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Impact of long-term changes in climate on groundwater resources in an arid setting

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Abstract Scenarios of shifts in climate calculated until 2200 were coupled with a groundwater model within an arid setting. Precipitation calculated by the climate model is converted to groundwater recharge, which is supposed to decrease by 45% during the next 200 years. Population growth models determine pumping rates of groundwater wells for human freshwater demand. Groundwater level decline and budgets are calculated for four greenhouse gas emission scenarios and for two population growth rate scenarios, respectively. Groundwater levels decline by up to 100 m until 2200 if a medium population growth scenario is assumed. However, if population grows with a smaller increase rate, a depletion of the aquifer may be prevented and a balance between in- and outflow can be reached again. Changes in climate have only a minor impact on the groundwater budget compared to human freshwater demand, emphasizing the importance of introducing new technologies to reduce water consumption in an arid environment in future.

Key words arid hydrology; climate change; groundwater management; population model; climate model; CO_2 emission

INTRODUCTION

In arid regions, groundwater resources are under great pressure as a result of high population growth, unsustainable consumption, poor management practices, and pollution (UNEP, 2007*)*. For a sustainable management of groundwater resources, the amount of recharge received by an aquifer is by far the most important. The hydrological water cycle and thus, groundwater recharge is affected by short-term and long-term changes in climate. The climate system is influenced by its own dynamics and by changes in external factors. External forcing includes natural phenomena as well as human-induced changes in the atmospheric composition with greenhouse gases, which act as a partial blanket for reflected longwave radiation. This blanket effect increases the Earth’s surface temperature (Christensen *et al.*, 2007). Human activities intensify the emission of greenhouse gases by combusting fossil fuels and deforestation. When the Earth’s average temperature increases some weather phenomena become more frequent and intense (e.g. heat waves and heavy rainfalls), while others become less frequent and intense (e.g. extreme cold events) (UNESCO-WWAP, 2006). Climate models provide a picture of future climate warming in response to increased greenhouse gas (GHG) concentrations. During the past 20 years, global population has continued to rise, increasing from 5 billion in 1987 to 6.7 billion in 2007, with an average annual growth rate of 1.4%. The depletion of aquifers results mainly from intense agricultural water demand, especially in arid climates. Many countries report declining water levels in their major aquifers at rates between one and three metres per year. In many aquifers, such as those in North Africa and the Arabian Peninsula, fossil waters are already being mined that will never again be replenished (Maragat, 2007). The quantity and quality of surface and groundwater resources are affected by population growth, rising resource consumption, as well as by climate change. Especially in arid settings in- and outflow volumes of a groundwater system are based on extreme values. In an arid environment precipitation is already low and is predicted to decrease in the near future (Christensen *et al.*, 2007) and a mismatch of population density and the natural replenishment of freshwater resources prevails. Within a multi-model approach a large-scale groundwater model can link the impact of climate change and population growth on groundwater resources. The climate model predicts inflow volumes from precipitation estimates that are related to recharge rates. Such models also estimate potential natural outflow values such as evaporation. Population models give a picture of population growth rates that are directly transferable to human freshwater demand and thus groundwater extractions rates.

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INVESTIGATED ARID SETTING

The investigated area is located in the southeast of the Arabian Peninsula and is roughly bound by the latitudes 21°03′ and 28°20′N and longitudes 46°45′ and 52°55′E (Fig. 1). The groundwater system consists of four partly interconnected aquifers (e.g. Bakiewicz *et al.*, 1982). These are the Neogene aquifer complex at the top, the Dammam aquifer complex, the Umm Er Radhuma (UER) aquifer, representing the most important aquifer in the eastern part of Saudi Arabia, and the Aruma aquifer at the bottom (Fig. 1). In most parts of the Arabian Peninsula arid to hyper-arid climate with extreme heat during the day and an abrupt drop in temperature at night prevails. On the Arabian Peninsula, the average annual temperature is around 25°C, with maximum values of 47°C in summer and minimum values of 3°C in winter. Present-day precipitation only occurs during the winter months and varies greatly in space and time. The long-term average annual rainfall amount is approx. 80 mm year^{-1}.

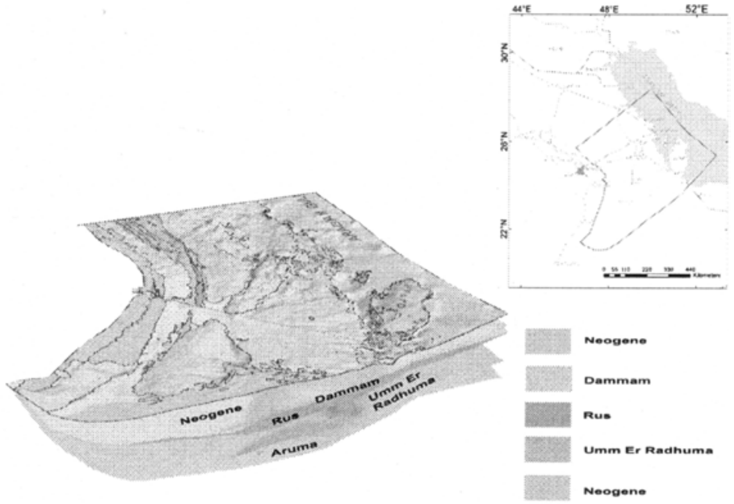

Fig. 1 Investigated aquifer systems on the Arabian Peninsular.

METHODS

A large-scale groundwater model within an area of 270 000 km^2 and a vertical extension of 800 m is linked with a climate model and a population growth model to predict the impact of climate change and human water demand on groundwater resources in a hydrologically sensitive arid setting during the next 200 years.

Global climate scenarios

The climate model is forced until 2100 with the predicted greenhouse gas (GHG) concentrations of the Special Report on Emissions Scenarios (SRES) (Nakicenovic & Swart, 2000). We selected two of the six SRES scenarios: A1B and B1. The A1B storyline describes a world of very rapid economic growth and introduction of new and more efficient technologies with a balance across fossil and non-fossil energy sources. The B1 storyline describes rapid changes in economic structures with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on environmental sustainability. Between 2100 and 2200 the climate model scenarios A1B and B1 are continued with constant GHG concentrations of 2100. Two more scenarios are used for the climate modelling. Scenario “dCO2” starts in 1860 with an initial CO_2 concentration of 280 ppm. This value increases with 1% per year. In 1930 the CO_2 concentration is already doubled and is kept constant for 300 years until 2230. Scenario “qCO2” continues after 1930 with a CO_2 increase by 1% per year. In 2000 the initial CO_2 concentration is four times higher than in 1860 and fixed over the following 300 years until 2300. In these simulations CO_2 is regarded as equivalent CO_2, which accounts also for the other greenhouse gases, and therefore lies within the range of the SRES scenarios (Cubasch *et al*., 2001). However, these simulations are sensitivity experiments, which only account for the impact of CO_2 doubling and quadrupling and do not represent possible scenarios of the development of CO_2 concentrations.

Climate model EGMAM

The climatic variables used as input for the groundwater model have been derived from simulations with the general circulation model (GCM) EGMAM (ECHO-G Middle Atmosphere Model, Huebener *et al*., 2007). It is based on the atmosphere ocean GCM ECHO-G (Legutke & Voss, 1999) but has been extended vertically into the stratosphere up to approx. 80 km. The atmosphere part ECHAM4 (Roeckner *et al*., 1996) has a horizontal resolution of T30 (approx. 3.75° × 3.75°) and with the vertical extension for EGMAM, a vertical resolution of 39 levels. It is coupled to the ocean model HOPE-G (Wolff *et al*., 1997) with a horizontal resolution of T42 (approx. 2.8° × 2.8°), an additional grid refinement at low latitudes giving a total of 21 layers. For the coupling a flux correction is applied for heat and freshwater exchange.

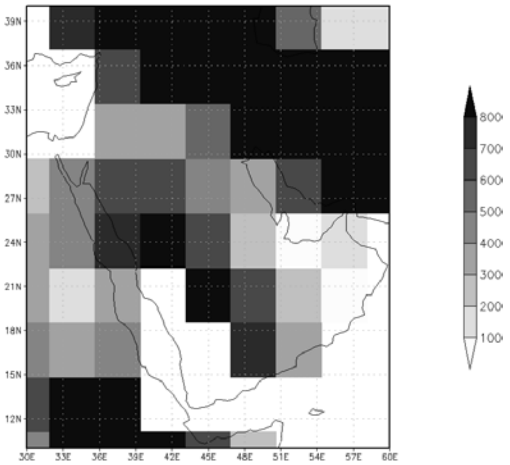

Fig. 2 Grid boxes of the global climate model EGMAM and orography (grey shading, in m) on the Arabian Peninsular.

To use the simulation results as input for the groundwater model, yearly values were selected and averaged over three grid boxes (49°O/28°N, 49°O/24°N, 52.5°O/24°N) that cover the model domain of the groundwater model (Fig. 2). The selected variables are total precipitation, evaporation, 2 m temperature and 10 m wind.

Climate forcing

On the Arabian Peninsula changes in atmospheric GHG concentrations mainly affect 2 m temperature (Fig. 3). All scenarios show strongly increasing temperature with increasing GHG concentrations and a much slower increase after concentrations are held constant. For A1B, temperature increases by >3°C until 2100, whereas for B1 temperature increases by <2°C. Until 2200 with constant GHG concentrations temperature increases in both scenarios only by 0.5°C. The lowest temperature is doubled for CO_2 concentrations with respect to the pre-industrial value of 280 ppm and highest temperature for quadrupled CO_2 concentrations. These scenarios show that a doubling in GHG concentrations results in a temperature increase of roughly 3°C over the Arabian Peninsula. Changes in precipitation are hard to identify in all scenarios as the year-to-year variability is very large, which is still the case for the 5-year running mean (Fig. 3). When comparing the scenarios with the largest difference in CO_2 concentration, namely dCO2 and qCO2, a tendency to less precipitation with higher CO_2 concentrations can be found. However, this difference is not significant.

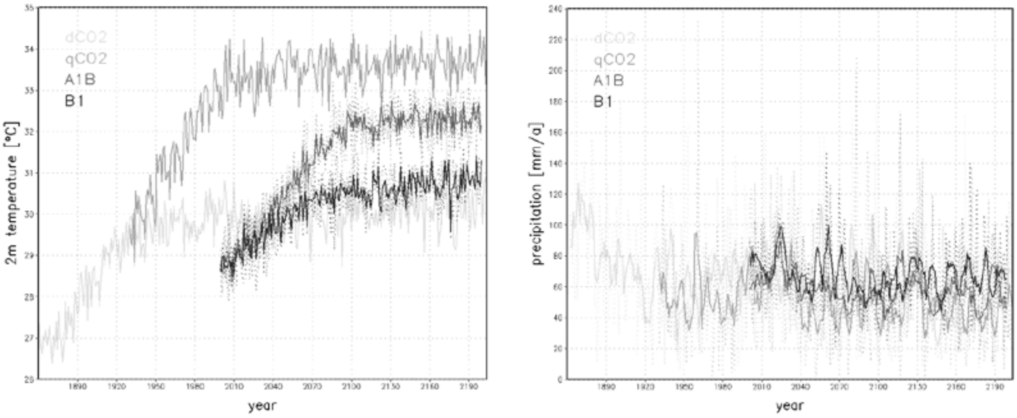

Fig. 3 Predicted changes in 2 m temperature and precipitation for four different GHG emission scenarios (qCO2, dCO2, A1B, B1) averaged over the three selected grid boxes. For temperature dotted lines show the single realisations and solid lines the ensemble means of A1B and B1. For precipitation dotted lines show the yearly values of the ensembles means and solid lines the 5-year running mean.

Population model

Large-range population projections are reported until 2300 (UN, 2004). In these projections, the world population peaks in 2075. After reaching its maximum the world population slightly declines, then increases again and reaches the level of 2050 in 2300. The UN (2004) describes three scenarios with high, medium and low population growth. Population growth rates mainly vary by fertility. Mortality assumptions are similar across all scenarios. Life expectancy follows a path of uninterrupted but slowing increase. Long-range international migrations are set to zero beyond 2050. The UN (2004) gives growth rates for each country of the world. According to the given population, growth rates of Saudi-Arabia groundwater extractions rates are increasing or decreasing following the population growth. The medium and low population growth scenarios were used in this study as the medium scenario already displays a high population increase and a huge rise of future freshwater demand. The low growth rate scenario is used to estimate the most positive development of a groundwater budget one can expect in future if new technologies are applied for water conservation, such as wastewater re-use, and new agricultural irrigation practices.

Large-scale groundwater model

The groundwater model is calculated using MODFLOW-2000 (Harbaugh *et al.*, 2000) as the unsaturated zone was disregarded within this large-scale model (Fig. 4). Four aquifer layers and one aquitard are discretizised. The model base equals the impermeable bottom of the multi-layer aquifer system, which is given by the clay units of the Aruma aquifer. The total model domain is discretized into 1.7 Mio elements. Natural inflow components are subsurface wadi inflow and groundwater recharge. Inflow is balanced by natural outflow components which are evaporation from sabkhas, spring discharge within the main oases, and discharge to the sea. Hydraulic conductivities, leakage and storage coefficients are distributed within distinctive zones capturing the main geological structures such as anticlines and faults. Hydraulic parameters are estimated by calibrating the observed drawdown from groundwater extractions between 1980 and today. Groundwater recharge produces the main natural inflow. Its spatial variability is calculated using the hydrological model of HEC-HMS (Scharffenberg & Fleming, 2009). Recharge varies in space between 0.5 mm year^{-1} within the sandy regions and increases up to 6 mm year^{-1} within the outcrop of the hard rock aquifers (Fig. 3). Recharge decreases in all zones between 1940 and 2007 with respect to changes in precipitation that occurred already during this period. Based on the average precipitation of 80 mm year^{-1} in 2007, scaling factors are derived (Table 1).

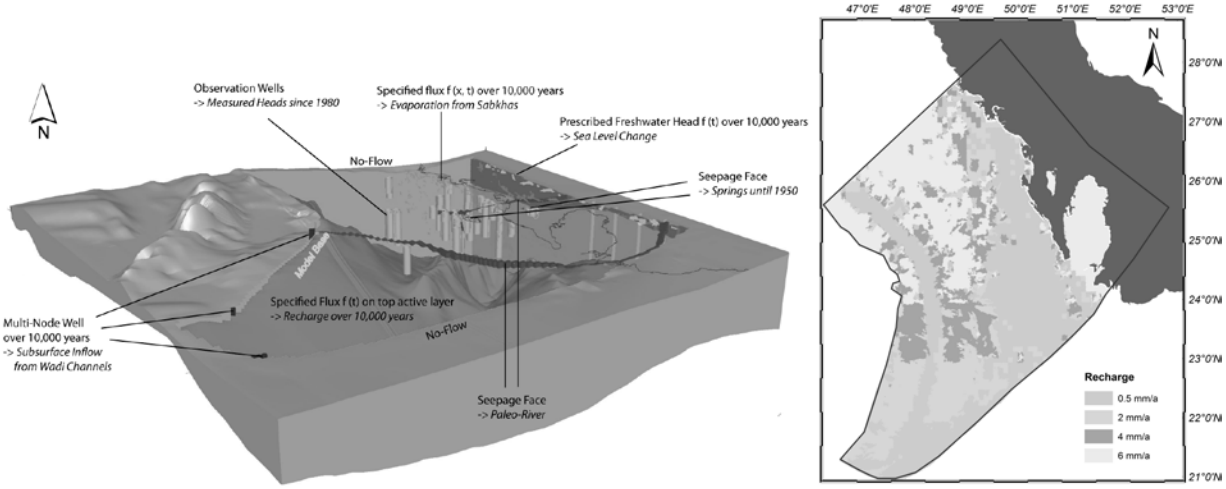

Fig. 4 Boundary conditions and calibration data to set-up numerical investigations with respect to changes in climate (left figure). Calculated recharge zones using HEC-HMS based on present-day precipitation, temperature, soil types (right figure).

Table 1 Scaling factors to adjust recharge due to changes in climate.

Present-day recharge (mm year^{-1})	0.5	2	4	6
Portion of precipitation that acts as recharge	<1%	2.5%	5%	7.5%

Precipitation of the four investigated greenhouse gas scenarios is for each year averaged over the three selected grid boxes of the climate model, and converted to recharge by applying those scaling factors for each of the zones (0.5 mm year^{-1}, 2 mm year^{-1}, 4 mm year^{-1}, 6 mm year^{-1}) (Table 1). This gives recharge rates of each zone changing with a temporal discretization of one year between 2007 and 2200. Groundwater inflow is balanced by natural outflow from spring discharge, evaporation from sabkhas and discharge to the Arabian Gulf. The investigated SRES scenarios postulate a sea level increase of 0.3 m to 0.4 m until 2100 (Meehl *et al.*, 2007). A maximum linear sea level increase of up to 1.4 m until 2100 is given by Rahmstorf (2007). We assigned this maximum sea level increase of 7 cm in 10 years between 2007 and 2200. Actual evaporation from sabkhas varies between 1940 and 2007 according to the yearly temperature variations that were measured at the meteorological stations. Future annual actual evaporation from sabkhas is obtained from calculated potential evaporation of the climate model. First pumping wells start extracting groundwater in 1940. In 1980, most of today's wells were already drilled. Between 1940 and 2007 groundwater extraction rates are estimated from satellite data of irrigation areas. After 2007 groundwater extraction rates are linked to the population growth rates. First, the medium population growth model is combined with the climate predictions for all four investigated emission scenarios (A1B, B1, qCO2, dCO2). This allows estimation of the impact of climate change on the groundwater budget. Second, the climate predictions of the emission scenarios are coupled with the low population growth model. This allows estimation of the impact of human freshwater consumption on the natural groundwater budget. Thus, the full range of future groundwater level decline and the resulting groundwater budget due to climate changes and population growth can be derived.

RESULTS AND DISCUSSION

Predicted long-term recharge changes due to shifts in climate

Precipitation calculated by the climate model is converted to recharge rates (Table 2). Recharge rates are highest for the emission scenario B1 as intense precipitation events are calculated more frequently in this scenario. Scenario A1B and dCO2 have lower long-term recharge rates than scenario B1. However, the scenario with the highest recharge oscillation is qCO2. This scenario contains some years with high, but also some years with very low precipitation (Fig. 4). This is related to the higher increase in 2 m temperature. Over the long-term, this scenario has the lowest averaged recharge rates of all scenarios. In summary, recharge decreases in all scenarios (Table 2) between 25% (B1) and 45% (qCO2) compared to present-day recharge.

Table 2 Calculated recharge rates (minimum, maximum, median) of the four current recharge zones with respect to the emission scenarios from 2007 to 2200.

Scenario	0.5 RZ min/max	0.5 RZ median	2 RZ min/max	2 RZ median	4 RZ min/max	4 RZ median	6 RZ min/max	6 RZ median
A1B	0.1/1.1	0.3	0.5/4.3	1.4	0.9/8.6	2.8	1.4/12.9	4.2
B1	0.1/1.0	0.4	0.3/4.0	1.5	0.6/7.9	3.0	0.8/11.9	4.5
qCO2	0.0/1.3	0.3	0.0/5.2	1.1	0.1/10.5	2.2	0.1/15.7	3.3
dCO2	0.1/1.1	0.3	0.2/4.3	1.3	0.4/8.6	2.6	0.6/12.6	3.9

RZ = Recharge Zone, the number gives the current recharge in mm year^{-1}

Impact of climate change and population growth on groundwater resources in an arid setting

Calculated future groundwater level fluctuations reflect the impact of changes in climate by means of recharge and evaporation as well as the impact of groundwater extraction rates due to increased population growth. The impact of shifts in climate is low compared to the high impact of pumping rates on the water level decline. All investigated climate scenarios result in a similar groundwater level differing by only 0.60 m in 2200 between the most “positive” scenario B1 and the most “pessimistic” scenario qCO2. Groundwater levels within the Umm Er Radhuma (UER) and Dammam drop in parallel. At the end of the simulation time, in 2200, the groundwater level falls 80–100 m below its present-day height, depending on the population growth. Groundwater levels are already in 2007 strongly affected by the enormous extraction rates that prevail since 1980 (Fig. 5). Within the most productive aquifers, the Dammam and Umm Er Radhuma, the water level decline continues after today with a high rate of 1.25 m per year until 2020. Then, according to a stagnancy of the population growth in 2025, the water level decline is reduced to 0.3 m per year until 2200. Within the Neogene the water level decline is more smooth. This results from lower groundwater extraction rates within the Neogene and the higher groundwater inflow from precipitation and upward vertical cross-formation flow into this shallow aquifer. The water level declines within the Neogene between today and 2200 by 15 m with an annual rate of 0.10 m. Groundwater level fluctuations do not directly respond to changes in population growth rates within this shallow aquifer.

Two different population growth scenarios with (i) low and (ii) medium increase rates were investigated. Both models mainly differ by their assumption about fertility. The simulation results demonstrate that if the freshwater demand rises in the same pattern as population growth, in the medium scenario enormous groundwater depletion will develop. Groundwater storage is only affected to a minor extent by shifts in climate (Fig. 6). The groundwater budgets computed from inflow volumes (recharge) minus outflow volumes (evaporation, discharge to the sea, spring discharge, pumping wells) show that at the end of the investigated period groundwater resources may recover again if freshwater demand increases only like population grows in the low increase

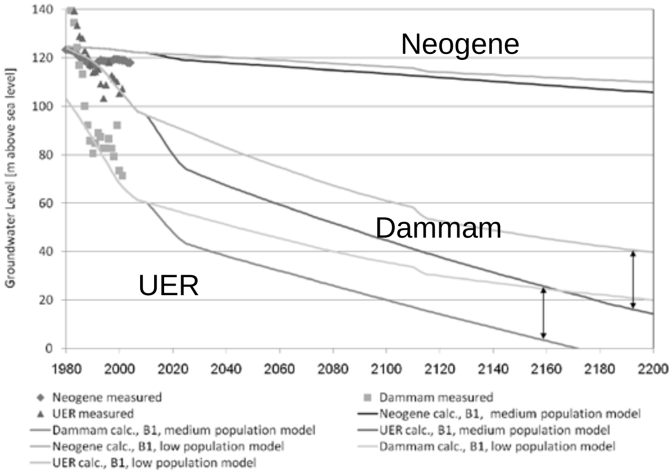

Fig. 5 Calculated groundwater level decline as response to population growth. Dots are measured groundwater levels between 1980 and today. Lines are model estimates until 2200.

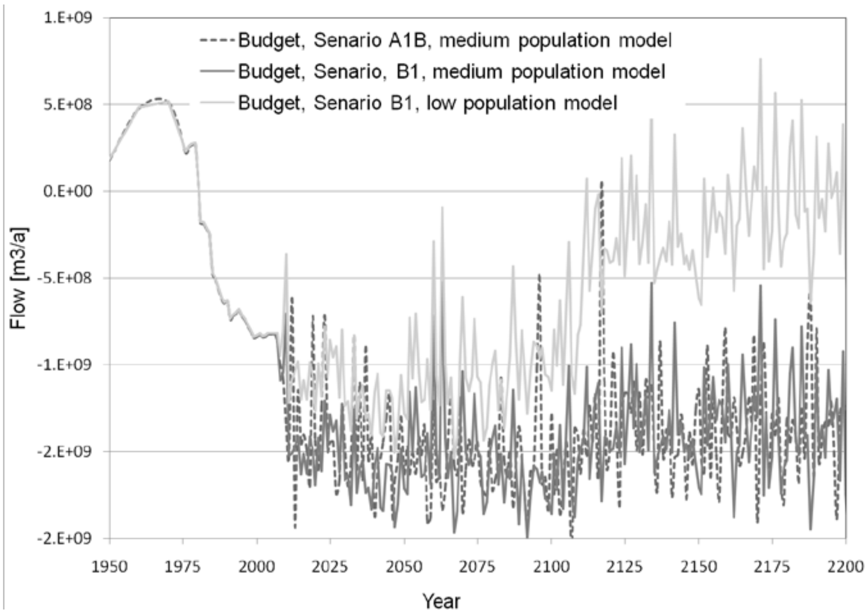

Fig. 6 Calculated groundwater budget as response to climate change and population growth for greenhouse gas emission scenarios B1 and A1B.

scenario. This means, for this population scenario inflow and outflow volumes are balanced by each other and natural groundwater resources will supply human freshwater demand. The groundwater budget is constrained in all scenarios by groundwater extraction rates. The difference in the population model will determine if a groundwater depletion of 4000 L per year and square metre (medium growth rate) must be expected in 2050 and will continue until 2200 or if a groundwater balance without a depletion (low growth rate) can be expected in 2200. For this large scale, discharge to the Arabian Gulf and evaporation from sabkhas is insignificant for the groundwater budget.

CONCLUSIONS

The numerical investigations demonstrate the impact of human freshwater demand on natural groundwater resources. Shifts in climate only secondarily influence the groundwater budget, while extracted groundwater volumes decide between storage or depletion conditions. This means, further investigations focusing on reducing the freshwater demand, especially for agricultural purposes in arid settings. Thus, a storage or replenishment of groundwater resources will only be possible by changing the way and volume of groundwater is consumed. Several possibilities that allow saving groundwater resources are available, or under development, such as desalination plants, wastewater re-use or new irrigation practices. Therefore, the main focus should be put on the development of such water saving or re-using technologies. Shifts in climate have already occurred and will occur in the near future. However, even in an arid setting their impact on the groundwater budget will be insignificant compared with human-introduced short-time forcing given by population growth and increased freshwater demand. However, results obtained from predictive modelling must be considered with care. Assumptions made for the population growth model are estimates and thus may differ in reality. Uncertainty prevails for the predictions of the climate model. Confidence is already high in variables such as temperature, but still low for precipitation. However, precipitation is the most important variable for calculating the impact of changes in climate on groundwater resources in arid settings.

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