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Large-Scale Modeling of the Groundwater Resources on the Arabian Platform

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Abstract: In arid regions, the available natural water resources are largely restricted to groundwater. The exploitation of groundwater resources becomes therefore often one of the dominant solutions to provide water for human and agricultural consumption, causing increasing pressure on the groundwater resources. In semi-arid and arid regions, the replenishment of groundwater from precipitation is very variable and groundwater is often of fossil origin or at least has been recharged over long times. In spite of the possibly low current recharge rates, the large extent and thickness of arid aquifers, such as in Saudi Arabia, store large amounts of water. Therefore, a precise quantification of the available groundwater resources including groundwater recharge is essential for the management of the limited water resources in arid regions. For a consistent assessment of the existing groundwater resources as well as the analysis of future exploitation scenarios, numerical modeling is a helpful tool. Though possible, this is not an easy task given the sparse data and the high uncertainties in their values. Our approach is to combine information and process knowledge from various backgrounds to simulate the development of the current situation during the last millennia and account for complex boundaries and spatial variability. This implies substantial pre-processing of data coming from remote sensing, geology, isotope studies, hydrogeology and hydrochemistry. Our mathematical groundwater model covers a large part of the Arabian platform. It comprises the Upper Mega aquifer system on the Arabian Platform, which consists of several hydraulically coupled aquifers. Due to the size of the model region on the one hand and the required model precision on the other hand, sophisticated modeling systems and substantial computational resources are required. Therefore, we base our work on the modeling system OpenGeoSys, because it includes a broad range of possible processes, it simulates coupled hydrosystems and is designed for parallel computing. Once the calibrated and validated model is available, different groundwater management scenarios can be evaluated in order to find an optimal management solution to satisfy the needs of the users. The model may serve as a prognostic tool for an Integrated Water Resources Management.

Key words: Groundwater modeling • Groundwater recharge • Arid regions • Open GeoSys • Arabian Peninsula

INTRODUCTION

In the framework of the International Water Research Alliance Saxony (IWAS), solutions for an Integrated Water Resources Management in hydrologically sensitive regions are developed. The Arabian Peninsula has been selected as one model region, because the problems related to water scarcity and the challenges of investigating its water resources are exemplary for arid areas all over the world.

In arid regions, available water resources are largely restricted to groundwater. The quantification of the available groundwater resources plays therefore an important role for the management of the limited resources. Demands are high, because high population growth rates lead to increased needs for food and feed crops. To meet these needs, agricultural fields are extended and large water-consuming center pivot irrigation systems are installed in many parts of the peninsula. As a matter of fact, between 75% and 80%

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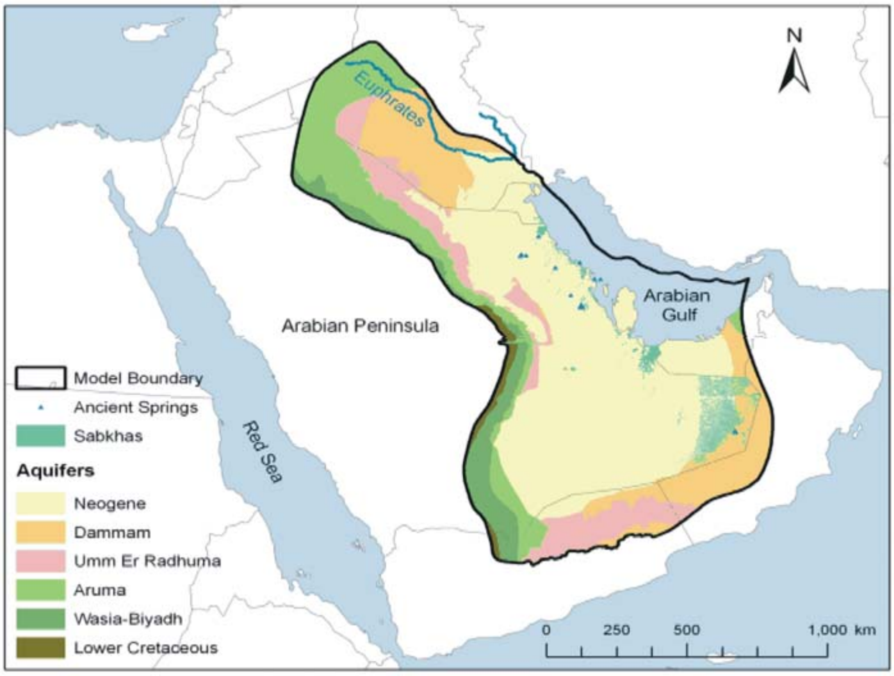

Fig. 1: Location of the study area showing the extent and outcrop of the principal aquifers of the Upper Mega Aquifer System on the Arabian Peninsula

of the water resources in the Gulf States are used for irrigation in agriculture [1].

The International Atomic Energy Agency (IAEA) estimated that much of the groundwater used in arid regions is fossil water, which is not sustainable [2]. Under present climatic conditions, the rate of groundwater recharge is very low, so that the groundwater resources will be exhausted one day if abstraction continues with present trends. In spite of the possibly low current recharge rates, large amounts of water may be stored in the aquifers due to their large extent and thickness. Determining the available water resources with high precision is required for protecting and conserving them to meet present and future water demands.

For a consistent assessment of the existing groundwater resources as well as the analysis of future exploitation scenarios, mathematical modelling is a helpful tool. Though possible, this is not an easy task given the sparse data and the high uncertainties in their values. Our approach is to combine information and process knowledge from various backgrounds to simulate the development of the groundwater resources during the last millennia and account for complex boundaries and spatial variability. This implies substantial pre-processing of data coming from remote sensing, geology, isotope studies, hydrogeology and hydrochemistry.

The present study builds on previous studies of the groundwater system in Saudi Arabia by the Ministry of Water and Electricity in cooperation with the Gesellschaft für Technische Zusammenarbeit (GTZ International Services) and Dornier Consulting and the Technische Universität Darmstadt (Germany). The main objective of the present study is to bring together all data from previous studies in order to set up a comprehensive model of the entire Upper Mega Aquifer System. This will enable us to gain a better understanding of the complete system behavior and to overcome problems related to boundary effects. Such problems may occur in cases where model boundaries do not match with natural boundaries and may lead to a strong dependence of the model results from the definition of the boundary conditions. Our approach is to cover the entire aquifer system in order to consider only natural boundaries.

Study Area: The boundaries of the study area were selected according to the extent of the Upper Mega Aquifer System. The study area covers a large part of the Arabian Peninsula and is part of the Arabian Platform (Figure 1).

The landscape is dominated by large peneplains, interrupted by escarpments and a few small hills [3]. In the south, the Rub' Al Khali desert dominates the landscape.

Elevations range from sea level at the coast of the Arabian Gulf up to 1,200 m above sea level at the Jawl Plateau in the south. The region lies within the great desert belt, characterized by high temperatures and semi-arid to hyper-arid climate zones. Average annual rainfall ranges from 220 mm/a near the escarpments in the northeast to less than 100 mm/a in the west [4] and average annual air temperatures vary between 28°C and 37°C [1]. Traces of old river systems are present throughout the study area [5, 3]. Most of these old river courses are still sporadically active at intense rain storms and may significantly contribute to groundwater recharge.

MATERIALS AND METHODOS

Data Base: During previous investigations, data from numerous sources have been compiled and pre-processed for further analyses [7-10]. Modeling studies have also been performed for selected areas within the Kingdom of Saudi Arabia. In the present study, all data is merged from the previous studies in order to set up a comprehensive hydrogeological model of the entire Upper Mega Aquifer System. We use mainly already pre-processed data from the previous studies if available, which are supplemented with newly acquired data if necessary.

Pre-processed Data Include:

- Extents and thicknesses of the different hydrogeological units,
- Hydraulic parameters of the different hydrogeological units,
- Distribution and evaporation rates of sabkhas,
- Locations and discharge rates of springs,
- Locations and abstraction rates of wells,
- Time series of piezometric heads at several wells,
- Maps of piezometric heads for different times,
- Development of the sea level of the Arabian Gulf for the last 10,000 years,
- Estimation of groundwater recharge rates (current distribution and development for the last 10,000 years),
- Maps of concentrations of total dissolved solids and
- Isotope data from groundwater samples.

Newly Acquired Data Will Include:

- Distribution of rainfall from remote sensing data,
- Improved spatially distributed estimation of recharge rates,
- Additional measurements of isotopes and rare earth elements,
- Results from ongoing geological and hydrogeological investigations.

Approach: All data are compiled in a Data Management System (DMS), which also allows the visualization of data. Analyzing the available data, a conceptual model of the aquifer system is developed comprising the identification of hydrogeological units, the parameterization of these units, the identification of system boundaries and the identification of the water budget components. All components of the conceptual model will be included in the DMS, which then enables the transformation of the data into a mathematical groundwater model. The numerical simulations will be carried out using the modeling system Open Geo Sys [11, 12], which includes a broad range of possible processes; it simulates coupled hydro-systems and is designed for parallel computing. The simulations will start 10,000 years BP to investigate the long-term transient development of the groundwater resources since the last ice age in order to conclude on the current natural state of the system (“predevelopment state”). From 1940 AD on, groundwater abstractions for agricultural, domestic and industrial use have to be included (“present state”).

RESULTS

Conceptual Groundwater Model: The conceptual groundwater model includes the different hydrogeological units and their properties, the system boundaries and the groundwater budget components including all in- and outflow components, which will be briefly discussed in the following.

Hydrogeological Units: The Upper Mega Aquifer System comprises a sedimentary succession of Jurassic to Tertiary age. The sediments mainly consist of sandstones, carbonates (limestone and dolomite) and evaporites (gypsum and anhydrite). The principal aquifers of this system are from bottom to top the Wasia-Biyadh, Umm Er Radhuma, Dammam and Neogene aquifer. Secondary aquifers are the Lower Cretaceous and the Aruma aquifer. These aquifers are partially separated by aquitards, namely the Shu’aiba aquitard, the Upper Wasia / Lower Aruma shale and the Rus aquitard. However, the Shu’aiba and the Rus aquitards appear to be not completely impermeable, but are rather connected via hydraulic windows resulting in cross-formation flow between the aquifers. The Upper Mega Aquifer System is separated from the Lower Mega Aquifer System by the Hith aquiclude.

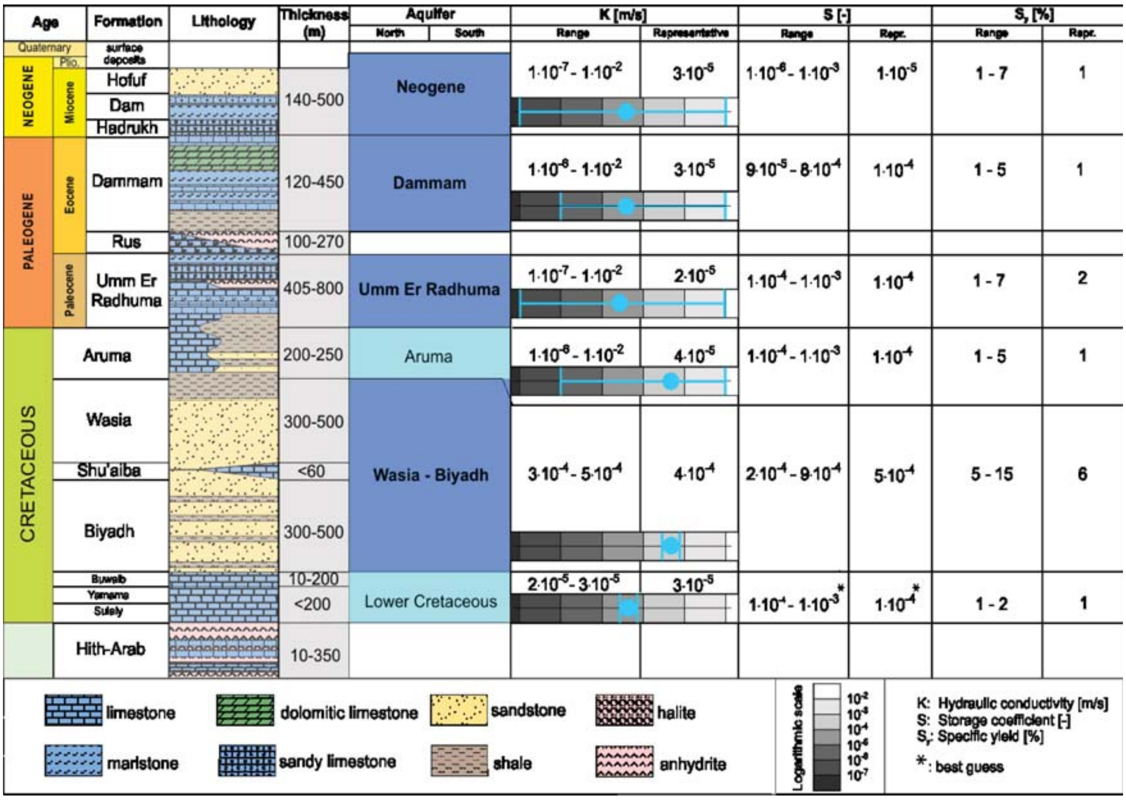

Fig. 2: Geological, lithological and hydrostratigraphical units of the Upper Mega Aquifer system on the Arabian Peninsula. The corresponding hydraulic properties (hydraulic conductivity K, storage coefficient S, specific yield S_y), their averages, representative values and ranges are shown on the right side.

From bottom to top, the following hydrogeological units have been identified (s. Figure 2):

Hith Aquiclude: The Upper Jurassic Hith Aquiclude consists of anhydrite that forms an effective seal extending over most of the Arabian Platform. In conjunction with the Arab evaporites it forms a part of the most important cap rock in the Middle East [13].

Lower Cretaceous Aquifer: The Lower Cretaceous aquifer is a secondary aquifer that represents a number of water-bearing units in the central part of Saudi Arabia. It comprises the Buwaib, Yamama and Sulaiy formation and consists of very fine or argillaceous limestones. The aquifer crops out along a 80 km wide stripe from Az Zulfi down to the southern Saudi Arabian border. The extent in east-west direction comprises an area from the outcrops down to the Arabian Gulf in the east. The Lower Cretaceous formations are important local aquifers in their respective outcrop areas, where they are cracked and weathered. With greater depth, the rock becomes less fractured and compact. Average hydraulic conductivity is $K = 3•10^{•5}$ m/s. The representative storage coefficient is $S = 1•10^{•4}$.

Wasia-Biyadh Aquifer: The Lower Cretaceous Biyadh aquifer represents the lowest member of the “Cretaceous Sands Aquifers”, where prevailing in its sandy facies. The Wasia aquifer comprises the water-saturated sandstones of the Middle Cretaceous Wasia formation. Both formations consist of an alternation of medium- to coarse-grained, poorly cemented sandstone with interbedded shale. In the western part of the study area, close to the outcrop, the Biyadh and overlying Wasia aquifers are in direct contact and form the Wasia-Biyadh aquifer, which is considered a principal aquifer in Saudi Arabia. In the eastern part, these two aquifers are separated by the Shu’aiba aquitard, consisting mainly of calcareous deposits, i.e. limestone, dolomite or dolomitic limestone. However, the hydraulic effectiveness as aquitard is doubtful and significant vertical leakage can be assumed.

The Wasia-Biyadh aquifer can be characterized as a porous sandstone aquifer. Due to its relatively poor cementation, the primary porosity is largely conserved and most likely dominates over the secondary porosity caused by fractures and bedding planes. Over major parts of the study area the Wasia-Biyadh aquifer is confined. Only in the extreme western part, unconfined conditions prevail. Average hydraulic conductivity is $K = 4 \cdot 10^{-4}$ m/s. The representative storage coefficient is $S = 5 \cdot 10^{-4}$.

Upper Wasia / Lower Aruma Aquitard: This aquitard comprises the shaly units of the Upper Wasia and Lower Aruma formations. Although the shales belong to two different formations, they can be considered as one hydrostratigraphic unit that separates the Wasia aquifer from the overlying Aruma and Umm Er Radhuma aquifers. In the central part of the study area, the deposition of the Upper Wasia shales reaches westward as far as few tens of kilometers east of the outcrop of the Wasia formation. There, the thickness of this unit ranges only between 20 m and 50 m. Towards the east, the Upper Wasia shales are overlain by the Lower Aruma shales to form a joined package that reaches a thickness of more than 500 m east of the Ghawar structure. The effectiveness of this aquitard/aquiclude is demonstrated by the high piezometric head difference between the Wasia aquifer and the overlying Aruma / Umm Er Radhuma aquifers. In the coastal area, a head difference of about 200 m is observed.

Aruma Aquifer: The Aruma aquifer represents a secondary aquifer and so far has been of relative minor importance for the water supply of the Kingdom. Lithologically, the Aruma formation is dominated by massive, partly dolomitised limestones and dolomites with subordinate marls and shales in the upper part of the formation. It can be characterized as a partly karstified fractured bedrock aquifer, where groundwater movement occurs along preferential flow paths formed by secondary openings, such as joints, fractures and bedding-plane openings, which are often enlarged by solution processes [5, 7]. It can be described as a leaky unconfined/confined aquifer, with unconfined conditions existing near the outcrop areas. In the larger part towards the east of the study area, the aquifer remains under leaky unconfined conditions. In the coastal regions of the Arabian Gulf, artesian confined conditions occur. Average hydraulic conductivity is $K = 4 \cdot 10^{-5}$ m/s. The representative storage coefficient is $S = 1 \cdot 10^{-4}$.

Umm Er Radhuma Aquifer: The Umm Er Radhuma aquifer represents a principal aquifer and is the most important aquifer in the eastern part of Saudi Arabia. The lithology of the Umm Er Radhuma formation is dominated by limestones, arenitic limestones, dolomitic limestones and dolomites, where subordinate marls and shales occur in the upper part of the formation. The formation thickness increases from its outcrops in the west of the study area towards the east to about 800 m at the Arabian Gulf. The mean thickness is about 400 m. The Umm Er Radhuma can be characterized as a karstified fractured bedrock aquifer. Groundwater movement occurs primarily through secondary openings, such as joints, fractures and bedding-plane openings, which are often enlarged by solution processes. In areas of mature karst conduits like pipes and caves, as well as dolines, closed depressions and sinkholes are developed. The karstification in vertical and horizontal direction is unevenly distributed leading to large heterogeneities in permeability and storativity. The Umm Er Radhuma aquifer can be described as a leaky unconfined/confined aquifer. Unconfined conditions exist at the outcrop areas and for some distance to the east until the piezometric surface intersects with the confining units of the Rus formation. In the larger part towards the east of the study area the aquifer remains under confined conditions. Near the shoreline of the Arabian Gulf, artesian confined conditions are indicated by coastal sabkhas, which are thought to be mainly fed by ascending groundwater. The values of hydraulic conductivity range between $K = 1 \cdot 10^{-7}$ m/s and $1 \cdot 10^{-2}$ m/s with an average of $K = 1.6 \cdot 10^{-5}$ m/s. The representative storage coefficient is $S = 1 \cdot 10^{-4}$.

Rus Aquitard: The Rus formation consists of soft limestones, dolomitic limestones, chalky limestones, shales and sulphates (gypsum and anhydrite) where present. A complete Rus succession contains large portions of sulphates that constitute an efficient aquitard between the underlying Umm Er Radhuma aquifer and the overlying Dammam aquifer complex. In areas where no sulphates occur, the Rus formation with its carbonates forms effectively an upward extension of the Umm Er Radhuma aquifer. These zones may serve as hydraulic windows between the Umm Er Radhuma and Dammam aquifers, where groundwater exchange is enabled across the confining units of the Lower Dammam.

Dammam Aquifer: The Dammam aquifer complex represents another principal aquifer. Lithologically, the formation is composed of a succession of limestones, dolomitic limestones, marls and subordinate shales. In the lower part of the formation marls and shales (Midra shale, Saila shale and Alveolina) are dominant, while in the upper part (Khobar, Alat) carbonate rocks prevail. The maximum thickness of the formation reaches 450 m with an average of 120 m. The Dammam aquifer complex is composed of two single aquifers (Khobar and Alat aquifers), which are partly separated by the thin marl units of the Alat Marl. The marl constitutes a leaky aquitard. However, for the purpose of this study, the Dammam aquifer complex is regarded as a single hydrostratigraphic unit. It can be characterized as a partly karstified fractured bedrock aquifer. Unconfined conditions exist at the outcrop areas including Qatar. In the larger part towards the east of the study area, the aquifer remains under leaky confined conditions. Near the shoreline of the Arabian Gulf and further to the east, the Dammam aquifer remains under artesian confined conditions. Artesian conditions also exist in a restricted area around Yabrin. In contrast to complete saturation within the regions of a confined aquifer, in the unconfined areas the saturated thickness is less than the total thickness of the formation. The values of hydraulic conductivity range from $K = 1 \cdot 10^{-6}$ m/s to $1 \cdot 10^{-2}$ m/s with an average of $K = 3.2 \cdot 10^{-5}$ m/s. The representative storage coefficient is $S = 1 \cdot 10^{-4}$.

Neogene Aquifer: The Neogene aquifer complex represents a principal aquifer consisting of a complex succession of marine, transitional and continental sedimentary rocks. The Hadrukh formation comprises sandstones, marls, sandy marls and sandy limestones, the Dam formation primarily marls, clays and sandy limestones near its base and the Hofuf formation sandstones and conglomerates with intercalations of thin limestones and marls. This succession grades inland, towards the west, into wholly continental deposits. The Neogene is dipping with an angle of approximately ~0.1° to the east, where it reaches its maximum thickness of 500 m within the study area. The Neogene complex is considered as one hydrostratigraphical unit, characterized as a mixture of karstified fractured bedrock aquifers and unconsolidated porous clastic aquifers. On a regional scale, it can be regarded as an unconfined aquifer. In the coastal regions and in the Arabian Gulf/Euphrates-Tigris basin areas the aquifer is artesian confined. Hydraulic conductivities range from $K = 1 \cdot 10^{-7}$ m/s to$1 \cdot 10^{-2}$ m/s with an average of $K = 2.8 \cdot 10^{-5}$ m/s. The representative storage coefficient is $S = 1 \cdot 10^{-5}$. The lower aquifer boundary in areas near the Arabian Gulf is composed of the marls of the Hadrukh formation. Further to the west, fine clastics and clays of the undifferentiated Neogene hydraulically separates the Neogene from the Dammam aquifer complex.

Tectonic Settings: In general, the formations are dipping gently from the outcrop areas in the west to the east. The constant dip of the formations is only interrupted by a series of mainly north-south trending anticlines and synclines which represent the major tectonic elements. These anticlines play an important role in the flow pattern of the aquifer system. The highest vertical hydraulic conductivities can be found along these structures. They show a higher fracture density and sometimes a reduction in primary thickness. These zones are important as they provide "hydraulic windows" between adjacent aquifers.

System Boundaries: The aquifer system boundaries are laterally defined by the physical extent of the hydrogeological units. The eastern limits are defined by the discharge area which consists of the Arabian Gulf and the thalweg of the Euphrates-Tigris basin in the northeast. The western boundary of the aquifers is given by their outcrops. The bottom of the aquifer system is formed by the top of the Hith formation. The Hith is considered impervious. A possible upward leakage from deeper aquifers is considered to be very small compared to groundwater exchanges within the aquifer system and can therefore be neglected. The top constitutes the Neogene aquifer complex representing the uppermost unit of the Upper Mega Aquifer System.

Groundwater Budget Components: Investigating the groundwater budget involves the identification of all inflow and outflow components of the system. In the study area, inflow occurs through groundwater recharge from precipitation and inflow through wadi channels. Natural outflow occurs through discharge to the Arabian Gulf and the Euphrates-Tigris basin, evaporation through coastal and inland sabkhas and springs (for the predevelopment state, Figure 3A). For the present state, spring discharge can be neglected since all springs went dry during the 1980s to 1990s, but abstractions from wells constitute a major outflow component (Figure 3B). The inflow and outflow components of the investigated system are described in the following section.

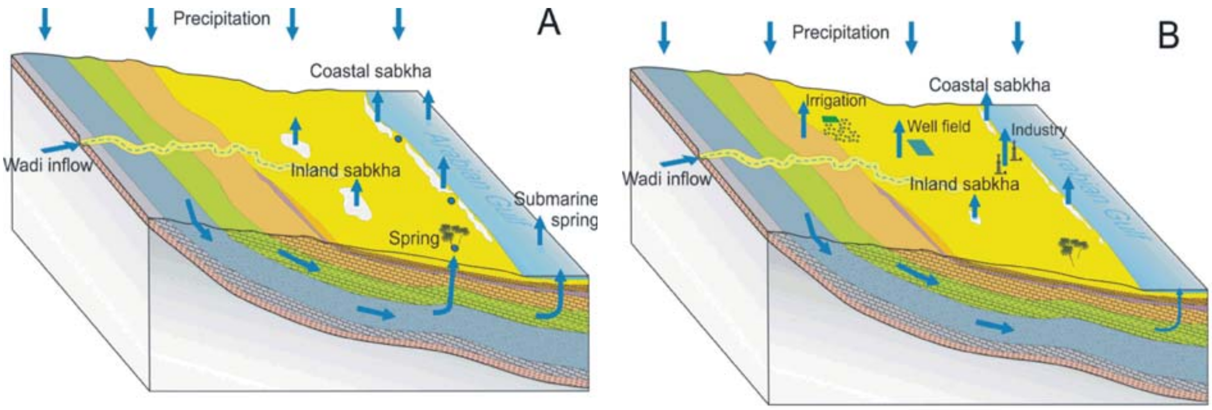

Fig. 3: Schematic sketch showing the different groundwater budget components for (A) the predevelopment state and (B) the present state

Inflow Components: The major inflow components are (i) groundwater recharge from precipitation and (ii) inflow through wadi channels.

- Historic groundwater recharge has been estimated from published precipitation data (e.g. [14-19]. Climate conditions changed over the last 10,000 years from more humid conditions after the last ice age to arid conditions for the last 5,000 years. As a first rough estimate it was assumed that 5% of the precipitation recharged the groundwater. Estimated recharge rates vary between 30 mm/a and 2.5 mm/a. Two periods of higher recharge rates can be identified between 10,000 and 5,000 years BP. During the last 5,000 years the climate was continuously arid with recharge rates similar to present recharge rates (~5 mm/a).

Present groundwater recharge rates have been determined for a large part of the study area within previous studies [7, 10] using the method of soil moisture balancing in GIS-based hydrological modeling. The method considers three different processes of groundwater recharge using the definition of [20, 21]:

- Direct groundwater recharge: the part of precipitation that moves directly through the unsaturated zone to the groundwater in excess of soil moisture deficits and evapotranspiration;
- Localized groundwater recharge: groundwater recharge resulting from horizontal surface concentration of precipitation in the absence of well-defined channels;
- Indirect groundwater recharge: percolation of water through the beds of surface water courses.

All relevant hydrological processes (precipitation, evapotranspiration, infiltration, surface runoff and channel flow) as well as catchments and soil properties were processed as gridded information in GIS. The hydrological model calculates the soil moisture balance, surface runoff, channel flow and infiltration.

Preliminary results indicate that in some parts of the study area, particularly in the south, no or negligibly small groundwater recharge occurs. This is not surprising, since these parts comprise the Rub' Al Khali desert, where very low precipitation coincides with thick deposits of Quaternary sands and infiltration of precipitation reaching the groundwater table is unlikely. Close to the western border of the study area, recharge rates of 15 mm/a and more were calculated. For the Arabian platform within the borders of the Kingdom of Saudi Arabia, present average annual groundwater recharge has been estimated to 112.5 m^3/s (3,550 MCM/a).

In the course of the project, spatially distributed recharge rates will be re-calculated for the entire study area including improved methods for the estimation of the rainfall distribution [22].

- Several wadi channels with catchment areas outside of the investigation boundary intersect the study area. These wadi channels are filled with sand and gravel deposits which form local porous aquifers. The underlying bedrock aquifers are recharged from these local aquifers by leakage.

For four major wadi channels (Wadi Ar Rimah-Al Batin, Wadi Hanifah, Wadi As Sabha and Wadi Ad Dawasir) estimated flow rates of the sand and gravel aquifers were available based on the geometry of the porous aquifers, the corresponding hydraulic conductivity and the slope of the groundwater surface, which was assumed equal to the slope of the ground surface [7]. The hydraulic conductivity of the Wadi aquifers was determined to $K = 1 \cdot 10^{-4}$ m/s and the thickness of the water-filled body was estimated to be about 100 m. The widths of the wadi channels were determined individually by a digital elevation map and validated by the size of the catchment area. The total inflow to the bedrock aquifers from the four wadi channels was estimated to 0.495 m^3/s (15 MCM/a).

Outflow Components: The major natural outflow components are the (i) discharge to the Arabian Gulf and to the Euphrates-Tigris basin, (ii) discharge through springs and (iii) evaporation from inland and coastal sabkhas. Anthropogenic outflow components comprise (iv) well abstractions for agricultural, domestic and industrial use.

- The Euphrates-Tigris basin and the Arabian Gulf represent natural boundaries for the groundwater model. The water table in the Arabian Gulf is simply at sea level, but the density of the salt water has to be considered and an equivalent freshwater head has to be determined from the salt water head. For transient simulations since the last pluvial period, the development of the sea level of the Arabian Gulf has to be taken into account, which can be found in [23]. For the present state, the discharge to the Arabian Gulf was estimated to 6.0 m^3/s (189 MCM/a). Discharge to the Euphrates-Tigris basin was estimated to 2.2 m^3/s (69 MCM/a) [7].
- Artesian spring discharge occurs at oases and at some submarine fresh water springs in the Arabian Gulf. The main oases regions in the study area are the Al Hasa oasis, the Al Qatif oasis and the oasis in the northern part of Bahrain. Measured discharge data from these spring systems are available from [24-26]. In the Al Hasa oasis, the springs had a total free flowing discharge of about 10 m^3/s (315 MCM/a) in the predevelopment state, in the Al Qatif oasis it was about 1.6 m^3/s (50 MCM/a). The springs in Bahrain had a total discharge of 2.8 m^3/s (88.3 MCM/a). Submarine spring discharge is of minor importance since discharge rates are very low (<0.009 m^3/s / 0.3 MCM/a for all submarine springs). However, the springs in all systems have fallen dry in the 1980s to 1990s and are therefore negligible for simulations of the present state.
- Evaporation from inland and coastal sabkhas constitutes the major natural outflow component of the Upper Mega Aquifer System. Estimations of sabkha evaporation rates vary from 520 mm/a [25, 7] to 100 mm/a [27]. Present average annual evaporation from sabkhas for the part of the study area within the borders of the Kingdom of Saudi Arabia was estimated to 30.8 m^3/s (970 MCM/a).
- Since 1940, the groundwater resources in the study area have been intensively exploited for domestic, agricultural and industrial use and particularly the agricultural water use shows a dramatic increase over the last 25 years. Present abstraction rates on the Arabian platform within the borders of the Kingdom of Saudi Arabia were determined to 414 m^3/s (13, 060 MCM/a) for agricultural use, 41 m^3/s (1,290 MCM/a) for domestic use and 22 m^3/s (700 MCM/a) for industrial use.

The conceptual model showing the aquifers and the in- and outflow components is displayed in Figure 4.

Assessment of the Groundwater Budget: Table 1 summarizes the components of the groundwater budget of the study area (within the borders of the Kingdom of Saudi Arabia) and gives an estimation of the uncertainties associated with the determined quantities. It becomes evident that agricultural water use is the most important budget component. Since abstraction rates can be obtained with relatively low uncertainty, this component, together with industrial and domestic water use, can be considered a reliable element of the groundwater model. The second most important budget component is groundwater recharge from precipitation. Recharge rates, however, are much more difficult to determine. Different recharge processes have to be considered and their determination involves the estimation of numerous parameters. Therefore, calculated rates of groundwater recharge must be considered highly uncertain and future research should focus on improved methods for a precise determination of groundwater recharge from precipitation.

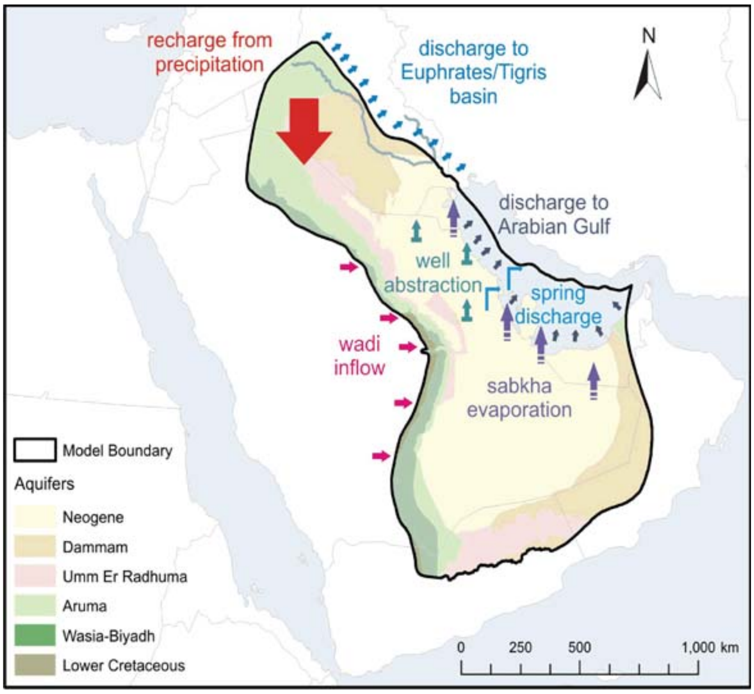

Fig. 4: Conceptual model of the Upper Mega Aquifer system, showing the in-and outflow components

Table 1: Groundwater budget of the Arabian platform (within the borders of the Kingdom of Saudi Arabia) for the present state (GTZ/DCo, 2006) and estimation of uncertainty

Budget component	Quantity [MCM/a]	Uncertainty
Inflow		
groundwater recharge from precipitation	3,550	high
inflow through wadi channels	15	medium
Outflow (natural discharge)		
spring discharge	0	low
inland and coastal sabkhas	970	medium
Arabian Gulf + Euphrates-Tigris	258	high
Outflow (well abstraction)		
agricultural water use	13,060	low
industrial water use	700	low
domestic water use	1,290	low

First Conclusions on the Groundwater Dynamics: Most of the groundwater recharge of the Upper Mega Aquifer System occurred during the last pluvial period under more humid climatic conditions, which ended about 5,000 years BP. Hence, for the major part of the study area, the groundwater stored in the aquifer system must be considered a non-renewable resource, or fossil groundwater.

The main groundwater flow of the Upper Mega Aquifer System is directed towards the Arabian Gulf and the Euphrates-Tigris basin, which represent the major discharge areas. The groundwater head contours in general follow the trend of the outcrop in the west and the Arabian Gulf coastline in the east.

Cross-formation flow may occur in certain parts of the study area between all described aquifers, leading to additional recharge and discharge of the individual aquifer units. For instance, in the west of the study area, the groundwater heads of the Aruma aquifer are lower than the heads of the overlying Umm Er Radhuma aquifer, leading to restricted downward flow of groundwater from the Umm Er Radhuma aquifer. Vice versa in the east, the groundwater heads of the Aruma aquifer are higher than the heads of the Umm Er Radhuma aquifer, which causes constrained upward flow of Aruma groundwater into the Umm Er Radhuma aquifer.

CONCLUSION

Data from various sources and previous studies have been brought together in order to set up a comprehensive model of the Upper Mega Aquifer System on the Arabian Peninsula. A conceptual model has been developed comprising the identification of hydrogeological units, the parameterization of these units, the identification of system boundaries and the identification of the water budget components. Agricultural water use and groundwater recharge from precipitation have been identified to be the most important components of the water budget. Next steps include the transfer of the conceptual model into a mathematical groundwater model. All available measurement data will be used for model calibration, including piezometric heads, spring discharge and isotope and hydrochemistry data. Step by step the model will be optimized through improved definitions of the boundary conditions and other relevant parameters. Particularly the estimation of the historic and present spatially distributed groundwater recharge will be the focus of future research. The successful representation of the historic development of the groundwater system by the model is a necessary precondition to use the model for predictions of future impacts of global change. Particularly climate change in concert with population growth and the resulting demand of water for domestic use and food production may increase the pressure on the limited water resources in the region. Once the calibrated and validated model is available, different groundwater management scenarios can be evaluated in order to find an optimal management solution to satisfy the needs of the users. The model may serve as a prognostic tool for an Integrated Water Resources Management.

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