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Geochemical, isotopic, and remote sensing constraints on the origin and evolution of the Rub Al Khali aquifer system, Arabian Peninsula

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Summary Chemical and stable isotopic compositions of groundwater samples from the Rub Al Khali (RAK) in southern Saudi Arabia were analyzed. Samples were collected from wells of variable depth (1.5–800 m) along the perimeter of the eastern half of the RAK including flowing artesian wells, pumped wells (formerly artesian), and shallow hand-dug wells encompassing those in sabkha areas. Data indicate that the water from the artesian and formerly artesian wells represents the contents of confined aquifers. Such water (Group 1) is isotopically depleted (δ^2H values ranging from −60‰ to −35‰), and has total dissolved solids (TDS) concentrations ranging from 1300 to 76,000 mg/L, indicating that much of the salinity is acquired in the subsurface. Water from shallow hand-dug wells including those in sabkha areas (Group 2) has experienced significant evaporation (δ^2H values ranging from −34‰ to +19‰) as well as salinization (TDS as high as 92,000 mg/L) by dissolution of sabkha salts including halite and gypsum. Stable isotope data for the Group 2 water samples define an evaporation trend line originating from the Group 1 water samples. This relationship indicates that the Group 2-type water evolved from Group 1-type water by ascending through structural discontinuities, dissolving evaporative salts, and undergoing substantial near-surface evaporation in groundwater discharge zones (sabkhas) characterized by shallow groundwater levels (<2 m). This interpretation is supported by the relatively unradiogenic Sr isotope ratios of groundwater samples (Sr^{87}/Sr^{86} = 0.70771–0.70874) that are inconsistent with that of modern seawater ($^{87}Sr/^{86}Sr$ = 0.70932). The RAK aquifer water represents either high-elevation recharge

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from the Red Sea Hills, and/or recharge largely formed of paleo-water precipitated during moist climate intervals of the late Pleistocene recharging aquifers cropping out at the foothills of the Red Sea mountains. This inference is supported by a progressive decrease in hydraulic head and increase in groundwater salinity from west to east, substantial precipitation over the Red Sea Hills, and a major E–W trending channel network that channels precipitation from the Red Sea Hills toward recharge areas. Analysis of 3-hourly TRMM (Tropical Rainfall Measuring Mission: 1998–2006) precipitation data and digital elevation data shows that 27% of the average annual precipitation (150×10^9 m^3) over the Arabian Peninsula is channeled toward the recharge zone of the RAK aquifer system, of which an estimated 4×10^9 m^3 a^{-1} to 10×10^9 m^3 a^{-1} of this water is partitioned as recharge to the RAK aquifer system. Additional integrated studies on recharge rates, sustainability, and water quality issues for the RAK aquifers could demonstrate that the RAK is one of the most promising sites for groundwater exploration in the Arabian Peninsula. Results highlight the importance of investigating the potential for sustainable exploitation of similar large aquifer systems that were largely recharged in previous wet climatic periods yet are still receiving modest modern meteoric contributions.

Introduction

The low rates of precipitation (<100 mm/yr) over many of the arid and hyper-arid parts of the world represent a serious challenge to organized efforts to populate and develop such areas. This problem is exemplified in the Saharan belt and in the Arabian Peninsula. At present, precipitation over the Sahara and the Arabian Peninsula is largely localized in high-elevation areas (e.g., Red Sea Hills in Egypt, Sudan, and Arabia), whereas the majority of the remaining lands in this area receive very little, if any precipitation. The current conditions contrast with the wet climatic periods that prevailed throughout the Late Pleistocene. In this manuscript, we show that large aquifers that were mainly recharged during wet periods and are still receiving modern contributions from localized precipitation can potentially provide opportunities for sustainable development.

Underlying the vast deserts of the Rub Al Khali (RAK), meaning the 'Empty Quarter', is one of the largest aquifer systems of the arid world, the Rub Al Khali Aquifer System (RAKAS) of the Arabian Peninsula. This aquifer extends for some 650,000 km^2 in the southern third of the Arabian Peninsula in southern Saudi Arabia, Oman, Yemen, and United Arab Emirates (Fig. 1). With the exception of a few settlements at the outskirts of the desert, the RAK remains largely uninhabited and undeveloped because of its harsh climatic conditions (temperatures > 50 °C in summer) and largely inaccessible terrain. The RAK encompasses the largest dune fields on Earth with some dunes reaching hundreds of meters high. These problems together with a lack of understanding of the area's groundwater potential have hindered plans for its development. In this manuscript, we present the results of a preliminary integrated investigation, involving geochemical, isotopic, field, and remote sensing data that addresses the origin and evolution of the groundwater of the RAKAS.

Understanding the origin, evolution, and magnitude of this major groundwater resource is crucial for optimal management of the RAK. This paper summarizes geochemical and isotopic data for 24 groundwater samples obtained during a sampling expedition to the RAK in February/March 2006. Interpretation of geochemical and isotopic data was conducted in the context of relevant geologic and hydrogeologic data sets including: spatial variations in hydraulic head, distribution of recharge areas (extracted from geologic maps), distribution of watersheds and drainage networks (extracted from digital elevation data), and temporal precipitation over the watersheds. The latter was extracted from 3-hourly TRMM (Tropical Rainfall Measuring Mission) precipitation data for a nine year time period of 1998–2006. We also show that there are indications that groundwater resources in the RAK are apparently significant compared to other areas in the Peninsula and offer development potential that merits further detailed investigations.

Geology, hydrogeology, landforms, and climate of the RAK

To date, only limited detailed studies have been conducted on the hydrogeology of the RAK in Saudi Arabia. These inadequacies will be addressed in part by examining our data sets in the context of the more thoroughly studied portions of the RAK in neighboring countries (United Arab Emirates and Oman) and that of areas of similar hydrogeologic and climatic settings in neighboring countries. Such an approach could potentially provide insights into the origin and evolution of groundwater in the study area.

Precambrian crystalline basement of the Arabian Shield crops out along the eastern margins of the Red Sea coastline forming the westernmost margin of the RAK terrain. The basement complex rocks are impermeable and groundwater in basement areas is found in fractures or in the alluvial aquifers within the wadi network dissecting these domains. Unconformably overlying the crystalline basement are thick sequences of sedimentary formations ranging in age from Cambrian to recent; they dip gently to the east and thicken in the same direction reaching thicknesses of up to 5 km in the vicinity of the Persian Gulf. These stratigraphic relationships are demonstrated in Fig. 2, a generalized schematic cross-section along a SW to NE trending transect.