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Evaluation of the hydrological contributions of permafrost to the thermokarst lakes on the Qinghai–Tibet Plateau using stable isotopes

Yuzhong Yang [a], Qingbai Wu [a,*], Hanbo Yun [a,b], Huijun Jin [a], Zhongqiong Zhang [a]

[a] *State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China*
[b] *Beiluhe Observation Station of Frozen Soil Environment and Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China*

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ABSTRACT

Considering the widespread distribution of thermokarst lakes and their significant influence on the hydrological cycle in permafrost regions on the Qinghai–Tibet Plateau (QTP), it is necessary to study their hydrological regimes, which are responding to ongoing climate-induced permafrost thaw. In this paper, water isotopic tracers were used to assess the temporal and interannual hydrological variations and the hydrological processes of two thermokarst lakes (TL-A and TL-B) associated with thawing permafrost in Beiluhe Basin on the QTP. The isotopic results revealed significant differences between the two thermokarst lakes: the TL-A showed more positive isotopic values and small fluctuations than TL-B did. This can be attributed to the hydrological discrepancies between them. Based on the water isotopic mass balance (IMB) model and estimated evaporation, the contributions of permafrost melt water and precipitation to the thermokarst lakes were determined. In both 2011 and 2012, the contributions of thawing permafrost water to thermokarst lakes were of significance, as high as 61.3%. The modeled isotopic composition of input water (δ_I), and the relationships between climatic factors and lake water isotopes were evaluated. Results suggested that the two lakes originated from multiple sources and confirmed the modeling process well. It also indicated that thawing of permafrost significantly affected the development and hydrological regime of thermokarst lakes on the QTP. It is necessary to emphasize the significant impact of thawing permafrost on the thermokarst lakes on the QTP. Findings demonstrate that ongoing permafrost thaw may have major implications for thermokarst landscapes as climate change continues.

1. Introduction

Thermokarst lakes are widespread in ice-rich permafrost regions because of permafrost degradation in response to gradual local disturbances, such as climate-change-induced deepening of the active layer, alterations in surface ground thermal regime due to engineering activities and lengthening of the ice-free seasons (Hinzman et al., 1997; van Everdingen, 1998; Niu et al., 2008a; Turner et al., 2010). Because of the heat-carrier feature of lake water, coalescence with other bodies of water can accelerate the expansion of thermokarst lakes, forming large lakes (Mackay, 1992). The permafrost distributions and ground ice conditions greatly influence the development of thermokarst lakes. Active thermokarst lakes are indicative of unstable permafrost (Smith et al., 2005), and hence, these waterbodies are highly sensitive to changing climate and permafrost conditions. The formation and expansion of thermokarst lakes have been shown by several authors to have an important impact on the hydrological cycle and generation of runoff in permafrost regions (Carey and Woo, 2001; Wang et al., 2009; Turner et al., 2014). As reported in these studies, the thermal impact range of thermokarst lakes on the ground extends to about 50 m in the horizontal direction (Li et al., 2014b). These lakes are major heat sources, responsible for accelerating the degradation of the surrounding permafrost. After several decades or longer, a perennial thaw layer called talik can form, and this talik can eventually penetrate the entire permafrost layer, with simultaneous and gradual lateral permafrost degradation. Some thermokarst lakes previously regarded as non-penetrative have become penetrative (Sun et al., 2012). The lateral thaw of permafrost has also accelerated on the Qinghai–Tibet Plateau (QTP) (Cui et al., 2010; Sun et al., 2012).

In recent decades, the QTP has undergone progressive warming (Cheng and Wu, 2007; Wu and Zhang, 2008), resulting in the changes in the surface thermal regime, deepening of the active layer and melting of ground ice near the permafrost table (Wu and Zhang, 2008, 2010). There are more than 1500 thermokarst lakes scattered across the QTP (Liu et al., 2009; Cui et al., 2010). Notably, about 69 thermokarst ponds and 234 shallow water pits were distributed along both sides of the Qinghai–Tibet Highway from Xidatan to Hoh Xil permafrost regions. These shallow pits finally developed into larger thermokarst lakes due to the long-term subsidence and precipitation-induced erosion of the lakeshore which further accelerated the expansion of thermokarst lakes (Niu et al., 2008a). The large surface area, quick growth of the

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[*] Corresponding author.
E-mail address: qbwu@lzb.ac.cn (Q. Wu).

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thermokarst lakes and ponds, and increased instability of existing lakes have a considerable influence on the thermal regime of the surrounding permafrost, the spatial distribution of surface water, and the hydrological cycles on the QTP.

During the past several decades, the stable isotopic method has been widely used in various fields of hydrology researches, such as precipitation (Yao et al., 2013), ice cores (Grootes et al., 1993), lake hydrological processes (Shi et al., 2014; Gibson et al., 2015), ground water circulation (Guo et al., 2015), and isotopic evolution in permafrost regions (Yang et al., 2013; Lacelle et al., 2014; Li et al., 2014a, 2016). In more recent years, a more robust method has been developed to use water isotope tracers to study thermokarst lakes, including the following: 1) analysis of hydrological variations in thermokarst lakes (Brock et al., 2007; Gibson et al., 2015); 2) assessment of the hydrological sources of thermokarst lakes (Wolfe et al., 2007; Yi et al., 2008); 3) quantitative determination of the water balance of thermokarst lakes and the hydraulic connection with river water (Brock et al., 2009), and 4) evaluation of the influence of hydrological processes on the water balance of thermokarst lakes (Turner et al., 2010, 2014; Gibson et al., 2015).

Studies of thermokarst lakes on the QTP have mainly concentrated on the permafrost change surrounding the thermokarst lakes and the resulting feedback effects (Cui et al., 2010; Lin et al., 2010; Niu et al., 2011; Ling et al., 2012; Niu et al., 2014; Pan et al., 2014; Wang et al., 2014). However, few attempts have been made to assess the hydrological connections and recharge sources of thermokarst lakes on the QTP. It is essential to evaluate the hydrological contributions of permafrost to the thermokarst lakes which present an opportunity to anticipate future thermokarst processes on the QTP under different climate regimes. This could also facilitate better a understanding of the water resource allocation on the QTP and their positions in the global hydrological cycles.

In this paper, two adjacent thermokarst lakes (TL-A and TL-B) near Beiluhe frozen soil station (E 92 zen soil″2 N 34n soil stat in the interior of the QTP that had similar climatic conditions were selected for the study of the isotopic hydrology and hydrological influence of permafrost on the thermokarst lakes (Fig. 1). The isotope mass balance (IMB) model and evaporation model (Craig and Gordon, 1965) were used to evaluate the characteristic source water of thermokarst lakes. The overall objectives of this paper are: 1) to describe the IMB model for two thermokarst lakes on the QTP; 2) to present the isotopic hydrological characteristics of different water components; and most importantly, 3) to evaluate the hydrological contributions of thawing permafrost to the representative thermokarst lakes on the QTP. The IMB model may also be effective for hydrological research of permafrost regions for which insufficient observational data are available and to a further understanding of the hydrological processes on the QTP.

2. Study area

The study area is located in the interior of the QTP (Fig. 1) at an elevation of 4600 m a.s.l. In this region, 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 (Fig. 2), 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., 2008b). The westerlies are prevailing throughout the year, with the higher wind speed in cold seasons than in warm seasons (Fig. 2).

The Beiluhe Basin, enriching in high ice-content permafrost, is a predominantly continuous permafrost region on the QTP (Niu et al., 2002). The freezing period lasts six to seven months. 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 >50%.

As recently reported, thermokarst lakes on the Beiluhe Basin have become more active in recent years from 1969 to 2010. Results showed a substantial increase in the number of lakes, reaching to 534 by 2010, with a total occupied area of 4.10 km^2 (Luo et al., 2015). These thermokarst lakes ranged in depth from 0.5 m to 2.5 m (Lin et al., 2010). They formed during different periods and have a significant influence on the thermal state of permafrost on the QTP (Niu et al., 2011).

Two target thermokarst lakes are about 460 m apart (Fig. 1). Field observations indicate that these two thermokarst lakes have nearly the same elevation (4636 m a.s.l) and climatic conditions, with a lake area of 1950 m^2 for TL-A and 400 m^2 for TL-B. During the warm season, the maximum depths of TL-A and TL-B are approximately 0.8 m and 0.6 m, respectively. They are both classified as shallow lakes, well-mixed, and unstratified (Gibson et al., 2010; Gibson and Reid, 2014). Lake TL-A, is located on a flatland covered by sparse desert steppe, and is a perennially system-closed lake with only minor surface runoff inflow. It is mainly replenished by precipitation and meltwater from thawing permafrost water (ground ice). However, the TL-B lies in the lower reaches of an upland surrounded by alpine meadow. It is a seasonal, through-flow lake that dries up in the cold season and gradually recovers when the temperature rises. It is characterized by a fast water exchange rate. According to field observations, TL-B becomes a low-lying pit when dried up in winter time. At this time, it receives snow blowing from prevailing westerlies. However, during the warm season, it accumulates snowmelt water and rain water from the surrounding alpine meadow and the nearby upper slope to supply the lake.

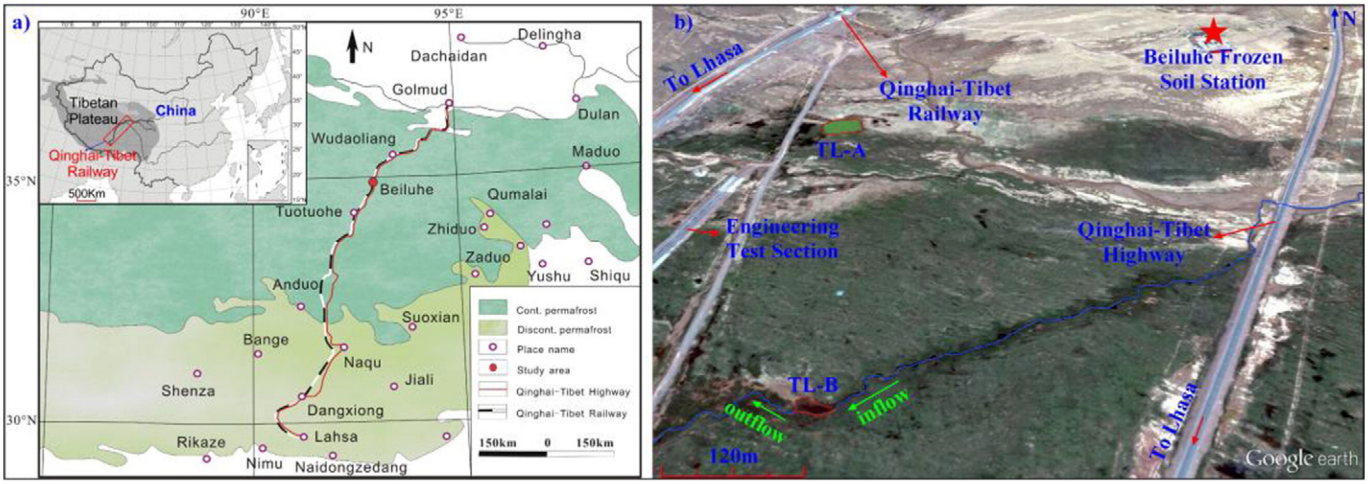

Fig. 1. Location of Beiluhe Basin on the QTP and the sampling sites of lake water.