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Noble gases reveal the complex groundwater mixing pattern and origin of salinization in the Azraq Oasis, Jordan

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ABSTRACT

Azraq Oasis in the eastern Jordanian desert is an important freshwater resource of the country. Shallow groundwater reserves are heavily exploited since the 1980s and in consequence the groundwater table dropped significantly. Furthermore, some wells of the major well field drilled into the shallow aquifer show an increasing mineralization over the past 20 years. A previous study using conventional tracers did not result in a satisfactory explanation, from where the salt originates and why only a few wells are affected. In this study, the application of dissolved noble gases in combination with other tracer methods reveals a complex mixing pattern leading to the very localized salinization within the well field. It is found that primarily the wells affected by salinization 1) contain distinctly more radiogenic ^{4}He than the other wells, indicating higher groundwater age, and 2) exhibit ^{3}He/^{4}He ratios that argue for an imprint of deep fluids from the Earth's mantle.

However, the saline middle aquifer below is virtually free of mantle helium, which infers an upstream from an even deeper source through a nearby conductive fault. The local restriction of the salinization process is explained by the wide range of permeabilities of the involved geologic units. As the wells abstract water from the whole depth profile, they initially pump water mainly from the well conductive top rock layer. As the groundwater table dropped, this layer fell progressively dry and, depending on the local conductivity profile, some wells began to incorporate more water from the deeper part of the shallow aquifer into the discharge. These are the wells affected by salinization, because according to the presented scheme the deep part of the shallow aquifer is enriched in both salt and mantle fluids.

1. Introduction

Azraq is situated in the northeastern Jordanian desert, about 90 km east of the capital Amman. Azraq used to be an oasis up to the early 1990s, with an extensive system of lakes and marshland fed by several springs (Nelson, 1985). At that time the oasis hosted a vivid ecosystem and was an important stop-over for migrating birds. In the early 1980s, however, the AWSA well field was drilled close to the oasis to supply the urban areas of Amman and Zarqa with drinking water. The groundwater abstraction from this well field of 15–20 million cubic meters per year (MCM/a) and a growing water demand for irrigation purposes in the vicinity of the oasis and the northern parts of the Azraq basin (in total 45 MCM/a) caused the groundwater table to drop by almost 1 m per year since then, and the springs fell dry in 1991 (Al-Momani et al., 2006).

Not only is overpumping a hazard for the Azraq ecosystem, but also the threat of deteriorating groundwater quality grows. While the AWSA well field produced high quality drinking water with little mineralization during the first years of operation, some of its wells show a rising salinity over the years (compare Fig. 1). This issue was addressed in a study conducted by the Water Authority of Jordan (Al-Momani et al., 2006), but the source of the salt could not be determined with certainty. The present study, applying dissolved noble gases as the main tracers, aims at shedding new light on the complex groundwater intermixing processes and the origin of salinization in the central part of the Azraq basin.

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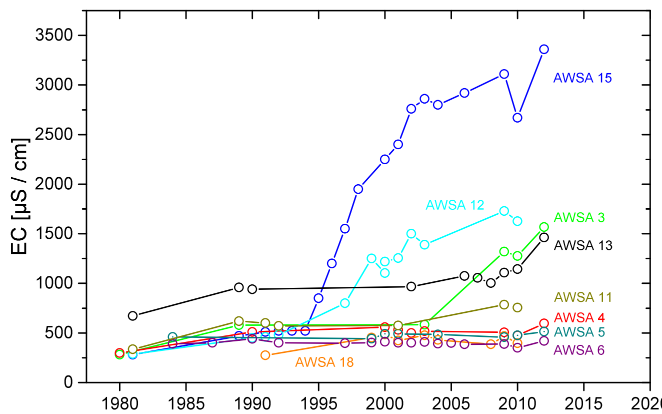

Fig. 1. Salt content development of the AWSA wells.

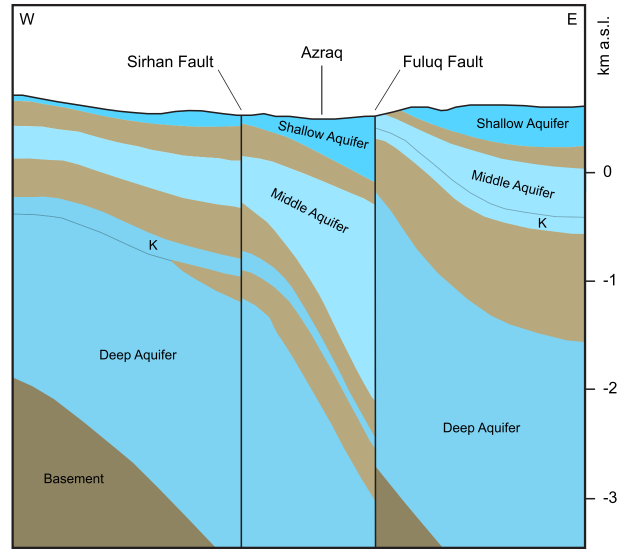

Fig. 3. Geologic cross-section in west–east direction, as indicated in Fig. 2. The shallow, middle and deep aquifer systems are displayed in blue, while the aquicludes are brown. The vertical displacement at the Fuluq fault is obvious. As the Kurnub aquifer (K) is located differently east and west of the Fuluq Fault, it is emphasized as being part of the deep aquifer system west of the Fuluq fault and connected to the middle aquifer east of it. Adapted from Margane et al. (2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Hydrogeologic setting

Azraq Oasis lies in a tectonic depression within the Azraq surface catchment basin, which extends into Syria and covers an area of about 12,800 km^2. Most precipitation occurs in the northern highlands around the mountain Jabal ad-Druze (compare the regional map in Fig. 2). The basin has no perennial rivers, but during storm events large amounts of water can be transported by wadi run-off from the highlands into the central playa (*Sabkha* in Arabic), where most of it evaporates.

In general, three major aquifer systems are present in the Azraq basin, which are shown in the cross-section in Fig. 3. The Ram and Kurnub sandstone aquifers of Cambrian to Lower Cretaceous age form the deepest aquifer system, which is present in almost the whole of Jordan. The upper limit of the deep aquifer is more than 1200 m below the surface in Azraq; hence, this aquifer is not exploited in this area. It is overlain by the formations of the Cenomanian to Turonian Lower Ajlun group (A1/6). These marl and limestone units are considered to act as an aquitard, separating the sandstone aquifers beneath from the Amman-Wadi Sir limestone aquifer above (B2/A7, Upper Turonian to Campanian-Maastrichtian). In Azraq this aquifer is often named the middle aquifer. It is recharged in the Jordan highlands in the west (see Fig. 2), and the hydraulic head gradient drives the groundwater flow in eastern and northeastern direction towards the Azraq oasis and beyond (Margane et al., 2002). Its mineralization is generally high in Azraq, so this aquifer is not utilized there as well. The middle aquifer is confined by the several hundred meter thick bituminous marl of the Muwaqqar formation (B3) of Maastrichtian to Paleocene age.

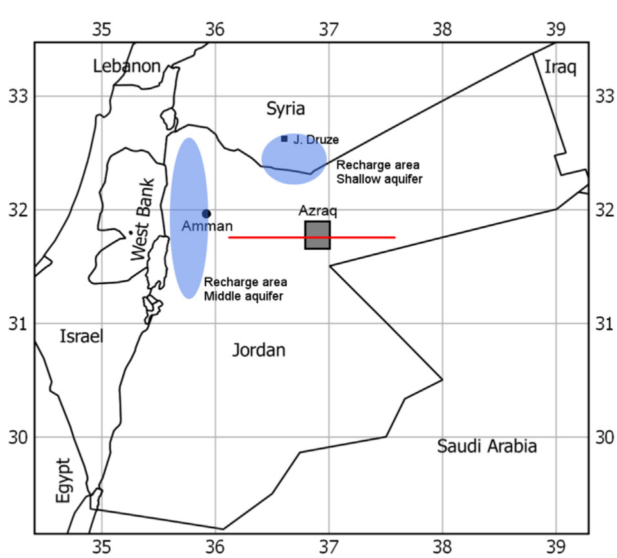

Fig. 2. The location of the Azraq Oasis in Jordan. The recharge areas of the shallow and middle aquifer systems are given in blue. The position of the cross-section in Fig. 3 is indicated by a red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The upper aquifer system (often termed the shallow aquifer) consists of four units: the Umm Rijam chalky limestone (B4, Paleocene to Eocene) right above the B3 aquiclude, the Wadi Shallala formation (B5, Eocene), the Harrat ash-Shaam basalt shield (Oligocene to present time), covering the northern part of the basin, and, in the center of the basin, the Quaternary sediments of the Sirhan formation. Groundwater recharge to the upper aquifer occurs dominantly in the northern part of the Azraq basin at the slopes of the mountain Jabal ad-Druze (Fig. 2). The general flow direction is towards the central oasis, where this study is focused (see map in Fig. 4). Under undisturbed conditions, two major spring fields fed the lakes of the oasis, thereby being the natural discharge of the upper aquifer in the Azraq Basin, but nowadays groundwater abstraction is the only discharge.

Due to the generally good water quality, the shallow aquifer in the Azraq basin is heavily exploited for agricultural as well as domestic purposes. The transmissivity of the fractured basaltic top layer is generally very high within the AWSA well field (up to 65,000 m^2/day), but varies strongly among the individual wells (Ayed, 1996; citing Humphreys and Sons, 1982). The lower part of the shallow aquifer, the B4 formation, is an aquifer, too, but its transmissivity is significantly lower than that of the basalts (the maximum is 660 m^2/day). The B5, located between the basalt and B4 units, acts as an aquifer in the southern part of the basin, but is considered an aquitard in the area of the former oasis and, namely, in the AWSA well field, where its thickness is around 70 m. In the