



Hydrochemistry and controlling mechanism of lakes in permafrost regions along the Qinghai-Tibet Engineering Corridor, China



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ABSTRACT

Lakes are the main water resource for migrating animals and herdsmen in permafrost regions along the Qinghai-Tibet Engineering Corridor (QTEC) and play a crucial role in regulating the balance between regional surface water and groundwater. Hydrochemical properties also affect the soil environment, ecological conditions, and hydrological cycle. In this study, 127 water samples were collected from lakes to analyze hydrochemistry characteristics. The results are discussed in the context of relationships between water chemistry and local conditions including climate, topography, and geology. The results showed that 43.3% of lakes are fresh, 19.7% are brackish, 18.9% are saline, 17.3% are brine, and only 0.8% are bitter. The dominant cation is Na^+ , followed by Mg^{2+} , Ca^{2+} , and K^+ . The dominant anion is Cl^- , followed by SO_4^{2-} and HCO_3^- in the northern section of study region; whereas Ca^{2+} , Na^+ , and HCO_3^- are the dominant ions in the lakes of the southern section. The higher concentrations of carbonate in the southern lakes reflect contributions from groundwater discharge. In contrast, the higher concentrations of sodium, chloride, and sulfate in the northern section indicate that they are dominated by the interaction of evaporates. Additionally, cation exchange, precipitation, and dissolution have also modified the distribution of hydrochemical compositions. Thermokarst processes, in particular, have induced changes in the hydrochemistry of lake waters in the permafrost regions of the QTEC, in that the ion concentrations are closely related to ground ice content. In the context of persistent climatic warming and steadily increasing anthropogenic activities, the salinity of lakes along the QTEC is likely to increase in the future.

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1. Introduction

Lakes are ubiquitous landforms in the permafrost regions of the North American Arctic, Siberia, and western Canada (Marsh et al., 2009; Morgenstern et al., 2013; Farquharson et al., 2016). They are also widely distributed in the high-altitude permafrost regions of the Qinghai-Tibet Plateau (QTP) (Niu et al., 2011). Some are thermokarst lakes, which were created by surface subsidence following the melting of ice-rich permafrost (van Everdingen, 2005). Others are nonthermokarst lakes that are mostly recharged from surface runoff, glacier meltwater, and groundwater (Zheng et al., 2002). In the context of a warming climate and increasing precipitation, lake areas in the interior of the QTP have been clearly increasing over the past few decades (Zhang et al., 2017). Indeed, the total surface area of some larger lakes ($>20 \text{ km}^2$) increased by 47% from 1973 to 2010 (Yan and Zheng, 2015). For example, during the past four decades, the number of thermokarst lakes in the Beiluhe River basin of the QTP rose by ~534,

amounting to an increase in area of 410 ha (Luo et al., 2015). The expansion of these lakes has inevitably led to a series of environmental issues, including soil, ecology, and hydrology changes (Gao et al., 2017). Sodium, which is the dominant cation in permafrost, is likely associated with sediments of marine origin (Kokelj et al., 2002). The formation and development of lakes will release sodium from permafrost into the soil system, producing sodic or locally salinized soil, and subsequently degrading alpine vegetation. In addition, the permafrost degradation caused by lake expansion may have also initiated substantial changes in groundwater dynamics (Cheng and Jin, 2013). Moreover, the related engineering issues should not be ignored.

The Qinghai-Tibet Engineering Corridor (QTEC) is a relatively narrow corridor (5 to 10 km wide) on the QTP, and engineering/infrastructure activities tend to be closely monitored or restricted because of the fragile environment (Guo et al., 2016). Engineering projects include the Qinghai-Tibet Highway (QTH), Qinghai-Tibet Railway (QTR), Golmud to Lhasa oil products pipeline, and Xining to Lhasa 110 kV transmission line. Many residents and towns in this area are distributed in this narrow corridor, and a new express highway will be constructed within a few years (Jin et al., 2008). Under the influence of persistent climate warming and steadily increasing anthropogenic activity, the

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thermokarst and nonthermokarst lakes are more widely distributed in the QTEC than in undisturbed areas (Lin et al., 2011). These lakes have two important impacts on the foundations of adjacent infrastructure. First, the thermal impacts are significant (Guo et al., 2016); second, saline sodium sulfate expansion when saltwater enters the foundations of the QTH and QTR (Wan, 2015) can be destructive. Moreover, the high salinity of salt lakes can corrode concrete bridge pile foundations. Therefore, evaluating the hydrochemical characteristics of lakes in the QTEC and providing reasonable suggestions for future engineering activities are necessary.

The major sources of solutes in natural waters include: (i) weathering of silicate and sulfide minerals and dissolution of carbonate and evaporate minerals; (ii) cyclic salts carried inland by precipitation from the sea; and (iii) anthropogenic inputs (Chen et al., 2005). As contributions from each hydrochemical source vary significantly in time and space (Thomas et al., 2015), studying hydrochemistry in natural waters can provide important information about environmental change (Han and Liu, 2000); illustrate the complex interactions between biological, chemical, and physical subsystems in a limited area (Stumm and Morgan, 1996; Wu, 2016); and explain the formation and evolution of water bodies using qualitative and quantitative methods (Huang et al., 2011; Cui et al., 2016). To date, studies on hydrochemical characteristics of surface waters in the QTP have primarily focused on the Qinghai Lake basin (Jin et al., 2010; Xiao et al., 2012; Cui et al., 2016), the Qilian mountainous area (Yang et al., 2012), geothermal fields in Lhasa (Guo et al., 2007, 2009), larger saline lakes in the Hoh Xil basin (Hu, 1997), and the headwaters of the Yangtze River (Wu et al., 2008; Jiang et al., 2015). However, relatively little attention has focused on variations in hydrogeochemical compositions of lakes along the QTEC.

The specific objectives of this study are threefold: (i) to characterize the hydrochemistry of lakes in permafrost regions, (ii) to identify the factors controlling the hydrochemical characteristics of the lakes, and (iii) to assess the roles of thermokarst processes on lake hydrochemistry. We expect that this work will be useful in understanding the relationship between groundwater and surface water.

2. Study area

The QTEC is largely underlain by high-elevation permafrost, which spans the area from Xidatan, Qinghai Province in the north, to Ando in the Tibet Autonomous Region in the south (32°23′–35°43′ N, 91°43′–94°08′ E; Fig. 1A). The total length of the permafrost section is about 630 km. In terms of elevation, the QTEC varies from 4480 to 5070 m asl, passing through a variety of mountains and hills, such as Mt. Kunlun, the Hoh Xil hill region, Mt. Kainxinling, Mt. Tanggula, and the Tuoerjiu Mountains. In addition, some main tributaries of the Yangtze River run through the QTEC, including the Chumaerhe, Tuotuohe, Dam Qu, and Beiluhe rivers (Jiang et al., 2015). In this study, the length of the permafrost region was divided into five subregions—the Chumaerhe high plain (CHP), the Hoh Xil hill region (HXHR), Tuotuohe basin (TuB), Tongtianhe basin (ToB), and the Mt. Tanggula region (MTR) (Fig. 1B)—based on differences in climate, hydrology, topography, geology, and distribution of the lakes. The CHP, HXHR, TuB, and ToB are in the northern section, and the MTR is in the southern section.

The permafrost regions along the QTEC are cold and dry and are accompanied by intense evaporation (Xie et al., 2012). In the study region, the mean annual air temperature (MAAT) is approximately -3.9°C and has risen at a rate of 0.036°C/a since the 1960s. The mean annual precipitation is ~ 340 mm and has risen at a rate of 1.72 mm/a. Mean monthly air temperatures over 0°C and highest mean monthly precipitation primarily occurs from May to September over the plateau. Moreover, the wind speed in cold seasons is higher than that in warm seasons because it is controlled by prevailing westerly winds (Niu et al., 2014).

The permafrost in the QTEC tends to be continuous and characteristically dominated by massive ground ice (Jin et al., 2008). Under the combined influence of persistent climatic warming and increasing anthropogenic activity, the average active layer thickness is ~ 2.4 m, ranging from 1.3 to 4.6 m along the QTH. This thickness has increased at a rate of ~ 7.5 cm/a from 1995 to 2007 (Wu and Zhang, 2010). The average mean permafrost temperature at a depth of 6.0 m is almost -1.6°C , ranging from -0.2 to -3.4°C . From 1996 to 2006, the temperature increased from 0.12 to 0.67°C , with an average increase of about 0.43°C (Wu and Zhang, 2008). Approximately 250 thermokarst lakes are spread across the CHP and HXHR along the QTR, with lake depths varying from 0.4 to 3.0 m and with an average size approaching 5580 m^2 (Niu et al., 2011, 2014). In addition, lakes are distributed in the TuB, ToB, and MTR (Fig. 1).

Geologically, the permafrost regions of the QTEC are located between the Bayan Har Fold Belt and the Tanggula Fold Belt, and the strata are mainly composed of Permian to Quaternary marine-terrestrial facies deposits. Some clastic rocks and carbonate sediments from the Permian and Triassic group are well exposed north of the Chumaerhe-Tongtianhe fault zone (Jiang et al., 2015), with bedrock lithology mainly composed of Paleozoic to Tertiary age marble, schist, gneiss, limestone, sandstone, and granite. South of the Chumaerhe-Tongtianhe Fault Zone, some carbonate rocks, intercalated with evaporates, volcanic rocks, and purple red clastic rocks from marine Jurassic strata, are well exposed (Wu et al., 2009); and the bedrock lithology is mainly composed of mudstone, glutenite, and limestone from the Jurassic to the Tertiary. In the MTR, the exposed strata are mainly a combination of Carboniferous to Permian crystalline limestone, sandstone, and slate, Late Triassic limestone and coal-bearing clastics, Early Jurassic conglomerate, sandstone, and shale, and Middle Jurassic sandstone and mudstone (Wang et al., 2010). Additionally, river terraces in the QTEC are covered with 1–2 m of alluvial, eluvial, glacial, and colluvial sedimentary strata and the floodplains are covered with 2–5 m of sandy gravel (Jiang et al., 2015).

3. Methods

3.1. Sampling, storage, and transport

In August 2013, water was sampled randomly from 127 lakes near the QTH. In total, 36, 21, 16, 8, and 46 water samples were collected from the CHP, HXHR, TuB, ToB, and MTR respectively. Brown, high-density polyethylene (HDPE) sample bottles of volume 250 mL were prewashed using a dilute HCl solution and prelabeled in the laboratory. In the field, a portable pH meter (PAR-116, Anrui Automation Instrument Co., Ltd., Shanghai, China) was employed to determine in situ water pH with a precision of ± 0.02 . The HDPE bottles were prerinsed with the water samples three times prior to sampling. Then, each sample was collected from 0.3 to 0.5 m depth below the lake surface, filtered immediately through a $0.45\text{-}\mu\text{m}$ nylon filter, and finally stored in the precleaned HDPE bottles. The collected water samples were refrigerated at approximately 4°C and later transported to laboratory for analysis in December 2013.

3.2. Sample analysis

Hydrochemical analyses were performed at the Key Laboratory of Ecohydrology of the Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China. Concentrations of K^+ and Na^+ were measured using flame photometry, those of Ca^{2+} and Mg^{2+} were measured using ethylene diamine tetraacetic acid (EDTA) titration, and those of HCO_3^- were measured using neutralization titration. Cl^- and SO_4^{2-} concentrations of Cl^- and SO_4^{2-} were tested using silver nitrate titration and EDTA indirect complexometric titration respectively (Bao, 2008).

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