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Unraveling of permafrost hydrological variabilities on Central Qinghai-Tibet Plateau using stable isotopic technique

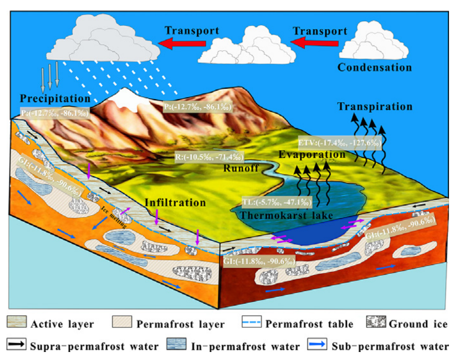
Yuzhong Yang [a], Qingbai Wu [a,b,*], Yandong Hou [c], Zhongqiong Zhang [a], Jing Zhan [a], Siru Gao [a], Huijun Jin [a]

[a] State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Beiluhe Observation Station of Frozen Soil Environment and Engineering, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[c] School of Civil Engineering, Lanzhou University of Technology, China

HIGHLIGHTS

- It is innovative to explore permafrost hydrology using stable isotopic method on the Qinghai-Tibet Plateau (QTP).
- The temporal variations of isotopes in precipitation, river, and lakes were determined, and source water was tracked.
- The ground ice in permafrost was considered as an indispensible water component involving in permafrost hydrology.
- The hydrological connections between different water bodies were identified.
- The permafrost variabilities on the QTP were discussed using conceptual model.

GRAPHICAL ABSTRACT



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ABSTRACT

Permafrost degradation on the Qinghai-Tibet Plateau (QTP) will substantially alter the surface runoff discharge and generation, which changes the recharge processes and influences the hydrological cycle on the QTP. Hydrological connections between different water bodies and the influence of thawing permafrost (ground ice) are not well understood on the QTP. This study applied water stable isotopic method to investigate the permafrost hydrological variabilities in Beiluhe Basin (BLB) on the QTP. Isotopic variations of precipitation, river flow, thermokarst lake, and ground ice were identified to figure out the moisture source of them, and to elaborate the hydrological connections in permafrost. Results suggested that isotopic seasonality in precipitation is evident, it is showing more positive values in summer season, and negative values in winter season. Stable isotopes of river flow are mainly distributed in the range of precipitation which is indicative of replenishment from precipitation. $\delta^{18}O$, δD of thermokarst lakes are more positive than precipitation, indicative of basin-scale evaporation of lake water. Comparison of δ_I values in different water bodies shows that hydrology of thermokarst lakes was related to thawing of permafrost (ground ice) and precipitation. Near-surface ground ice in BLB exhibits different isotopic characteristics, and generates a special δD-$\delta^{18}O$ relationship (freezing line): $\delta D = 5.81\delta^{18}O-23.02$, which reflects typical freezing of liquid water. From isotopic analysis, it is inferred that near-surface ground ice was mainly recharged by precipitation and active layer water. Stable isotopic and conceptual model is suggestive of striking hydrological connections between precipitation, river flow, thermokarst lake, and ground ice under degrading permafrost. This research provides fundamental comprehensions into the hydrological processes in

* Corresponding author at: State Key Laboratory of Frozen Soil Engineering, Cold and Arid regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China.
E-mail address: qbwu@lzb.ac.cn (Q. Wu).

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permafrost regions on QTP, which should be considered in investigating the influence of thawing permafrost on the hydrological cycle on QTP.

1. Introduction

Qinghai-Tibet Plateau (QTP) is known as the "Asian Tower" (Xu et al., 2008). The permafrost accounts for more than half of the total area of the plateau (Zhang et al., 2000; Zhou et al., 2000). It plays importantly hydrological roles in protecting water resources and keeping ecological security (Wang et al., 2007), and exerts enormous effects on the plateau hydrological cycle and water balance (Xu et al., 2014). Previous study suggests that QTP has undergone progressive warming in recent years (Wu and Zhang, 2008). Climate warming-induced permafrost degradation results in the changes of the surface thermal regime, deepening of the active layer and melting of ground ice near the permafrost table (Wu and Zhang, 2008, 2010). It indicates that large amounts of water from thawing permafrost (melting of ground ice) will permeate into active layer (or Talik) to replenish surface water or supra-permafrost water which may increase the discharge amount and lake water (ground water) level. These changes would alter the recharge form and amount of thawing permafrost to surface water, and significantly altered the water cycle in permafrost regions (Yang et al., 2002; Cheng and Jin, 2013; Zhang et al., 2013). The QTP is characterized by harsh climate and high elevation, with scarcity of historical hydrology data which increased difficulties in investigating of permafrost hydrological cycle, and limited current understanding of fundamental hydrologic processes in permafrost regions. Stable water isotopes are usually used in the hydrological processes studies (Kendall and McDonnell, 2012), which provide great convenience and technical support to study permafrost hydrology on QTP.

Recent years, the stable isotopic method has been widely used in cold region hydrology researches, to investigate runoff generation process (Carey et al., 2013; Windhorst et al., 2014), to separate permafrost hydrological contribution to surface runoff (Li et al., 2014; Guo et al., 2015; Yang et al., 2016c), to explore active layer hydrology (Streletskiy et al., 2015; Throckmorton et al., 2016), and to illustrate ground ice evolution in permafrost regions (Lacelle et al., 2013; Vasil'chuk et al., 2016; Yang et al., 2016a). And, the method was successfully used in permafrost regions on the QTP to constrain the hydrological processes (Yang et al., 2016b; Song et al., 2016), to study the source water of alpine river water using hydrograph separation method (Cui and Li, 2015; Li et al., 2016), and to constrain the ground ice source in permafrost (Yang et al., 2016a, 2017).

Although previous studies have investigated the surface hydrology and the ground ice in permafrost on the QTP, studies of systemically hydraulic connections between different water components and hydrological variabilities related to permafrost and active layer are rare, even though the Beiluhe Basin (BLB) contains substantial high-ice content permafrost (Wu et al., 2015). This study hydrologically links the precipitation, river, thermokarst lake, and ground ice by using stable isotopic method and aims to: (1) determine the stable isotopic variations and recharge source of precipitation, river flow, thermokarst lake, and ground ice in BLB permafrost region; (2) identify the hydraulic connections between different water bodies and illustrate the hydrological variabilities in BLB permafrost region. This offers the potential to evaluate the effects of thawing permafrost (ground ice) on hydrological regime of surface water and water resources on the QTP.

2. Study location

The BLB is located on the Central of QTP (Fig. 1) with an average elevation exceeding 4600 m a.s.l. The mean annual air temperature can be as high as −3.88 °C. It reaches its highest value, 21.3 °C, in mid-July and lowest, −21.4 °C, in late January. Most precipitation takes place from April to September, making up 92% of the total. Mean annual precipitation is 368 mm. However, the mean annual evaporation was up to 1538 mm from 2003 to 2006 (Niu et al., 2008). The westerlies are prevailing throughout the year, with the higher wind speed in cold seasons than in warm seasons.

The BLB, enriching in high ice-content permafrost, is a predominantly continuous permafrost region on the QTP (Niu et al., 2002). The mean annual ground temperature ranges from −1.8 °C to −0.5 °C, the permafrost thickness ranges from 20 m to 80 m, and the active layer varies in thickness from 1.61 m to 3.38 m (Wu et al., 2015). Within the permafrost, massive ground ice (including soil) has a typical thickness of 1.0 m to 2.0 m, and the volumetric ice content is greater than 50%.

In this study, two rivers (River-A, River-B) and two thermokarst lakes (TL-A, TL-B) nearby Beiluhe Frozen Soil Station (Fig. 1) were selected as our surface water components. The two rivers are seasonal rivers covered by alpine meadow. The TL-A is a perennially closed-system lake, and The TL-B is a seasonal, through-flow lake that dries up in the cold season. Additionally, to unravel the effect of permafrost thaw on the hydrological cycle in BLB, two areas (**LOC-A**, **LOC-B**; Fig. 1) were selected for permafrost drilling work to obtain ground ice samples near the permafrost table (hereafter called near-surface ground ice; Yang et al., 2013a). A total of 14 boreholes were completed, 11 from **LOC-A** in 2014, and 3 from **LOC-B** in 2011. **LOC-B** is covered by alpine meadow with vegetation coverage of 70–80%. The permafrost table is about 1.8–3 m. **LOC-A** is mainly covered by meadow of approximately 80%, and is characterized by distribution of substantial thaw pits. The permafrost table is distributed between 2.3 and 2.6 m. Soil-bearing ice layers were enriched near the permafrost table. Accordingly, the selected two areas were ideal sites to trace the hydrological effect of melting of ground ice.

3. Materials and methods

3.1. Water sampling methods

Field investigations were conducted over 2011–2014 periods at BLB permafrost region on Central QTP. Sampling work from precipitation, river flows, thermokarst lakes, and ground ice for the stable isotope analysis was completed at the BLB. The geographical data of each sampling site were recorded using a handheld GPS receiver. Meteorological data required were recorded at the Beiluhe Frozen Soil Station.

The event-based precipitation samples were collected during 1 June 2011 to 1 April 2014 at Beiluhe frozen soil station (Fig. 1). Once the precipitation stopped, rain samples were immediately stored in sealed 30 ml HDPE bottles. Snow samples were preferentially melted in room temperature and immediately stored. A total of 81 precipitation samples were collected. Totally, 74 and 71 water samples were obtained from River-A and River-B, respectively. Additionally, lake water sampling work was completed from TL-A and TL-B, and 69 and 64 samples were collected, respectively.

A total of 93 near-surface ground ice (0–3 m; Yang et al., 2013a) samples were obtained, 12 samples from LOC-B, and 81 samples from LOC-A. During ice sampling processes, disposable PE gloves were used for every sample. The outer layer of each ice sample was chipped off to avoid contamination. Ground ice samples were preserved in PE bottles and kept frozen until analysis.