Journal of Hydrology: Regional Studies 18 (2018) 31–49

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Origin and residence time of groundwater based on stable and radioactive isotopes in the Heihe River Basin, northwestern China

L.J. Zhao[a,b,*], C.J. Eastoe[c], X.H. Liu[b,d], L.X. Wang[e], N.L. Wang[a], C. Xie[a], Y.X. Song[d]

[a] Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Sciences, Northwest University, Xi'an 710069, China

[b] Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

[c] Department of Geosciences (retired), University of Arizona, Tucson, AZ 85721, USA

[d] School of Geography and Tourism, Shaanxi Normal University, Xi'an 710119, China

[e] Department of Earth Sciences, Indiana University–Purdue University Indianapolis (IUPUI), Indianapolis, IN 46202, USA

ARTICLE INFO

Keywords:
Heihe River Basin (HRB)
Groundwater origin
Residence time
Stable and radioactive isotopes
Northwestern China

ABSTRACT

Study region: The Heihe River Basin (HRB) is one of several arid basins in which runoff from the Qilian Mountain recharges basin aquifers.

Study focus: A basin-wide dataset ($\delta^{18}O$, D, ^{3}H and ^{14}C) is used to determine the present and past relationships between precipitation, surface runoff and recharge, to constrain groundwater residence times, and to infer Holocene climate change.

New hydrological insights for the region: Groundwater in the upper region (UR) of HRB has ($\delta^{18}O$, δD) clustered near (−8.0, −46‰), consistent with present-day Qilian Mountain precipitation. Tritium of groundwater > 26 TU indicates post-bomb recharge. Mountain runoff provides recharge to alluvial-fluvial aquifers in the Middle Region (MR) and Lower Region (LR) along the main river of the HRB. Between 1986 and 2001, anthropogenic tritium releases affected north-central China, affecting HRB precipitation. Irrigation reflux strongly affects isotopes in basin groundwater, generating anomalous samples with low tritium and post-bomb ^{14}C, or high tritium and pre-bomb ^{14}C. Stable isotopes in Qilian Mountain runoff have evolved in response to climate change. A 1‰ shift in $\delta^{18}O$ since 1960 coincides with drying of the Aral Sea, possibly affecting moisture advected from the west. A 6–8‰ shift before 12 ka may indicate the former extent of the South Asian monsoon.

1. Introduction

Hydrogen and oxygen isotopes in different water pools are widely used as tracers of hydrological processes such as precipitation, groundwater recharge, groundwater-surface water interactions, hydrograph separation, basin water hydrology, and evolution of surface or soil waters undergoing evaporation (Fontes, 1980; Mazor, 1991; Gat, 1996; Clark and Fritz, 1997; Gibson et al., 2005; Li et al., 2015; Farid et al., 2015; Soderberg et al., 2013). Stable O and H isotopes are useful in groundwater studies because they are conservative environmental tracers, and their usefulness is enhanced if local isotope effects in precipitation, expressed in terms of the local meteoric water line (LMWL) are well understood (Simpkins, 1995; Kaseke et al., 2017). In interior continental basins, the LMWL takes account of the evaporation of recycling of surface moisture, and possible effects of temperature and precipitation amount (Dansgaard, 1964; Rozanski et al., 1993; Aravena et al., 1999; Tian et al., 2007; Zhao et al., 2011; Zhao et al., 2014). Dansgaard

* Corresponding author at: College of Urban and Environmental Sciences, Northwest University, Xi'an, Shann'xi, 710069, China.
E-mail address: zhlj@lzb.ac.cn (L.J. Zhao).

https://doi.org/10.1016/j.ejrh.2018.05.002
Received 12 January 2018; Accepted 4 May 2018

(1964) expressed the combined effects of such processes as "deuterium excess", d-excess = δD − 8 δ^{18}O.

Tritium (^{3}H or T) is a short-lived isotope of hydrogen with a half-life of 12.43 years (Unterweger et al., 1980), and is currently the most commonly employed radioisotope used to identify modern recharge within the last 50a. Before 1952, the annually-averaged concentration of tritium in precipitation was lower than 10 TU at mid-latitudes. Atmospheric nuclear testing between 1952 and 1970 generated a spike of atmospheric tritium, peaking at about 6000 TU in summer 1963–1964 in the north hemisphere (International Atomic Energy Agency (IAEA), 2016). Tritium remains measurable in meteoric water recharged during and since the bomb spike in most areas (Eastoe et al., 2011), but tritium in pre-bomb meteoric water, recharged prior to 1952 or in some cases prior to the 1940s, has decayed to levels below usual detection limits. Therefore tritium can be used to distinguish pre- and post-bomb recharge. The measurement of ^{14}C in dissolved inorganic carbon (DIC), is useful for dating groundwater with longer residence times, e.g. 2–30 ka (Zuber et al., 2004; Eastoe et al., 2010; Benjamin, 2015; Farid et al., 2015).

The arid to semi-arid Heihe River Basin (HRB) of 130,000 km^2 is the second largest inland drainage basin of China. It is a complex system of mountains, agriculture and oases, and a classic example of hydrological response to climate change, overprinted by human activities. It consists of three regions, namely the upper region (UR, the source area in the Qilian Mountains), the middle region (MR, Yingluoxia to Zhengyixia in Fig. 1: incorporating the Zhangye, Linze, Gaotai basins and Jiuquan) and lower region (LR, the Jinta-Dingxin and Ejina basins). Both the MR and LR lack locally-derived perennial surface runoff because of low rainfall, and are entirely dependent on groundwater and surface water ultimately originating from the UR of the Heihe River. In the MR and LR, large quantities of water are exploited for domestic consumption, agriculture and industry, and to maintain oases. Currently, sustainable groundwater use is threatened by increasing population, and expansion of irrigated agriculture and industry in the MR and LR (Cheng et al., 2009). Detailed hydrogeological information such as total resource and renewal rate of groundwater is essential for improving water resources management.

Previous isotope studies in the HRB have addressed the sources of deep groundwater (Chen et al., 2004; Qian et al., 2006), groundwater replenishment (Zhang et al., 2004), interaction of unconfined groundwater and surface water (Nie et al., 2005), recharge, residence time and renewability of groundwater (Chen et al., 2004), and groundwater circulation (Chen et al., 2006; Zhang et al., 2005). In addition, environmental factors affecting values of δ^{18}O in precipitation (Wang et al., 2008; Zhao et al., 2012a), the contribution of different water sources to surface runoff (Wang et al., 2009; Zhao et al., 2011), and the origin of moisture in the headwaters area of the HRB (Zhao et al., 2011) have been reported. The HRB aquifers are heterogeneous, leading to different estimates of recharge rates. Estimation of recharge is difficult owing to temporal and spatial variability of rainfall and recharge processes. Recently, Jasechko et al. (2014) suggested that winter recharge is dominant in the MR on the basis of published isotope data. Their analysis, however, is debatable because recharge originates mainly as high altitude summer precipitation.

In this article, previously published measurements of δ^{18}O, δ^2H, ^{3}H and ^{14}C (Chen et al., 2004; Zhang et al., 2005; Chen et al., 2006; Gan et al., 2008; Gates et al., 2008; Jia et al., 2008; He et al., 2012, 2013) are combined with new data with the aims (1) of constraining relationships between surface water and groundwater, (2) determining recharge sources of unconfined groundwater (above 80 m depth) and confined groundwater (below 80 m), and (3) estimating groundwater residence times at regional scale. During the course of the study, a further aim emerged: explaining large temporal changes in the isotope composition of recharge. The results of this study have implications for dynamics of regional water resources, both in the HRB and in other arid regions of northwestern China.

2. Study area and hydrogeological settings

The HRB (96°42′ to 102°04′ E; 37°45′ to 42°40′ N) has an area of 130,000 km^2 (Fig. 1). The elevations of the UR, MR and LR range from 5000–2000, 1700–1300 and 1450–910 m above sea level, respectively. The principal physiographic features include the Qilian Mountains (the UR) at the southern boundary, a corridor plain (the MR) at the foot of the Qilian Mountains, and a broad northern plain (LR) bordering low mountains and the Alashan Plateau in the Badain Jaran Desert and Mongolia.

In the UR, mean annual temperature is −3.0 to 4.0 °C, and annual precipitation ranges from 200 to 600 mm, most falling in summer. Rivers originating in the Qilian Mountains are the main recharge source for groundwater in the HRB, and there is little evaporative loss in the UR (Chen et al., 2006). The mountain aquifers are mainly fractured, weathered rock and in deeper structural fractured zones, with direct hydraulic interaction. Water circulates fast through the fractures, and groundwater is commonly connected with the surface water, and is directly recharged from snow-melt and glacial ice-melt. Such aquifers discharge into the mountain rivers.

The MR and LR, separated by the Northern Mountains and Longshoushan Mountains (Fig. 1), comprise alluvial and fluvial plains underlain by unconsolidated Quaternary strata about 1000 m thick in the MR, and thinning gradually northwards. The southern sub-basin of the MR, consists of alluvial fans abutting the Qilian Mountains and floodplains. Mean annual temperature is 3.0–7.0 °C. Annual precipitation ranges from 50 to 150 mm, and the typical evaporation rate is 2000–2200 mm/year (Gao, 1991). In Zhangye (MR), between 1986 and 2003, 87% of annual precipitation fell from June to October (International Atomic Energy Agency (IAEA), 2016). Rain events are infrequent, and insufficient to generate runoff. The Quaternary aquifer system of the south-sub-basin includes an unconfined zone in up to 1000 m of gravel and sand in the piedmont plain, and a confined zone in 50–200 m of silty sand in the floodplain (Chen et al., 2006).

The LR in the Jinta-Dingxin and Ejina areas has a mean annual temperature near 8 °C. The mean annual precipitation is only 42 mm, while mean potential evaporation is 2300–3700 mm/year. Quaternary aquifers consist of unconsolidated eolian, fluvial and lacustrine units 50–500 m thick, thinning and fining gradually northwards. Single or multiple sand lenses are separated by clay layers. The northern sub-basin of the LR, in the Jinta-Dingxin and Ejina areas, has a mean annual temperature near 8 °C. The mean