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Challenges for an Integrated Groundwater Management in the Kingdom of Saudi Arabia

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Abstract: Despite a long history of water related research in arid areas some fundamental issues are not satisfactory resolved yet and further research is needed. In Saudi Arabia therefore a research collaboration between between the Ministry of Water & Electricity (MoWE) of the Kingdom of Saudi Arabia, the Helmholtz Centre for Environmental Research (UFZ), the Technical University of Darmstadt (TUD) and GTZ-International Services was founded. The major goal of this research collaboration is to get an in-depth understanding of the water balance, hydrochemical evolution and the fundamental characteristics of large, regional aquifer systems in arid areas covering tousands of km^2. The sound understanding of the local and regional hydrogeological conditions, available resources and water budgets, ideally leads to an integrated water resources management approach. The projects might serve as a blueprint for the investigation of other large scale aquifer systems, especially in other arid areas of the world, e.g. northern Africa, southern Africa, Australia or central Northern America where very similar conditions exist with mining of especially large scale aquifers.

Key words: Challenges · Groundwater · Management

INTRODUCTION

The Kingdom of Saudi Arabia is known as one of the most water scarce countries in the world. It relies on three types of water resources – renewable water resources, non-renewable groundwater resources and desalinated seawater.

Only a relatively small part of the country, situated on the Arabian Shield, receives enough precipitation enabling a water supply that is based on renewable water resources. As seawater desalination and the subsequent water transportation via pipelines are energy-intensive and thus costly, also areas that can be supplied by this source are limited and mainly restricted to the coastal areas. Hence, large parts of the Kingdom depend on non-renewable groundwater resources that were recharged during pluvial times thousands or even ten thousands of years ago.

Currently, the country faces significant population growth due to the rapid economic development and meeting the resulting water demand has become a major challenge. The actual total water consumption for 2009 is about 19.3 BCM/a (611 m^3/s) where about 14 BCM/a (444 m^3/s) are taken from non-renewable groundwater resources. This amount equals about 73% of the total water consumption.

In the seventies and eighties of the last century, a first countrywide assessment of the water resources was carried out, which was the basis for the national water master plan of the Kingdom. With growing water demand, a reassessment was necessary. Therefore, in 2002 the Ministry of Water & Electricity launched a project to investigate all aquifers in the Kingdom. Since then, several aquifer studies were carried out or are in progress. Today, the Saq-, Umm Er Radhuma-, Wajid-, Wasia-Biyadh-Aruma-study are already finished. In the near future, the Dhruma-Minjur-, the Rub' Al Khali-, the Tihama- and the Arabian-Shield-study including the Harrats will be finalized.

The main objectives of all these studies are (1) the assessment of the groundwater resources and (2) the assessment of the groundwater budget. The questions to be answered are: how much groundwater is still available, what is its quality and what are the in- and outflows to the aquifers? To answer these questions, robust and reliable data are needed, which can only be

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acquired by applying the latest technologies in groundwater sciences. Furthermore, research is needed for a better understanding and quantification of special features. Therefore, a research cooperation between the Helmholtz Centre for Environmental Research (UFZ), the Technical University of Darmstadt (TUD), GTZ International Services and the Ministry of Water & Electricity was founded. The research topics focus on (1) estimation of groundwater recharge, (2) large scale groundwater modeling, (3) smart groundwater mining and (4) groundwater radioactivity. All these investigations are the prerequisite for the smart and efficient managing of the groundwater resources and central part of the future water strategy of the Kingdom of Saudi Arabia.

Geological and Hydrogeological Background: On the Arabian Plate, two different geological regions can be distinguished – the Arabian Shield in the west and the Arabian Platform bordering the Shield to the east. The Arabian Shield mainly consists of crystalline basement composed of Precambrian continental crust. In some areas, this basement is overlain by Cenozoic volcanic rocks – sub-aerial flood basalts (Figure 1).

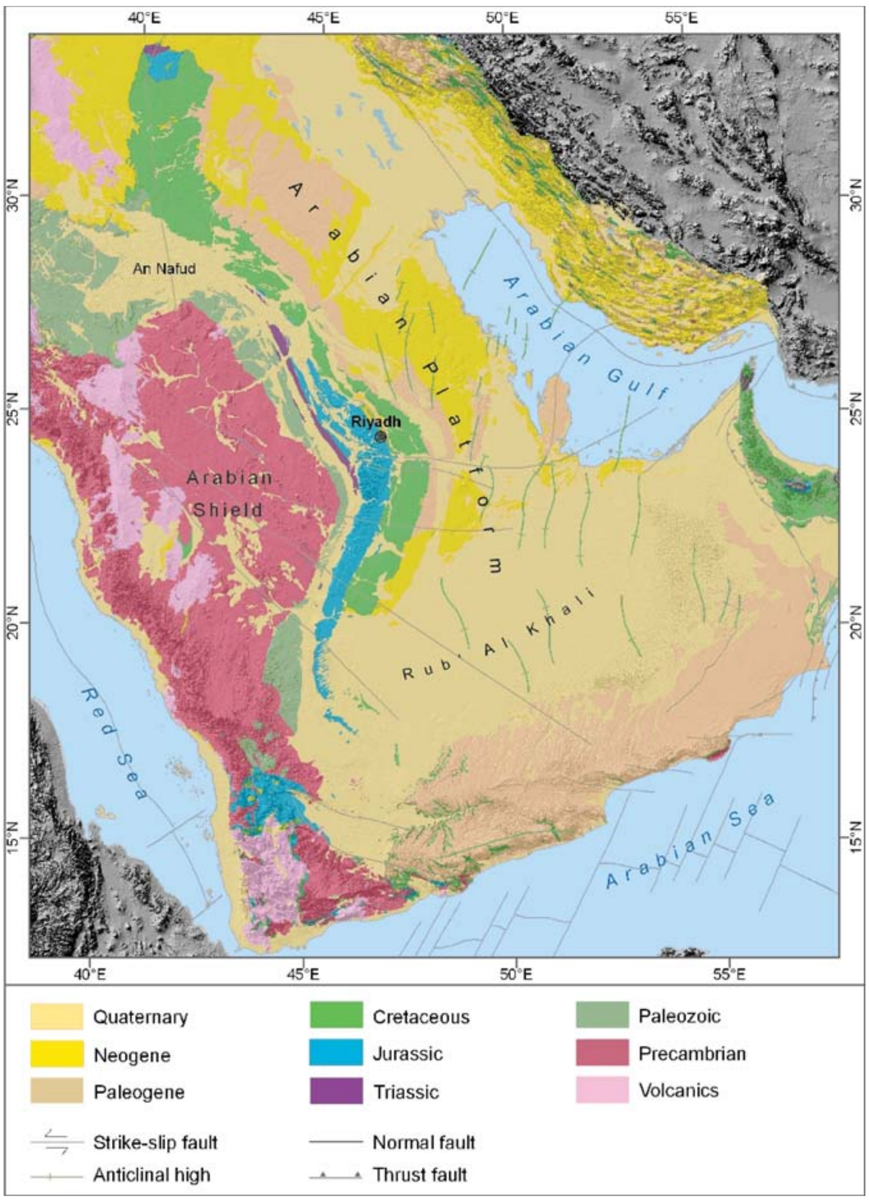

Fig. 1: Simplified geological map of the Arabian Peninsula

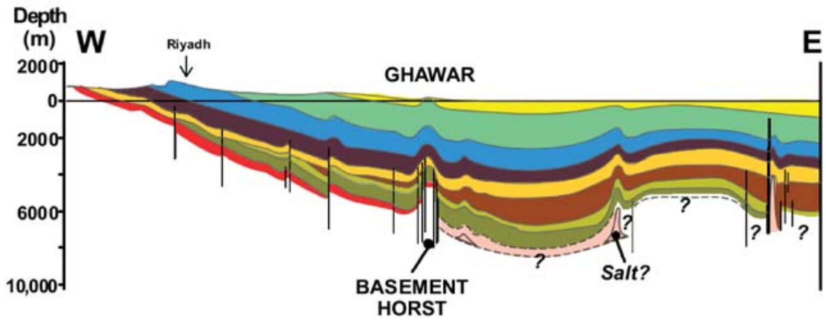

Fig. 2: Geological cross section showing the dipping of the formations from the western outcrop areas to the Arabian Gulf in the East

By contrast, the Arabian Platform is characterized by an up to 12 km thick succession of sedimentary rocks deposited during the Paleozoic, Mesozoic and Cenozoic eras and is mainly composed of siliciclastic rocks and carbonates. The Paleozoic strata are largely sandstones with subordinate shales. The Mesozoic and Cenozoic comprise widespread accumulation of shallow marine carbonate sequences in alternation with terrestrial as well as marine siliciclastic and mixed carbonate-siliciclastic deposition. Very thin layers of evaporites are also parts of the Phanerozoic succession, especially in the Late Jurassic Arab and Hith formations. The youngest deposits of Quaternary age include limestones, unconsolidated silts, sands and gravels, as well as sabkhas, ephemeral lake sediments and wadi-sediments. [1, 2].

In general, the formations are dipping from the Western outcrop areas towards the East. The constant dip of the formations is only interrupted by a series of mainly North-South trending anticlines and synclines representing the major tectonic elements. Faulting is nearly absent [3] (Figure 2).

The sedimentary succession can be subdivided into two major aquifer systems. The 'Upper Mega Aquifer System' with the Wasia-Biyadh, Umm Er Radhuma, Dammam and Neogene as the principal aquifers and the 'Lower Mega Aquifer System' with the Wajid and the Dhruma-Minjur as the principal aquifers. The Wasia-Biyadh and the Dhruma-Minjur are separated by upper Jurassic to lower Cretaceous limestones forming an aquitard. Groundwater movement occurs primarily through secondary openings, such as joints, fractures, fissures and solution voids. The main horizontal flow component is directed from the outcrop areas towards the Arabian Gulf in the East and the Euphrates-Tigris basin in the North-East.

In general, the relatively slow groundwater movement causes long residence times within the aquifers. Therefore, the main portion of the groundwater is fossil water and has been dated by isotope analyses, e.g. as being more than 20,000 years old in the Al Hassa area [3, 4]. 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'.

Open Research Questions and Scientific Approach: The proposed research activities will be performed in the framework of the IWAS initiative (http://www.iwas-sachsen.ufz.de). IWAS tackles specific research questions within five world regions. Some of the most pressing water problems worldwide will be addressed, e.g. water supply and sanitation, water and agriculture, ecosystem services and extreme events and processes. In Saudi Arabia, new solutions for the characterization and the sustainable management of the scarce water resources of arid areas are explored. Especially the following topics are in focus:

Groundwater Recharge: For groundwater resources management, the rate of aquifer replenishment due to groundwater recharge is one of the most important factors and unfortunately also one of the most difficult to derive with sufficient accuracy. In general, the potential evaporation by far exceeds the precipitation limiting groundwater recharge. Groundwater recharge mechanisms can be defined as direct or diffuse recharge (direct vertical percolation of precipitation through the unsaturated zone), indirect recharge (percolation to the water table through the beds of surface water courses i.e. wadis) and localized recharge (water concentrated in local depressions percolating to the groundwater). As aridity increases, the contribution of direct recharge to total recharge is likely to decrease, although due to the large areas potentially eligible for direct groundwater recharge, also very low direct recharge rates of a few millimeters per year can significantly add to the water resources. Indirect recharge and localized recharge may dominate in arid areas. Field studies in Saudi Arabia and the United Emirates showed that especially the well sorted dune sands enable an effective percolation of precipitation. However, precipitation is limited and highly variable in space, time and intensity. In addition, the role of the thick unsaturated zone typical for arid environments may complicate recharge estimations. For semi-arid regions with a shallow vadose zone it is assumed that water fluxes measured below the root-zone reflect groundwater recharge. Assuming a thick vadose zone, recharge may not be similar in magnitude or even in direction compared to the water flux just below a root zone (if a root zone is present at all).

Currently applied direct groundwater recharge estimation methods give point-information, with only limited value on a regional scale. Regional information, available through the analysis of climate or remote sensing data are also not sufficient to display the complex and time-variable processes e.g. in the thick unsaturated zone. A multi-scale research approach is therefore suggested to better estimate groundwater recharge in arid areas. Scales and proposed research packages are.

Laboratory Scale: In column experiments, accompanied by numerical modeling, effective infiltration and evaporation will be measured for precipitation depths and initial and boundary conditions that can be expected in arid areas. Threshold values, e.g. for soil water saturation, infiltration capacities, temperature gradients, precipitation intensities will be derived that can be used for the interpretation of regional data.

Local Field Scale: Potential groundwater recharge areas (local depressions, wadis) will be identified in the field and by using direct-push equipment the vertical soil moisture distribution will be analyzed and through tailored TDR equipment monitored over extended periods of time. If the groundwater table can be reached, high resolution vertical sampling of the uppermost part of the water column will be performed. Multi-element isotope analysis including Tritium, D, ^{18}O and ^{36}Cl will be used to determine the vertical age distribution of extractable water samples. With this, estimates on actual and historical groundwater recharge due to indirect or local recharge can be given. For comparison, similar studies will be performed in areas with potential direct groundwater recharge.

Regional Scale: On a regional scale, data from weather radar, climatic stations and remote sensing will be collected. By combining these data with the results from the laboratory and local scale, time dependent potential maps for groundwater recharge will be derived that take processes variable in space and time into account. As a result, areas can be identified that, due to favorable morphology and surface/ subsurface conditions are likely to produce significant groundwater recharge. Combining this knowledge with climatic data, a conversion of e.g. precipitation data into groundwater recharge data should be feasible, also allowing to estimate the effects of climatic changes on the resources.

Large-Scale Groundwater Modeling and Smart Groundwater Mining: A sustainable use of groundwater resources in Saudi Arabia might be unrealistic due to limited groundwater recharge and growing water demand for agricultural irrigation, domestic supply and industry. Therefore, a management concept based on ‘safe yield’ is desirable, but might in some cases not be achievable. Instead, ‘smart mining’ concepts have to be developed with the aim to use the resources in the most efficient way. This is especially important considering the heterogeneity of regional aquifer systems in terms of water quality. Quality limitations may have natural reasons, e.g. slow circulation leading to an increase in salinity, as does salt water intrusion at the coastlines. High evaporation of groundwater in discharge areas results in salt deposits and high saline shallow aquifers. In addition, radioactivity might be a problem especially considering the large sandstone aquifers typical for the Arabian Peninsula. As a further problem, the occurrence of low quality water might be random.

These problems are likely intensified by overpumping aquifers, leading e.g. to hydraulic shortcuts between layered aquifers or to intrusion of highly mineralized waters out of low permeability zones due to the drastic loss in hydraulic heads. Not considering these factors can lead to early water quality deterioration at a well field and to a decrease of the usable amount of water.

Profound mathematical optimization concepts considering these factors are scarce, especially on a regional scale. Also optimization criteria are difficult to define as a result of diverging interests. Stakeholders from agriculture, industry and the public sector compete for priority ranking. In any case, it has to be differentiated between the benefits of exploitation and the negative side effects. This requires a profound understanding of the aquifer as a dynamic system responding to interferences caused by water abstraction.

Groundwater models considering these necessities can be used to predict the effects of groundwater abstraction varying in space and time and support decisions leading to optimized management strategies, ideally aiming to a safe yield. In the context of smart mining, models are the key to maximize the benefit of the available water resources and to minimize water quality deterioration until alternative freshwater sources are available or until depletion.

Within the modeling process, the estimation and reduction of uncertainties is required, which leads to the “inverse problem” in groundwater modeling. Strategies for the reduction and estimation of uncertainties are needed. Problems are (1) the ill-posedness of parameter estimation, (2) that no unique solution may exist and (3) that measurement errors make the results unreliable. Ways out are the reduction of degrees of freedom by e.g. introducing geological and hydrogeological ‘a priori’ knowledge. Our ability to adequately predict future changes in groundwater resources will consequently rely on our ability to understand the development of the groundwater systems in the past. We suggest to calibrate groundwater models with past information, e.g. information on aquifer genesis, aquifer analogue studies, data on palaeo climate or palaeo water levels, or on landscape evolution. Also chemical data, e.g. isotope data on groundwater ages can be used to establish benchmarks for model calibration. The high quality groundwater studies already available in the Ministry will be used as data sources for the setup of the respective models.

Groundwater Radioactivity: Uranium, which heads two of the three natural decay chains, occurs in virtually all igneous, hydrothermal and sedimentary geological environments. The original source of uranium, however, is igneous rocks, with granites showing in general highest activity concentrations. Derived from granitic or related metamorphic host rocks, sandstones may also contain substantial amounts of disperse uranium. However, intra-cratonic basins filled with flat-lying continental fluvial sandstones may contain especially high uranium concentrations typically showing patchy distribution patterns. The uranium found in such deposits is derived from weathering and leaching of uranium-rich granitic/metamorphic rocks adjacent to the basin under oxidizing conditions. The actual deposits accumulate as weakly oxidized leachate, containing dissolved uranium, passes a reducing interface in the sandstone (e.g. natural sulfides or organic material such as coal, oil or gas). The reduced uranium precipitates as uraninite, the primary ore mineral of uranium (roll-front). In general, regional redox environments and arid to semi-arid climates at the time of deposition are critical factors for the formation of uranium deposits.

Sandstone uranium deposits account for approximately 30% of annual global uranium production. Large sandstone aquifers are also the main source of fresh water in arid areas. Examples are the so called "Nubian Sandstone Aquifer System" in North Africa, which is shared by Egypt, Libya, Sudan and Chad, the Saq and Wajid sandstone aquifer on the Arabian Peninsula, or the Karoo sandstone in Botswana, Namibia and South Africa. For example, the Karoo sandstone is being explored successfully for uranium.

Depending on the redox conditions, the groundwater in the mentioned aquifers may contain significant amounts of radionuclides that are potentially hazardous to human health if that water is used for drinking water purposes or irrigation.

However, the distribution of radionuclides in the aquifer is patchy and difficult to predict as it might be random, or localized to zones with favorable redox conditions. In addition, pumping of such waters might result in changing redox conditions and in mobilization or precipitation of radionuclides.

Groundwater management can be seriously affected by these processes as the risk for water quality deterioration due to radionuclides is difficult to predict. If radiochemical contaminations have to be suspected in an aquifer, an undifferentiated analysis of all potentially present nuclides at all wells is not an appropriate approach. Instead only the most relevant isotopes should be looked for, preferably in wells that fulfill certain petrographic and hydrochemical criteria. We propose to determine such criteria and to identify indicator parameters serving as proxies for elevated radioactivities. In this context, it will be analysed whether significant correlations between radionuclide concentrations and parameters like TDS, O2, Eh, Mn, Fe, Ba, Rn and gross alpha/gross beta radioactivity exist.

Moreover, the radionuclide data will be compared to concentrations of radionuclides in the potential host rocks. The latter will be obtained through measurements with a portable radiation detector in the outcrops and by geophysical borehole loggings, namely natural (spectral) gamma ray measurements.

CONCLUSIONS

Due to results of several extensive aquifer studies performed in Saudi Arabia over the last years, the Kingdom has in the meantime a good overview about the available water resources stored in the large aquifer systems of the Arabian Peninsula. It is therefore a recognized fact, that the current overexploitation and groundwater mining leads to a depletion of the resources that requires immediate action. Several measures are already in place especially regarding the agricultural sector.

However, despite a long history of water related research in arid areas some fundamental issues are not satisfactory resolved yet and further research is needed. Our research approaches have the major goal to get an in-depth understanding of the water balance, hydrochemical evolution and the fundamental characteristics of large, regional aquifer system covering thousands of km^2.

By applying a broad range of laboratory, field, analytical and modeling tools, it is expected that not only site specific results will be obtained but the general underlying processes will be identified. The chosen tools will therefore be evaluated in terms of their general applicability to the basic problems.

With this, the projects might serve as a blueprint for the investigation of other large scale aquifer systems, especially in other arid areas of the world, e.g. northern Africa, southern Africa, Australia or central Northern America where very similar conditions exist with mining of especially large scale sandstone aquifers.

In the view of sound water resources management the project is of overriding importance as an in depth understanding of an aquifer system might prevent poor decisions and enables an optimization of water use.

REFERENCES

1. GTZ/DCo – Gesellschaft für Technische Zusammenarbeit / Dornier Consulting, 2009a. Detailed Water Resources Studies of Wasia-Biyadh and Aruma Aquifers. Phase I Completion Report, Ministry of Water and Electricity, Kingdom of Saudi Arabia, unpublished.
2. GTZ/DCo – Gesellschaft für Technische Zusammenarbeit / Dornier Consulting, 2009b. Detailed Water Resources Studies of Wajid and Overlying Aquifers. Volume 11 – Groundwater Quality – Hydrochemistry, Draft Final Report, Ministry of Water and Electricity, Kingdom of Saudi Arabia, unpublished.
3. Bakiewicz, W., D.M. Milne and M. Noori, 1982. Hydrogeology of the Umm Er Radhuma aquifer, Saudi Arabia, with reference to fossil gradients. Q. J. Eng. Geol., 15: 105-126.
4. Moser, H., E. Pak, W. Rauert, W. Stichler and J.G. Zötl, 1978. Regions of investigation: Gulf coastel region and its hinterland. Isotopic composition of waters of Al Qatif and Al Hassa areas. In: Al-Sayari, S.S. and J.G. Zötl, 1978. Quaternary Period in Saudi Arabia. Vol. 1: Sedimentological, Hydrogeological, Hydrochemical, Geomorhological and Climatological Investigations in Central and Eastern Saudi Arabia, Springer.