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Research papers

# Exploring the ground ice recharge near permafrost table on the central Qinghai-Tibet Plateau using chemical and isotopic data

Weihua Wang [a,b,c], Tonghua Wu [a,*], Lin Zhao [a], Ren Li [a], Xiaofan Zhu [a,c], Wanrui Wang [b], Shuhua Yang [a,c], Yanhui Qin [a,c], Junmin Hao [a,c]

[a] *Cryosphere Research Station on the Qinghai-Tibet Plateau, State Key Laboratory of Cryosphere Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China*

[b] *College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China*

[c] *University of Chinese Academy of Sciences, Beijing 100049, China*

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A B S T R A C T

Thawing permafrost on the Qinghai-Tibet Plateau (QTP) has great impacts on the local hydrological process by way of causing ground ice to thaw. Until now there is little knowledge on ground ice hydrology near permafrost table under a warming climate. This study applied stable tracers (isotopes and chloride) and hydrograph separation model to quantify the sources of ground ice near permafrost table in continuous permafrost regions of the central QTP. The results indicated that the ground ice near permafrost table was mainly supplied by active layer water and permafrost water, accounting for 58.9 to 87.0% and 13.0 to 41.1%, respectively, which implying that the active layer was the dominant source. The contribution rates from the active layer to the ground ice in alpine meadow (59 to 69%) was less than that in alpine steppe (70 to 87%). It showed well-developed hydrogeochemical depth gradients, presenting depleted isotopes and positive chemical gradients with depth within the soil layer. The effects of evaporation and freeze-out fractionation on the soil water and ground ice were evident. The results provide additional insights into ground ice sources and cycling near permafrost table in permafrost terrain, and would be helpful for improving process-based detailed hydrologic models under the occurring global warming.



## 1. Introduction

Most of the Qinghai-Tibet Plateau (QTP) is underlain by permafrost, which is vulnerable to climate change. Global warming in recent decades has resulted in permafrost degradation, which further has significant impacts on the hydrological and ecological processes (Qin et al., 2016), leading to the variations in hydrological conditions and redistribution of subsurface water (Throckmorton et al., 2016). The knowledge of fundamental hydrologic processes in permafrost regions is limited, which influences future predictions of regional hydrologic cycling (Helbig et al., 2013; Painter et al., 2013). There have been some literatures to analyze recharge and cycling in tundra rivers (Blaen et al., 2014), lakes (Anderson et al., 2013), groundwater (Carey et al., 2013) and active layer water (Throckmorton et al., 2016), but few on ground ice near permafrost table (Yang et al., 2016a). Ground ice is a distinctive feature of permafrost terrain, and could be a potential water source and a proxy index of past climates (Yoshikawa et al., 2013). The large amount of ground ice was discovered in permafrost regions, of which the total volume is approximately 9528 $km^3$ (Liu and Chen, 2000; Zhao et al., 2010). The ground ice near the permafrost table is thawing under warming climate, which influences water and heat exchange, energy budget, greenhouse gases release (Cheng and Wu, 2007). Consequently, it is of great significance to understand ground ice recharge and cycling near the permafrost table on the QTP.

Natural tracers, such as geochemical constituents and stable isotopes, have been widely used to study runoff components and flow paths (Uhlenbrook et al., 2002; Gibson et al., 2017). The method has been introduced into frozen soil regions to investigate the water sources of ground ice using end-member mixing analysis method (EMMA) (Merlivat and Jouzel, 1979; Gilbert et al., 2016). Lorrain and Demeur (1985) stated that ground ice probably formed from the infiltration of glacier meltwater in the arctic permafrost regions in Canadian, by analyzing the ice isotopic variation characteristics. The same conclusion was drawn at the Tuktoyaktuk area, western Arctic coast, Canada (Mackay and Dallimore, 1992).

* Corresponding author.
*E-mail address:* thuawu@lzb.ac.cn (T. Wu).

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The research in the Mackenzie Delta and Yukon Coastal Plain regions showed that the $^{18}O$ value of modern ice-wedges can be significantly different from relict ice wedges, indicating different paleoclimatic conditions (Michel, 1990). Yang et al. (2016a) revealed that near-surface ground ice (0–3 m depth) formed mainly from modern precipitation in the Kunlun Mountain Pass on the QTP, China. Meanwhile, some progress has been made about the ground ice near permafrost table. The water content near permafrost table was increasing based on the analysis of field data (Zhao et al., 2000; Hinkel et al., 1996). Cheng (1983) figured out the mechanism of repeated-segregation for the formation of thick layered ground ice near permafrost table. However, there were still little field-based research which explored the sources of ground ice near permafrost table. In addition, the freeze-out fractionation effect for isotope compositions would occur during the unfrozen pore water refreezing into ground ice, which would increase the uncertainty of the results for hydrograph separation model (Harris et al., 2007). Chloride ion, as widely distributed in various water components, is the stable structure of chlorine and not sensitive to oxidative-reductive conditions and pH (Huang et al., 2017), hence is considered as a suitable natural tracer in alpine regions (Clark et al., 2001).

In this study, the geochemical conservative tracer chloride ions were used in hydrograph separation to explore the recharge sources and contribution ratios of ground ice near permafrost table in the continuous permafrost regions on the central QTP. We attempted to combine stable isotopic and hydrochemical tracers to determine water sources of ground ice near permafrost table. The results were expected to fill the fundamental knowledge gap on the sources of ground ice near permafrost table, and provide theoretical foundation for understanding the hydrological processes in permafrost regions of the QTP.

## 2. Methods

### 2.1. Site description

All samples were collected along the Qinghai-Tibet Highway (QTH), which winds through the continuous permafrost regions on the hinterland of QTP (Fig. 1). The eight sampling sites include Xidatan1 (XDTB), Xidatan2 (XDTMS), Kunlunshan (KLS), Qingshuihe (QSH), Wudaoliang1 (WDLMS), Wudaoliang2 (WDLH), Kekexili (KKXL) and Wenquan (WQ), whose elevations range from 4488 to 4960 m above the sea level (91.900–94.091°E and 33.100–35.720°N) with a relatively smooth terrain (the slope of each site is less than 5°) (Table 1). The active layer thickness ranges from 1.5 to 3.1 m for the eight sampling sites. The mean annual air temperature ranges from −5.3 to −2.2 °C and the mean annual precipitation ranges from 212 to 310 mm (obtained from National Meteorological Information Centre, China Meteorological Administration), and the mean annual evaporation is 1200–1470 mm, characterized by a plateau sub-frigid semiarid climate (Li et al., 2012). The annual change of precipitation shows a seasonal distribution, with about 83% of the total rainfall mainly occurring from May to September (Zhao et al., 2008). The mainly vegetation ecosystems

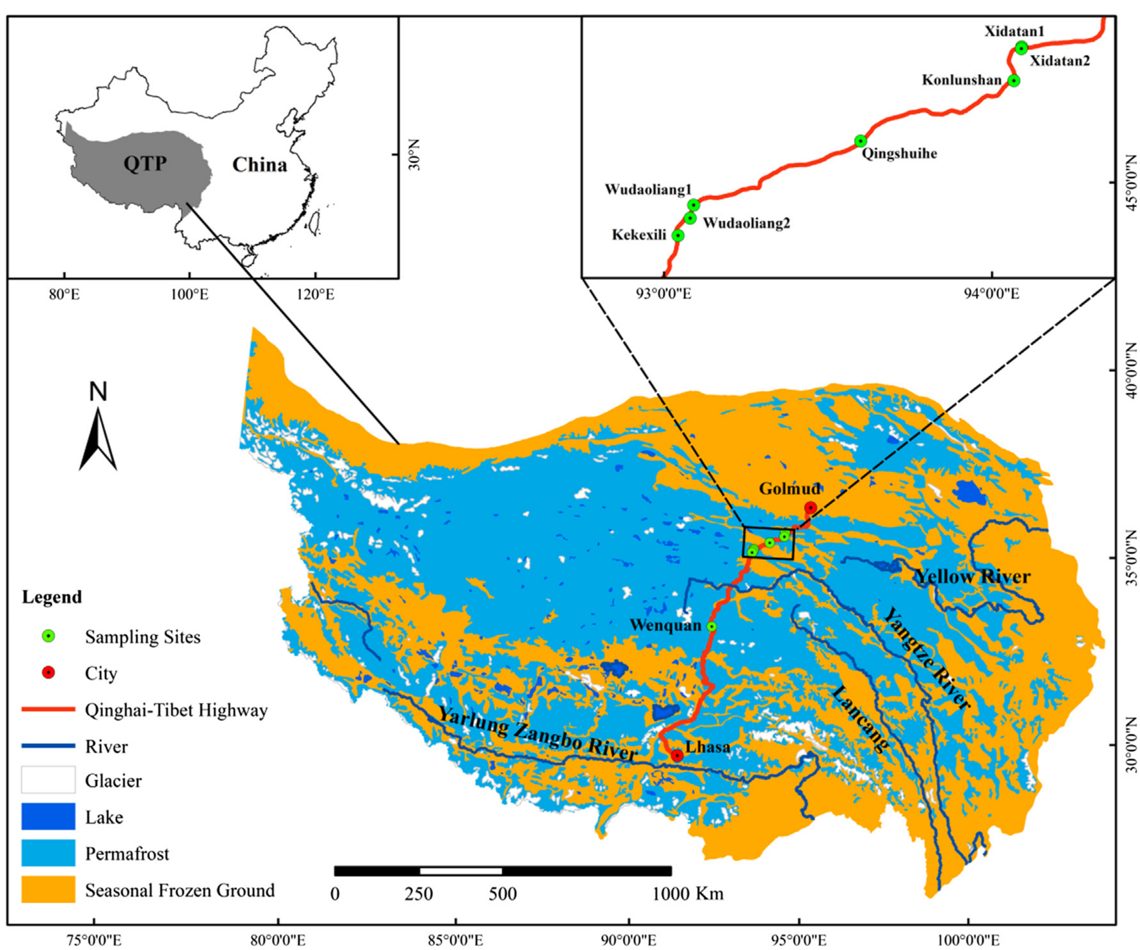


**Fig. 1.** Location of the study area and sampling sites.