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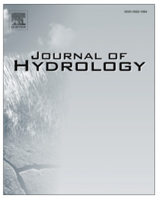

Temporal ^{222}Rn distributions to reveal groundwater discharge into desert lakes: Implication of water balance in the Badain Jaran Desert, China

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SUMMARY

How lake systems are maintained and water is balanced in the lake areas in the Badain Jaran Desert (BJD), northeast of China have been debated for about a decade. In this study, continuous ^{222}Rn measurement is used to quantify groundwater discharge into two representative fresh and brine water lakes in the desert using a steady-state mass-balance model. Two empirical equations are used to calculate atmospheric evasion loss crossing the water–air interface of the lakes. Groundwater discharge rates yielded from the radon mass balance model based on the two empirical equations are well correlated and of almost the same values, confirming the validity of the model. The fresh water and brine lakes have a daily averaged groundwater discharge rate of 7.6 ± 1.7 mm d^{-1} and 6.4 ± 1.8 mm d^{-1}, respectively. The temporal fluctuations of groundwater discharge show similar patterns to those of the lake water level, suggesting that the lakes are recharged from nearby groundwater. Assuming that all the lakes have the same discharge rate as the two studied lakes, total groundwater discharge into all the lakes in the desert is estimated to be 1.59×10^5 m^3 d^{-1}. A conceptual model of water balance within a desert lake catchment is proposed to characterize water behaviors within the catchment. This study sheds lights on the water balance in the BJD and is of significance in sustainable regional water resource utilization in such an ecologically fragile area.

1. Introduction

Radon-222 ($T_{1/2} = 3.83\ d$) is a conservative gas tracer which is highly concentrated in groundwater due to alpha-recoil supply from the parent isotope ^{226}Ra in solid phase (Asikainen, 1981; Ku and Luo, 1992; Luo et al., 2000; Tricca et al., 2000; Porcelli, 2008). High ^{222}Rn activity concentrations in groundwater, fairly sensitive ^{222}Rn analysis by commercial and portable ^{222}Rn monitor (RAD7; Durridge, 2007) and conservative behavior during the hydrological processes make it an ideal tracer to study its migration and transport from groundwater to various environments such as estuaries, watersheds and rivers (Cable et al., 1996; Burnett and Dulaiova, 2003; Cook et al., 2003; Tse and Jiao, 2008; Gleeson et al., 2009). ^{222}Rn utilization in groundwater discharge studies in lakes has gained considerable attention in recent years due to the high-resolution temporal radon measurement with RAD7-AQUA and research interests in groundwater discharge to terrestrial lakes (Dimova and Burnett, 2011; Kluge et al., 2012). RAD7-AQUA is one accessory of RAD7 with a much higher radon detection limit and less equilibration time (Dimova and Burnett, 2011; Schubert et al., 2012a,b). Conventionally, a radon mass balance model is used to quantify groundwater discharge in various aquatic systems in which radon is mainly lost by evasion at the water–air interface (Schmidt et al., 2010; Dimova and Burnett, 2011; Dugan et al., 2012; Burnett et al., 2013; Dimova et al., 2013; Kummu et al., 2014; Malgrange and Gleeson, 2014; Su et al., 2014). Attempts are made by researchers to figure out ^{222}Rn partition at the air–water interface under different temperature and salinity (Schubert et al., 2012a,b). Moreover, different empirical evasion equations are used to calculate the radon flux across the interface in lake systems (Dimova and Burnett, 2011; Burnett and Dimova, 2012). However, those radon-based groundwater discharge studies were mainly conducted in the freshwater lakes and limited ^{222}Rn based studies have been conducted in the brine lakes.

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The Badain Jaran Desert (BJD) has more than 100 lakes among the high sand dunes. The desert has an annual precipitation of 40–120 mm yr^{-1} (Yang and Williams, 2003) but the lake surface potential evaporation ranges from 2600 to 4000 mm yr^{-1} based on different sources of literature (Chen et al., 2004; Yang et al., 2011; Dong et al., 2013). Potential evaporation of sand dune surface is estimated to be around 200 mm yr^{-1} (Chen et al., 2004). The mechanism for maintaining the permanent lakes has been controversial since the total potential evaporation of the lake surface and sand dune far exceeds the regional precipitation. According to the past studies, the possible recharge sources of the BJD lakes are classified into four types: direct atmospheric precipitation recharge, near-source recharge, remote source recharge and paleo-source change (Chen et al., 2004; Ma and Edmunds, 2006; Gates et al., 2008; Yang et al., 2010; Dong et al., 2013). To better understand the sources of lake water and the mechanisms maintaining the lake water balance, more detailed isotopic hydrological, geomorphologic and meteorological studies and observations are in great need on both local and regional scales. Lakes in the desert are normally regarded as terminal lakes as they serve as the sink of groundwater and solutes (Zlotnik et al., 2009, 2010). Similar lakes are also found in semiarid and arid environments in North America, Africa and Australia (Yechieli and Wood, 2002). Solutes are transported into the lakes, stored and concentrated over time. Thus, most of the desert lakes are hypersaline terminal lakes. Some desert lakes can be fresh or subsaline if there exists outflow-induced mass loss and these lakes are called flow through lakes (Turner and Townley, 2006; Zlotnik et al., 2009, 2010).

The Badain Jaran Desert, located at the western Inner Mongolia, is the third largest desert (about 50,000 km^2) in China. It is bounded by Heishantou Mt. to the south and Yabulai Mt. and Beidai Mt. southeast and by lowland Ejina Basin to the west and north (Fig. 1a). Lakes within the inter-dune depressions have various sizes, shapes and solute concentrations of lake water (Fig. 1b). Current lake elevations range from 1500 m in the southeast to 900 m above the sea level in the northwest, which produces the hydraulic gradient from SE to NW (Jiao et al., 2015). The only nearby river of the desert is Heihe River which is down-gradient of the lake water tables and not considered a possible regional recharge sources (Yang and Williams, 2003; Ma and Edmunds, 2006; Gates et al., 2008; Yang et al., 2010; Dong et al., 2013; Jiao et al., 2015). Inter-dune lakes are most possibly formed by wind erosion and spring emergence induced by aquifer replenishment (Yang and Williams, 2003). The area has an average temperature of −10 °C in January and 25 °C in July. Sparse vegetation like typical arid shrub species of Artemisia, Agriophyllum, Achnatherurn are scattered around the lake banks (Ma and Edmunds, 2006; Yang et al., 2010).

The objective of this study is to estimate the groundwater discharge in two representative lakes, one fresh and one hypersaline, in the Badain Jaran Desert with temporal ^{222}Rn model. Radon evasion mechanism at water–air interface is also investigated in both lakes. The goal is to reveal the water balance and evaluate total groundwater discharge in the two desert lakes.

2. Methodologies

2.1. Field campaign and site description

Field campaign to the Badain Jaran Desert was carried out from Aug 17 – Sep 12 2013. Two typical lakes, Badain-E lake and Sumujilin-S lake are selected to conduct sampling and in situ measurements (Fig. 1c & d). Badain-E lake, located at the northeast of the desert, is a small and shallow freshwater lake with an average depth of 1.5 m and an area of 10,900 m^2. It is bounded to the west and east by large sand dunes with a height ranging from 20 to 200 m; the south part is mainly wetland (Fig. 1d). It is suggested that the fresh lake is formed recently due to site change of spring emergence formed by wind erosion and shifting dunes (Yang et al., 2003; Yang and Williams, 2003). Sumujilin-S, located at the center of the Badain Jaran Desert, is bounded by high sand dunes of around 400 m and is a brine lake with a lake water salinity more than 90 PSU. The brine lake has a large area of 1.23 km^2 and an average depth of 8 m. Obvious seepage zones are witnessed at the lake bank, as indicated by fresh groundwater springs or seeps at the lake bank, which suggest fresh groundwater input into the brine lake.

2.2. Data collection, sampling, analysis and calibrations

Continuous ^{222}Rn measurements were performed to detect ^{222}Rn temporal variations in the two lakes. The radon instrumentation (RAD AQUA®, Durridge) was set up at the lake shore of the fresh water lake and on the pre-built dock in the brine lake. Lake water (from ≈ 30 cm depth) was pumped up with commercial DC submersible pumps driven by 100 AH DC lead-acid batteries at a flow rate ranging from 2 to 3 L min^{-1} and delivered into the top of an air–water mixing chamber where radon is equilibrated between water and air. The wet vapor is delivered into a 12-Inch Passive DRYSTIK and dried with a large dry unit. ^{222}Rn in the vapor was circulated into the RAD7 detector via inner pumps and detected via α-decay accounts. To precisely measure the radon-in-air concentrations, the measuring protocol was set to sniff mode with a measuring interval of 30 min. The uncertainties of in situ ^{222}Rn measurement are 15–25% (1σ) with sniff protocol in this study. Temperature in the mixing chamber was recorded every 10 min with HOBO® temperature probe. Continuous measurements in fresh water lake started from 12:00 pm Aug 25, 2013 to 1 pm Aug 26, 2013, less than planed due to bad weather condition. Measurement in the brine lake started from 1:30 pm Aug 28 to 6:00 am Aug 30 2013. Wind speed was obtained from pre-installed weather station (RainRoot Tech®, Beijing) by China University of Geosciences (Beijing) at the height of 2 m above lake water table. The recording interval is 30 min. Lake water level is recorded with divers (DI 701, Schlumberger Co.) installed at the lakebed near the lake shore. The recording interval is 2 min.

A pore water sampling transect was conducted in each of the two lakes with pushing point samplers (M.H.E, Co.) and the pore water was pumped by a peristaltic pump (Moore et al., 2006; Lee et al., 2012; Luo et al., 2014). Three vertical profiles were sampled in the freshwater lake transect and five in the brine lake (Fig. 2). Portable devices were used to measure some chemical and physical parameters of lake water and porewater, e.g., pH was measured with HACH pH probes, dissolved oxygen with DO meter (Oxi 330i®, WTW Co.), and EC and temperature with temperature-level-conductivity meter (TLC; Solinist. Co.). The salinity of some porewater samples for the brine lake was far beyond the maximum detection limit of TLC meter and samples were diluted 20 times with purified water before the measurements. 50 ml porewater was collected in Nalgene tubes for major ion analysis and 250 ml porewater was collected into glass vials following the guide of RAD7 H_2O for ^{222}Rn analysis (2007). Generally, the inner pump of RAD7 will run for five minutes, aerating water in the vials and delivering the radon in vapor into the RAD7. After five minute equilibrium, RAD7 starts four more five – minute counting periods. To prevent significant ^{222}Rn decay loss, radon porewater samples were analyzed with RAD7 soon after the continuous measurement was finished at each site. Porewater samples for cation analysis were stored under 4 °C till analysis. Samples were filtered with 0.45 μm PTFE filters and analyzed with ion chromatography (ICS-1100, Dionex) in the hydrogeological laboratory in The University