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Impact of a thermokarst lake on the soil hydrological properties in permafrost regions of the Qinghai-Tibet Plateau, China

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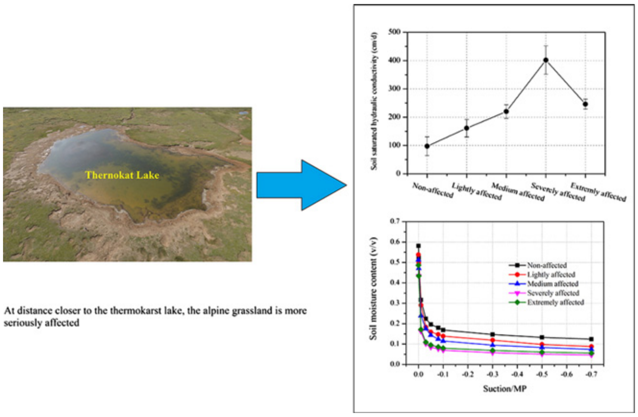
HIGHLIGHTS

- Thermokarst lakes are a potentially serious hazard affecting soil properties.
- The formation of thermokarst lake increased the soil hydraulic conductivity in around areas.
- Thermokarst lakes influence soil properties by altering vegetation distribution.

GRAPHICAL ABSTRACT



At distance closer to the thermokarst lake, the alpine grassland is more seriously affected

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ABSTRACT

The formation of thermokarst lakes can degrade alpine meadow ecosystems through changes in soil water and heat properties, which might have an effect on the regional surface water and groundwater processes. In this study, a typical thermokarst lake was selected in the Qinghai-Tibet Plateau (QTP), and the ecological index (S_L) was used to divide the affected areas into extremely affected, severely affected, medium-affected, lightly affected, and non-affected areas, and soil hydrological properties, including saturated hydraulic conductivity and soil water-holding capacity, were investigated. The results showed that the formation of a thermokarst lake can lead to the degradation of alpine meadows, accompanied by a change in the soil physiochemical and hydrological properties. Specifically, the soil structure turned towards loose soil and the soil nutrients decreased from non-affected areas to severely affected areas, but the soil organic matter and available potassium increased slightly in the extremely affected areas. Soil saturated hydraulic conductivity showed a 1.7- to 4.1-fold increase in the lake-surrounding areas, and the highest value (401.9 cm d^{-1}) was detected in the severely affected area. Soil water-holding capacity decreased gradually during the transition from the non-affected areas to the severely affected areas, but it increased slightly in the extremely affected areas. The principal component analysis showed that the plant biomass was vital to the changes in soil hydrological properties. Thus, the vegetation might serve as a link between the thermokarst lake and soil hydrological properties. In this particular case, it was concluded that the thermokarst lake adversely affected the regional hydrological services in the alpine ecosystem. These results would be useful for describing appropriate hydraulic parameters with the purpose of modeling soil water transportation more accurately in the Qinghai-Tibet Plateau.

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1. Introduction

The melting of ice-rich permafrost affects the extent of ground surface settlement, and typically, thermokarst lakes form in the closed depression areas (Niu et al., 2014). Thermokarst lakes are a common landscape feature in permafrost regions; they are extensively distributed in the arctic and subarctic regions of Siberia, Alaska, and Canada, as well as in high mountainous regions at low latitudes (Dallimore et al., 2000; Edwards, 2012; Niu et al., 2012; Morgenstern et al., 2013; Zhang et al., 2014). The increasing number of thermokarst lakes has been proposed as an indicator of permafrost change (Karlsson et al., 2012). Similarly, studies have shown that in the Beiluhe basin of the Qinghai-Tibet Plateau, the number of thermokarst lakes has increased by approximately 534, with an expansion of about 410 ha in their coverage area, between 1969 and 2010 (Niu et al., 2011; Luo et al., 2015); this change is likely being driven by human activities, climate change, and permafrost warming (Luo et al., 2015; Niu et al., 2015). The formation and development of thermokarst lakes is not only a substantial risk factor in terms of building and infrastructure damage (Lin et al., 2011), it might even alter landforms and ecosystem functions in high and cold regions (Lin et al., 2010; Levy et al., 2013; Séjourné et al., 2015). Presently, research aimed at the above issues is mainly focused on: (1) the development and temporal evolution of thermokarst lakes (Matthews et al., 1997; Jorgenson and Shur, 2007; Toniolo et al., 2009; Morgenstern et al., 2011; Niu et al., 2015), (2) studying the thermal effects on adjacent permafrost (Ling and Zhang, 2003; Burn, 2005; Lin et al., 2010; Lin et al., 2011), (3) estimation of carbon release (Walter et al., 2006; Walter et al., 2007; Brosius et al., 2012; Wu et al., 2014), and (4) investigation of the involved engineering activities, ecological processes, and environmental changes (Wang et al., 2012b; Godin et al., 2014; Wang et al., 2014). Taking into account the processes that affect the horizontal transfer of water and heat, thermokarst lakes have the potential to strongly affect the surrounding soil environment, and yet, very few studies have investigated the variations in soil hydrological properties of such affected areas.

Alpine meadows are widespread in thermokarst lake affected areas in the QTP (Wang et al., 2012a). This type of ecosystem is very sensitive to the direct and indirect effects of global climate change, overgrazing, human activity, and changes in the rodent population size (Wen et al., 2010). Thermokarst lakes are an important hydrothermal resource that can change the alpine vegetation environment by influencing energy and water exchanges between water bodies and surrounding subsoil, which might lead to the deterioration of alpine meadow, consequently reducing the vegetation coverage and species richness (Wang et al., 2012b). The degradation of alpine meadows is accompanied by corresponding changes in the physical and chemical properties of soil, and the soil might become exposed in places where vegetation damage is severe. In general, these changes would enhance the differences in soil hydrological properties among thermokarst lakes affected areas.

The moisture content of a soil is extremely important, as it facilitates nutrient transport. Changes in the soil moisture content, coupled with soil nutrient changes could drive successive changes in species composition, species diversity, vegetation coverage, etc. (Yang et al., 2003; Yang et al., 2013). In addition, the soil hydrological properties play a key role in determining water movement and storage, and local soil properties are typically related to soil erosion patterns and regional hydrological cycles (Saco et al., 2007; Martínez et al., 2014; Mahdizadeh Khasraghi et al., 2015). Among the various soil hydrological properties, hydraulic conductivity is an important parameter that governs landscape changes, as it influences key aspects of the water cycle, including infiltration and net percolation (Valipour and Montazar, 2012a, 2012b; Huang et al., 2016). Variations of another property, namely, the soil water-holding capacity, reflect the response of the soil structure to soil moisture, and high soil water-holding capacities are more conducive to the growth of plants in water-limited ecosystems. The above soil hydrological properties are influenced by several factors, such as: (1) physical and chemical properties of soil (Zeng et al., 2013), (2) vegetation type, coverage, and root gravimetric density (Mahe et al., 2005; Liu et al., 2013), (3) wet-dry cycles or freeze-thaw processes (He et al., 2015; Huang et al., 2016), (4) the thermal regime of the infiltration water and soil (Suttisong and Rattanadecho, 2011), (5) meteorological conditions (Zhou et al., 2008), and (6) anthropogenic activity (Taddese et al., 2002). Therefore, soil hydrological properties are often found to vary in time and space.

The main objective of this study was to understand the variety and range of soil hydrological properties in the thermokarst lake-affected areas and to determine the main factors that contribute to changes in soil hydrological properties. This study is expected to provide insight into the mechanisms of thermokarst lake-induced alpine meadow ecosystem degradation in permafrost regions of the entire QTP.

2. Materials and methods

2.1. Characteristics of the study area

The study area was located in the Hoh Xil hill region of the QTP (Fig. 1), which is the primary area of QTP that experiences permafrost occurrence. Considering the data from several past decades (1957–2012), the mean, maximum, and minimum air temperature of this region were −5.24 °C, 22.4 °C, and −37.7 °C, respectively. The annual mean precipitation was 288 mm (Fig. 2), while the mean daily relative humidity was 57.6%. Rainfall occurs mainly between June and September, and it accounts for 83% of the total annual precipitation in the study area. The total precipitation is normally <10 mm during the freezing season, which lasts November–April. Meanwhile, the annual variation of air temperature in the study area (+0.027 °C/annum) over the past 60 years has shown increasing trends, similar to that of precipitation processes (+1.54 mm/annum). Typically, the monthly mean air temperature exceeds 0 °C only in July and August; the peak air temperature of 5.5 °C is reached in August, whereas the lowest air temperature of −16.7 °C is usually reached in January. In general, freeze-thaw erosion cycles are the dominant soil erosion pattern in the study area, which is under the influence of dry-cold climate conditions.

Alpine meadow and alpine steppe are the two major vegetation types in the study area. The dominant plant species are *Kobresia pygmaea* C.B. Clarke and *K. humilis* (C.A. Mey.) Serg in alpine meadow, and *Stipa purpurea* Grisebach, *Carex moorcroftii* Falc., and *Lobularia maritima* in alpine steppe. The soil of the study area is classified as mattic cryic cambisols as per the Chinese taxonomy (National Soil Survey Office, 1998) or as cambisols by the Food and Agriculture Organization-United Nations Educational, Scientific, and Cultural Organization (FAO-UNESCO, 1974). The soil is characterized by the presence of a mattic epipedon (Oo), which is an organic matter-rich soil horizon. The content of clay and silt is low and the sand content is relatively high. In the study region, the thickness of permafrost ranges from 30 to 100 m, the depth of the active layer ranges from 1.5 to 2.5 m, and the temperature of permafrost ranges from −1.0 °C to 2.0 °C (Wu and Zhang, 2008).

About 41 thermokarst lakes, with an average size about 2000 m^2 and a total size of 8.3×10^4 m^2, are distributed throughout the Hoh Xil hill region, which is adjacent to the Qinghai-Tibet railway. The lakes in the study area are relatively small compared with those in the Kunlun mountainous region, Chumaerhe High Plain, and Beiluhe basin, but they are much deeper, i.e., almost all the lakes have a depth >1 m, while one of them is almost 3 m deep. Approximately 28% of the lakes are elongated in shape, whereas 52% are elliptical (Niu et al., 2011).

2.2. Layout of the observation plots

During the warm season of 2014 (study duration: 28 July–4 August), a representative thermokarst lake in Hoh Xil hill region was chosen as the study subject (Latitude: 35°12′6.9″ N, Longitude: 93°05′12.2″ E;