in the water budget.

Geographically separated, the water fluxes through the margins into the different aquifer complexes are shown in Figure 7. The recharge of the whole model domain is (551 MCM/yr). Beside the remarkable amounts of annual recharge that replenishes the DSA through its outcrops in the Southern Dessert, that complex receives a large amount of water through water exchange in the Ram/Disi aquifer, resulting in a net inflow of 134 MCM/yr from Saudi Arabia. However, the loss of water via discharge into the JDSR (582 MCM/yr) and the Dead Sea (623 MCM/yr) is fairly exceeding the inflow. Particularly along the SE' shore of the saline lake the strongest outflows occur in front of the wadi mouths of Mujib, Hammad, Zarqa Main and Sweimeh, while model nodes in between show insignificant fluxes only. The locations of these discharge hot spots correspond well to observed thermal anomalies (e.g. Mallast et al., 2013) and observed outlets (Kottmeier et al., 2016; Watson et al. 2019) at the Dead Sea's shore. That UCA loses a considerable amount of 197 MCM annually into the Yarmouk Gorge. Both aquifer systems are affected by high abstraction rates from well fields in the DSA (91 MCM/yr) and UCA (407 MCM/yr). The study concludes that real abstraction rates are higher than official values.

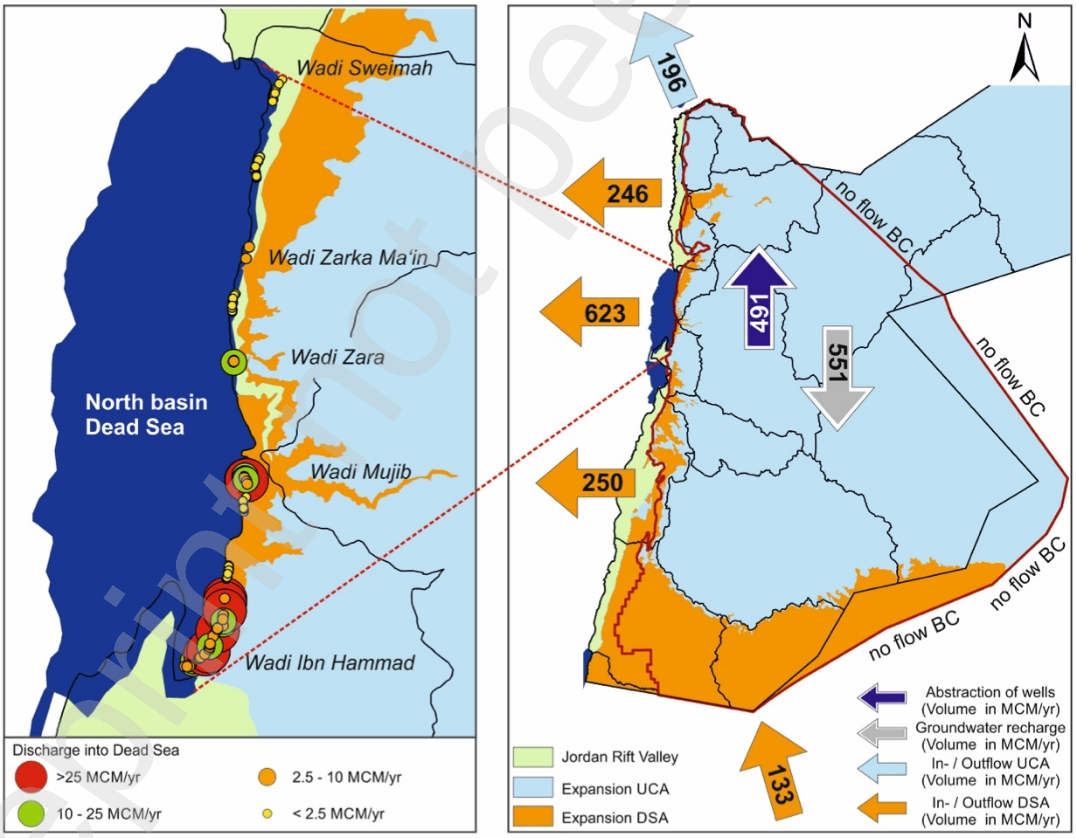


Fig. 7: shows the averaged (1970-2015) annual water fluxes through the model margins, individually for both aquifer complexes. The focus map of the Dead Sea illustrates the geographical location of the major outlets along the Dead Sea.

4.2. Future Scenarios

From modelling the past including and excluding abstraction (scenarios I and II), it becomes obvious, the observed regionally dropping groundwater tables are rather the result of overdraft than of fluctuating groundwater recharge amounts (ref. Fig. 6). However, climate change is a progressive phenomenon, which negatively influences precipitation rates in the Middle East (Hoerling et al. 2012) and as a consequence also groundwater recharge rates (Siebert et al., 2014). To evaluate, how climate change and its predicted facets may influence recharge rates and hence groundwater reservoirs is of high value for Jordan's water management. To gain such estimates for both aquifer complexes, the calibrated flow model was forced for the period 2015-2081 with groundwater recharge time series from the hydrogeological model for Jordan (Rödiger et al., 2020) as described above. They were produced obtaining climatic data sets for a moderate (RCP 4.5) and a severe (RCP 8.5) scenario from RICCAR (2020). Since the evaluation of demographic or socio-economic development is beyond the scope of that study, we kept withdrawal from Jordan's aquifers as high as in 2014 (566 MCM/yr) and the dropping rate (1 m/yr) of the Dead Sea steady.

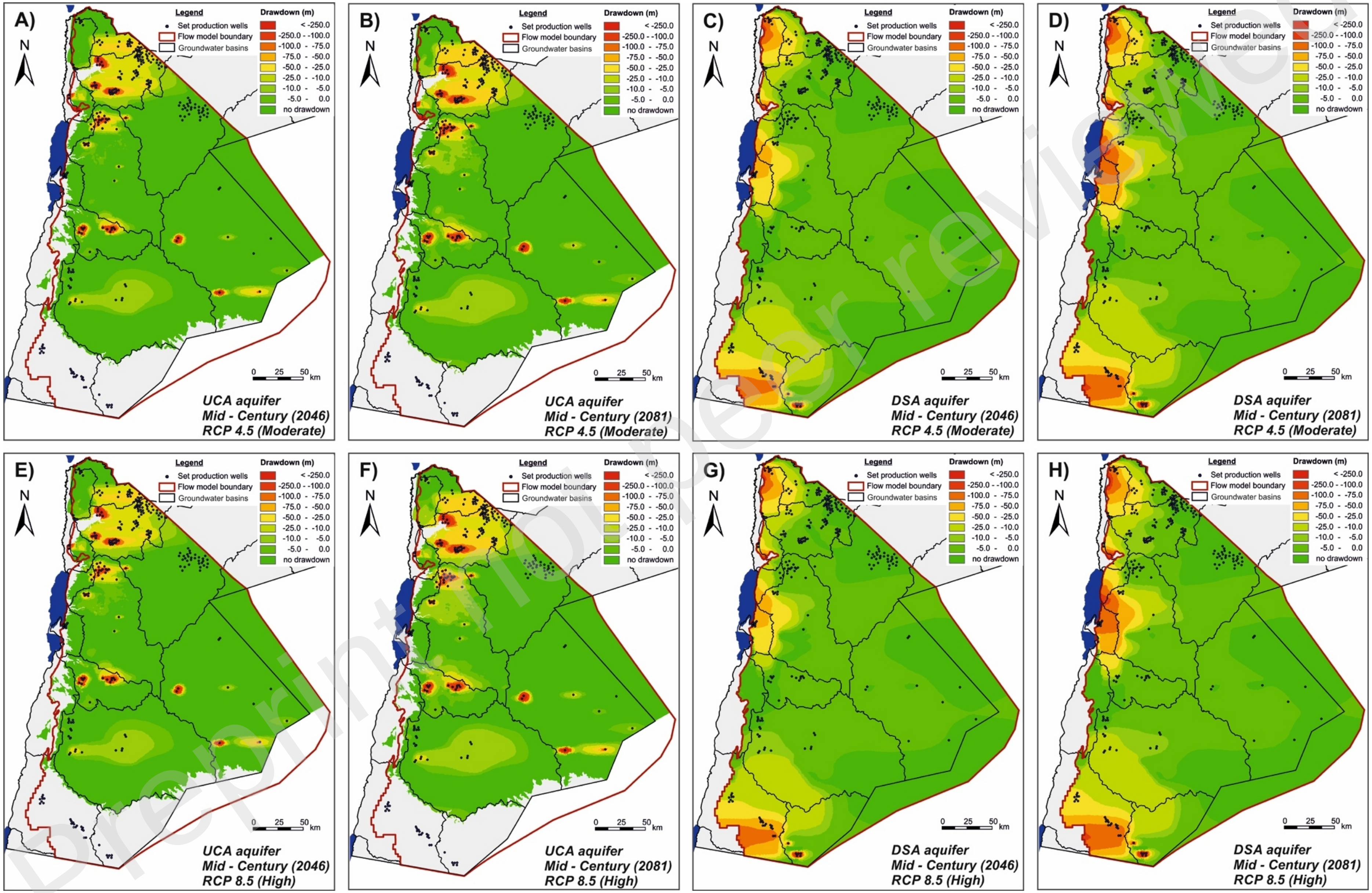
As in the historical simulations already observed, groundwater tables in both aquifer complexes react regionally different (Fig. 8). Interestingly, the developing water tables in both UCA and DSA react not as sensitive to different RCPs as expected. However, most areas, which are already affected from overdraft in 2015 show an intensification of dropping water tables.

UCA. By the end of the simulation in 2081 and whatever RCP is applied, the already well-developed depression cones increase further, particularly in the north, in the Yarmouk and Zarqa areas, which is severely affected (Figs. 8 B, D). In the latter, groundwater tables drop by 30 m in the western and southern parts of the Zarqa valley. In the southern Jafr Basin, the groundwater depression nearly quadrupoles from 60 to 100 km in E-W direction and from ca. 20 to 50 km in N-S direction. The WMH, which is the current agricultural backbone of Jordan, groundwater recharge will be reduced by up to 30 mm/yr (Rödiger et al., 2020), which leads to a drop of groundwater levels by 20-25 m in the Mujib and Hasan Basins. By 2081, more than 50% of Wadi Mujib basin will be affected by that. In contrast, except agricultural and urban agglomerations, groundwater levels in the Eastern and Southern Judean Dessert stay constant.

DSA. As the UCA, the DSA aquifer complex is extending the areas of impact, which already suffer from dropped groundwater tables, particularly in the far south in Wadi Rum area, where the groundwater depression extends much farther NE ward. The area where the water table will decrease by more than 70 m, relative to 1970 increases after 2015 at least enfold

(Figs. 8 E; G). The scenarios show also that the further falling Dead Sea water level will have a serious impact on the connected groundwater bodies. In almost 60 years it must be assumed, that the water level in the immediate vicinity of the Dead Sea will drop by up to 150 m compared to 1970. The lowering of the water level leads to a significant increase in the area that is affected by the direct sinking of the Dead Sea (Figs. 8 F; H).

460



A)
B)
C)
D)
E)
F)
G)
H)
Legend
Set production wells
Flow model boundary
Groundwater basins
Drawdown (m)
< -250.0
-250.0 - -100.0
-100.0 - -75.0
-75.0 - -50.0
-50.0 - -25.0
-25.0 - -10.0
-10.0 - -5.0
-5.0 - 0.0
no drawdown
UCA aquifer
Mid - Century (2046)
RCP 4.5 (Moderate)
UCA aquifer
Mid - Century (2081)
RCP 4.5 (Moderate)
DSA aquifer
Mid - Century (2046)
RCP 4.5 (Moderate)
DSA aquifer
Mid - Century (2081)
RCP 4.5 (Moderate)
UCA aquifer
Mid - Century (2046)
RCP 8.5 (High)
UCA aquifer
Mid - Century (2081)
RCP 8.5 (High)
DSA aquifer
Mid - Century (2046)
RCP 8.5 (High)
DSA aquifer
Mid - Century (2081)
RCP 8.5 (High)

Fig. 8: shows the difference of groundwater tables compared to those in 1970 in the UCA (A-B-E-F) and DSA (C-D-G-H), respectively. Forward simulations cover the period 2015-2081 and are forced by recharge applying RCP 4.5 (upper row A-D) and RCP 8.5 (lower row E-H). Difference maps were produced for selected time steps: at the middle of the simulation period 2046 (1st and 3rd column) and at the end in 2081 (2nd and 4th rows).

5. Conclusions

The major aim of the study was to assess anthropogenic and natural effects on the groundwater resources inn both mega aquifers, the UCA and DSA of Jordan, which was particularly challenged by the very limited data availability concerning recharge and abstraction. The high spatial data uncertainty could be improved by the stepwise calibration of the model. In combination with spatially distributed recharge calculations through hydrological modelling, the sparsely available data were enriched and allowed the reconstruction of general trends, which only fail to fully reproduce seasonal variations. The developed model is the first of its kind, in where the results of hydrological modelling that accounted for 45 years of monthly time-series of groundwater recharge were coupled to force a transient groundwater flow model.

The general groundwater flow regime of the DSA complex is largely determined by the main inflow from the Arabian Peninsula and the discharge into the Dead Sea. Additionally, the DSA receives comparably low amounts from Syria and the Iraq as well as through the outcrop band in the south of the country. The UCA complex however receives much higher direct recharge amounts and loses most of its water naturally into the Lower Yarmouk Gorge in the north of Jordan and in the Wadis flanking the JDSR. Both aquifer systems show significantly different groundwater flow directions and hydraulic heads.

Considering the heterogeneity and development of all the different hydrogeological formations, the evolution of groundwater tables in both aquifer complexes could be modelled synchronously for the period 1970-2015. Comparing the rare time series of monitoring wells, simulation results usually resemble their temporal variability and long term trends, which also proves the applied groundwater abstraction rates to be in a realistic range. Based on them, the model reproduces the regionally dramatic dropping groundwater heads in all groundwater basins. The growing depression cones with diameters in the scale of kilometres developed were mainly the product of the excessive pumping during the second half of the 1970s, but they exist. Across the nation, almost all urban areas and agricultural agglomerations are affected by these effects, which are not yet related to climate change but overdraft. Since both aquifer complexes extend beyond the administrative borders of Jordan, strongly affected areas such as Wadi Rum area in the south (DSA) and the Zarqa-Mafraq-Sabha area in the north (UCA) also have an impact on the groundwater heads outside Jordan.

Simulations applying predicted moderate (RCP 4.5) and severe (RCP 8.5) climate scenarios indicate a serious aggravation of that situation. All areas, which were affected by groundwater depletion in 2015 will aggravate. Cones of depression enlarge, already within the coming 20 years, indicating that aquifers are locally and regionally already at their limits. The further dropping of the Dead Sea will let the DSA water table dropping along the shore by more than 150 m compared to 1970, which affects that aquifer even some 100 km east of the JDSR and may enhance outflow into the Dead Sea (>750 MCM/yr). However, these forward simulations until 2081 do not consider any demographic or socio-economic change that would require higher pumping rates during the coming decades. However, predictions concerning population development in Jordan expect an increase of 40-95% compared to 2015 (DOS, 2016), which equals a population growth in total numbers from 9.7 Mio. to about 13-19 Mio. inhabitants until 2050. From these numbers it is striking, the obtained results of forward simulation for 2046 and 2081 should be taken as lowest boundary of the possible realisations that may occur.

The presented modelling framework enables the assessment of aquifer complexes on a large scale, even under data scarcity and to come up with realistic results, which allow water resources managers to evaluate their resources strategies. Though it was developed for Jordan, the principle is fully transferable to other areas worldwide, allowing (i) relative fast estimations of groundwater reservoir development even on a large scale and (ii) investigation of long-term effects of overdraft.

Credit authorship contribution statement

Tino Rödiger: Conceptualization, Writing - original draft. Stefan Geyer: Funding acquisition, Data curation. Taleb Odeh: Data curation, Investigation, Resources. Christian Siebert: Conceptualization, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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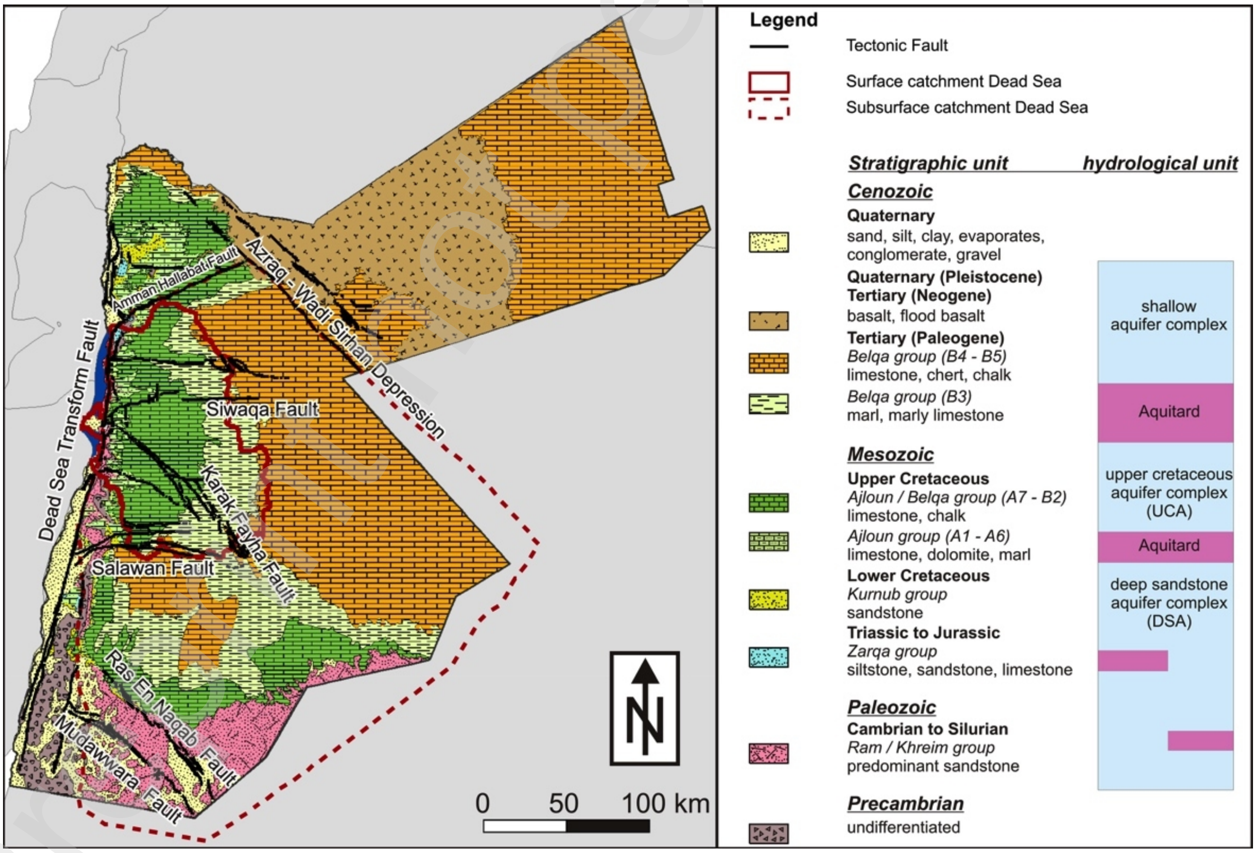
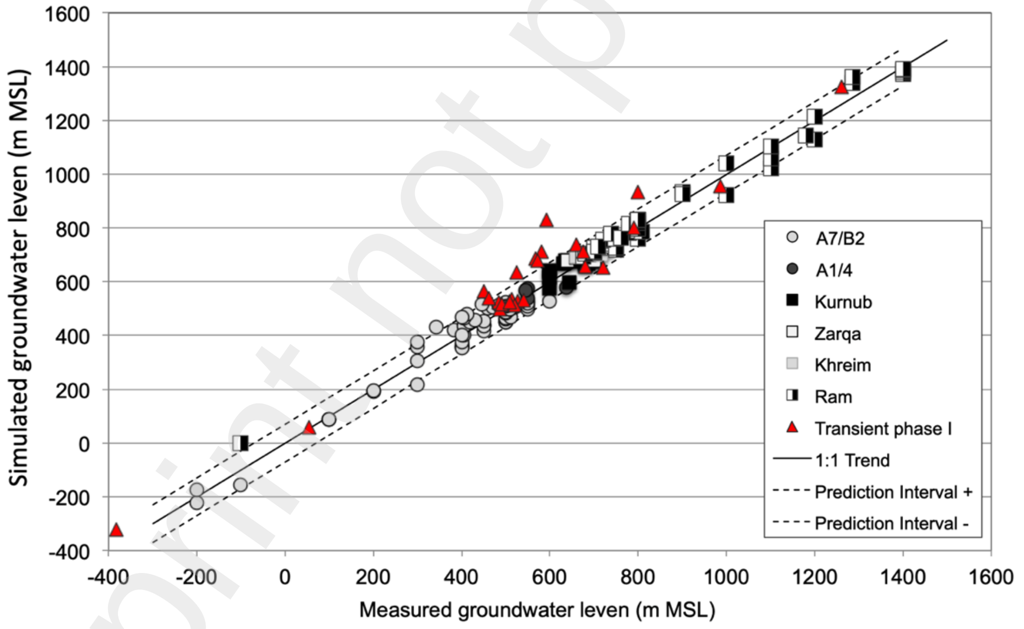
7. Supplement



S1: Geological map of Jordan. Within the legend, the geological units were assigned the hydrogeological properties (aquifer, aquiclude).

S2: Calibration parameters and results for the modelled hydrogeological units of the study area

Layer	Geological unit	Hydrogeological unit	No. pilot points	Calibrated hydraulic conductivities (m/s)			Mean thickness (m)	Storage coefficient
				Min	Max	Mean		
1	B4/5	Aquifer	200	1.0×10^{-9} (x) 1.0×10^{-9} (z)	5.4×10^{-3} (x) 6.3×10^{-3} (z)	8.48×10^{-5} (x) 3.82×10^{-6} (z)	98.72	9.73×10^{-5}
2	B3	Aquiclude	200	4.3×10^{-10} (x) 2.2×10^{-12} (z)	4.9×10^{-3} (x) 2.3×10^{-4} (z)	4.61×10^{-5} (x) 1.81×10^{-6} (z)	117.45	9.73×10^{-5}
3	A7/B2	Aquifer	400	1.9×10^{-11} (x) 5.5×10^{-12} (z)	5.7×10^{-3} (x) 9.6×10^{-5} (z)	2.01×10^{-4} (x) 1.09×10^{-6} (z)	298.93	9.73×10^{-5}
4	A5/6	Aquiclude	200	1.2×10^{-12} (x) 1.2×10^{-12} (z)	1.9×10^{-4} (x) 3.2×10^{-5} (z)	5.49×10^{-6} (x) 3.39×10^{-8} (z)	37.46	9.73×10^{-5}
5	A1/4	Aquifer	400	1.0×10^{-10} (x) 3.7×10^{-11} (z)	5.5×10^{-3} (x) 1.8×10^{-4} (z)	4.67×10^{-5} (x) 6.33×10^{-7} (z)	149.65	9.73×10^{-5}
6	Kurnub	Aquifer	400	6.3×10^{-11} (x) 1.0×10^{-12} (z)	5.4×10^{-4} (x) 2.1×10^{-8} (z)	2.28×10^{-5} (x) 1.04×10^{-9} (z)	170.98	9.73×10^{-5}
7	Zarqa	Aquiclude	200	1.0×10^{-7} (x) 1.3×10^{-10} (z)	5.6×10^{-4} (x) 2.2×10^{-6} (z)	1.28×10^{-5} (x) 1.55×10^{-7} (z)	627.28	9.73×10^{-5}
8	Khreim	Aquiclude	100	1.0×10^{-9} (x) 9.0×10^{-11} (z)	1.8×10^{-3} (x) 3.3×10^{-5} (z)	4.41×10^{-5} (x) 6.64×10^{-7} (z)	175.29	9.73×10^{-5}
9	Ram	Aquifer	400	1.0×10^{-9} (x) 1.9×10^{-11} (z)	5.7×10^{-3} (x) 3.4×10^{-4} (z)	3.76×10^{-4} (x) 8.12×10^{-6} (z)	1698.5	9.73×10^{-5}



S3: Regression analysis showing accordance between measured and simulated groundwater levels (R^2 = 0.98).

S4: Minimum and maximum annual transfer (flux) of water across the domain margins, gained for the period 1970-2015 for transient conditions (MCM = million cubic meter). Positive numbers represent gain of water into the aquifer complexes; negative numbers represent loss to the outside world.

Flux boundary	**Flux (+ Inflow / - Outflow) (MCM / a)**			**Literature (MCM / a)**	**Source**
	Mean	**1970**	**2014**		
Dead Sea (DSA)	*-623*	*-519*	*-676*	*-90* *-210* *-444* *-600*	*Salameh and Udluft (1985)* *MWI (2005)* *BGR (1991); JICA (1995);* *MWI and BGR (2019)*
Border to Saudia Arabia (DSA)	*+134*	*+109*	*+127*	*50* *269* *300*	*BGR (1991)* *MWI and BGR (2019)* *MWI (2005)*
Yarmouk Gorge	*-197*	*-128*	*-185*	*-125* *-122*	*Salameh and Bannayan (1993)* *Margane et al. (2002)*
Jordan Valley	*-246*	*-251*	*-243*	*-215* *-223*[#] *-122**	*Courcier et al. (2005)* *Rödiger et. al (2017)*[#] *JICA (1995)*[+]
Arava Valley	*-250*	*-230*	*-260*		
Pumping rates of abstraction wells	*-491*	*-177*	*-566*		*NWMP 2004* *NRA and GTZ (1977)* *MWI (2005)* *MWI and BGR (2019)*

* Contains partly Yarmouk River and Wadi Al Arab

[#] Northern part of the Jordan Valley only

[+] Southern part of the Jordan Valley only

S5: Water budget analysis of the whole model domain for transient conditions (average values for model period 1970 – 2015) (MCM = million cubicmeter)

	mean inflow (MCM / year)	**mean outflow (MCM / year)**
Constant head	398.59	-1062.27
Flux	867.02	-1448.76
Wells	0	-498.57
Recharge	551.56	0
Storage	2457.15	-1265.89
Total	**4274.33**	**-4275.49**
Total Inflow - Outflow	**- 1.16 MCM / year**	