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Isotopic and chemical composition of precipitation in Riyadh, Saudi Arabia

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ABSTRACT

Only limited data on the isotopic and chemical composition of Riyadh rain are currently available. In this study, we complement these data by analyzing integral samples covering 28 precipitation events between 2009 and 2013. Results of stable isotope analyses are used to establish a Local Meteoric Water Line: $\delta^2H = 5.22(\pm 0.38) \cdot \delta^{18}O + 14.8(\pm 0.9)$ ‰. Moisture source-related isotopic fingerprints are masked by the continental effect, the altitude effect, sub-cloud evaporation, and moisture recycling. The study of one event for intra-storm variability revealed strong isotopic depletion due to rainout and Rayleigh distillation processes, thus highlighting the general need for integral samples. Tritium analyses of grab samples from 12 events yielded concentrations between 2.8 and 6.4 tritium units (TU), which are close to the natural background of a few TU.
Major ion concentrations and ratios indicate that solutes are predominantly derived from atmospheric dust originating from limestone outcrops and sabkha deposits. The latter play a role with respect to the elevated $Cl^-$and Na^+ contents, but are probably also responsible for the $SO_4^{2-}$and a part of the Ca^{2+} found in Riyadh rain. Observed intra- and inter-storm variabilities of major ion levels necessitate the collection of integral samples and the calculation of precipitation-weighted means, respectively.
The obtained isotopic signatures and the precipitation-weighted mean Cl^-concentration (9.5 mg L^{-1}) may be useful in groundwater assessments, e.g., for the identification of modern recharge and quantification thereof by means of the Chloride Mass Balance method.

1. Introduction

For arid countries like Saudi Arabia, a thorough groundwater resources assessment is crucial to enable sound water management. In such studies, the stable water isotopes oxygen-18 (^{18}O) and deuterium (^2H) provide a powerful tool to investigate the provenance of groundwaters and the (paleo)climatic conditions during their replenishment. However, to evaluate the isotopic signature of groundwater, that of current precipitation must also be known (Gat, 1971; Wagner and Geyh, 1999).

Usually, such data are retrieved from the closest monitoring station of the Global Network of Isotopes in Precipitation (GNIP, IAEA/WMO, 2015) database. Although the database lists six stations for Saudi Arabia, none of them provides a significant amount of $\delta^{18}O$ and δ^2H analyses (1–13 analyses per station). Even if the entire Arabian Peninsula is considered, the list of stations with a significant data set (i.e., >20 analyses) is rather limited (Fig. 1): Bahrain (Bahrain), Salalah (Oman), and Qairoon Hairiti (Oman).

Another source for such isotope data is scientific articles. In this respect, the study by Alyamani (2001) is noteworthy. The author reports isotope analyses for 51 rain samples collected at eight locations in Western Saudi Arabia (4–10 analyses per location; see Fig. 1 for study area). Yet, robust isotope data are not available for vast parts of the country. This includes central Saudi Arabia, where some of the major aquifer systems of the Arabian Peninsula have their outcrops, i.e., recharge areas (Fig. 1; MAW, 1984; Powers et al., 1966; USGS and ARAMCO, 1963). The isotopic data sets reported for the above-mentioned GNIP stations cannot be expected to be representative for central Saudi Arabia, e.g., because of the continental effect (e.g., −0.3‰/100 km for $\delta^{18}O$ in the Sahara, Sonntag et al., 1976). Also the altitude effect causes significant isotopic shifts (−0.08‰/100 m for $\delta^{18}O$ in W Saudi Arabia, Alyamani, 2001; −0.15‰/100 m for $\delta^{18}O$ in N Oman, Weyhenmeyer et al., 2002).

Due to a lack of isotope data, a Local Meteoric Water Line (LMWL) has never been established for this region (Alsaaran, 2006; Job et al., 1978). Hence, researchers studying groundwater or the unsaturated

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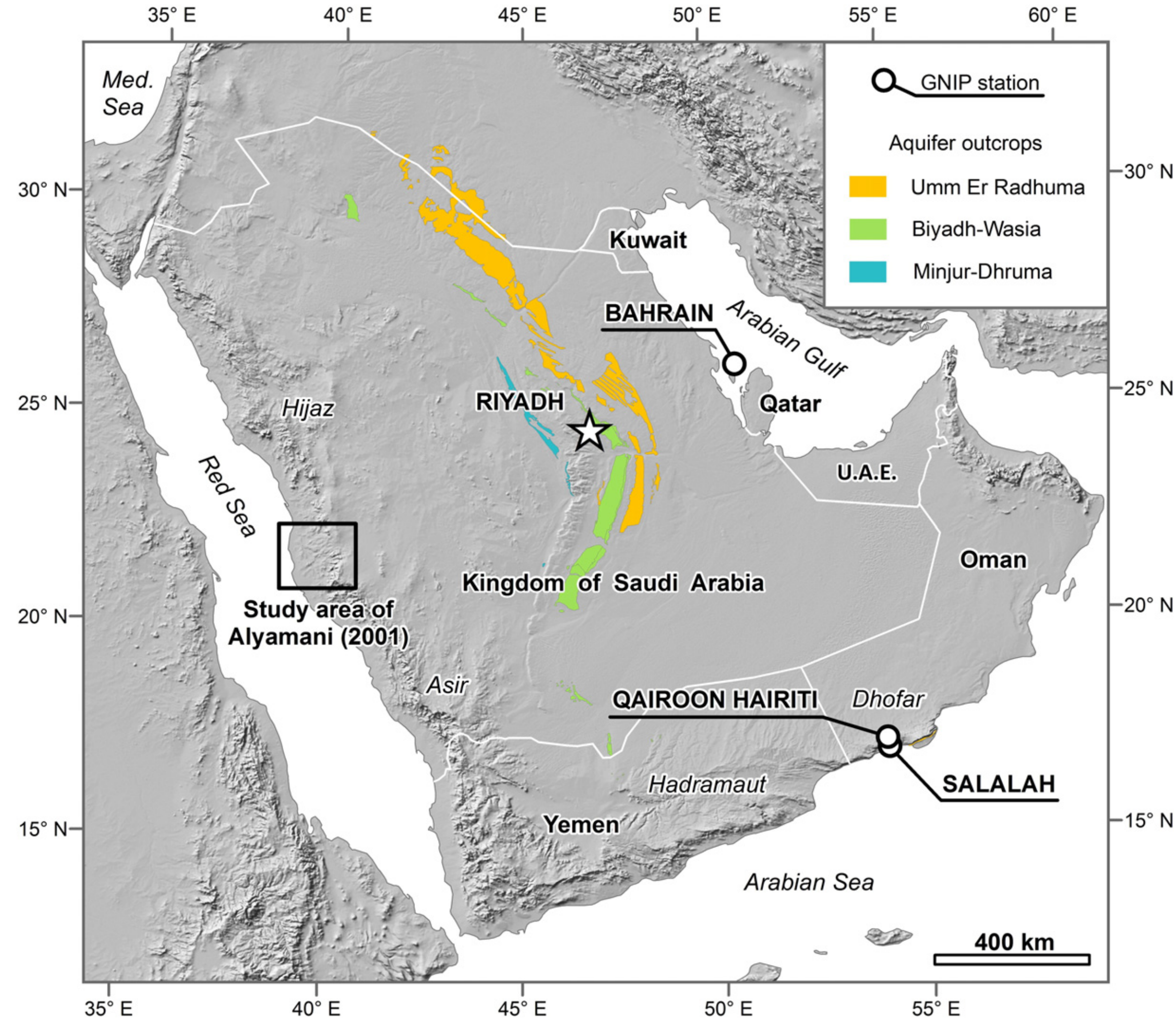

Fig. 1. Map showing the countries of the Arabian Peninsula and the available GNIP stations with more than 20 analyses of $\delta^{18}O$ and δ^2H in precipitation (shaded relief from Natural Earth, 2015). Moreover, the map includes the study area of Alyamani (2001, see text) and the outcrops of some major aquifers of Saudi Arabia (MAW, 1984; Powers et al., 1966; USGS and ARAMCO, 1963).

zone had to seek alternative data sources for precipitation-related data needed for comparison. Some used the Global Meteoric Water Line (GMWL, $\delta^2H = 8 \cdot \delta^{18}O + 10‰$; Craig, 1961) as a workaround (Al-Harbi et al., 2008; Bazuhair et al., 1994; Shampine et al., 1979; Subyani, 2004). Others utilized data from the Bahrain GNIP station (BRGM, 1981a; Dincer et al., 1974; Job et al., 1978), despite the distance (Bahrain–Riyadh: 420 km) and difference in elevation (600 m). A few also collected their own, event-based samples — particularly consulting companies working for the Ministry of Agriculture and Water (now Ministry of Water & Electricity): BRGM (1976, n = 7), BRGM (1977, n = 10), GDC (1980, n = 2). While it is common practice to collect samples on a monthly basis (IAEA/WMO, 2015), event samples are occasionally advocated. Crawford et al. (2013) emphasize the opportunity to study the relationships between isotopes in precipitation and synoptic scale weather systems, e.g., by identifying moisture sources of individual events using back-trajectory analysis (compare Leguy et al., 1983). Nevertheless, the quantity of available event-based data is not sufficient to calculate a LMWL, making additional analyses necessary.

Apart from ^2H and ^{18}O, hydrogeologists frequently utilize the radionuclide tritium (^3H) in groundwater studies, mainly for identifying modern replenishment. The isotope is produced naturally by cosmic radiation, but thermonuclear bomb tests conducted in the 1950s–1980s caused a dramatic rise of ^3H concentrations in the atmosphere. Due to washout and decay, atmospheric concentrations have mostly reached natural levels again (Clark and Fritz, 1997). Therefore, groundwater dating relying on bomb-produced tritium in precipitation is close to its expiry date (Fontes, 1985; Kazemi et al., 2006). However, the natural cosmogenic ^3H can also be utilized for the estimation of groundwater residence times (Clark and Fritz, 1997; Kazemi et al., 2006). Unfortunately, current ^3H levels in Saudi rainwater are unknown.

Besides the isotopic signature of rainfall, its chemical composition is relevant. Knowledge of precipitation chemistry can contribute to an understanding of global element cycling in the atmosphere (Ahmed et al., 1990) and of air mass circulation (Edmunds, 2010). Rainfall can also be considered the “titrant” in hydrogeochemical processes, being the initial solvent in water–rock interaction (Edmunds, 2010). Additionally, chloride concentrations are a key parameter in the Chloride Mass Balance method for estimating groundwater recharge (Edmunds, 2010) and insufficient data lead to additional uncertainty in the calculation (Bazuhair and Wood, 1996).

Hydrochemical data on rainfall are scarce in arid and semi-arid regions (Ahmed et al., 1990) and particularly in parts of Africa (Edmunds, 2010) and the Arabian Peninsula (Alabdula'aly and Khan, 2000). For central Saudi Arabia, only a few publications are available. Handy and Tucker (1984) report on the chemistry of 12 rain events