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Use of multiple age tracers to estimate groundwater residence times and long-term recharge rates in arid southern Oman

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ABSTRACT

Multiple age tracers were measured to estimate groundwater residence times in the regional aquifer system underlying southwestern Oman. This area, known as the Najd, is one of the most arid areas in the world and is planned to be the main agricultural center of the Sultanate of Oman in the near future. The three isotopic age tracers ^{4}He, ^{14}C and ^{36}Cl were measured in waters collected from wells along a line that extended roughly from the Dhofar Mountains near the Arabian Sea northward 400 km into the Empty Quarter of the Arabian Peninsula. The wells sampled were mostly open to the Umm Er Radhuma confined aquifer, although, some were completed in the mostly unconfined Rus aquifer. The combined results from the three tracers indicate the age of the confined groundwater is < 40 ka in the recharge area in the Dhofar Mountains, > 100 ka in the central section north of the mountains, and up to and > one Ma in the Empty Quarter. The ^{14}C data were used to help calibrate the ^{4}He and ^{36}Cl data. Mixing models suggest that long open boreholes north of the mountains compromise ^{14}C-only interpretations there, in contrast to ^{4}He and ^{36}Cl calculations that are less sensitive to borehole mixing. Thus, only the latter two tracers from these more distant wells were considered reliable. In addition to the age tracers, $\delta^{2}H$ and $\delta^{18}O$ data suggest that seasonal monsoon and infrequent tropical cyclones are both substantial contributors to the recharge. The study highlights the advantages of using multiple chemical and isotopic data when estimating groundwater travel times and recharge rates, and differentiating recharge mechanisms.

1. Introduction

Arid and semiarid areas are characterized by limited water resources with groundwater often being the only permanent fresh water available for drinking and irrigation. Current low precipitation and high temperatures greatly limit inputs to these subsurface reservoirs. The climatic conditions of these dry areas have long precluded settlement or farming, the anthropogenic water demand, here as output from the subsurface reservoir, was therefore negligibly low. This has changed within the last century and especially in the last 50 years, mainly because of intensified agricultural production with irrigated groundwater (Siebert et al., 2010; WWAP, 2015). Nowadays, heavy groundwater abstraction is a fact in many arid or semiarid areas worldwide (Foster and Loucks, 2006). Consequently, an imbalance between input (groundwater recharge) and output (groundwater abstraction) occurs, leading to depletion of groundwater levels and reductions of groundwater in storage. Groundwater depletion is widely recognized in many aquifers around the globe (Konikow and Kendy, 2005; Wada et al., 2010; Scanlon et al., 2012; Aeschbach-Hertig and Gleeson, 2012). In arid and semiarid areas the degree of impact is often unclear because datasets on predevelopment conditions, abstraction rates and groundwater levels are often missing; in some cases neither one is available. Similarly, sources and quantities of current

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recharge as today's input to the system, the residence times of the bulk of the groundwater in the system, and the size of the groundwater reservoir are usually difficult to assess and in most cases unknown. Furthermore, it has to be taken into account that the reservoirs were most likely filled during more humid periods in the past. These occurred over the last million years, during about 10 glacial periods (Lisiecki and Raymo, 2005).

Arid areas often contain old groundwater because low recharge rates are not sufficient to flush out the aquifers. A number of studies have used environmental isotopes including ^{14}C (Bretzler et al., 2011; Cartwright et al., 2012; Plummer and Glynn, 2013), ^{36}Cl (Guendouz and Michelot, 2006; Mahara et al., 2009), or noble gases (Kulongoski et al., 2008; von Rohden et al., 2010) to estimate current and past recharge rates and the age structure of groundwater systems in arid or semiarid regions. All of these tracers are subject to site-specific problems, such as how to determine the initial concentrations at recharge for ^{14}C (e.g. Kalin, 2000) and ^{36}Cl (Davis et al., 1998) best or how to quantify the subsurface influx of helium (Solomon and Cook, 2000). A well-recognized approach to overcome some of these problems is the combination of the above mentioned (among other) dating tracers (Lehmann et al., 2003; Stadler et al., 2010; Herczeg and Leaney, 2011; Plummer et al., 2012). However, the analysis of these tracers is often costly. Moreover, only a few studies have combined groundwater ages in the range of >5 ka with numerical flow models to provide criteria for an improved water resources management (Sanford et al., 2004).

This lack of knowledge and the associated forecasting uncertainty is one reason for the ongoing and increasing heavy groundwater abstraction in many regions worldwide. This is also the case for the present study site: the Najd region in the southern government Dhofar of the Sultanate of Oman (Fig 1). Previously, ^{14}C data has suggested that the bulk of the groundwater in the region is between 4000 and 40,000 years old and would have been recharged mostly during the last glacial maximum (Clark et al., 1987; Al-Mashaikhi, 2011). However, the ages do not show a systematic pattern or development within the Aquifer system, which makes it difficult to detect recharge areas and to explain the changes in age by the hydraulic gradients in the aquifers. Since it is planned that the Najd region will become the main agricultural area of the Sultanate of Oman in the near future, this lack of knowledge makes it difficult to evaluate and to forecast the impacts of the planned large scale groundwater abstractions on the groundwater system.

^{36}Cl decay and the accumulation of ^{4}He both provide the possibility to calculate groundwater residence times up to the million year range. Both tracers were used in the present study to determine more accurate constraints for the residence times of Najd groundwater. Information on the source of the water, the water type and climatic conditions during recharge were gained from stable isotope and chemistry data.

The main objectives of this study are (1) to assess the suitability of the age tracers ^{4}He, ^{14}C and ^{36}Cl for the age range of the investigated groundwater system, (2) to estimate the groundwater residence time based on a combination of the suitable age tracers, and (3) to assess and elucidate the conditions or processes that may cause discordant ages for the single age tracers.

The mean groundwater residence times and the water sources complement the conceptual model of the Najd flow system, which so far was based on hydraulic information, such as water levels and hydraulic gradients. The refined conceptual model as well as the age data of the present study will be presented elsewhere and will improve the parameterization of a numerical flow model simulating the regional groundwater flow and the recharge history of the Najd aquifer system.

2. Study site and hydrogeological setting

The Najd area, located in the Sultanate of Oman in the south-east of the Arabia Peninsula is an arid area extending north from the Dhofar Mountains out into the Rub Al-Khali desert. The Najd covers an area of approximately 90,000 km^2 and is bounded by its border with Yemen in the west, Saudi Arabia in the north, and the Al-Wusta governorate in the east (Fig. 1).

Dhofar as the administrative region can be divided into three regions: the Najd, the <15 km wide semiarid coastal plain, and the intervening Dhofar Mountains. Whereas the southern part of the Dhofar Mountains has steep slopes, the elevation declines very gently towards the north-east. The terrain in the central Najd is comprised of a stony and sandy plain. Wadi channels, partly representing draining patterns from former pluvial periods, pervade the plain in a south-south-west to north-north-east direction. The northern part of the Najd is covered by large sand dunes, which are part of the Rub Al-Khali desert and extend into the Kingdom of Saudi Arabia (Fig. 1).

The agricultural development in the area started in the 1970's and 1980's when water exploration wells in considerable numbers were drilled. The centers of abstraction are the farm areas in the central Najd, north of the city of Thumrait and the city of Thumrait itself. The abstractions have resulted in falling groundwater levels, with declines reaching 50 m at some locations.

2.1. Climate

The Najd is part of one of the most arid areas in the world, with a mean air temperature of 26.3 °C (station Thumrait 1986–2009) and minimum and maximum values of 6.2 °C and 44.7 °C, respectively (Al-Mashaikhi et al., 2012). In the far northern area of Dhofar (the dunes of the Rub Al-Khali desert) temperatures as high as 50 °C have been reported. On the southern slopes of the Dhofar Mountains, the yearly amount of rainfall has reached 299 mm a^{-1}, many times the rate of the interior area, with a mean value of approximately 30 mm a^{-1} (station Thumrait 1980–2009) (Al-Mashaikhi et al., 2012).

There are indications of more humid conditions in previous times in the south of the Arabian Peninsula, including the Dhofar region in particular (e.g. Clark and Fontes, 1990; Fleitmann and Matter, 2009; Rosenberg et al., 2011). Pluvial wadi channels pervade the ground surface and are observable in the field and on satellite images. These channels begin in the Dhofar Mountains and run in a north-easterly direction. Their course and morphology prove that large, intermittent surface flows have been occurring in the area for a long time.

The annual monsoon with its orographic rainfall distribution is the most reliable source of precipitation for the Dhofar area (Hildebrandt et al., 2007). Today, the monsoon does not reach the Najd but is limited to the south side of the Dhofar Mountains. This is caused by the Dhofar Mountains that block the monsoon airflow towards the interior area and an inversion layer limiting the vertical extent of the cloud cover (Abdul-Wahab, 2003). The monsoon precipitation consists of ongoing light rain, drizzle and mists, which last for a few days up to months (June–September).

The only direct sources of rain to the Najd are rare storm events, so-called cyclones that vary strongly in their spatial and time dimension. They occur infrequently every 3–7 years and can bring heavy rainfall and huge amounts of water to the area in relatively short time periods, lasting hours to days. They sometimes result in heavy surface runoff (Wadi-runoff) lasting for several days, as it was observed for example after cyclone 06-A in October 1992 (Macumber et al., 1995) and in October/November 2011 after tropical cyclone Keila caused heavy rain and floods in Dhofar