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Contribution from frozen soil meltwater to runoff in an in-land river basin under water scarcity by isotopic tracing in northwestern China

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ABSTRACT

Cryosphere meltwater has been recognized as an important source of local water resources. However, there are few assessments on the contribution from frozen soil meltwater. In this study, we quantify the fraction from frozen soil meltwater and glacier snow meltwater to runoff in Shiyang River, an in-land river basin of northwestern China, where glaciers were disappearing and frozen soil was in degradation. A large number of samples for precipitation, surface water, groundwater, frozen soil meltwater and glacier snow meltwater have been collected and analyzed for their isotopic compositions. Results indicated that runoff was mainly generated from the cryosphere belt, and it was found that frozen soil meltwater was responsible for 20%, on average, of the outlet river water during flood season in the basin. The contribution rates from frozen soil meltwater to the outlet river runoff changed among the seven sub-basins. The results confirmed that frozen soil meltwater has played an important role in runoff of in-land river basins, and evaluating its influence on the hydrological process under a climate warming scenario is of great significance.

1. Introduction

The cryosphere is by nature highly sensitive to any climate change. Global warming has the potential to significantly reduce water storage in the forms of snow, glacier and frozen soil in cold regions. The reduction of water storage in these forms will alter hydrological, geomorphological and ecological processes (Huth et al., 2004; Gibson et al., 2005; Li et al., 2010a, 2010b, 2011, 2012; Peng et al., 2010, 2012; Vanderzalm et al., 2011; Yao et al., 2012, 2013; Penna et al., 2014; Wang et al., 2015; Engel et al., 2015; Sun et al., 2015). For many cold basins, the hydrological change will impact on the availability of water resources and the timing and magnitude of floods and low flows (Eckhardt, 2008; Liu, 2008; Liu et al., 2008; Kong and Pang, 2012; Pu et al., 2013; Li et al., 2014a, 2014c, 2015). There has already been evidence of significant changes taking place. For example, a rise of mean sea level globally by 0.76 mm/a in the period of 1993–2010 has been estimated, mainly due to the increased melting of glacier and snow (IPCC, 2013). Projections of future changes in the cryosphere are important for highlighting risks posed by climate changes. Modeling is an important tool for deriving projections. For the projections to be reliable, models must be based on sound understanding of physical processes. Field measurements of key processes are critical for improving scientific understanding and for validating modeling results. In this study, we conduct extensive measurements in a large basin to understand the amounts and pathways of the contributions to basin runoff from the melting of snow, glacier and frozen soil water.

Glacier and snow melt when temperature rises above the freezing point, and the meltwater finds its way to basin drainage as runoff. Contributions of glacier and snow to total runoff vary among basins, influenced by climatic and geophysical conditions of the basins. There have been many studies, reported in the literature of glacier and snow contributions to runoff based on field observations. Glacier and snow meltwater was found to account for 53% in the Baishui River basin during the wet season (Pu et al., 2013), 55% in the Hailuogou basin during 1994–2004 (Li et al., 2010b) and 63–78% during 2013 (Xing et al., 2015), 63–93% in the Heishui Valley of Hengduan Mountains (Liu et al., 2008), 14% in the Qilian Mountains during 1961–2006 (Gao et al., 2011a, 2011b), 42% in the Tarim River basin during 1961–2006 (Gao et al., 2010), as much as 75% in western United States (Stewart et al., 2004; Miller et al., 2014), 67% in the Qinnguata Kuussua tributary (Yde et al., 2015), 65% in the Eastern Italian Alps during August (Engel et al., 2015), and 58–72% in the Italian Alps (Penna et al., 2014).

Frozen soil meltwater in cold basins influences runoff with a number of ways (Smith et al., 2007). When soil water is frozen, infiltration capacity is diminished. Further freezing of infiltrated snow meltwater will form another layer of impervious ground ice. This layer will facilitate quick runoff of unfrozen surface water (Muskett and Romanovsky, 2009; Karen and James, 2009; Ye et al., 2009). When soil temperature rises above freezing point, water frozen in the soil starts to melt. This releases soil pore space

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to facilitate infiltration of surface water, and in some cases also elimination of soil and groundwater. Some of the frozen soil meltwater may drain directly to become surface runoff, especially at a steep slope. Some of the meltwater may reach the groundwater, and eventually drain off as spring water (Zhang et al., 2003; Yamazaki et al., 2006; Smith et al., 2007; Frampton et al., 2011; Semenova et al., 2012, 2013; Gustafsson and Destouni, 2013; Quinton and Baltzer, 2013). As temperature rises above and drops below freezing point, the active layer of soil changes significantly, and this can affect groundwater recharge and therefore discharge of groundwater to surface drainage. Despite our understanding at a conceptual level of the physical processes involved, there is little study of basin scale field data reported in the literature on the contribution of meltwater from frozen soil to basin runoff. This study conducts field measurements to estimate this contribution, as well as contributions from snow and glacier.

The study region is the Shiyang River basin, located at the eastern end of Hexi Corridor in northwestern China, with an area of 4.16×10^4 km^2 and an annual average precipitation of 300 mm. Glacier coverage has been decreasing, now with an area of 30.21 km^2. Frozen soil covers about 27% of the total basin area. This study provides, for the first time in this basin, quantitative estimates of contributions from meltwater of snow, glacier and frozen soil. Of particular significance is the data on frozen soil meltwater contribution, which has rarely been studied. The isotopic tracer techniques have been employed in this study, which are widely used in field measurements and estimation (Hooper et al., 1990; Hooper, 2003), and it has been used to identify the recharge sources of stream water in some in-land river basins (Kong and Pang, 2012; Li et al., 2014a; Li et al., 2014c; Sun et al., 2015; Wang et al., 2015; Zhou et al., 2015). In this study, the isotope geochemistry of surface water and groundwater has been analyzed to identify their interactions. The method of EMMA was used to quantify the contributions of meltwater from snow, glacier and frozen soil to runoff at the basin river outlet. The contribution from the cryosphere belt (regions covered by glacier or snow or frozen soil) to local water resources has also be determined. Furthermore, the hydrological process and the influence of frozen soil meltwater to basin runoff have been considered and discussed.

2. Data and methods

2.1. Study region

The Shiyang River, which is located between Badain Jaran Desert and Tengger Desert, is one of three in-land river basins in the Hexi region and lying in the eastern Qilian Mountains (Fig. 1). The basin occupies an area of 4.16×10^4 km^2 (101°41′–104°16′E and 36°29′–39°27′N). The seven sub-basins of headwater rivers from east to west are Dajing, Gulang, Huangyang, Jinta, Xiying, Dongda and Xida River (Table 1), respectively. The average water resource is 16.61×10^8 m^3, of which surface runoff is about 15.61×10^8 m^3 and groundwater is 1.00×10^8 m^3. All the tributaries of the main stream have a similar seasonal flow distribution in the basin. The river discharge is mainly originated by precipitation and meltwater in summer, and is mainly supplied by groundwater in winter. The air temperature shows a significant increase from April, and the river discharge also increases with precipitation from May to September. The total discharge from April to May is about 16% of the total annual discharge. Most of the precipitation occurs from June to September, and the total river discharge accounts for 64% of the total annual discharge during these four months. The river discharge starts to decline from October, and the total river discharge from October to December is about 13.4% of the total annual discharge (Zhong, 2011). Glaciers are only distributed in three sub-basins of Shiyang River, comprising (from east to west) the Jinta River, Xiying River and Dongda River (Shi, 2008), and these glaciers only covered an area of 30.21 km^2 (Zhang et al., 2010). In the whole basin, frozen soil has accounted for 27% of the total basin area (Niu et al., 2011).

The basin spans over three climate zones from south to north. The south cold semiarid to semihumid zone at Qilian Mountains (altitude 2000–5000 m) has an annual precipitation of 300–600 mm. The middle cool arid zone at the flatland of Hexi Corridor (altitude 1500–2000 m) has an annual precipitation of 150–300 mm. The north temperate arid zone (altitude 1300–1500 m) has an annual precipitation of less than 150 mm. At the Minqin oasis and near the edge of Tengger Desert, the annual rainfall is only about 50 mm. Annual precipitation shows a seasonal distribution, with approximately 90% of the total rainfall occurring from May to October. Vegetation was mainly distributed in the mountain region at an altitude scope from 2000 m to 3600 m in the Shiyang River basin, including an alpine meadow belt, alpine grassland belt, alpine forest belt and alpine farmland. In addition, an oasis covered an area of 7549.43 km^2, which accounted for 18% of the total basin area, while other areas are dominated by desert in the middle and lower reaches of the basin (Wen et al., 2013). Due to its arid climate, limited water resources and inappropriate water-related human activities, the area has developed serious loss of natural vegetation, gradual soil salinization and desertification, which have greatly impeded the sustainable development of agriculture and economy in the basin.

2.2. Sampling and methods

2.2.1. Precipitation

As shown in Table 1, precipitation samples were collected for each precipitation event at different altitudes in six stations of Xidahe, Jiutiaoling, Anyuan, Wuwei, Yongchang and Minqin in the Shiyang River basin (Fig. 1). A total of 343 event-based precipitation samples were collected at the study region between July 2013 and June 2014. After collection, all samples were immediately sealed in plastic bags and stored in a cold laboratory at −18 °C. During sampling collection, precipitation amount, air temperature, wind speed, and relative humidity were recorded at corresponding automatic meteorological stations in three mountainous sampling stations, and metrological data for other stations is from Wuwei, Yongchang and Minqin national meteorology observation stations.

2.2.2. Surface water

A total of 129 river water samples at different altitudes during the flood season from Dajing River, Gulang River, Huangyang River, Jinta River, Xiying River, Dongda River and Xida River have been collected, including tributary streams. 10 spring samples from the mountainous region and 11 reservoir water samples from the Shiyang River basin have also been taken in this study. 20 shallow well samples (with depths <100 m) and 15 irrigation water samples from water channels (canal system seepage and farmland irrigation water seepage) have also been collected (Fig. 1). Other isotopic data for shallow and deep wells (depths ranging from 200 m to 300 m) in the Minqin basin (23 samples) is from Zhu et al. (2007); and data in the Jingchang basin (39 samples) is from Ma et al. (2010).

2.2.3. Frozen soil meltwater

The samples have been collected in the frozen soil region by means of the excavation of the soil profile, and then the meltwater samples were collected underneath the soil profile. All together 12 soil profiles and 36 samples are used in this research (Fig. 1).

2.2.4. Glacier snow meltwater

22 samples have been collected in the source regions of Dongda River and Xiying River by two ways. Firstly, samples have been collected underneath the snowpack at Ningchan River glacier No. 3; secondly samples have been collected from the glacier front once a month during the flood season (Fig. 1).

Before analysis, all samples were stored at 4 °C in a refrigerator without evaporation. Precipitation and surface water samples were analyzed for $\delta^{18}O$ and δD by means of laser absorption spectroscopy (liquid water