Development of a thermokarst lake and its thermal effects on permafrost over nearly 10 yr in the Beiluhe Basin, Qinghai-Tibet Plateau

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ABSTRACT

The thermal influence of a thermokarst lake on permafrost in the Beiluhe Basin of the Qinghai-Tibet Plateau was examined over nearly 10 yr (2006–2014), and lake development involved both downward and lateral heat transfers. Downward heat transfer rapidly thawed 8 m of permafrost beneath the lake bottom center, forming a through talik (i.e., year-round unfrozen ground in permafrost that is open to top and unfrozen layers beneath permafrost) by October 2008. Lateral heat transfer resulted in permafrost temperatures and permafrost table depths at the lakeshore that decreased with distance from the lake. In 2014, the maximum differences in the mean annual ground temperature and permafrost table depth within 75 m of the lake were 0.4 °C and 0.8 m, respectively. The horizontal extent of the talik has expanded gradually from the lake center to the lakeshore. The development of the thermokarst lake on the Qinghai-Tibet Plateau is discussed in terms of four stages, initiation, development, stabilization, and termination, resulting from changes in the surface energy balance.

INTRODUCTION

The Qinghai-Tibet Plateau (QTP) is underlain predominantly by high-altitude permafrost (Zhou et al., 2000). Permafrost on the QTP has undergone rapid degradation due to steadily increasing infrastructure activities, e.g., construction (1954) and rehabilitation (1990s to 2000s) of the Qinghai-Tibet Highway (QTH), construction of the Golmud to Lhasa Oil Products Pipeline in 1972–1977, the Lanzhou-Xi’ning-Lhasa fiber optics cables in 1997, a 110 kV transmission line in 2005–2006, and the Qinghai-Tibet Railway (QTR) in 2001–2008; in addition, there has been persistent climate warming of ≥ 0.3 °C/yr over the past 50 yr (French, 1996; Wu et al., 2005; Jin et al., 2008). These perturbations have caused significant increases in active-layer thickness (ALT), permafrost temperature, and thawing of ice-rich ground (Wu and Zhang, 2008; Lin et al., 2011a), leading to reductions in soil strength and soil volume (consolidation), ground subsidence, and the development of thermokarst landscapes (Niu et al., 2008; Lin et al., 2010).

Thermokarst lakes (or thaw lakes) are common features that result from thaw settlement of the ground surface (Kääb and Haeberli, 2001). Thermokarst processes may serve as indicators of the response of ice-rich permafrost to temperature changes in cold regions. However, over the past several decades human activities have become a primary factor in thermokarst development on the QTP (Lin et al., 2011b). Heavy vehicle operations have destroyed or removed the vegetation and left many small pits on the surface that have subsequently filled with water, leading to the development of ponds and thermokarst lakes.

When a lake forms, it constitutes a major heat source to the surrounding permafrost (Ling and Zhang, 2004). The mean annual temperature at the lake bottom is ≥ 0 °C, except for very shallow lakes (Niu et al., 2011). Therefore, it is generally believed that thermokarst lakes cause the greatest natural thermal degradation at the ground surface from patterns determined by climate (Lachenbruch et al., 1962). Thermokarst lakes that retain a year-round liquid water supply maintain a positive heat flux into surrounding frozen ground; this causes the adjacent permafrost to warm and degrade (Lin et al., 2010, 2011c). This heat transfer may accelerate talik (i.e., year-round unfrozen ground in permafrost areas) development, increase the lake depth, and even eradicate underlying permafrost (Williams and Smith, 1989).

Maximum rates of lakeshore retrogression of ~1.8 m in 2007–2008 at a typical 2-m-deep thermokarst lake in the Beiluhe Basin on the QTP were reported (Lin et al., 2010). The thermokarst lake influenced the surrounding permafrost, resulting in a 0.7 m increase in thaw depth at the lakeshore edge compared to adjacent terrain. Ice thickness and water temperature at the surface and bottom of a thermokarst lake (BLH-A Lake) in the Beiluhe Basin in 2007–2008 were characterized in Lin et al. (2011c); based on those studies, Niu et al. (2011) discussed the distribution and geometry of thermokarst lakes along the Qinghai-Tibet Engineering Corridor. However, these data were limited to a short period (2007–2009), and recent lake development and thermal conditions have not been reported. Based on the previous studies and continued field monitoring of a thermokarst lake on the QTP, the objectives of this paper were to: (1) examine lateral thermal erosion over nearly 10 yr at the lake and the associated changes in active-layer depth (ALD) and permafrost temperature at
the lakeshore, (2) document the thermal disturbance of the lake to permafrost in the vertical domain, and (3) discuss the processes causing thermokarst lake formation and present a model of lake development for the Beiluhe Basin. These findings expand on results presented in Lin et al. (2010), spanning a longer period that allows a complete conceptual model of lake development to be presented.

**STUDY AREA AND LAKES**

The Beiluhe Basin occupies a large portion of the Hoh Xil Nature Reserve region, between 4500 and 4600 m elevation in the interior of the QTP, 350 km from Golmud City (Fig. 1). The regional climate is cold and arid. Data recorded from 2005 to 2010 indicated a mean annual air temperature of –3.55 °C; the highest value (14.1 °C) was registered at the end of July and the lowest (–21.6 °C) in early February. Between 2003 and 2006, mean annual precipitation (rain and snow) and evaporation were 368 mm and 1538 mm, respectively (Niu et al., 2008); most of the precipitation (92%) occurs between April and September, so there is little snow cover in winter.

Permafrost with >20% volumetric ice content is continuous in the basin and the mean annual ground temperature is –1.8 to –0.5 °C. The active-layer thickness is 1.8–3.0 m and the permafrost is generally 20–80 m thick; the geothermal gradient is 1.5–4.0 °C/100 m (Lin et al., 2010; Lin, 2011).

Thermokarst lakes are widely distributed in the basin (Fig. 2A). The mean lake area in the region is 8500 m²; the largest lake is >60,000 m², and the smallest is <1200 m² (Niu et al., 2011). Lake depths are typically ~0.5–2.5 m. Approximately 70% of the lakes are elliptical in shape, and 13% are elongate. Field investigations have shown that the ice thickness is 50–70 cm and that ~85% of the lakes do not freeze to the bottom in winter (Lin, 2011). The thermokarst lakes developed in low-lying ground where ice-rich permafrost or massive ground ice exists.

In order to determine the long-term thermal influences of thermokarst lakes on permafrost, a typical thermokarst lake (Fig. 2B) has been observed since 2006. This lake is located on the west side of the QTP, 100 m from the embankment at kilometer marker K1133. It is elliptical in shape, 150 m × –120 m, and has an area of ~15,000 m². The lake is of the closed perennial type and has a depth of as much as 2 m. The maximum ice thickness is ~0.7 m.
**METHODS**

Ground temperatures were measured using multiconductor cables containing regularly spaced thermistors installed in boreholes. In February–March 2006, six holes (boreholes 1–6) were drilled under and near the lake (Fig. 3), and the temperature cables were cased in anti-rust tubes. Boreholes 1 and 2 were drilled within the lake to 60 m and 40 m depth, respectively (Fig. 3). Boreholes 3–6 were drilled along the lakeshore to 15 m depth. Boreholes 1 and 2 were instrumented with 53 and 45 individual thermistors, respectively, with 0.5 m spacing in the upper 10 m, 1 m spacing between 10 and 28 m, and 2 m spacing below 28 m. In boreholes 3–6, there were 30 thermistors per cable with uniform 0.5 m spacing. The data acquisition system included two DT500 data loggers (dataTaker Pty Ltd, Australia) powered by solar batteries, and thermistor cables (assembled at the State Key Laboratory of Frozen Soil Engineering, Chinese Academy of Sciences). The measurement accuracy of the thermistors was ±0.02 °C, and the precision of the system was 0.3%. Measurements were recorded every 3 h beginning in March 2006 and were ongoing for nearly 10 yr.

Mean daily values were calculated for each sensor to the nearest 0.1 °C. The average increases in mean ground temperatures at each borehole were calculated using the least-square fitting method. The depths of the permafrost table and permafrost base were determined by linear interpolation from ground temperatures obtained at each borehole, and the depth was reported to the nearest centimeter. Analysis of variance was used to examine relations between ground temperatures. The model of lake development was based on the long-term field observations and our informed judgement. Near ground surface temperature ($T_{ns}$) was estimated at each borehole from the sensor at 0.5 m depth, and the annual mean permafrost temperature ($T_g$) was commonly defined at the depth of zero annual amplitude; we generally regard the mean ground temperature at 10–15 m as $T_g$ herein.

**RESULTS**

**Thermal Influence of the Thermokarst Lake on Permafrost with Depth**

Figure 4 presents the thermal regime beneath the lake at the two boreholes from March 2006 to December 2014. As shown in Figure 4A, positive ground temperatures persist throughout the year at borehole 1 in the lake center to depths >60 m, so that a talik at least 60 m deep exists. Therefore, it was inferred (Lin et al., 2010) that permafrost beneath the lake bottom had thawed completely given its original thickness in the basin before 2006. In addition, isotherms decreased in depth from 2006 to 2014. For example, the 3 °C isotherm shifted from 35 m depth in 2006 to 42 m in 2014, indicating that ground temperatures have been gradually rising and the long-term effect of the lake on permafrost is significant.
Thermal data from borehole 2 indicated permafrost thaw and subsequent complete degradation (Fig. 4B). When drilling commenced in March 2006, the permafrost thickness was ~15.3 m. The permafrost table and base were located at –13.9 m and –29.2 m depth, respectively. Since then, the permafrost table has descended slightly, but the permafrost base has rapidly ascended. By March 2007, the permafrost had thinned by ~1.1 m (to 14.2 m thick), the permafrost table had descended by ~0.1 m (to –14.0 m), and the permafrost base had risen by ~1.0 m (to –28.2 m). By March 2008, the permafrost thickness had been reduced to 7.8 m (permafrost table and base moved to 14.6 m and 22.4 m depth, respectively). By October 2008, the permafrost had thawed completely, indicating that a layer of permafrost nearly 8 m thick degraded in <1 yr.

This record of permafrost degradation implies that the thawing occurred first at the permafrost table. With the heat input persistently into the permafrost from above and below, the temperature was brought to ~0 °C, after which the thawing progressed rapidly. The data from boreholes 1 and 2 highlight the significant and rapid effects of the thermokarst lake in this region with relatively warm and thin permafrost.

Profiles of mean annual ground temperature for boreholes 1 and 2 are shown in Figure 5 to further examine the thermal disturbance over time. Although the increase in ground temperatures at borehole 1 from the lake bottom to 33 m depth was not significant, temperatures at 33–60 m depth have steadily increased (Fig. 5A). In contrast, ground temperatures at each depth at borehole 2 have increased consistently. The mean rate of increase in ground temperature at borehole 1 was 0–0.09 °C/yr, with the maximum value at 40 m depth (Fig. 6). However, the rate of increase was 0.02–0.31 °C/yr at borehole 2, and the maximum value appeared at 5–8 m depth (Fig. 6). The rate of increase was greater at borehole 2 than at borehole 1. This may be because the thawed sediments of borehole 1 are already in thermal equilibrium, while borehole 2 is still adjusting toward equilibrium. The rate of increase may slow at borehole 2 as ground ice and permafrost thaws, and equilibrium is approached.

Thermal Influence of the Thermokarst Lake on Permafrost in the Horizontal Domain

Near Ground Surface Temperatures (T$_{ns}$)

The lateral thermal disturbance can be documented by examining variations in permafrost temperature and the permafrost table at four of the boreholes adjacent to the lake. With limited solar radiation and snow depth on the QTP, T$_{ns}$ variations followed the approximately sinusoidal air temperature pattern (e.g. Lin et al., 2015a, fig. 7 therein). The measured T$_{ns}$ in 2006–2014 ranged from –0.3 to –1.1 °C at borehole 3, 0.6 to –0.7 °C at borehole 4, 0.6 to –0.4 °C at borehole 5, and –0.5 to –1.7 °C at borehole 6. These temperatures were not statistically distinct because the lakeshore is ~1.0 m higher than the...
water surface, so the thermal effect of the water body did not cause differences in $T_{ns}$. However, the annual maximum and minimum $T_{ns}$ at the boreholes had slight variations, likely related to heterogeneous surface conditions.

**Increasing ALD**

Figure 7 presents variations in ALD at the four boreholes in 2006–2014. The deepest active layer was at borehole 3 (241 cm in 2006 to 272 cm in 2014), while the shallowest active layer was at borehole 6 (180 cm in 2006 to 192 cm in 2014). The mean ALD at borehole 4 (213 cm in 2006 to 254 cm in 2014) was slightly deeper than at borehole 5 (204 cm in 2006 to 240 cm in 2014). The mean ALDs were all >1.8 m, and all >0.8 m below the water surface (Fig. 7). Therefore, the thermal flux of the water body may mainly cause the differences in ALD at the boreholes. The ALD was generally deeper near the lake edge and became progressively shallower with distance from the lakeshore to undisturbed conditions (Lin et al., 2010). The distance between boreholes 3 and 6 was ~75 m, and the differences in ALD between the sites were 0.6–0.8 m, corresponding to a lateral gradient of ALD increase of 76–107 cm/100 m in 2006–2014.

The ALD increased by ~10–40 cm at each borehole from 2006 to 2014 in association with the increases in lake temperature. The greatest increases were in boreholes 3, 4, and 5 near the lake, increasing by 31, 41, and 36 cm, respectively, at a rate of ≥4 cm/yr. However, the increase at borehole 6 was slower (<2 cm/yr), and the total increase was only 12 cm. The lowering permafrost table demonstrates that the thermokarst lake has had a great effect on the local permafrost in the lateral direction, causing gradual degradation from the center of the lake to the lakeshore.
Increasing Annual Mean Permafrost Surface Temperature ($T_{ps}$)

Ground temperatures near the surface of permafrost from the four boreholes are presented in Figure 8. The annual regime comprises a relatively short cooling season and a long period between May and November when the temperature increases slowly toward the maximum value. The drop in temperature following freezeback of the active layer was sudden at each borehole, occurring first at borehole 6, the coldest borehole furthest from the lake, but was more gradual at borehole 3 near the lake. At all times, $T_{ps}$ was higher at borehole 3 than at the other boreholes, and temperatures decreased with distance from the lake. Moreover, the annual maximum temperature at permafrost surface at each borehole increased year by year, but variations in annual minimum temperature were irregular.

The $T_{ps}$ data for 2006–2014 are presented in Figure 9. Over this period, $T_{ps}$ from borehole 3 was almost the same as borehole 4, but was higher than at the other two boreholes. The lowest $T_{ps}$ was recorded at borehole 6 and the highest at borehole 3. The $T_{ps}$ values at all sites have been increasing over time.
Warming Annual Mean Permafrost Temperature \( (T_g) \)

As depth increases, ground temperatures integrate spatial variation in the surface temperature field over large areas, and the temperature wave is dampened. Therefore, \( T_g \) is less variable than \( T_{ps} \). \( T_g \) steadily increased from 2006 to 2014 (Fig. 10). The highest \( T_g \) was at borehole 3 (–1.0 °C in 2006 to –0.6 °C in 2014), while the lowest was at borehole 6 (–1.3 °C in 2006 to –1.2 °C in 2014). In 2006–2009, \( T_g \) at borehole 4 was close to that at borehole 3, but after 2009, \( T_g \) at borehole 3 increased rapidly. \( T_g \) at borehole 5 was between the values of boreholes 6 and 4. Like \( T_{ps} \), \( T_g \) increased toward the lake edge. The difference in \( T_g \) between borehole 3 and 6 during the study period was 0.3–0.6 °C, corresponding to a lateral thermal gradient of 0.4–0.8 °C /100 m.

The \( T_g \) at the four boreholes increased by 0.1–0.4 °C from 2006 to 2014 in association with the increases in lake temperature. The greatest increase in \( T_g \) was 0.4 °C at borehole 3, a rate of increase that exceeded 0.05 °C/yr. However, the increase in borehole 6 was lower (total 0.1 °C; rate 0.01 °C/yr). The increase in \( T_g \) indicates that the lake has influenced the local permafrost laterally at depth.

DISCUSSION

Factors Controlling Thermokarst Initiation and Development

Based on observations during recent decades, we have summarized important factors in the initiation and development of thermokarst lakes on the QTP (Table 1). The factors were classified into three types: (1) changes in site conditions, (2) anthropogenic disturbances, and (3) climate-induced causes. Human activities have directly influenced thermokarst initiation on the QTP, especially near the QTH and QTR. Our observations indicate that thermokarst processes began in these areas following infrastructure construction. A comparison of two surveys along the QTH provided enough evidence to confirm this result. In 2007, ~69 thermokarst lakes and 234 water pits existed on both sides of the QTH from the Xidatan Basin to the Hoh Xil Hill region, and they occupied areas of ~1.5 × 10^4 m^2 and 1.0 × 10^3 m^2, respectively (Niu et al., 2008).
By September 2009, the surface area covered by water had increased to $3.5 \times 10^5 \text{ m}^2$, and new ponds had begun to appear because of disturbances, including vehicle traffic and damage to vegetation from a highway improvement project started in 2008 (Lin et al., 2011b). Because no trees grow in the tundra environment on the QTP, forest fires are not a source of active-layer deepening and thermokarst subsidence as they are in other regions (Mackay, 1995; Burn, 1998). However, overgrazing and infrastructure such as maintenance stations, parking lots, and the buildings in the towns of Wudaoliang and Tuotuohe would certainly accelerate permafrost thaw and thermokarst activities because of artificial heat sources (e.g., heated buildings, pipelines, utilidors).

Although site conditions (Table 1) cannot be direct causes of thermokarst initiation, they are closely related to the level of thermokarst activity. Changes in local factors may initiate, retard, or counteract thermokarst activity. Under the same conditions of surface disturbance and air-temperature changes, sites with greater vegetation cover and a thicker surface organic mat, thick overburden, low ice content, low ground thermal conductivity, and low mean annual ground temperature are not as prone to thermokarst initiation, while the opposite conditions may increase the susceptibility of permafrost to thaw by local disturbances. Furthermore, changes to water bodies from sources like precipitation, springs, and rivers may also create conditions that increase ground thawing hazards.

### TABLE 1. FACTORS INFLUENCING THE INITIATION AND DEVELOPMENT OF THE THERMOKARST LAKE IN THE BEILUHE BASIN, ALONG THE QINGHAI-TIBET ENGINEERING CORRIDOR

<table>
<thead>
<tr>
<th>Causes</th>
<th>Item</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site (local factor) conditions</strong></td>
<td>Local topography</td>
<td>Plains or basins are favorable to the accumulation of melt water, precipitation and/or runoff.</td>
</tr>
<tr>
<td></td>
<td>Vegetation and surface organic mat</td>
<td>Surface organic cover serves to protect permafrost. However, if it is damaged or removed, the effect is lost.</td>
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<tr>
<td></td>
<td>Flowing water</td>
<td>Ponding on the ground surface and surface or underground flow will accelerate the thaw of permafrost. Improved drainage or diversion of drainage and refreezing of underground pools may retard or counteract the development of thermokarst lakes.</td>
</tr>
<tr>
<td></td>
<td>Overburden thickness</td>
<td>If the overburden is thin, then soil erosion more readily exposes underlying ice-rich permafrost.</td>
</tr>
<tr>
<td></td>
<td>Ice content</td>
<td>The thaw of permafrost with high ice content causes surface deformation and facilitates the accumulation of melt water, whereas terrain underlain by ice-poor sediments that are stable upon thawing only undergo thaw consolidation.</td>
</tr>
<tr>
<td></td>
<td>Ground thermal conductive properties</td>
<td>Ground with high thermal conductivity transfers more heat to melt ground ice and retain water present in the depression.</td>
</tr>
<tr>
<td></td>
<td>Mean annual ground temperature</td>
<td>Warming permafrost (higher mean annual ground temperature) thaws more easily than cold permafrost under the same environmental conditions, and slight disturbances or temperature increases may result in changes in permafrost and thermokarst initiation.</td>
</tr>
<tr>
<td><strong>Anthropogenic disturbances</strong></td>
<td>Linear engineering construction</td>
<td>Digging during engineering activities destroys vegetative cover and the surface organic mat, and may remove overlying soil, exposing ice-rich permafrost and allowing it to thaw.</td>
</tr>
<tr>
<td></td>
<td>Overgrazing</td>
<td>Overgrazing may lead to a reduction in the vegetation cover and increase the absorption of solar radiation.</td>
</tr>
<tr>
<td></td>
<td>Vehicles rolling</td>
<td>Passing of heavy trucks leaves tracks and pits, resulting in the trampling of vegetation and damage of grassland, promoting the thaw of permafrost.</td>
</tr>
<tr>
<td></td>
<td>Building of supporting complexes and residential areas</td>
<td>Some supporting complexes and residential areas may change the heat exchange between the buildings and frozen ground, resulting in ground warming, a steady increase in permafrost table depth, and permafrost thaw.</td>
</tr>
<tr>
<td><strong>Climate-induced causes</strong></td>
<td>Warmer summer</td>
<td>Warmer air temperature in summer accelerates the thaw of permafrost and the lowering of the permafrost table, so that the maximum freezing depth may become less than the maximum thaw depth. A talik may therefore initiate, promoting settlement of the surface and water accumulation.</td>
</tr>
<tr>
<td></td>
<td>Continentality</td>
<td>Increased continentality may initiate disturbances to the ground surface, and decreased continentality may retard or counteract the thawing process.</td>
</tr>
<tr>
<td></td>
<td>Mean annual air temperature</td>
<td>Climate warming will lead to extensive degradation of the permafrost and induce a series of thawing hazards.</td>
</tr>
</tbody>
</table>
temperatures and result in thermokarst activity. Unlike in Alaska (Jorgenson et al., 2001), there is little snow cover on the QTP. Heavy sleet occurs from August to October and may influence thermokarst activity; however, this has not yet been reported.

The effect of climatic factors on thermokarst activity, and particularly the influence of climate warming, has been reported in many investigations (Burn, 1992; Jorgenson et al., 2001; Murton, 2009). In our opinion, the initiation of thermokarst lakes on the QTP is not solely linked to climatic warming (e.g., Burn and Smith, 1988, 1990). However, once a thermokarst lake has formed, climate warming promotes the thaw of ice-rich permafrost, leading to rapid thermokarst activity and lake expansion. In the short term, anthropogenic disturbances to permafrost are more apparent than those stemming from natural conditions. The effect of human-induced disturbances even seems to override the effect of climatic changes in controlling lake evolution in the region. Overall, thermokarst lake initiation is often complex and influenced by several factors, and a combination of increasing air temperature and human activities may raise ground temperatures, accelerating permafrost degradation and the initiation and development of thermokarst lakes.

Process of Thermokarst Initiation and Development

Based on long-term observations of numerous thermokarst lakes on the QTP, the evolution of thermokarst lakes may be divided into four phases: initiation, development, stabilization, and termination (Fig. 11). However, some processes in certain lakes may not be clearly observed because of differences in the regional or site geological conditions. In areas with homogeneous permafrost characteristics, the evolutionary pattern is basically consistent.

Initiation

On the QTP, thermokarst activity usually commences when the surface vegetation or organic mat (Fig. 11A) is disturbed or removed by, for example, cutting, vehicle traffic, and cracking (Fig. 11B). The resulting heat absorption can raise the ground temperature sufficiently to thaw the underlying ice-rich permafrost. In addition, changes in the groundwater flow, precipitation accumulation, or rising summer air temperatures may create heat sources that lead to thermokarst activity. Surface runoff and/or precipitation then start to gather in subsided areas (section A in Fig. 11B), and a small pond is formed within a few years.

The low albedo (<10%) (Mackay, 1995; Burn, 1998; Murton, 2009) and high heat absorption of water bodies causes the underlying frozen ground to warm rapidly, particularly if the water is shallow and darkened by dissolved organic material (Fig. 11C).

Development

As water continues to accumulate, lakes that do not freeze to the bottom maintain a positive heat flux into the ground, causing the adjacent permafrost to be shallow and warm. The heat source promotes continued thawing of ice-rich permafrost underlying the disturbed surface (section B in Fig. 11D), and further subsidence occurs as the active layer deepens.

Ground warming may promote lateral expansion of the lake. When the surface subsidence reaches a critical depth, the lakeshore begins to crack (section C in Fig. 11E). The cracks widen gradually and develop more rapidly in the warm season (Lin et al., 2010). Waves on the lake cause mass wasting at the shoreline and slumping of material into the water (Lin et al., 2010, Fig. 5 therein). Lakeshore retrogression increases the lake area, seemingly an irreversible effect as long as the lake does not drain and the supply of icy sediment is not exhausted (Fig. 11F).

Stabilization

In the stabilization stage, lake growth ceases, the heat exchange between the ground and the atmosphere is nearly in equilibrium (Lin et al., 2011c), and the lake has not drained (Fig. 11G). In areas where permafrost is thin, complete degradation may have occurred by this point. However, if the permafrost is thick or the mean annual ground temperature is low, thermokarst activity often ceases and the ground surface stabilizes before a through talik (i.e., one open to top and unfrozen layers beneath permafrost) forms (Lawson, 1982; Burn, 2002; Murton, 2009). However, permafrost beneath most lake bottoms in the Beiluhe Basin is thawed completely at the stabilization stage. This is due to the thin (50–70 m deep) and warm (~1.8 to ~0.5 °C) permafrost. Nonetheless, permafrost persists under the bottoms of ~15% of the lakes (Lin et al., 2015b).

The stabilization stage does not necessarily occur in all lakes. For example, a thermokarst lake may initiate, develop, and then drain rapidly by encountering a drainage system before it can stabilize, particularly where the permafrost is thin and the sediment permeability is high.

Termination

In the Beiluhe Basin, a through talik may form beneath lake bottoms after the stabilization stage (Lin et al., 2011c; Ling et al., 2012). Some lakes underlain by high-permeability substrates or underground fissures may then drain downward (Fig. 11H). Other lakes, underlain by low-permeability substrates, cannot be drained through taliks, but can be reduced in volume from periods of high evaporation and low precipitation. We have observed many drained basins along the QTR and QTH where vegetation has been reestablishing on older exposed lake bottoms (Fig. 11I). Permafrost begins to
Figure 11. Diagram of a thermokarst lake evolution in the Beiluhe Basin. (A–C) Initiation stage. (A) Undisturbed surface and stable stratum. (B) Disturbed surface (by cutting or rolling). (C) Initial pond with the increasing solar radiation and increasing water. (D–F) Development stage. (D) Initial thermokarst lake with vertical thermokarst development. (E) Developing thermokarst lake with vertical and lateral thermokarst development. (F) Rapidly developing thermokarst lake with lake sedimentation and talik (see text) in nonsteady state. (G) Stabilization stage. A mature thermokarst lake with energy balance between the output and input and full development of a talik. (H–I) Termination stage. (H) Water-level decline and partial draining and partial refreezing of a former talik. (I) Vegetation and permafrost begin to regrow. Note: A–I in brackets in the upper left corner are the numbers of the figure, and the uppercase letters A, B, and C in sections B–H refer to a section of lake.
aggregate and periglacial features develop concurrent with vegetation growth and organic mat accumulation as the surface energy inputs are reduced. Vegetation growth may result in active-layer thinning and the trapping in permafrost of ice lenses formed at the base of the active layer, thus heaving the ground surface. However, this is not evident at lake basins that have very recently drained.

**Erosion Effect and Talik**

Data from the six boreholes indicate that the lake thermally eroded adjacent permafrost both vertically and laterally, promoting lateral expansion and vertical deepening of the water body. Vertical deepening was not monitored because the lake may have initiated 800 yr ago (Lin et al., 2014), and the present thermal state is approaching equilibrium, so the lake is now deepening slowly. However, the average lateral expansion was ~1.0 m/yr in 2006–2008 (Lin et al., 2010). Water depths above the 2 lake boreholes were 2.5 m and <1.0 m. The mean annual lake-bottom temperatures at boreholes 1 and 2 in 2006–2008 were ~5.5 and 4.3 °C (Lin et al., 2010, 2011c; Niu et al., 2011). Persistent year-round positive temperatures will eventually degrade permafrost completely.

The complete thaw of permafrost beneath the lake bottom may facilitate lake drainage through the talik. The cylinder- or hourglass-shaped talik was discussed in Burn and Smith (1990) and Niu et al. (2011). The talik shape was cylindrical in the east side and hourglass shape in west side of the lake (see Lin et al., 2011c, fig. 3 therein). Usually the presence of a permeable talik indicates that the lake will drain. However, the water body persists due to the low permeability of the underlying weathered mudstone substrate. The drainage of thermokarst lakes may affect local surface water budgets, ecosystems, and landscape stability. Thermokarst processes may also increase atmospheric CO₂ by exposing frozen organic matter to decomposition and have been linked to ecosystem degradation on the QTP (Yang et al., 2011). Thermokarst activity also contributes to increased winter runoff in large rivers in the region, and may affect groundwater tables as water is redistributed within the hydrologic system (Jin et al., 2009).

The complete permafrost degradation below the center of the lake occurred before 2006, but we do not know the exact timing. However, permafrost thawed completely at borehole 2 by 2008. Ground temperature and ALD were observed to decrease with distance from the lake. Field observations indicated that the depth of the permafrost table has changed significantly from the lake center to the shore (Lin et al., 2010). We expect that the permafrost base has also changed. However, boreholes 3–6 did not extend through the permafrost in 2006 and no field data demonstrated this effect before 2014. At borehole 2, the permafrost base changed considerably in 2006–2008 (Fig. 5), indicating that the lake has had an effect on the permafrost base, and allowed the talik to expand laterally. However, the vertical thermal erosion was greater than that in the horizontal direction.

**CONCLUSIONS**

This paper examined the development of a thermokarst lake in the Beiluhe Basin, and demonstrated the impact of the thermal disturbance on surrounding permafrost. The following conclusions were drawn based on a detailed examination over 9 yr of permafrost temperatures at 6 boreholes.

1. Thermokarst lakes on the QTP may initiate from disturbances such as changes in regional or site conditions, warming climate, and human activities.

2. The initiation and development of thermokarst lakes in the Beiluhe Basin on the QTP may be divided into four stages, initiation, development, stabilization, and termination.

3. Thermokarst processes included heat transfer in both vertical and lateral directions. The long-term thermal impact in the vertical direction accelerated the thaw of permafrost beneath the lake bottom, resulting in the formation of a through talik under the lake. Ground temperatures and the depth of the permafrost table decreased moving away from the lake center toward undisturbed values, highlighting the thermal effect of the lake in the horizontal domain.

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