The Hydrogeology of Al Hassa Springs

Ali Saad Al Tokhais [1] and Randolf Rausch [2]
1. Ministry of Water & Electricity of the Kingdom of Saudi Arabia, Riyadh, Saudi Arabia.
2. GTZ International Services
Riyadh, Saudi Arabia

Abstract

Al Hassa Oasis in the Kingdom of Saudi Arabia is one of the largest natural oases of the world. The cultivated area in the Al Hassa region was about 12,000 hectares during former times. The enormous size of the farming area was made possible by the immense volume of groundwater discharging from the underlying aquifers under natural artesian pressure. In the Al Hassa Oasis the groundwater came up in about 280 springs. While many of the smaller springs were privately owned, most, including the largest, were linked to a communal irrigation system. The groundwater discharge originated from the underlying aquifer system, which comprises Aruma aquifer, Umm Er Radhuma aquifer, Dammam aquifer complex, and Neogene aquifer complex. The aquifers are partly interconnected to each other. Because of intensive fracturing along the Ghawar anticline, preferential flow paths are developed. They connect the different aquifers and force the groundwater to discharge in the Al Hassa oasis. The total spring discharge for the predevelopment state was about 315 MCM/a (Vidal 1951/52). It can be shown that this discharge rate was more or less constant during several hundred years. During this time, a complete sustainable agriculture and water use existed. Due to the rapid economic growth, the water demand has increased since the middle of the last century, showing a dramatic increase after 1975. Most of the water demand was covered by groundwater. At present time, the total groundwater abstraction in the Al Hassa region is about 712 MCM/a. Now, the groundwater budget is no longer in equilibrium. The water abstracted is taken from storage. That means groundwater mining takes place. As a consequence of the overexploitation of the resources, a decline in groundwater levels is observed. The famous springs in the Al Hassa oasis were running dry. The measured drawdowns during the last 30 years range from about 70 m to 150 m. The diameter of the cone of depression is well over 60 to 100 km. If the current groundwater abstraction continues at the present rate, several wells in the Neogene and the Dammam aquifer complex will completely fall dry and the cone of depression will extend. To satisfy the water demand deeper wells must be drilled. Furthermore, a deterioration of groundwater quality will occur, caused by up coning of deeper saline groundwater.

Results from groundwater flow simulations carried out within the Umm Er Radhuma Study of the Ministry of Water & Electricity showed that a reactivation of the Al Hassa springs would be theoretically possible. Under the assumption that groundwater is only abstracted for domestic use, while groundwater abstraction for agricultural and industrial water will be shut down, the groundwater levels would rise again. Consequently, the springs might start flowing again after a recovery period of about 20 years.

Keywords: Al Hassa Oasis, Umm Er Radhuma Aquifer, Groundwater Flow Simulation, Groundwater Management.

Introduction

Al Hassa Oasis with its capital Al Hofuf is the largest oasis in the Kingdom of Saudi Arabia and one of the largest spring-fed oases in the world. On an area of about 12,000 hectares mostly date palms were cultivated in former times. The enormous size of the farming area was made possible by the immense volume of groundwater discharging from the underlying aquifers under natural artesian pressure.

In Al Hassa Oasis the groundwater came up from about 280 springs (VIDAL 1951). In the middle of the last century the total spring discharge was about 315 MCM/a (10 m^3/s). There was a big variation in discharge and some of the springs produced more than 1 m^3/s (e.g. 1.3 m^3/s Ayn Haql). Figure 1 shows some historical pictures of the springs. While many of the smaller springs were privately owned, most, including the largest, were linked to a communal irrigation system. The traditional irrigation system was smart and efficient: the water was distributed by gravity flow, and was used several times at different height levels of the oasis. Beyond their use as a basis of Hasawi existence, the springs and pools had an important social value as an amenity for relaxation and hygiene. The sulphurous spring at Ayn Najm, to the west of Al Hofuf, used to be a highly regarded resort.

Together with the adjacent oasis of Al Qatif, the oasis on Tarut Island, and the oasis in Bahrain, the region was settled since the Neolithic period, some 7,000 years ago (see Figure 2). The abundance of fresh water from springs and the strategic location on the crossroads of the trading routes between the Indus Valley, Oman, and Mesopotamia were the basis for the development of the Dilmun culture (5,200 until 2,300 a B.P.), one of the earliest civilizations of mankind (BIBBY 1996).

Today the springs are no longer flowing. Due to overexploitation of the groundwater resources the groundwater levels have fallen dramatically and the springs are dried up.

Figure 1: Historical photos from springs in Al Hassa Oasis from 1937 to 1965. Today the springs are dried up (pictures from FACEY 2000).

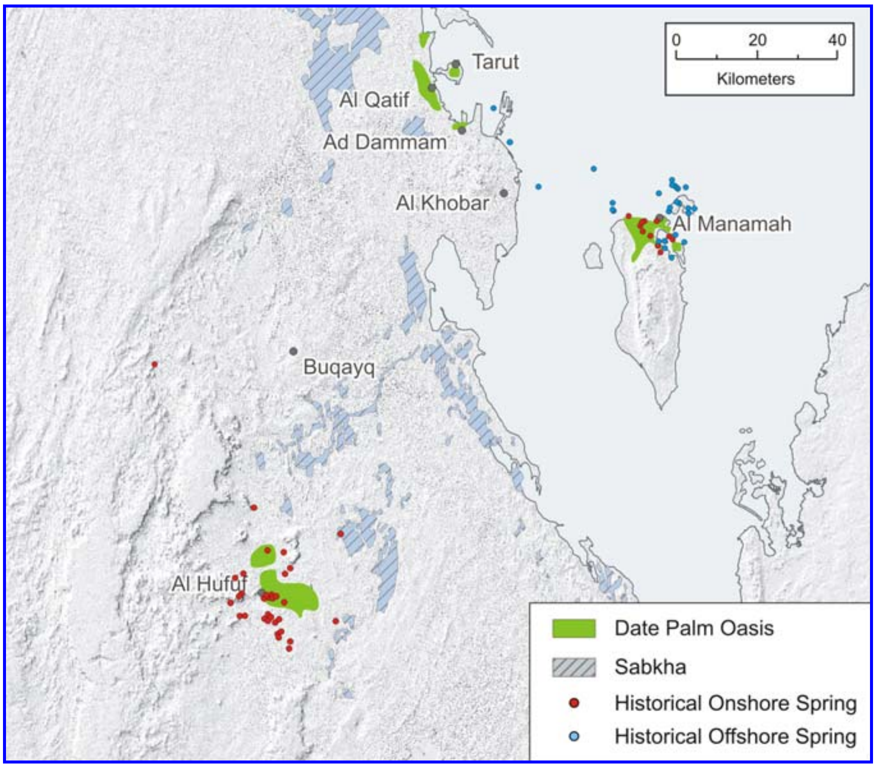

Figure 2: Map showing the location of ancient date palm oasis and major historical springs in Al Hassa Oasis, Al Qatif Oasis, Tarut Island, and Bahrain.

At the beginning of the last century the spring discharge of Al-Hassa Oasis was about 10.0 m^3/s, the discharge in Al Qatif about 1.6 m^3/s, and the discharge in Bahrain about 2.8 m^3/s. Note that some submarine springs existed, which discharged directly into the Arabian Gulf. In terms of total discharge, the land springs by far outweighed the submarine springs. Most of submarine springs were located in the tidal zone. Today all springs are dried up.

Geology and Hydrogeology

The springs of Al Hassa belong to the huge "Euphrates-Gulf-Rub Al Khali Basin". The Late Cretaceous and Tertiary formations of Aruma, Umm Er Radhuma, Rus, Dammam, and Neogene form a complex multi-aquifer system (BRGM 1977, AL-SAYARI & ZÖTL 1978, GDC 1980, BAKIEWICZ et al. 1982, JADO & ZÖTL 1984, HÖTZL et al. 1993, WAGNER & GEYH 1999, MoWE 2007).

The sedimentary succession consists of carbonates (limestone and subordinate dolomite), sulphates (anhydrite and gypsum), and subordinate marls and shales (see Figure 3). The total thickness ranges from 800 m to 2,500 m, increasing towards the Arabian Gulf. In general, the formations are dipping from the outcrop areas in the west towards 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.

The aquifers are partly interconnected. The Umm Er Radhuma aquifer and the Dammam aquifer are separated by the Rus formation that consists of evaporites, marls and limestones. The Rus formation, which generally acts as an aquitard between both aquifers, forms a joint aquifer in some areas where it is represented by fissured carbonates or where dissolution of evaporite layers has created secondary permeabilities. The lower part of the Aruma formation, which consists of shales and clay, acts as an aquitard, separating the aquifer system from the underlying Wasia aquifer.

The groundwater system in the study area consists of four partly interconnected aquifers (see Figure 4). These are:

- Neogene aquifer complex at the top – a mixture of karstified fractured bedrock aquifers and unconsolidated porous clastic aquifers,
- Dammam aquifer complex – a partly karstified fractured bedrock aquifer,
- Umm Er Radhuma aquifer – a karstified fractured bedrock aquifer, and
- Aruma aquifer at the base – a karstified fractured bedrock aquifer of minor importance.

Spring discharge in Al Hassa Oasis originated from this aquifer system. Because of intensive fracturing along the Ghawar anticline, preferential flow paths are developed. They connect the different aquifers and force the groundwater to discharge in Al Hassa Oasis. From hydrochemical data, isotope hydrogeological data, temperature data, and hydraulic information it can be concluded that the water discharging from the karst springs at Al Hassa from the Neogene originates from the deeper Umm Er Radhuma aquifer (BRGM 1977, GDC 1980, BAKIEWICZ et al. 1982, WAGNER & GEYH 1999). In the Al Hassa area the underlying Wasia aquifer is completely isolated from the overlying Umm Er Radhuma aquifer. The $\delta^{18}O$-content of the Wasia groundwater shows features completely different from those of the Umm Er Radhuma aquifer (SHAMPINE et al. 1979).

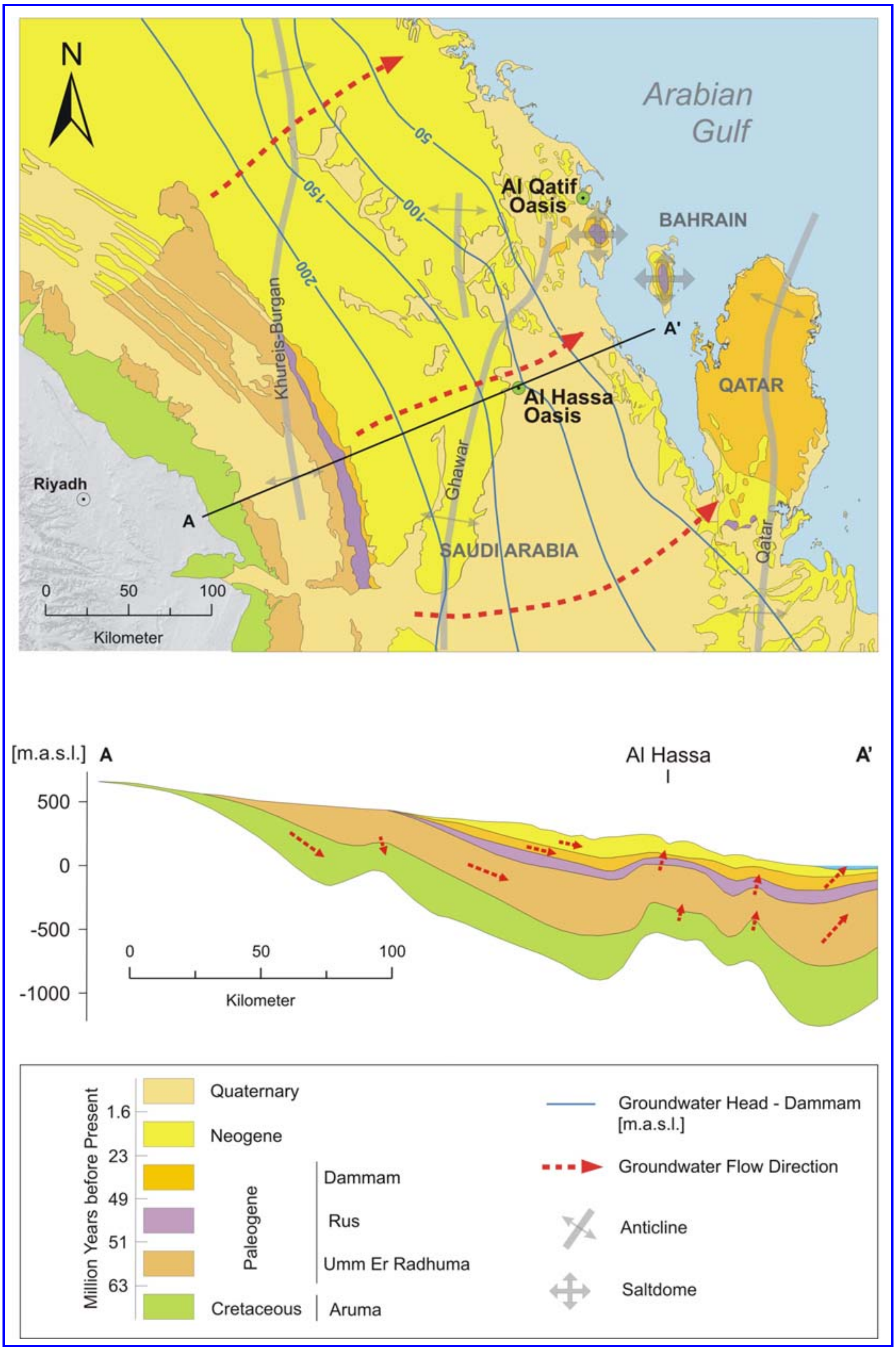

Figure 3: Geology and hydrogeology of the study area. The map and the corresponding cross section present the main geological units, the major tectonic elements, the groundwater head distribution, and the general groundwater flow direction.

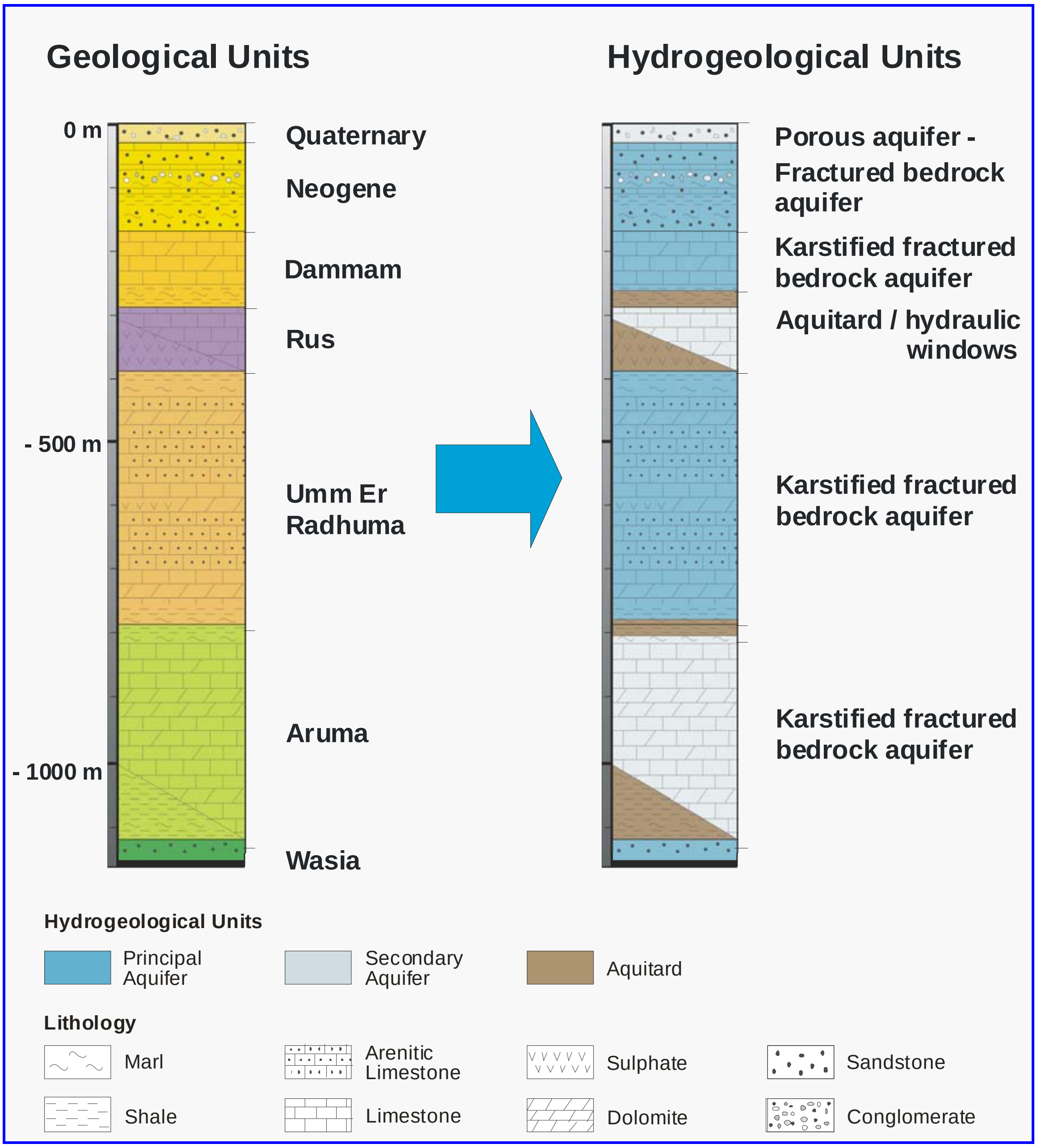

Figure 4**:** Schematic sketch, illustrating the hydrogeological units of the aquifer system. The hydrogeological units are the result of different hydrogeological properties, which are determined by the lithological characteristics of the geological units.

The main groundwater flow of the aquifer system is directed from the outcrop areas in the west towards the Arabian Gulf. The groundwater movement within the aquifer system occurs primarily through secondary openings, such as joints, fractures, and bedding-plane openings, which are often enlarged by solution processes. The aquifer properties for the different aquifers in Al Hassa area are listed in the following table.

Aquifer	K_{mean} [m/s]	K_{min} – K_{max} [m/s]	S [-]	S_y [-]
Neogene	$2.8 \cdot 10^{-5}$	10^{-7} - 10^{-2}	10^{-4} - 10^{-3}	0.01 - 0.07
Dammam	$3.2 \cdot 10^{-5}$	10^{-6} - 10^{-2}	10^{-5} - 10^{-3}	0.01 - 0.05
Umm Er Radhuma	$1.6 \cdot 10^{-5}$	10^{-7} - 10^{-2}	10^{-4} - 10^{-3}	0.01 - 0.07
Aruma	$3.9 \cdot 10^{-5}$	10^{-6} - 10^{-2}	10^{-5} - 10^{-3}	0.01 - 0.05

K: hydraulic conductivity, S: storage coefficient, S_y: specific yield.

It can be seen that the average hydraulic conductivities of the single aquifers are in the same magnitude. Differences are in the mean variation, respectively in the range. The corresponding storage coefficients range from $S = 1 \cdot 10^{-5}$ to $1 \cdot 10^{-3}$. The specific yield ranges from 0.01 to 0.07.

Unconfined conditions of the Aruma and Umm Er Radhuma aquifers exist at the outcrop areas and for some distance to the east, until the groundwater head surface intersects with the confining units of the aquitards. In the larger part towards the east the aquifers remain 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. Unconfined conditions of the Dammam aquifer complex occur at the outcrop areas. Confined conditions exist in areas, where the aquifer is covered by thicker Neogene units. Near the shoreline of the Arabian Gulf and further to the east the Dammam aquifer remains under artesian confined conditions.

In general, the relatively slow groundwater movement causes long residence times within the aquifer system. Therefore, the main portion of the groundwater is fossil water and has been dated by isotope analyses with an age of over 20,000 years in Al Hassa area (MOSER et al. 1978, BAKIEWICZ et al. 1982). Besides insignificant groundwater recharge by recent precipitation and its infiltration within the outcrop areas, additional recharge and discharge occurs by downward- and upward leakage of groundwater from the different aquifers, causing a ‘cross formation flow’.

Groundwater salinity increases from west to east in the Aruma and Umm Er Radhuma aquifers (see Figure 5). It ranges from 300 mg/l in the western outcrop regions to more than 5,000 mg/l in the coastal area. In Al Hassa region the groundwater has salinities between 1,000 and 2,000 mg/l. The increase in salinity is accompanied by a shift in the major ion facies: While calcium-bicarbonate waters prevail in the outcrop area, calcium-sulphate waters occur in the central region of the aquifer system. In the coastal area sodium and chloride are the major ions (MOWE 2007, DIRKS 2007, DIRKS et al. 2007). This sequence of groundwater evolution is commonly referred to as ‘CHEBOTAREV sequence’ (CHEBOTAREV 1955). Salinities of the Dammam and Neogene aquifers are in the same range like Umm Er Radhuma and Aruma aquifers, but salinity distribution is patchier and does not follow a west-east trend.

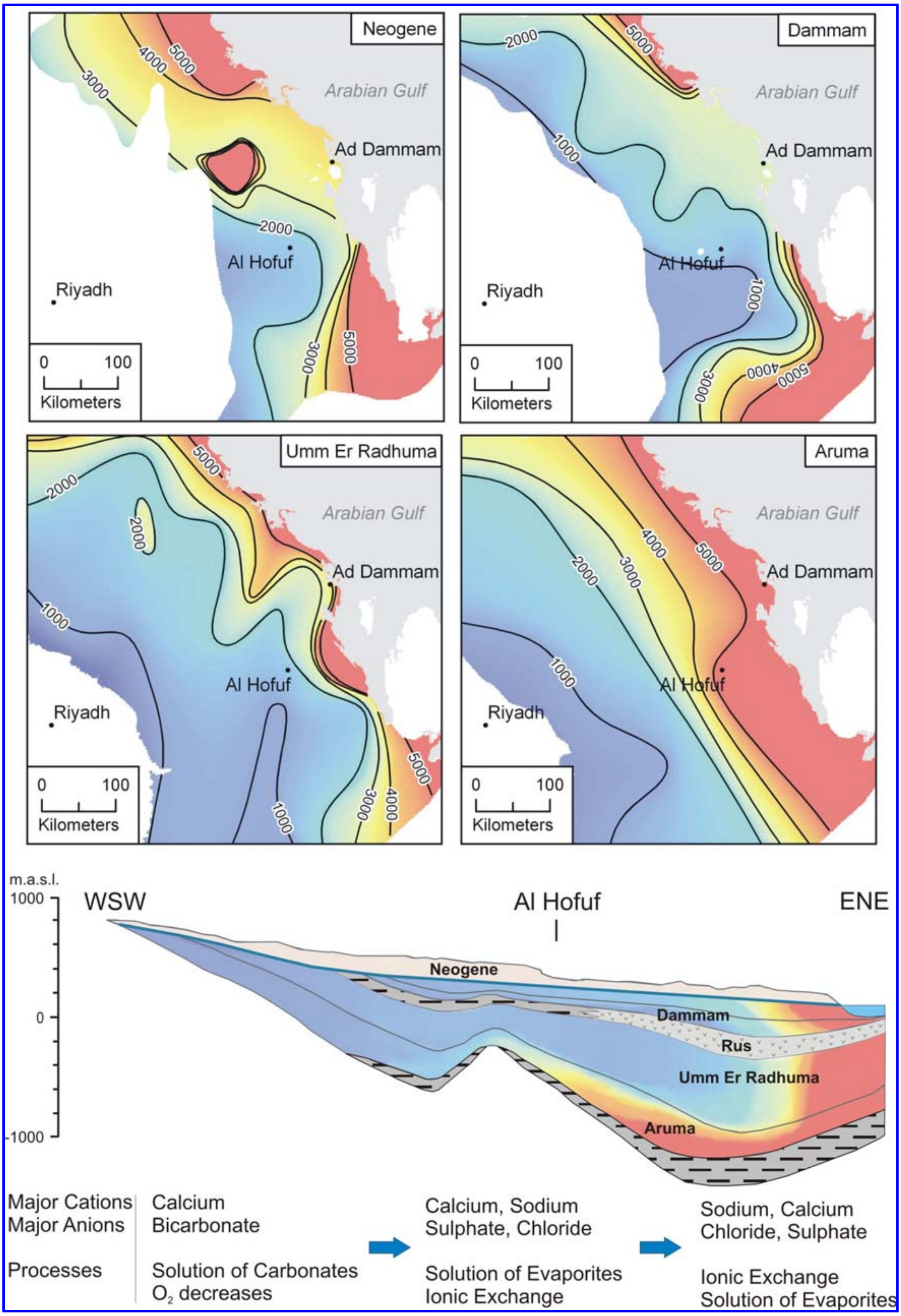

Figure 5: Maps showing the areal distribution of the total dissolved solids concentration of the groundwater in the Aruma, Umm Er Radhuma, Dammam, and Neogene aquifer in Al Hassa area. The cross-section presents the hydrochemical evolution of groundwater along its flow path.

Karstification plays an important role within the aquifer system, consisting predominantly of carbonates. Karst phenomena like sinkholes and caves are observable in the outcrop areas of the Aruma and Umm Er Radhuma formation (HÖTZL et al. 1993). Moreover, evidence of sub-surface karstification could be frequently encountered during drilling, particularly within the Umm Er Radhuma carbonates. Under the present climatic conditions active karstification is negligible. The karst of the studied formations is mainly the result of palaeo-karstification, developed under wetter climatic regimes in the geological past. Karstification of the Umm Er Radhuma Formation at its western extent started already shortly after its deposition and the subsequent regression during the Lower Eocene, while to the east marine sedimentation continued. The karstification continued throughout the entire Eocene period and prevails in the westernmost areas until today. Beside the exposed Umm Er Radhuma on the palaeo-main-land to the west, emerged areas also existed in the east during this period, which was due to the tectonic uplift movements of anticlinal structures. Sporadic emersion of at least one of these structures, the Ghawar Anticline, occurred. Consequently erosion of the already deposited Rus and karstification of the exposed Umm Er Radhuma was enabled. In addition, the development of karst above the uplifted structures was promoted by the higher degree of fracturing in this zone due to bending of strata. Further karstification occurred in post-Eocene times, after the final, widespread emersion of the Arabian Platform.

Discharge of Al Hassa Springs

The temporal development of spring discharge for the last 10,000 years in Al Hassa Oasis is presented in Figure 6. The spring discharge is simulated with a regional groundwater flow model for the Umm Er Radhuma and the overlying aquifers. The groundwater recharge was derived from historical rainfall and temperature data. These data were estimated mainly from isotope analyses. Furthermore, the rise of the sea level in the Arabian Gulf after the last ice age was taken into consideration. The Arabian Gulf is the main discharge area of the aquifer system.

From the rainfall and temperature graphs it can be seen that after very dry climatic conditions in the Late Pleistocene the climate changed during the Early and Mid Holocene (8,000 to 5,000 a B.P.) to more humid and warmer conditions. At about 6,800 a B.P., in the Neolithic wet phase, a precipitation maximum of more than 400 mm/a occurred (KUTZBACH & STREET-PERROTT 1985, ISSAR 2003). During this time many rivers were flowing and lakes existed on the Arabian Peninsula. From 4,500 to 1,400 a B.P. the humid climate changed to arid and hyper-arid conditions (BUTZER 1958, FLEITMANN et al. 2003). Until today the climate persisted arid with a small increase in humidity between 1,400 and 700 a B.P. (FLEITMANN et al. 2003).

10,000 a B.P. the sea level in the Arabian Gulf was about 30 m lower than today. The rise in sea level after the ice age was relatively fast. About 6,000 a B.P. the recent sea level was reached. Since then it showed only small fluctuations.

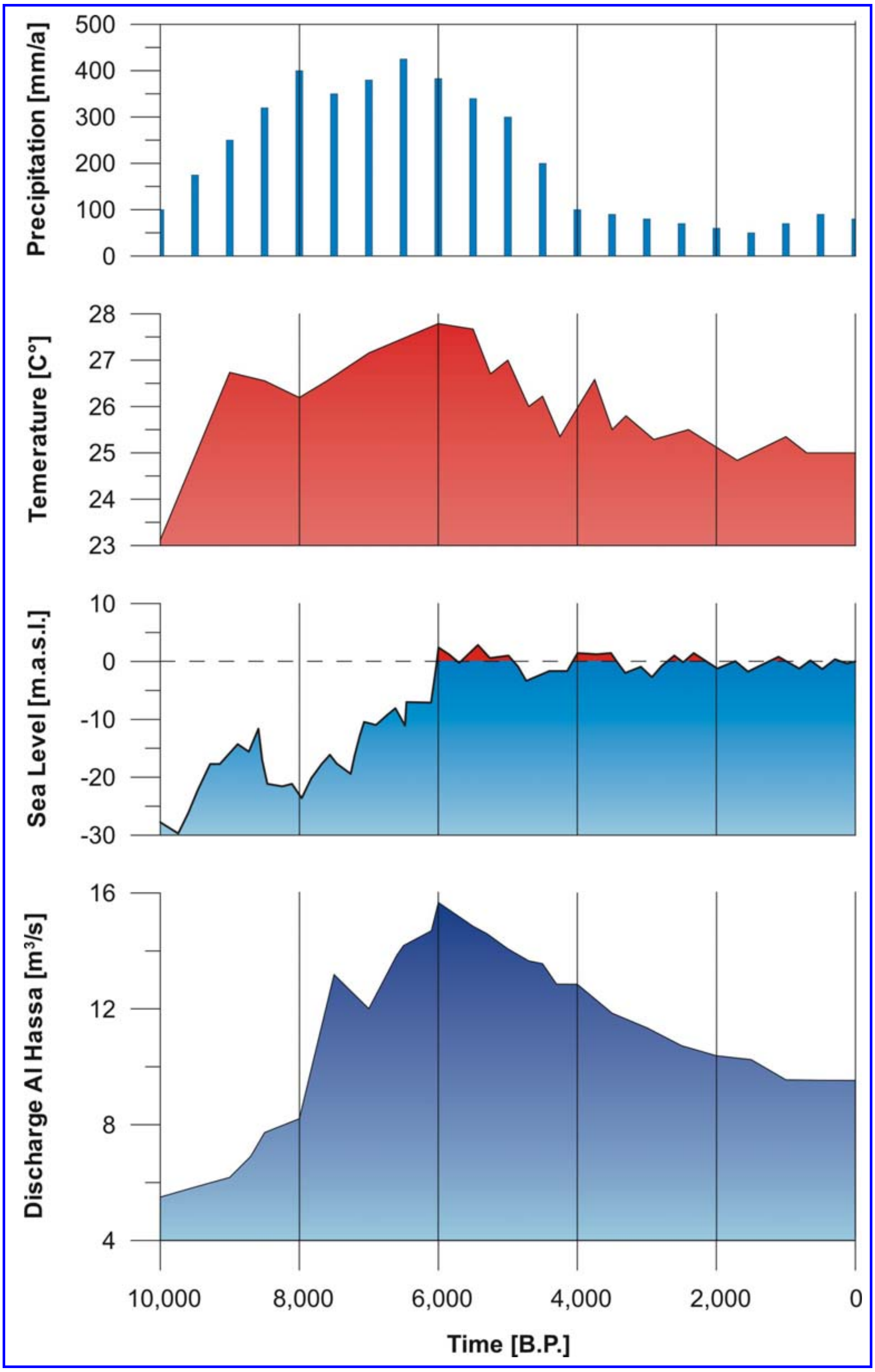

Figure 6: The graphs show the temporal development of precipitation, average annual temperature, sea level change in the Arabian Gulf and the simulated discharge of the springs of Al Hassa for the last 10,000 years. It can be seen that the spring discharge correlates highly with the precipitation. Because of the climate change during the last 10,000 years big fluctuations in spring discharge are obvious.

It can be assumed that the aquifers were only partly filled at the end of the last ice age. During 10,000 to 8,000 a B.P. the aquifers were filled up again. Groundwater levels were rising and the spring discharge in Al Hassa Oasis increased. Their maximum discharge was about 505 MCM/a (16 m^3/s). In the area of the Arabian Gulf coast the groundwater head in the Umm Er Radhuma aquifer system reached the ground surface at this time, evoking artesian conditions: the springs in Al Qatif area and in Bahrain started to flow about 7,000 a B.P. Since 6,700 a B.P. the precipitation – and as a consequence groundwater recharge – continuously decreased, causing a decrease of groundwater heads.

During the middle of the last century the discharge was about 315 MCM/a (10 m^3/s). This discharge rate was more or less constant during several hundred years before. During this time, a complete sustainable agriculture and water use existed. Due to the rapid economic growth, the water demand has increased since the middle of the last century, showing a dramatic increase after 1975 (see Figure 7). Most of the water demand was covered by groundwater. At present time, the total groundwater abstraction in the region of Al Hassa is about 712 MCM/a (22.6 m^3/s). Now, the groundwater budget is no longer in equilibrium. The abstracted groundwater is taken from aquifer storage. That means groundwater mining takes place. As a consequence of the overexploitation of the resources, a decline in groundwater levels is observed. The springs in the Al Hassa Oasis are running dry. The measured drawdowns during the last 30 years range from about 70 m to 150 m (Figure 8). The vertical groundwater flow direction has changed. Now groundwater from the upper parts of the aquifer system flows down to the deeper parts of the aquifer system. The diameter of the cone of depression is well over 60 km to 100 km (see Figure 9). If current groundwater abstraction continues at the present rate, more wells in the Neogene and the Dammam aquifer complex will fall dry and the cone of depression will extend. To satisfy the water demand, deeper wells tapping the underlying aquifers must be drilled. Furthermore, a deterioration of groundwater quality will occur, caused by upconing of deeper saline groundwater.

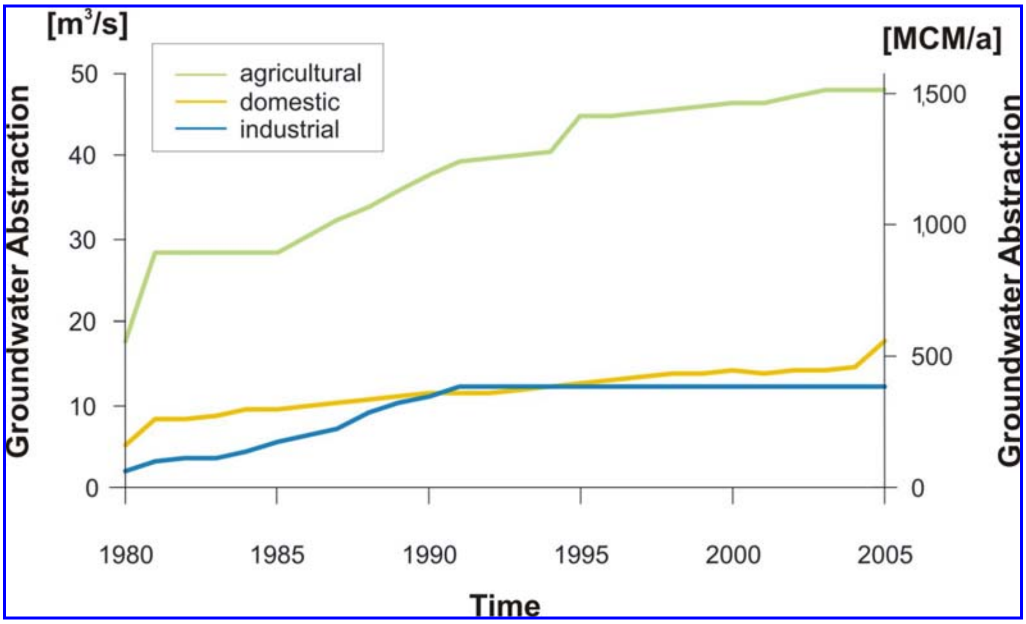

Figure 7: Temporal development of groundwater abstraction from 1980 to 2005 for agricultural, industrial, and domestic water use from the Umm Er Radhuma and overlying aquifers in the eastern part of Saudi Arabia.

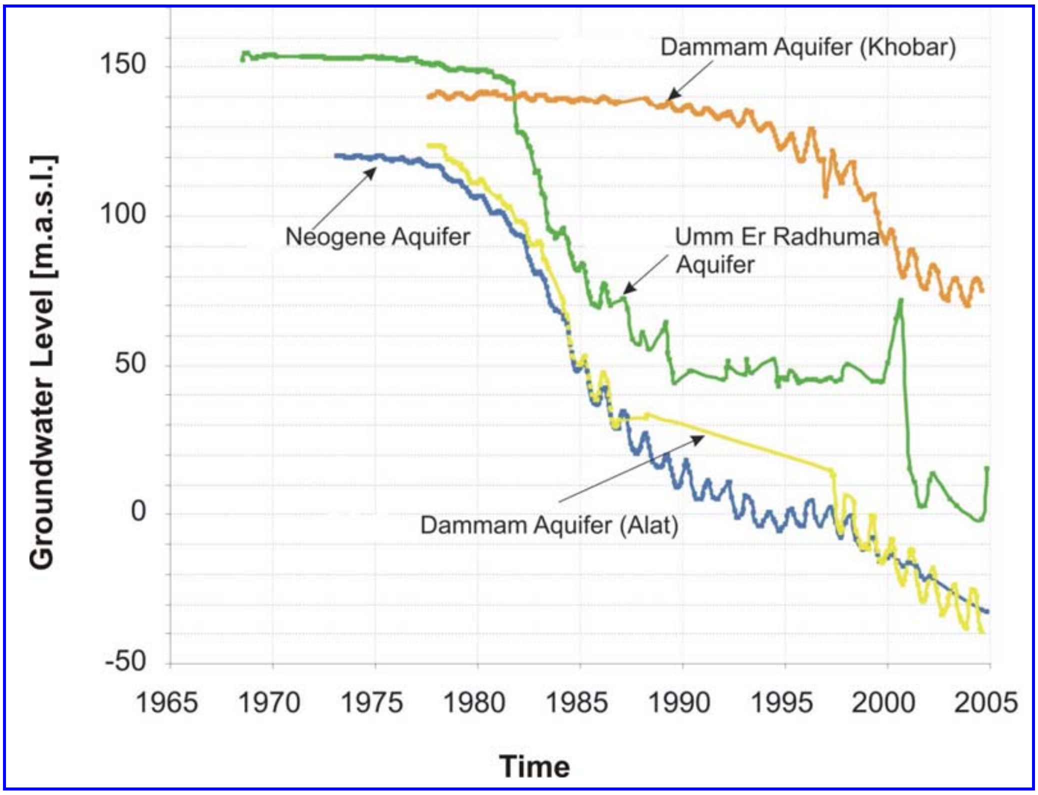

Figure 8: Examples for long-term declines in groundwater levels for selected observation wells of the Umm Er Radhuma, Dammam, and Neogene aquifer in the region of Al Hassa due to non sustainable groundwater abstraction.

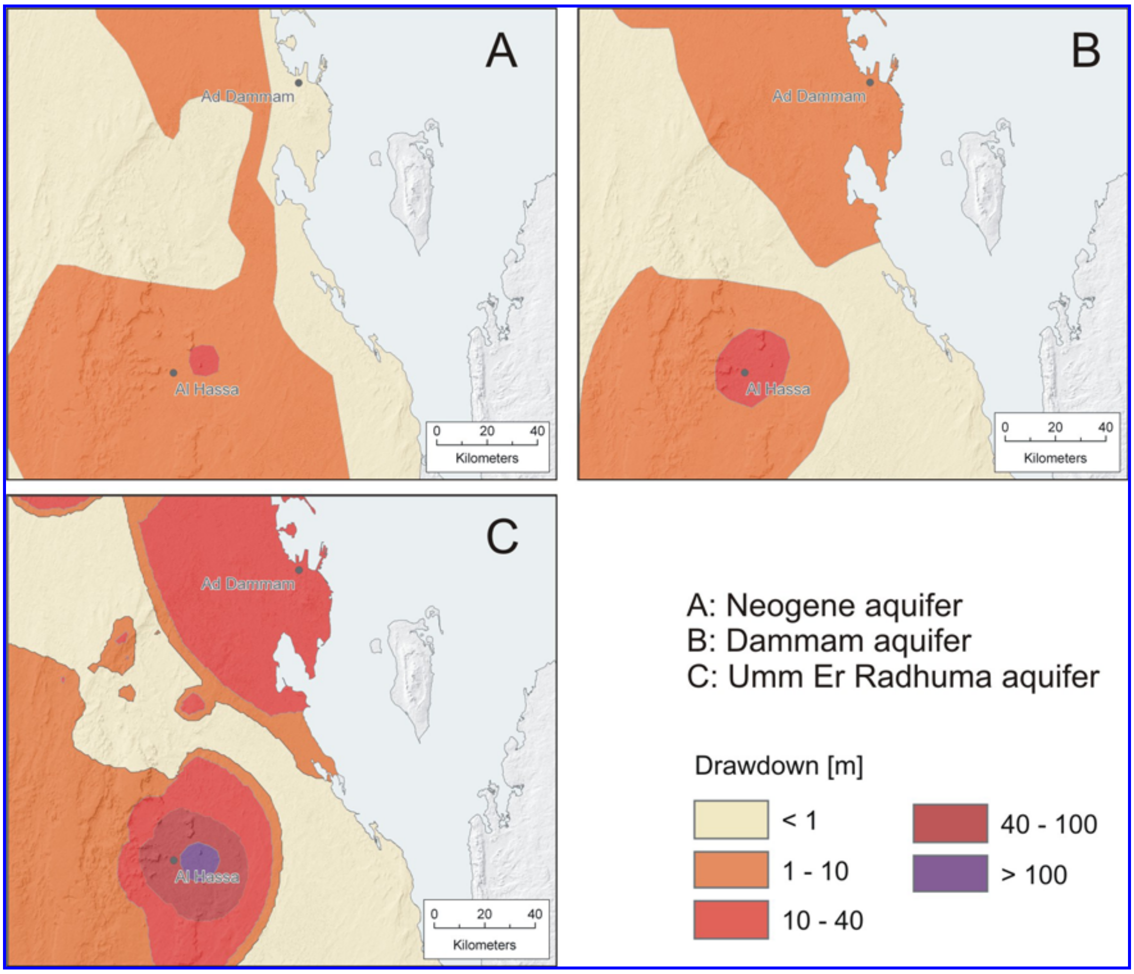

Figure 9: Spatial extent of the cones of depression in the Umm Er Radhuma, Dammam, and Neogene aquifer for 2004.

The situation is alarming not only for Al Hassa Oasis, but for the complete aquifer system. Considering the central most populated region of the aquifer system, which can be delineated to the west by the aquifer outcrop, to the east by the Arabian Gulf, to the north by the line Az Zulfi to Al Khafji, and to the south by the line Al Kharj, Harad to Salwah, we find that the groundwater resources left in storage are limited. An appraisal of the remaining resources in this area results in a total usable amount of fresh water in storage of about 80,000 MCM. From which 18,000 MCM are stored in the Aruma aquifer, 49,000 MCM in the Umm Er Radhuma aquifer, 5,000 MCM in the Dammam aquifer, and 8,000 MCM in the Neogene aquifer. If groundwater abstraction continues at current rates, the groundwater resources in this area will be exhausted within the next 30 to 40 years.

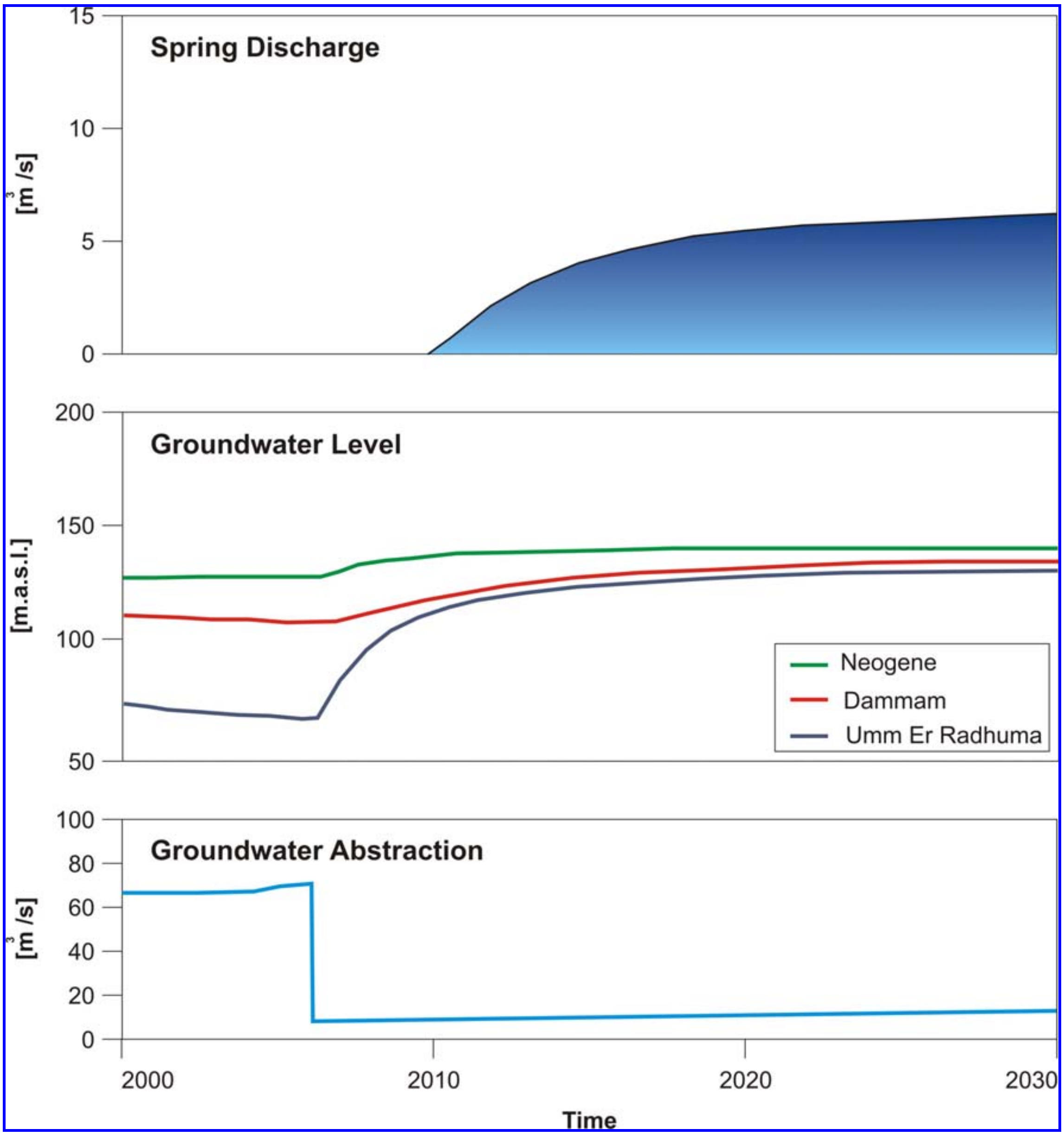

Figure 10: Temporal development of groundwater abstraction, groundwater level, and spring discharge for the period from 2000 to 2030. Results from a prognostic flow simulation under the assumption that groundwater abstraction for agriculture and industry is shut down from 2005 on. Only domestic water consumption increases. A recovery of the groundwater levels will be observed in the Al Hassa Oasis (recovery Umm Er Radhuma about 100 m). The springs in Al Hassa Oasis will flow again, with a maximum discharge rate of 6 m^3/s. The former spring discharge amounting 10 m^3/s will never be reached again.

The only possibility to solve this problem is a rigorous approach by cutting the water consumption for agriculture and using water saving devices. Results from groundwater flow simulations carried out within the Umm Er Radhuma Study of the Ministry of Water & Electricity (MoWE 2006) showed that a reactivation of Al Hassa springs would be theoretically possible (see Figure 10). Under the assumption that groundwater is only abstracted for domestic use, while groundwater abstraction for agricultural and industrial water will be shut down, the groundwater levels would rise again. Consequently, the springs might start flowing again after a recovery period of about 20 years. Yet, it must be mentioned that the former spring discharge of 315 MCM/a (10 m^3/s) will not be reached again. Because of the mining of the groundwater resources a maximum recharge of 189 MCM/a (6 m^3/s) is expected.

Conclusions

From the fate of Al Hassa springs important lessons for the future groundwater use and management can be learned. Under the prevailing climatic conditions, replenishment of the Umm Er Radhuma and overlying aquifers does not compensate even for the naturally occurring outflows from the system. The largest and most important groundwater resource on the Arabian Peninsula is definitely non renewable. The groundwater reserves developed over a long period of time in the distant past. The exploitation of these reserves can last only several decades. A wise and smart groundwater management of the remaining resources in Al Hassa area and in the Kingdom of Saudi Arabia is a must.

In future a sustainable use of the water resources and in particular of the groundwater resources is needed (AL TOKHAIS 2006). This will be achieved within the framework of Integrated Water Resources Management, which guides the water policies to be implemented in the near future. Following actions are to be implemented:

- Broad based water demand management.
- A comprehensive program for the reduction of groundwater abstraction to achieve a more sustainable aquifer management.
- A comprehensive program for the use of non conventional water resources, including desalinated seawater, brackish groundwater, and waste water reuse.
- Institutional arrangements suitable for Integrated Water Resources Management.
- Increasing the role of the private sector in water sector management.

Recommendations

- Improve Integrated Water Resources Management to achieve optimal use of groundwater resource.
- Decrease non renewable groundwater abstractions while increasing irrigation efficiency.
- Implement a virtual water program for agriculture production.
- Make groundwater protection (quantity and quality) everybody’s responsibility.

If these actions will be taken and the recommendations will be followed, an optimal use of the non-renewable groundwater resource is guaranteed for the future of the Kingdom of Saudi Arabia.

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