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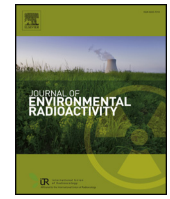

Evaluation of groundwater discharge into surface water by using Radon-222 in the Source Area of the Yellow River, Qinghai-Tibet Plateau

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ABSTRACT

Understanding hydrological processes in the Source Area of the Yellow River (SAYR), Qinghai-Tibet Plateau, is vital for protection and management of groundwater and surface water resources in the region. In situ water measurements of exchange rates between surface water and groundwater are, however, hard to conduct because of the harsh natural conditions of the SAYR. We here present an indirect method using in situ ^{222}Rn measurements to estimate groundwater discharge into rivers and lakes in the SAYR. ^{222}Rn was measured in rivers, lakes, groundwater and springs during three sampling periods (2014–2016), and the results indicate large variability in the concentration of the isotope. The data also indicate decreasing ^{222}Rn trends in groundwater in the cold season (the Feb-2015 sampling period) which may be linked to frequency of capturing ^{222}Rn in the frozen ground caused by geocryogenic processes. In addition, permafrost spatial extent and freeze-thaw processes have strongly affected the hydrological conditions in the region.

1. Introduction

The Source Area of the Yellow River (SAYR), within the Qinghai-Tibet Plateau, is dominated by permafrost and is characterized by high elevation (> 4000 m) and cold conditions. Water resources represent a critical part of the fragile environment in the SAYR and there is rising concern about permafrost degradation, which may significantly alter hydrological conditions and thereby affect water resources distribution and interplay between surface water and groundwater (Hui et al., 2015). Ge et al. (2011) found that annual groundwater discharge to the surface could increase by three-fold under an increasing air temperature scenario of 3 °C per 100 years. Consequently, estimating exchange between these water reservoirs is vital to understand changes in the hydrological processes of the SAYR (Cartwright et al., 2011, 2014). The harsh conditions and lack of hydrogeological data, however, constrain the efforts to provide detailed investigation of the SAYR.

The low permeability of permafrost is expected to hamper interaction between groundwater and surface water. This suggestion assumes that groundwater is stored in frozen ground as ice and only small amounts of water in the active layer could discharge to the surface. Consequently, precipitation is considered the main source of surface water in permafrost regions (Hinzman et al., 1993; Kane et al., 1981). This conclusion was, however, challenged by investigating the water chemistry and isotopic composition and some studies indicate that groundwater was one of the major suppliers for rivers in permafrost regions (Carey and Quinton, 2004; Gibson et al., 1993; Obradovic and Sklash, 1986). Metcalfe and Buttle (2001) found that groundwater comprised about 50% of the total river discharge. Boucher and Carey (2010) found that groundwater comprised up to 70% of the total river discharge in their study case. These investigations were carried out in areas other than the SAYR and mostly numerical modelling was applied to explain part of the exchange rates between surface water and groundwater in the SAYR (Ge et al., 2011). The results of the numerical modelling suggested up to 9% of mean annual river flow of the Chumar River located in the SAYR was recharged by groundwater. Although the numerical modelling provided first information, it was considered

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highly uncertain because of complicated thermodynamic processes of the permafrost (Ma et al., 2005; Sato et al., 2008). Accordingly, a combination of numerical modelling and empirical data will provide better estimates of hydrogeological conditions in the SAYR. In the investigation presented here, we have combined these two approaches with the aim of further the understanding of the hydrogeological conditions through measurements of the radioactive isotope ^{222}Rn in surface water and groundwater in the SAYR region.

Radon (^{222}Rn; $T_{1/2}$ = 3.8 days) occurs in groundwater as a result of alpha-recoil from the decay of its parent isotope radium (^{226}Ra) (Sakoda et al., 2011). ^{222}Rn can be a potential tracer of exchange processes between groundwater and surface water due to its conservative and chemically stable (noble gas) nature and the higher concentration (usually 2-3 orders of magnitude) in groundwater than in most surface waters (Cook et al., 2008; McCallum et al., 2012). As an ideal tracer to study groundwater migration and transport, ^{222}Rn has been applied to assess groundwater discharge into lakes (Dimova et al., 2013; Kluge et al., 2007), streams and rivers (Kurth et al., 2015; Ortega et al., 2015; Unland et al., 2015), canals (Chanyotha et al., 2014), estuaries (Burnett et al., 2003; Burnett and Dulaiova, 2003) and many other cases of groundwater-surface water interaction. The approach is extended here to high altitude areas, where the environment is commonly harsh and traditional hydrological methods are difficult to implement. Preliminary investigation by Zheng et al. (2016) suggested rather appreciable difference in ^{222}Rn concentration between groundwater (an average of 2.8 $*10^4$ Bq/m^3) and surface water (an average of 2.3$*10^3$ Bq/m^3) in the SAYR. The authors also calculated a groundwater fraction of up to 19% in a river located in the ShuangChaGou basin. These results were promising to start a more systematic collection of ^{222}Rn data in the SAYR region.

In the investigation presented here an effort was performed to collect ^{222}Rn data from the water systems (groundwater, rivers, lakes and springs) in the SYAR to evaluate spatial and to lesser extent temporal distribution patterns of the isotope and interactions between groundwater and surface water. The data were collected during three sampling campaigns (Sep-2014, Feb-2015 and May-2016) for which seasonal temperature effects by freeze-thaw processes of permafrost are discussed.

2. Site description

The SAYR (33°56′ ~ 35°31′N, 95°55′ ~ 98°41′E) refers to the catchment area above Duoshixia (34°46′25.15′′N, 98°80′09′′E) which is in the heartland of the Qinghai-Tibet Plateau (Fig. 1). The SAYR is bordered by three great mountain ranges on the west, south and north, namely the Geshigeya Mountains, the Bayan Har Mountains and the Buqing Mountains, respectively. The SAYR has a total catchment area of 2.5$*10^4$ km^2 and has an altitude varying from 4100 m to 5442 m. The SAYR slopes approximately 1.5° from north to south and 3° from west to east. Alpine meadows and steppes are the main landscapes in the SAYR (Li et al., 2016).

Sources of water in the SAYR include direct precipitation, snowmelt water, ice-melt water, groundwater and tributaries inflow. The climate of SAYR is semi-arid alpine with an annual average air temperature lower than −4 °C. Lakes and rivers freeze over for more than 7 months of the year. The annual precipitation is around 300 mm, 70–80% of which falls in the warm season (May to September). The annual evaporation is about 1000–1500 mm, which greatly exceeds precipitation (Hui et al., 2015). The Yellow River flows from north-west to south-east and with an average discharge of 22.6 m^3/s from 1955 to 2005 as recorded by the Huang'he'yan Hydrological Station (34°53′7.09′′N, 98°10′18.84′′E, station HS1 in Fig. 1). Eight tributaries occur upstream of HS1 with a catchment area larger than 300 km^2 (Ding et al., 2006). The SAYR includes more than 4000 lakes with a total water surface of 1664.6 km^2, 48 of which have a water surface larger than 0.5 km^2. The two largest lakes in the SAYR are NgÖring Lake and Gyaring Lake (Fig. 1) and both are fresh water lakes. The NgÖring Lake (34°46′ ~ 35°05′N, 97°32′ ~ 98°54′E) has a water surface area of 610.7 km^2, and average water depth of 17.6 m (in the year 2000). The deepest part of the NgÖring Lake is 34.7 m and its total water volume is 10.76$*10^9$ m^3. The Gyaring Lake (34°49′ ~ 35°01′N, 97°03′ ~ 98°27′E) is smaller with a water surface area of 526.1 km^2, maximum depth of 13.1 m and water volume of 4.67$*10^9$ m^3. Madoi County, which is located near HS1, is the most important populated settlement with a total population of less than 15000 (Jin et al., 2009).

The SAYR region is dominated by continuous and discontinuous permafrost and seasonally frozen soil (Figs. 2–4). Elevation-related climate zoning as well as lakes and rivers reflect a mosaic of various types of frozen ground in the SAYR and influence seasonal freeze-thaw processes. Seasonally frozen soil occupies areas at elevation lower than 4250 m asl and melting occurs during May–September. (Jin et al., 2009; Li and Cheng, 1996).

The area covered in the work presented here represents the catchment above the Ji'mai hydrological station (station HS3 in Fig. 1, 33°46′4.44′′N, 99°39′27.72′′E) which includes the conventional SAYR and beyond. Hydrological station HS2 (Fig. 1, 34°36′8.99′′N, 98°16′13.44′′E) is located along the largest tributary (named as T1) between HS1 and HS3. In addition, there are other 2 main tributaries between HS1 and HS3 hereafter named as T2 and T3 from upstream to downstream respectively (Fig. 1).

3. Sampling and analysis methods

Water samples were collected along the Yellow River and country roads (gray lines in Fig. 1) during three sampling periods. The first sampling periods was in the warm season from 26th Sep 2014 to 30th Sep 2014 and the data were published (Zheng et al., 2016). Samples from 9 river water, 10 lake water and 7 groundwater were collected in the first sampling period (Fig. 2). The second sampling period was in the cold season from 8th Feb 2015 to 12th Feb 2015 and the third sampling period was in the warm season from 21st May 2016 to 25th May 2016. In the second sampling period 7 samples from rivers, 4 from lakes and 7 water samples under iced spring cones were collected (Fig. 3). In the third sampling period 14 samples from rivers, 18 from lakes and 11 from groundwater were collected (Fig. 4).

The sampling of surface water from rivers and lakes was performed at about 30 cm below the water surface by a submersible pump. River water was obtained from the middle part of the river. Lake water was collected as far as possible from the shore. In the Feb-2015 sampling period, when rivers and lakes were frozen, water samples were obtained through a hole that was drilled in the more than 1 m thick ice. Drilling was also applied for the ice cone formed by natural spring to collect underlying water. Groundwater was collected from wells of the residents. Although the wells are used extensively, we have pumped the wells for 10 min before sampling to obtain fresh groundwater. However, in the Feb-2015 sampling period, the weather condition got extremely harsh and the residents moved to lowland areas. Consequently, water samples under iced spring cones were treated as groundwater. Sample GW25 was obtained from a 20 cm depth borehole from a wetland near a lake (Fig. 4).

^{222}Rn concentration in the water was analyzed by a widely used portable commercial α detector RAD7 and the RAD H_2O accessory (Durridge Company, USA) within 24 h of sample collection. To improve precision and lower the detection limit for surface water, the cycle measurement time was extended to 20 min for each of the 4-counting cycles. ^{222}Rn concentration in water was corrected for time laps between sampling and analysis.

The sampling location was recorded by a handheld GPS (eTrex® 20, GARMIN). Measurements of pH, electrical conductivity (EC) and water temperature were made in situ (PHH-7200, OMEGA). Data of air temperature, relative humidity (RH) and wind velocity were collected in