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Quantitative evaluation on the influence from cryosphere meltwater on runoff in an inland river basin of China

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ABSTRACT

Under climate warming, increasing attention is being directed towards high altitude regions where glaciers are shrinking and frozen soil is in degrading. This study, taken Taolai river in Qilian Mountains as an example, is to quantify the relative contributions of cryosphere meltwater to outlet river, based on 221 water samples from precipitation, river, groundwater and meltwater during 2013–2014. The results indicated that cryosphere meltwater accounted for 49% of the total runoff in the source region, and this contribution rate decreased to 21% at the outlet of basin. In addition, precipitation and meltwater from cryosphere belt has contributed up to 78% of the outlet river runoff. An inverse altitude effect of stable isotopes for river water and groundwater is likely to occur, which is caused by the relatively larger contribution rate of frozen soil meltwater in the source region. The results could provide a comprehensive overview on the influence from cryosphere meltwater to hydrologic process in cold basins.

1. Introduction

Under the current phase of global climate warming, the increasing attention is being directed towards high altitude regions for shrinking glaciers and degrading frozen soil (IPCC, 2013). Loss of snow and ice-masses can alter spatial and temporal dynamics in bulk basin runoff, especially with important changes in the relative contributions of cryosphere meltwater, including glacier snow meltwater and frozen soil meltwater to stream flow. Consequently, the altered water source contributions are accompanied by changes to fluvial, solutes, sediments and thermal regimes and, thus, channel stability and habitats (Huth et al., 2004; Gibson et al., 2005; Eckhardt, 2008; Liu et al., 2008; Yan et al., 2012; Kong and Pang, 2012; Li et al., 2011, 2014, 2015a, 2015b). And what's more, most central Asian countries or regions rely on meltwater for agriculture, domestic, and industrial uses, such as northwestern China (IPCC, 2013).

At present, the cryosphere shrinking process is accelerating, along with the yearly increasing meltwater, which would obviously apply a profound impact on hydrologic process and water cycle, and especially on water resources management and flood controls in cold basins (Yao et al., 2012, 2013; Penna et al., 2014; Li et al., 2014; Wang et al., 2015; Engel et al., 2015; Sun et al., 2015a, 2015b). On a global scale, the observed contributions from glacier snow meltwater to the mean sea level rise were 0.76 mm/a during 1993–2010 (IPCC, 2013), and this contribution is 0.12 mm/a from China glacier snow meltwater during 1961–2006 (Ren et al., 2011). On a basin scale, the earlier onset of ablation for glaciers and frozen soil has resulted in the period of minimum discharge occurring earlier during the past 20 years. The increase of meltwater leaded to the changes of the intra-annual water cycle (Li et al., 2010a, 2010b, 2011; Pang et al., 2012). Sorg et al. (2012) pointed out that there is a need for more integrative studies to address changes in all runoff components (that is, precipitation, groundwater, and meltwater from snow, glaciers and frozen soil) for better appraisal of the degree of cryosphere depletion and subsequent changes in river runoff of inland river basins. For the purpose of predicting future changes of regional water resources, it is necessary to gain a good understanding on the contribution from cryosphere meltwater including frozen soil meltwater to mountainous discharge, and to assess the magnitude and variability of hydrologic response to cryosphere fluctuation.

Numerous studies have confirmed that the contribution of glacier snow meltwater to water resources, due to temperature rise, is subject to seasonal and inter-annual climate variations. These contributions changed with glacier and snow covers and depended on the characteristics of the alpine basin (IPCC, 2013). The average contribution rate of glacier snow meltwater to runoff is 14.1% in Qilian Mountains during the period of 1961–2006 (Gao et al., 2011). Glacier snow meltwater accounted for 54.6% of the annual mean runoff in Hailuogou basin at

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Gongga Mountain during 1994–2004 (Li et al., 2010a). Within the Yanggong basin at Yulong Mountains, the increasing magnitudes of glacier snow meltwater from 1979 to 1988 to 1994–2003 were far exceeding the increases of precipitation and river discharge (Li et al., 2010b). For Tarim river basin, the contribution of glacier snow meltwater to river runoff was approximately 41.5% during 1961–2006 (Gao et al., 2010). In the Heishui valley of Hengduan Mountains, the contribution of glacier snow meltwater to river runoff varied from 63.8% to 92.6% (Liu et al., 2008). In the Baishui river catchment of Yulong Mountains, on average, 53.4% of the runoff came from glacier snow meltwater during the wet season (Pu et al., 2013). Path analysis showed that glacier snow meltwater represented about 63–78% of the total discharge in Hailuogou river basin during 2013–2014 (Li et al., 2010a). As much as 75% of the water supply in the western United States comes from snowmelt (Stewart et al., 2004). In the Qinnguata Kuussua tributary, glacier snow meltwater from the Russell glacier and Leverett glacier sub-catchments accounted for 7% and 67% of the total runoff water, respectively (Yde et al., 2015). Meltwater contribution to runoff was high in June and July (up to 27%), whereas the maximum contribution was reached in August (up to 65%) at two nested glacial catchments of the Eastern Italian Alps (Engel et al., 2015). The overall meltwater contribution during the three observation years ranged between 58% and 72% at a glacial catchment in the Italian Alps (Penna et al., 2014). On average, annual baseflow was only 13–45% of discharge during the snowmelt period in the upper Colorado river basin (Miller et al., 2014).

Frozen soil meltwater also made some contributions on runoff in cold basins (Smith et al., 2007; Lu et al., 2013; Li et al., 2016). On the one hand, frozen soil meltwater may drain directly to become surface runoff, especially at steep slope; on the other hand, the meltwater may reach the groundwater, and eventually drain off as spring water (Frampton et al., 2011; Semenova et al., 2012, 2013; Quinton and Baltzer, 2013; Li et al., 2014). Many previous researches had confirmed the influence from frozen soil degradation on runoff because its degradation resulted in the decline or disappearance of soil impermeability and therefore supplied the groundwater with more surface water under climate warming, which has been founded in these rivers or regions: the upper Songhua river in Northeast China (Liu et al., 2003), Yukon, Lena, Yenisei and Ob rivers at Arctic (Ye et al., 2003; Walvoord and Striegl, 2007), Manasi river in Tianshan Mountains (Liu et al., 2006), Lhasa river in Tibetan plateau (Gong et al., 2006), Burkin river in Altay Mountains (Liu et al., 2007), the Keliya river in the Kunlun Mountains (Huang et al., 2008), the Siberia river (Ye et al., 2009), and upper Yellow river, Heihe river and Shule river in Western China (Niu et al., 2011). Yet, qualitative analysis has not been involved in estimating the contribution of frozen soil meltwater.

Recently, many researchers have discussed the climatological and hydrologic signals of waters in east branch of Heihe river basin through stable isotope studies (Wang et al., 2009; Yang et al., 2011a, 2011b; Zhao et al., 2011; Li et al., 2015a, 2015b). Thus, taking Taolai river basin as an example, which is the west branch of Heihe river basin located at the central Qilian Mountains in Northwestern China, this study is aiming 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, and to determine the water contribution from cryosphere belt (regions covered by glacier or snow or frozen soil above the multiyear frozen soil lower boundary) to local water resources. It is expected that our study will improve the knowledge of water resources utilization and management in in-land river basins under climate change.

2. Data and methods

2.1. Study basin

Taolai river, the west branch of Heihe river basin, in the central Qilian Mountains at 97°16′–99°12′E, 38°24′–39°36′N (Fig. 1), is located in a typical arid region of northwestern China (Appendix A). The elevation ranges from 2300 m at the lower point to about 5300 m at the headwaters of the basin, with a drainage area of 7095 km^2 (Fig. 1). The climate belongs to the cold semi-arid mountainous zone. Annual mean air temperature is less than 0.5 °C, and annual mean precipitation increases from about 150 mm in the low-mountain/hill zone to about 450 mm in the high-mountain zone. Precipitation increases 13.5–15.4 mm for every 100 m in elevation (Li et al., 2009). Based on the observation during 1960–2010, the annual average runoff is 6.2×10^8 m^3 with steadily intra-annual variability and mainly concentrated on summer and autumn. The basin shows markably vertical zonality, where the ecosystem patterns include dry shrubbery grassland, forest grassland, sub-alpine shrubbery meadow, alpine cold-desert meadow, and alpine frozen soil-snow-glacier from low to high altitude. The main soil types in the region are alpine meadow soil, alpine steppe soil, frigid desert soil, gray cinnamon soil and gray-brown desert soil. According to Glacier Inventory of China I (Wang et al., 1981, 2011), 503 glaciers were listed within a total estimated area of 218.51 km^2 over the basin in the 1960s, and frozen soil is widely distributed in the basin (Zhou et al., 2000). Glaciers and frozen soil had experienced heavy melting due to the continuous temperature rise and concurrent precipitation increase since the 1960s (Huai et al., 2014).

2.2. Sampling and laboratory analysis

Precipitation samples were collected for each precipitation event in two stations of Tuole (38.8°N, 99.24°E, 3367 m) at the source region and Jiayuguan (39.75°N,98.27°E, 2337 m) at the river outlet of the basin (Fig. 1). Tuole is the only national meteorology observation station, whiles Jiayuguan is the national hydrology observation station at the outlet of the basin. A total of 80 event-based precipitation samples were collected in the basin from November 2013 to October 2014. After collection, all samples were immediately sealed in plastic bags and stored in a cold laboratory at −18 °C. During the sample collection process, precipitation, air temperature, wind speed, and relative humidity were recorded at corresponding meteorological stations. A total of 52 river water samples in Tuole and Jiyuguan stations have been collected once every two weeks. Meanwhile, 52 groundwater samples have also been taken in synchronization with river water at these two stations. Frozen soil meltwater has been collected in different altitudes by the excavation of soil profile. Altogether, 6 soil profiles and 19 samples are taken into this research (Fig. 1). Glacier snow meltwater samples have been collected once a month during the ablation period by two ways: one way is to collect the sample underneath the snowpack at glacier accumulation area; another way is to collect the sample in the glacier front. Altogether, 18 samples are used in this study (Fig. 1).

Before analysis, all samples were stored at 4 °C in a refrigerator without evaporation. Precipitation and surface water samples were analyzed for δ^{18}O and δD by means of laser absorption spectroscopy (liquid water isotope analyzer, Los Gatos Research DEL-100) at Key Laboratory of Ecohydrology of Inland River Basin, Chinese Academy of Sciences. Results are reported relative to the Vienna Standard Mean Ocean Water (VSMOW). Measurement precisions for δ^{18}O and δD were better than 0.5‰ and 0.2‰, respectively.

Hooper et al. (1990) and Hooper (2003) introduced the end-member mixing analysis model (EMMA) using chemical/isotopic compositions in waters. The EMMA tracer approach has been a common method for analyzing potential water sources contributing to stream flow. This tracer approach assumes that the chemical/isotopic compositions in the water are spatio-temporally constant and any variations are of a result of water mixing along flow path. Herein a three end-member mass-balance mixing model is employed to calculate the contribution of up to three water sources in runoff water, and the description for this method was detailed in previous research (Li et al., 2014).