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Evaluation of thermokarst lake water balance in the Qinghai–Tibet Plateau via isotope tracers

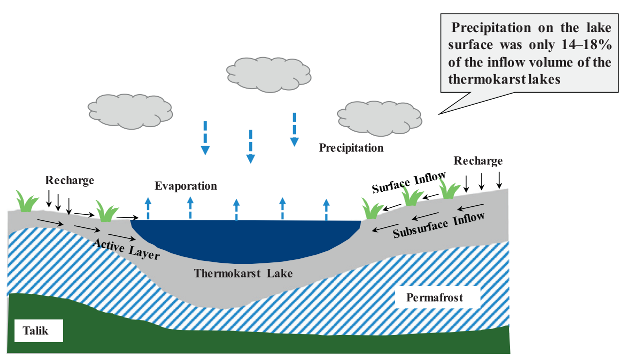
Zeyong Gao [a,c,d], Fujun Niu [a,b,*], Zhanju Lin [a], Jing Luo [a], Guoan Yin [a], Yibo Wang [d]

[a] State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, CAS, 320 Donggang West Road, Lanzhou, Gansu Province 730000, PR China
[b] South China Institute of Geotechnical Engineering, School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510006, PR China
[c] University of Chinese Academy of Sciences, 19 Yuquan Road, Beijing 100049, PR China
[d] College of Earth and Environment Sciences, Lanzhou University, 222 Tianshui South Road, Lanzhou, Gansu Province 730000, PR China

HIGHLIGHTS

- Permafrost is vital to maintain the water balance of thermokarst lakes.
- Precipitation is the main resource of thermokarst lakes.
- Loss of thermokarst lake water was mainly caused by evaporation.

GRAPHICAL ABSTRACT



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ABSTRACT

Thermokarst lakes are a ubiquitous landscape feature, which widely distributed in the pan-arctic and some low latitude regions, and are associated with regional hydrological processes. The studies were taken to obtain a better understanding of the water balance of thermokarst lakes in the Qinghai–Tibet Plateau (QTP) in order to gain insight of the regional hydrological cycle. The characteristics of the stable isotopes $\delta^{18}O$ and δD were investigated in precipitation, permafrost meltwater, and thermokarst lake water in the continuous permafrost region of the QTP and analyzed the lake water balance using the isotope mass model. The results showed that the δD–$\delta^{18}O$ relationship in the thermokarst lakes ($\delta D = 5.45\,\delta^{18}O - 18.95$) differed from that of the local precipitation ($\delta D = 8.30\,\delta^{18}O + 18.49$) and permafrost meltwater ($\delta D = 5.78\,\delta^{18}O - 23.41$), and the mean isotope compositions in the thermokarst lakes were −7.2‰ in $\delta^{18}O$ and −58.0‰ in δD. The more positive isotope signals in thermokarst lakes than in the precipitation and permafrost meltwater revealed that the lakes had experienced stronger isotope enrichment. Additionally, the evaporation-to-inflow ratio (E/I) values were < 1 in most of the thermokarst lakes (84%), which might be explained by the recent expansion of the lake surfaces. However, 16% of the thermokarst lakes had shrunk, owing to thermokarst erosion, lateral expansion as the temperature increases, and lower recharge volume. Moreover, precipitation on the lake surface was only 14–18% of the inflow volume in the thermokarst lakes, and the surface-subsurface inflow and permafrost meltwater are very important for recharging the lakes and maintaining the water balance. The results of this study provide a comprehensive understanding of the influence of climate warming on hydrological processes in the permafrost regions in the QTP.

* Corresponding author at: State Key Laboratory of Frozen Soil Engineering, Northwest Institute of Eco-Environment and Resources, CAS, 320 Donggang West Road, Lanzhou, Gansu Province 730000, PR China.
E-mail address: niufujun@lzb.ac.cn. (F. Niu).

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1. Introduction

Thermokarst lakes were formed by the melting of massive ground ice or the thawing of ice-rich permafrost, which was then followed by local ground subsidence and water gathering in the depressions created. Thermokarst lakes are a ubiquitous landscape feature, which occur in pan-Arctic lowlands (Polishchuk et al., 2017) and some high mountains at low latitude (Niu et al., 2011), where ice-rich permafrost exists. As an indicator of permafrost change (Karlsson et al., 2012), thermokarst lake size and abundance has been changing as permafrost thawing has increased. In the northern high latitudes, most of the thermokarst lakes are shrinking owing to catastrophic lake drainage events in the Kolyma Lowland, Alaska's North Slope, and Western Alaska (Riordan et al., 2006; Nitze et al., 2017). However, lake areas in Central Yakutia have increased remarkably by 48.8% because of wetter and warmer climate conditions there (Nitze et al., 2017). Additionally, in the lower latitude regions of the Qinghai–Tibet Plateau (QTP), the number of thermokarst lakes increased by almost 534 and the total area of all lakes expanded by about 410 ha from 1969 to 2010 in the Beilu River basin (Luo et al., 2015). Some large lakes expanded by 20.2% in area and by 8.7 m in water depth, and the growth rate of total lake area between 1999 and 2000 was 5.0 times that between 1976 and 1999 (Lei et al., 2013). This variability in thermokarst dynamics may be associated to the spatial differences in surface geology, landscape feature position, and permafrost characteristics (Nitze et al., 2017). Recent studies have identified that thermokarst lakes are an important source of greenhouse gases (Walter et al., 2007; Wik et al., 2016), but also affect the ecosystem processes, soil environment, and infrastructure stability of the lakeshore (Lin et al., 2010; Guo et al., 2016; Gao et al., 2017b). Thermokarst lakes also play an important role in providing habitat for wildlife and drinking water for herdsman and in influencing regional hydrological cycles (Gao et al., 2017b).

During the development of a thermokarst lake, the lake bottom thermal conditions change and the permafrost, which is considered the aquitard, even in shallow water (Roy-Leveillee and Buren, 2017). The linkage between groundwater and surface water is constructed after formation of the talik. Thereafter, the thermokarst lake water discharges to the groundwater or the groundwater supplies the thermokarst lakes (Cheng and Jin, 2013). As for QTP, increased precipitation can also recharge thermokarst lakes, as can the indispensable resource of permafrost melting water. Until now, the quantitative water mass budget of thermokarst lakes in the QTP has been poorly understood. Recent studies have shown that lateral suprapermafrost flow can be a major driver of the rapid increase in thermokarst lakes (Pan et al., 2017; You et al., 2017). Furthermore, other studies demonstrated that the melting of ice-rich permafrost could contribute 61.3% of the water to thermokarst lakes (Yang et al., 2016). In addition, some studies indicated that the increased volume of larger lakes (>10 km^2) was dominated by the increased net precipitation (74%) and that the ground ice melting water due to permafrost degradation only contributed 12% (Zhang et al., 2017). However, these results were based on a single lake or only large lakes. The hydrological regimes of thermokarst lakes in the QTP are expected to be varied and complex under the background of climate warming, thus studies need to be conducted at the lake-specific scale in order to improve the comprehensive science-based monitoring programs for adequate assessment of the water balance and hydrological processes in the QTP.

Stable isotope tracers (^{18}O and D) have been effectively applied for identifying hydrological conditions because they are diagnostic and sensitive and samples of such are easily obtained during fieldwork (Tondu et al., 2013). According to the method from Gibson and Edwards (2002) and Gonfiantini (1986), the ratio of evaporation-to-inflow (E/I) was derived from the isotope mass balance and water mass balance and was widely adopted to study the water balance in thermokarst lakes in subarctic regions (Tondu et al., 2013; Turner et al., 2010; Lamhonwah et al., 2017) and in some large lakes in the QTP (Kang et al., 2017; Wu et al., 2017). Lake hydrology in the QTP has proven difficult to monitor owing to logistical challenges and some uncertainties in the field surveying; therefore, the isotope tracer technique has provided a valuable chance for studying the cold region hydrology in this no-man's land.

The aims of the current study were to improve the understanding of water balance of thermokarst lakes by using isotope tracers from a continuous-permafrost-distributed region and to quantify the water loss from evaporation. The specific objectives of this research were to (1) present isotope characteristics of different hydrological components in a thermokarst-lake-distributed region, (2) evaluate the role of evaporation in the water balance of thermokarst lakes, and (3) identify the contributions of different water inputs to thermokarst lakes. It is expected that the results of this study will be useful for answering the questions regarding how thermokarst lakes evolve and their hydrological effects in the future.

2. Method

2.1. Study area

The study was conducted in the Chumaerhe high plain (CHP), Hoh Xil hill region (HXHR), Beiluhe basin (BLB), and Tuotuohe basin (TUB), all of which are located in the interior of the Qinghai–Tibet Plateau (Fig. 1). In the period 1957–2015, the region received an average of ~300 mm in precipitation annually, of which >90% falls in the warm season (May–October). The mean annual air temperature (MAAT) ranged from −2.9 °C to −6.9 °C, and has risen at a rate of 0.03 °C/y. According to the measured data from the Wudaoliang and Tuotuohe meteorological stations, the mean annual evaporation in the study area was ~1430 mm during the 2000–2015 period and the high evaporation rates were attributed to the westerly cold and dry air masses (Li et al., 2016). In addition, the daily hydroclimate factors of average relative humidity, air temperature, and evaporation at the Wudaoliang and Tuotuohe weather stations are shown in Fig. 2 and were higher in the warm season. The study region was underlain with permafrost, which was characterized by ice-low, ice-saturated, ice-layer with soil (Zhao et al., 2010). From 1995 to 2007, the averaged active layer thickness (ALT) was ~2.41 m and ranged from 1.32 m to 4.57 m along the Qinghai–Tibet Highway, and the mean increasing rate of the ALT was ~7.5 cm/y (Wu and Zhang, 2010).

Thermokarst lakes, of which the average area is 5580 m^2, are widely distributed in the Qinghai–Tibet Plateau Engineering Corridor (QTEC), and almost 250 thermokarst lakes are spread between the Kunlun Mountain pass and the Fenghuo Mountain pass (Niu et al., 2011). The lake depth varies from 0.4 m to 3 m, and almost 23% of the lakes are elongated and 56% are elliptical (Niu et al., 2011). From November to April, thermokarst lakes are completely frozen, and the maximum thickness of ice is almost 0.7 m (Lin et al., 2017). The water type is mainly controlled by evaporation–crystallization, and the lakes are slightly alkaline, with pH values ranging from 7.4 to 10.6 (Gao et al., 2017a). Therefore, evaporite salt films containing halite, calcite, dolomite, gypsum, and trona are common in the dry lakebeds and at the lake margins (Gao et al., 2017a). Alpine wet meadow and alpine meadow are the two main vegetation types and are widely distributed around the thermokarst lakes in the Hoh Xil hill region, Beiluhe basin, and Tuotuohe basin. However, the dominant vegetation types are alpine steppe and alpine desert in the Chumaerhe high plain.

2.2. Sampling and laboratory analysis

2.2.1. Field work

Lake water samples were randomly acquired from 130 thermokarst lakes spanning the permafrost regions of the Chumaerhe high plain, Hoh Xil hill region, Beiluhe basin, and Tuotuohe basin in August and September of 2017 in order to investigate the hydrological dynamics of the lakes. The reprehensive thermokarst lake landforms in different