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The influence from the shrinking cryosphere and strengthening evopotranspiration on hydrologic process in a cold basin, Qilian Mountains

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ABSTRACT

Under a warming climate, the cryosphere shrinking is accelerating and the evopotranspiration is strengthening, which have caused the spatial and temporal changes of water resources and water cycle in inland river basins. With a vast area of 1.0×10^4 km^2 and an annual average evopotranspiration of 515 mm, the influence from recycling moisture to precipitation and the contribution from cryosphere meltwater to runoff have been quantified in source region of Heihe river basin at the central Qilian Mountains, where 365 glaciers locate within an area of 77.22 km^2, whiles frozen soil accounts for 80% of the region. Results indicated that frozen soil meltwater and glacier snow meltwater have contributed by 28% and 7%, on average, to the outlet river water in the basin, respectively. It was founded that evaporation and transpiration moisture were responsible for 10% and 17%, on average, of local precipitation, respectively. These findings provide new progresses on isotopic hydrology of cold basin, which will strengthen further understanding on the role of frozen soil meltwater and local moisture recycling in the water cycle for inland river basins.

1. Introduction

Qilian Mountains is the water sources region for three inland river basins from west to east, which are Shulehe river, Hiehe river and Shiyanghe river. The mountain runoff of Shulehe river had been presenting an increasing trend owing to the rise of glacier snow meltwater and precipitation (Lan et al., 2012), and its base flow also increased in 1954–2009. During this period, precipitation is a major influence factor on its variation (Dong et al., 2014). Annual runoff showed a fluctuation increase in Taolaihe river at the central Qilian Mountains during 1961–2010, but it is no statistically positive correlation with precipitation variation (Xu et al., 2008). In the upper and middle reaches of Heihe river basin, the mean annual runoff also gradually increased during the past 60 years under precipitation rise and heavy cryosphere melting (Cui et al., 2015), and the increasing trend has accelerated after 1998 (Guo et al., 2011). Runoff in Shiyanghe river displayed a decreasing trend during 1961–2005, especially in summer, and runoff series had a statistically positive correlation with precipitation and evaporation variation (Li and Liu, 2011). For Xiyinghe river of Shiyanghe river basin, the overall trend of runoff was going down during 1961–2009, although precipitation was gradually increasing with the strengthening evaporation under temperature rise (Liu et al., 2013). In addition, the decreasing trend has also been detected for annual runoff in Gulanghe river and Zamuhe river of Shiyanghe river basin during the past 48 years (Xu et al., 2007). As mentioned above, it exhibited the regional differences for runoff variation in Qilian Mountains under precipitation rise. Thus, there are two scientific questions to be answered: (1) as the cryosphere basin, what is the influence from glacier, snow and frozen soil meltwater on runoff variation? (2) under temperature rise, whether or not the strong local evaporation and transpiration made some contributions on precipitation increase?

The results from isotopic tracers have been widely used in water cycle studies (Craig, 1961; Tian et al., 2007; Barras and Simmonds, 2008; Gao et al., 2011; Vodila et al., 2011; Ren et al., 2013; Zhai et al., 2013; Li et al., 2015a; Cai et al., 2015).This can be used to determine stream flow components with different environmental conditions (Huth et al., 2004; Kortatsi, 2006; Han et al., 2010; Kong and Pang, 2012; Kong et al., 2013; Li et al., 2015b), and to clarify the mechanisms controlling stream water behavior and to delineate flow paths and flow systems in a catchment scale (Huth et al., 2004; Eckhardt, 2008; Guo et al., 2014; Li et al., 2016a, 2016b). Furthermore, isotopic tracers have been employed to investigate biogeochemical cycling (Gibson et al., 2005; Wu et al., 2009; Li et al., 2015c), and to identify the residence time of stream water and to investigate mechanisms affecting stream

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water chemistry (Yuri and Peiffer, 2009; Kling and Nachtnebel, 2009). Additionally, it is often used for analyzing possible water vapor source area contributions to precipitation and evaluating the contribution of the recycling moisture to precipitation (Liu, 2008; Peng et al., 2012; Kong et al., 2013; Hu et al., 2014; Rios-Entenza et al., 2014). Using an isotopic technique, Gat and Matsui (1991) calculated that evaporation from the surface of fresh water bodies provided approximately 20–40% of local atmospheric vapor in the Amazon basin. Similarly, Gat et al. (1994) estimated the contribution of evaporation from North America's Great Lakes to the continental atmosphere of the entire region to be ~5–16% in summer. In Qinghaihu lake, the monthly contribution of lake evaporation to basin precipitation ranged from 3.03% to 37.93%, with an annual contribution of 23.42% or 90.54 mm, the majority of which concentrated in summer (Cui and Li, 2015).

In recent decades, great efforts have been devoted to exploring the climatological and hydrologic signals of waters in Heihe river basin through stable isotope studies (Wang et al., 2008; Wu et al., 2010; Zhao et al., 2011a, 2011b; Yang et al., 2011a, 2011b; Zhao et al., 2011a, 2011b). These researches not only extended the knowledge and understanding on the temperature effect, the precipitation amount effect and the Local Meteoric Water Line (LMWL) equation, but also confirmed the hydraulic connection among precipitation, surface water and groundwater, and founded precipitation in the upper-basin constituted the primary source for surface water and shallow groundwater of the basin (Zhang and Wu, 2007a, 2007b; Wang et al., 2008; Wu et al., 2010; Zhao et al., 2011a, 2011b). These results demonstrated that the monthly δ^{18}O and δD of precipitation are negative in cold seasons and positive in warm seasons (Li et al., 2015a). Some researchers discovered the frequent exchange between groundwater and river water with the groundwater recharge and renewal in the middle basin, and indicated that shallow groundwater was primarily recharged by river water (Wu et al., 2004; Chen et al., 2006a, 2006b; Qian and Wang, 2008; Jia et al., 2008; Zhang et al., 2009; Nie et al., 2010; Yang et al., 2011a, 2011b, 2011c; Qin et al., 2011). Other researchers also verified that the deep groundwater is of late Pleistocene ages except which marginally recharged by modern river water in the Ejina area (Zhang et al., 2006; Zhu et al., 2008), Badain Jaran Desert (Zhao et al., 2011a, 2011b) and Zhangye basin (Zhang et al., 2005). In addition, there are some hydrograph separation studies in sub-basins of the region (Wang et al., 2008; Yang et al., 2011a, 2011b; Li et al., 2014). However, these studies have not assessed the contribution of frozen soil meltwater to runoff. Furthermore, the quantitative understanding on the role of recycling moisture to local precipitation still remains unclear in source region of Heihe river basin.

Thus, in this study, we take the source region of Heihe river basin as the study object, which locates at the central Qilian Mountains with an area of 1.0×10^4 km^2 and an annual average precipitation of 400 mm. There are 365 glaciers within an area of 77.22 km^2 in 2011, whiles frozen soil region accounts for 80% of the basin area (Wang et al., 2011). The basin has recently been the focus of attention due to the recognition of the increasing stress on its water resources and ongoing environmental degradation. Effectively evaluating the influence from the shrinking cryosphere and the strengthening moisture recycling becomes critical for regional sustainable development. So the aim of this paper is two folds: (1) to quantify the relative contributions of frozen soil meltwater and glacier snow meltwater to outlet river water using δ^{18}O and d-excess as a proxy, respectively; (2) to determine the relative contributions of recycling moistures from evaporation and transpiration moisture to precipitation during the growing season from May to October. The study provides new progresses on understanding isotopic hydrology of inland river basin, which will strengthen further knowledge on the role of frozen soil meltwater and local moisture recycling in the water cycle, as well as benefiting the water resources management and enhancing its relevance to sustainable development in the future.

2. Data and methods

2.1. Study region

Heihe river, the second largest inland river basin of China, in the central part of the Hexi Corridor at 98°–101°30′E, 38°–42°30′N (Fig. 1), is located in a typical arid region that suffers from serious water scarcity. In this study, the source region of Heihe river basin is selected as the study area, whose elevation ranges from 2000 m at the lower point to about 5500 m at the headwaters, with a drainage area of 10009 km^2 in the central Qilian Mountains (Fig. 1), which is the main runoff

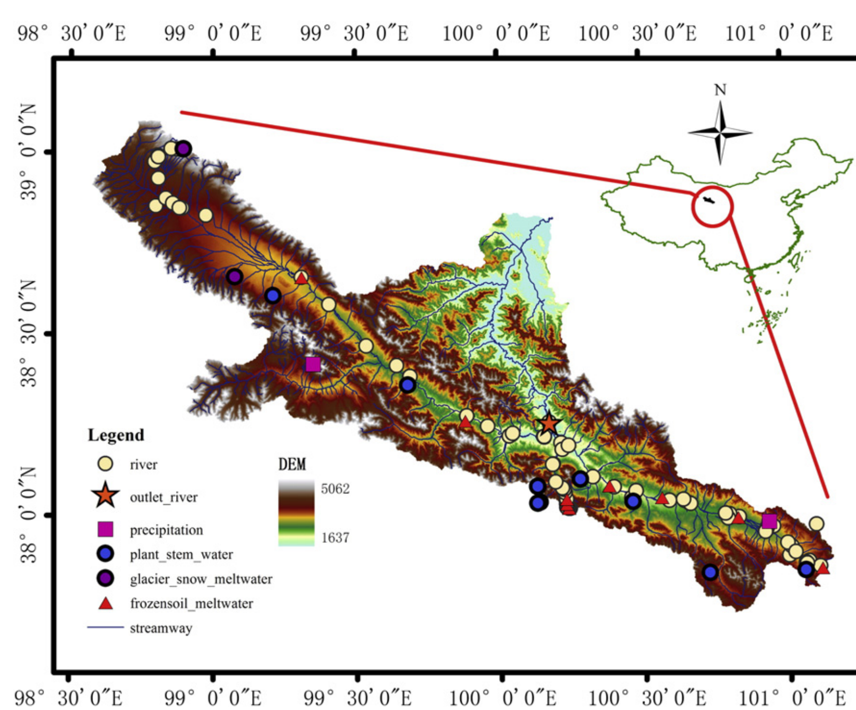

Fig. 1. Source region of Heihe river basin and the distribution for all sampling sites.