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Key Points:
- We constructed statistically significant power-function regression equations to estimate lake volume based on DEMs derived from images
- We found the different results in 1999 and 2008 through compared the water supply rate before and during a GLOF
- Quickly released intermediate- and short-term water storage by glaciers probably will increase the risk of GLOF

Supporting Information:
- Supporting Information S1

Correspondence to:
Y. Ding,
dyj@lzb.ac.cn

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Quick Release of Internal Water Storage in a Glacier Leads to Underestimation of the Hazard Potential of Glacial Lake Outburst Floods From Lake Merzbacher in Central Tian Shan Mountains

Donghui Shangguan[1,2], Yongjian Ding[1,3], Shiyin Liu[4], Zunyi Xie[5], Tino Pieczonka[6], Junli Xu[1,7], and Bolot Moldobekov[8]

[1]State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China, [2]Department of Geography, University of Zurich, Zurich, Switzerland, [3]University of Chinese Academy of Sciences, Beijing, China, [4]Institute of International Rivers and Eco-security, Yunnan University, Kunming, China, [5]Centre for Biodiversity and Conservation Science, School of Earth and Environmental Sciences, University of Queensland, St Lucia, Queensland, Australia, [6]Institute for Cartography, Technische Universität Dresden, Dresden, Germany, [7]Surveying and Mapping Department, Yancheng Teachers University, Yancheng, China, [8]Central-Asia Institute for Applied Geosciences, Bishkek, Kyrgyzstan

Abstract Glacial meltwater and ice calving contribute to the flood volume of glacial lakes such as Lake Merzbacher in the Tian Shan Mountains of central Asia. In this study, we simulated the lake's volume by constructing an empirical relationship between the area of Lake Merzbacher, determined from satellite images, and the lake's water storage, derived from digital elevation models. Results showed that the lake water supply rate before Glacial Lake Outburst Floods (GLOFs) generally agreed well with those during the GLOFs from 2009 to 2012 but not in 2008 and 2015. Furthermore, we found that the combination of glacial meltwater and ice calving is not enough to fully explain the supply rate during GLOFs in 1996 and 1999, suggesting other factors affect the supply rate during GLOFs as well. To examine this further, we compared the water supply rate before and during GLOF events in 1999 and 2008. We inferred that quickly released short-term and intermediate-term water storage by glaciers have likely contributed to both flood events in those years. This study highlights the need to improve our understanding of the supply component of outburst floods, such as irregularly released stored water may lead to GLOF events with generally three different types: case I (singular event-triggered englacial water release), case II (glacier melt due to temperature changes), and case III (englacial water release mixed with glacier melt).

Plain Language Summary Glacial lake outburst is one of natural hazards related to glaciers. The glacier lake outburst flood (GLOF) of Merzbacher which almost occurs every year threatens lives, livelihoods, and infrastructure both in the mountains and downstream, posing myriad challenges for the communities. The regional warming leads to the increasing to supply for the Lake Merzbacher from Inylchek glacier. Importantly, quickly released intermediate- and short-term water storage by glaciers probably contributed to floods, which increase flood volume and lead to severe risk on the downstream socioeconomy.

1. Introduction

A growing body of evidence suggested that glacial lakes develop and expand during periods of glacier recession, particularly in the context of contemporary climate change (Bolch et al., 2011; Wang et al., 2013; Yao et al., 2010). Glacial lakes are common in High Mountain Asia and some pose a significant risk of lake outburst floods, which are one type of jökulhlaup (a subglacial outburst flood) (Iwata et al., 2002; Janský et al., 2010; Richardson & Reynolds, 2000; Zhang et al., 2015). Lake Merzbacher (42°13′N, 79°52′E, about 3250 m above sea level (asl)) is a glacial lake located in the Kumarik Catchment, in the upper reaches of the Aksu River (Figure S1 in the supporting information). Lake Merzbacher is composed of a lower lake and an upper lake which are connected by the Merzbacher River (Glazirin, 2010). The lower lake is an ice-dammed lake (Häusler et al., 2016; Merzbacher, 1905) that has produced a total of 62 recorded outbursts between 1932 and 2008, most of which occurred in July, August, and September (Shen et al., 2009). Such Glacial Lake Outburst Floods (GLOFs) can cause great damage to infrastructure and human populations surrounding the glacial lakes, including destruction of bridges and damage to agricultural and industrial land

(Wortmann et al., 2014). Large floods also stress local disaster relief funds (Jongman et al., 2014). Therefore, a scientific assessment of the status of glacial lakes and of their potential to trigger outburst floods is critical for adaptation to these hazards.

The cause of these sudden releases of water from the lower lake is still not well understood; however, researchers believe that release of the lake's water begins when the ice dam created by the advancing southern Inylchek Glacier floats upward, thereby opening a system of englacial channels within the glacier and releasing the water they contain (Wortmann et al., 2014). Rising air temperatures and thinning of the ice dam created by this glacier appear to be the two main reasons for outburst floods, and the peak discharge (Q_{max}) of the floods has increased as a result of climate warming (Glazirin, 2010; Ng et al., 2007).

Monitoring and assessment of potential glacial hazards are the key to their mitigation (Richardson & Reynolds, 2000). The timing, peak discharge (Q_{max}), and flood volume (V_t) of jökulhlaups are three key parameters that define a GLOF (Kingslake & Ng, 2013b; Liu, 1992; Ng et al., 2007) and are important for providing early warning of a flood and reduction of economic losses (Huggel et al., 2002; Osti et al., 2013). The duration of jökulhlaup flood discharges and the flood volume have been well simulated using numerical models (Kingslake & Ng, 2013b; Ng & Liu, 2009) and data from satellite images (Xie et al., 2013). However, despite these successes, it has proven difficult to predict GLOFs (e.g., GLOF in winter and GLOF with double peaks) that result from increasing temperatures, since these above mentioned approaches did not consider the englacial water storage.

Several methods can be used to estimate a glacial lake's storage volume, such as the stereophotogrammetry approach that has been used for Lake Merzbacher (Kuzmichenok, 1984); the development of an empirical formula for the maximum lake depth to simulate the volume of lakes in the Tian Shan Mountains (Konovalov, 1991), Swiss Alps (Huggel et al., 2002), and Bhutan (Osti et al., 2013); and the use of high-resolution echo sounder SONAR such as the SyQwest Hydrobox in the Tian Shan Mountains (Janský et al., 2010) and the Himalaya (Yao et al., 2012). The amount of water stored in and released from a glacial lake can also be used to calculate the peak discharge during an outburst flood and subsequent evolution of the flooding (Georgiou et al., 2009; Yao et al., 2012).

A numerical model that coupled a thermomechanically evolving subglacial channel, distributed cavity drainage, and basal sliding along a subglacial flood path was developed to model the flood discharge from Lake Merzbacher (Kingslake & Ng, 2013a). However, the model depended on an accurate assessment of the lake's volume, which was not available at the time of that study. Since the lake's basin is composed of ice, the subsurface ice melted and deformed as a result of regional warming, and these changes affected the behavior of the northern Inylchek Glacier (Sorg et al., 2012). The lake basin and lake volume both varied in response to these changes. Although the river discharge measured at the Xiehela hydrological station, 75 km downstream from the lake (Kingslake & Ng, 2013b; Ng et al., 2007), can be used to quantify the volume of released flood water, we lack adequate knowledge of the lake's volume (Wortmann et al., 2014). Field surveys are prohibitively difficult or expensive in most glacial areas and cannot be performed repeatedly at short intervals to assess changes in the lake area and volume, so a faster and more economical approach is urgently needed. Since there was relatively little water remained in Lake Merzbacher after a GLOF, we were able to survey the lake and determine its storage capacity by using ground mapping, remote sensing, and other tools (Fujita et al., 2013). Satellite observations with high-spatial resolution (e.g., SPOT-5 and ALOS) have been widely applied to obtain measurements of glacial topography (Berthier & Toutin, 2008; Uchiyama et al., 2008). Thus, remote sensing technique offers a promising approach that allows the development of a digital elevation model (DEM) that could be used to rapidly calculate lake volume. If satellite data with sufficient temporal resolution are available, this would potentially allow monitoring of the growth of lake volume by hypsometric analysis (Zhang et al., 2017) in real time and the prediction of GLOFs.

The initial lake volume, water supply rate, and water-equivalent calving flux (c) are three important factors that affect the flood volume (Ng & Liu, 2009). It is also useful to estimate the glacial meltwater supply to the lake during the flood event. In this study, we used the model of Ng et al. (2007) to estimate Lake Merzbacher's water supply. This model is based on the parameterization of a temperature index (see Text S1) (Ng & Liu, 2009). We defined the water-equivalent calving flux as a constant. No previous studies suggest that other factors contribute to the flood volume of Lake Merzbacher. However, the fact that the lake's outburst floods occur irregularly, sometimes even outside the expected summer period, indicates that other supply mechanisms probably exist; therefore, we compared water supply rates before GLOFs and during GLOFs in several years. Through this work, we found inference of another englacial supply source.

2. Data and Methods

Table S1 summarizes the satellite data that were the basis for our analyses of the lake's area. All DEMs were processed using version 2011 of the Leica Photogrammetric Suite (www.hexagongeospatial.com) (Shangguan et al., 2015) (Figure S6). The spatial resolutions of the DEMs (Table S1) were resampled to a common resolution of 30 m (by means of bilinear interpolation) based on the UTM WGS84 reference system. A coregistration to remove the horizontal and vertical offsets before differences analysis was used in this study (Nuth & Kääb, 2011). We used SPOT-5 high-resolution geometric DEM data combined with ALOS DEM data (to compensate for missing data in the two DEMs; see Text S2) to determine the lake's extent and to extract a DEM that would let us determine its storage capacity. We constructed a relationship between the lake's area and volume based on these data. Using the relationship, we calculated the lake's water supply rate and flood volume between 2008 and 2012 using a series of area changes derived from HJ1A/1B satellite images (Xie et al., 2013). We analyzed the water source for the flood volume and discussed possible causes of the flooding. The overall data analysis procedure is depicted by Figure S2 and the associated Text S2.

2.1. Relationship Determination Between Lake Area and Volume

The water storage capacity was expressed using an empirical relationship between surface area and volume (Huggel et al., 2002; Zhang et al., 2017). To provide this relationship, we analyzed the DEM data from the following data sets: the 1974 KH-9 (earthexplorer.usgs.gov), the 2000 SRTM (http://www2.jpl.nasa.gov/srtm/), and the 2008 SPOT/2006 ALOS DEM (see supporting information for details). We calculated the projected area, surface area, and surface volume by using the surface volume tool in version 9.3 of ArcGIS (http://www.esri.com/) relative to a given base height. We then generated an area-volume dependency curve (Figure 1). We constructed statistically significant power-function regression equations to estimate lake volume based on data from 1974 (Figure 1a), 2000 (Figure 1b), and 2008 (Figure 1c):

$$V_{1974} = 0.0153S^{1.1433} \tag{1}$$

$$V_{2000} = 0.0128S^{1.3584} \tag{2}$$

$$V_{2008} = 0.0160S^{1.4510} \tag{3}$$

where V represents the lake's volume (km^3) in the indicated year and S represents the lake's surface area (km^2). All three regressions were strong and significant ($R^2 > 0.94$, $p < 0.05$).

2.2. Extraction of Initial Lake Volume, Water Supply Rate, and Flood Volume From 2008 to 2012

We obtained the total lake area from Xie et al.'s study, which was conducted from 2009 to 2011 (Xie et al., 2013). In addition, we added the lake areas in 2008 and 2012 derived from satellite data (Table S1). The initial lake volumes were calculated by using equations (1) to (3), with the lake area close to the time of a GLOF in each year as the input parameter. On this basis, the initial lake volume between 2008 and 2012 ranged from 0.60×10^8 to 1.19×10^8 m^3. We calculated the mean water supply rate before a GLOF as follows (Ng & Liu, 2009):

$$Q_i = \frac{V_{i+1} - V_i}{t} \tag{4}$$

where Q_i represents the water supply rate (m^3 s^{-1}) between times i and $i + 1$, V_i and V_{i+1} represent the volumes (m^3) at times i and $i + 1$, and t represents the time interval between times i and $i + 1$.

2.3. Hydrologic Parameters Obtained From Field Observations

Our hydrologic data came from records obtained from Xiehela Station, which is located downstream of the lake (Figure S1). The peak flood quantity passing through the mouth of the Inylchek glacier differs from the Xiehela gauging station (41°34′N, 79°37′E, 1487 m asl) (Glazirin, 2010). This is because the discharge recorded

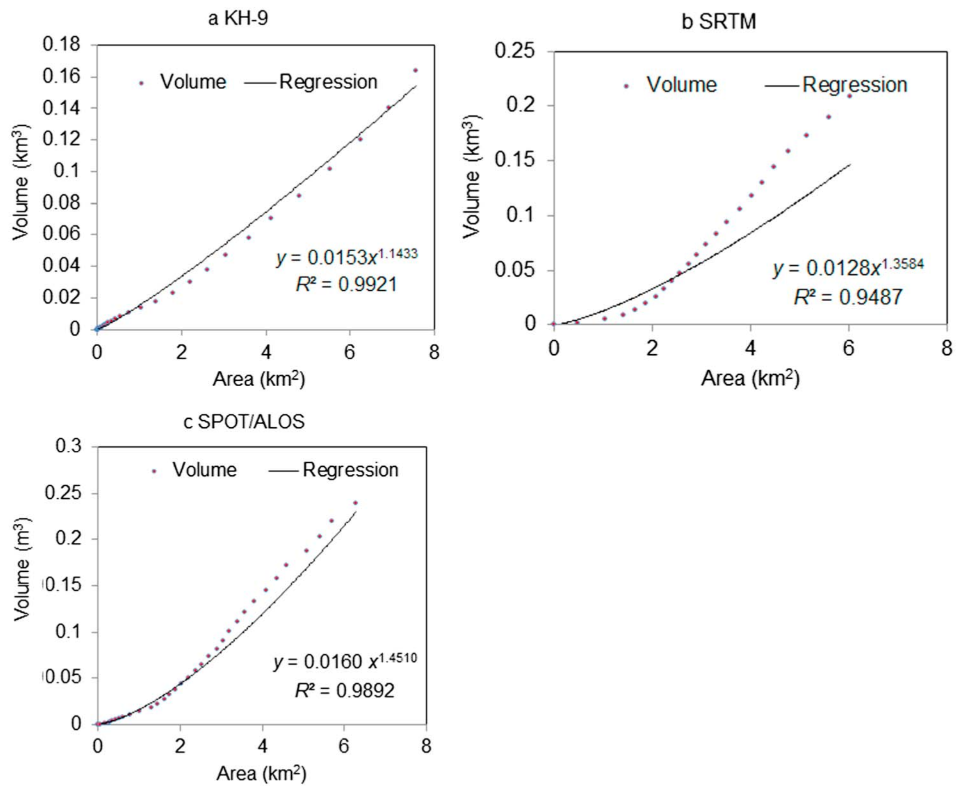

Figure 1. The relationships between the area and volume of Lake Merzbacher based on the analysis of three sets of digital elevation model data: (a) KH-9, (b) SRTM, and (c) SPOT/ALOS. All regressions were statistically significant ($p < 0.05$).

at Xiehela Station represents the combination of two components: the base flow and the quick flow that results from the released water (Fan et al., 2013); Figure S3 provides an example from 2005. The recession of the quick flow that results from flooding is fast and shows a steep curve, whereas the recession of the base flow is slow and gentle because of the different flow processes that cause that flow. We therefore used inspection of the flow curves (e.g., Figure S4) to separate base flow from the postrelease quick flow (Ng et al., 2007). Ng et al. (2007) proposed that the water supply rate combines the effects of precipitation, glacial meltwater, and ice supplements derived from glacier kinematics. Melt rates were observed to vary from 2.8 to 6.7 cm d^{-1} with a mean of 4.4 cm d^{-1} in 2005 (Hagg et al., 2008). In comparison with glacier melt, the maximum precipitation was 28.9 mm before the flood peak of the GLOF (Table S2); hence, the water supply rate from precipitation was less than glacier meltwater. Furthermore, precipitation during spring and summer accounts for 90% annual precipitation and the share of solid precipitation increases with altitude in Kumarik catchment (Aizen et al., 1997; Kundzewicz et al., 2015). Consequently, streamflow in a heavily glaciated catchment like the Kumarik catchment is controlled by temperature at daily, monthly, and seasonal scales since precipitation is stored in glacier and snow areas (Kundzewicz et al., 2015).We expressed the mean water supply rate during a GLOF as follows:

$$Q_j = \frac{V_f - V_h}{t} \tag{5}$$

where Q_j represents the mean supply rate during the GLOF (m^3 s^{-1}), v_f represents the flood volume observed at Xiehela Station (m^3), V_h represents the initial lake volume (m^3), and t represents the flood duration (s).

3. Results

3.1. Water Supply Rates

Figure 2 shows the mean water supply rates from area-volume changes before GLOFs between 2009 and 2012. The mean supply rates ranged between 4.0 and 60.0 m^3 s^{-1} (Figure 2). The maximum mean supply

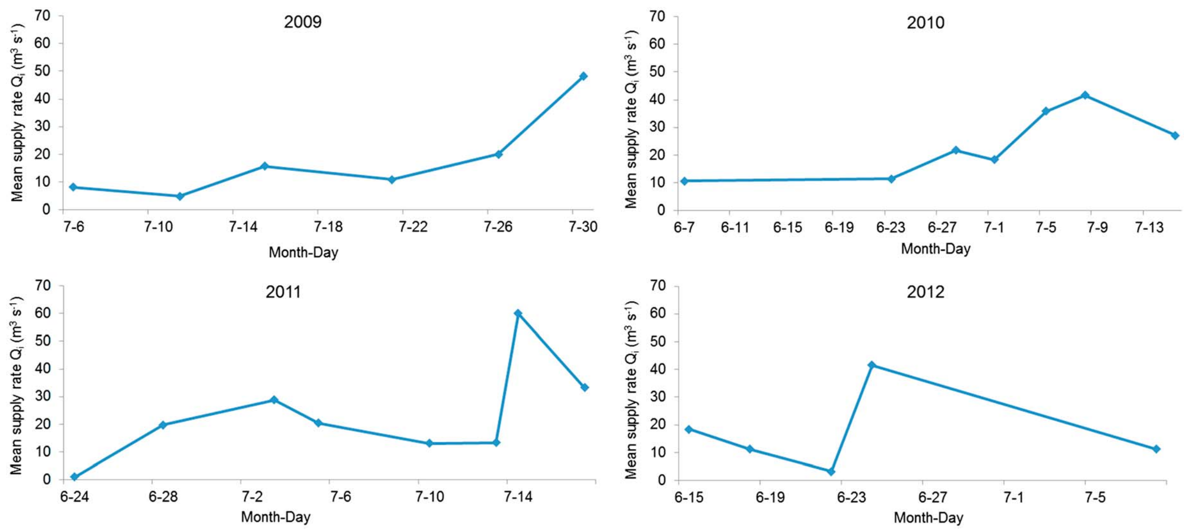

Figure 2. Mean water supply rates (Q_i) from 2009 to 2012 derived from formula (4).

rate before the GLOF derived from volume changes in 2008 was 30.9 m^3 s^{-1}, versus rates of 41 to 60 m^3 s^{-1} in the other years (Table 1). The supply rate during a GLOF could not be measured by using area-volume changes due to the opened englacial channels. Instead, we calculated the supply rate during a GLOF using the difference between flood volumes observed at Xiehela Station and initial lake volumes. The supply rates before a GLOF and during a GLOF were less than 70 m^3 s^{-1} from 2009 to 2012. However, the supply rate during the 2008 and 2015 GLOFs was larger than 200 m^3 s^{-1}, which is roughly 7 times that before the GLOF and between 3 and 4 times the maximum supply rate from 2009 to 2012. Thus, it is important to investigate why the supply rate during the 2008 and 2015 GLOFs was so large. These results suggest that other components contributed to the supply rate during the GLOFs.

3.2. Two Components of the Flood Volume Supply

Glacial meltwater and icefall (calving) are likely to be the two main components of the flood volume supply (Georgiou et al., 2009; Liu & Fukushima, 1999). To estimate variations in the water supply rate induced by temperature, we used the temperature index and degree-day approaches (Text S1), with data recorded at Tian Shan Station and reanalysis data as input parameters (Figures S1 and S4), since reanalysis data can make up for the deficiencies from Tianshan Station (Kalnay et al., 1996; Ng et al., 2007).

Table 1
Water Supply Rate (Q_i) and Flood Volume Derived From the Lake Volume Changes and Observations at Xiehela Station

			Water supply rate (Q_i, m^3 s^{-1})			Flood volume ($\times 10^8$ m^3)
	Lake area (km^2)	Initial lake volume ($\times 10^8$ m^3)	Maximum before the GLOF, derived from lake volume changes	During the GLOF, derived from the difference between flood volume at Xiehela Station and the initial lake volume	Duration (days)	Observation at Xiehela Station
2008	3.50	0.99	30.9	236.1–295.1	4–5	2.01/2.07[a]
2009	3.33	0.92	48.2	68.0	<8	1.39
2010	3.83	1.12	41.7	47.6	<9	1.49
2011	3.21	0.87	60.0	60.2	5	1.13
2012	2.41	0.57	41.5	46.3	<7	0.85
2015[b]	~3.0	0.79	43.1	>300	5	>2.1

[a]The value of 2.01 was observed at Xiehela Station, and the value of 2.07 was simulated by Kingslake and Ng (2013a). [b]The area was about 2.7 km^2 based on data from the China-Brazil Earth Resources Satellite (CBERS-04) on 22 July 2015. Based on data from the present study, we estimated that the area was about 3.0 km^2 at the beginning of the GLOF.

The results of this analysis suggested that the number of degree-days of positive temperatures after peak discharge were less than the number of degree-days of positive temperatures for the same number of days before the peak discharge in 1999, 2005, 2009, 2012, and 2015, even when we applied a 2 day time lag for the runoff from the lake to reach Xiehela Station (Table S3). The number of degree-days of positive temperatures after the peak discharge was slightly larger than the number of degree-days of positive temperature for the same number of days before the peak discharge in 2010 and 2011, although the difference was less than 3.0°C. Hence, according to our temperature-index model and our degree-day model (Text S1), the glacial meltwater supplied to the lake before the peak discharge was not larger than the water supplied to the lake after the peak discharge. Even if the temperature changed by 1.0 to 3.0°C, the supply rate changed by a maximum of 27.3 $m^3 s^{-1}$. The maximum water supply rates were 60.0 and 41.5 $m^3 s^{-1}$ in 2011 and 2012, respectively (Table 1). Hence, although we cannot get the exact supply rate, we can estimate the magnitude of the supply rate with less than a maximum of 87.3 $m^3 s^{-1}$.

Icefalls have been observed at the beginning of the filling of the lake, and the area of floating ice increased slightly during a GLOF (Xie et al., 2013) due to the ice dynamics, which added about 0.12×10^8 m^3 ice (7% of the estimated maximum lake volume) (Mayer et al., 2008). This indicates that the water-equivalent calving flux occurred mostly before a GLOF. Consequently, the water supply rate due to the calving flux did not vary greatly because the volume due to the water-equivalent calving flux was part of the initial lake volume in our calculations.

3.3. Water Storage by Glaciers

Water storage by glaciers includes short-, intermediate-, and long-term storage, which result from runoff within mountainous drainage basins at different time scales (Huss, 2011; Jansson et al., 2003). Long-term storage releases water from melting snow and ice in response to climate change. Intermediate-term storage reflects runoff characteristics such as internal water storage and subglacial storage, whereas short-term storage includes singular storage events that result from changes in melting conditions (Jansson et al., 2003). For example, englacial lake outburst floods and glacier surges commonly lead to long-term buildup of water storage followed by a short-term release. However, short-term and intermediate-term glacial storage have not been reported to be causes for outburst floods.

In this study, we derived short-term and intermediate-term water storage by glaciers from discharge records at Xiehela Station. There were two peak flood discharges in both 1999 and 2005 (Figures 3 and S3). In 1999, the first peak flood (1,940 $m^3 s^{-1}$) occurred on 19 July 1999, with a flood volume of about 0.171 km^3, followed by a second peak flood (2,100 $m^3 s^{-1}$) on 31 July 1999, with a flood volume of about 0.187 km^3 (Figure 3a). It was observed from Landsat ETM+ images (acquired on 25 July 1999) that Lake Merzbacher was filled with water; thus, the lake must have filled again between 20 and 29 July, after the first peak discharge, and then drained again. The average water supply rate of the second flood was 200 to 250 $m^3 s^{-1}$, which was like that in 15 July 2008. However, the temperature decreased by about 2°C during the period around the two floods (Figure 3b). After the second flood, the observed discharge at Xiehela Station remained larger than 1,000 $m^3 s^{-1}$ for several days. We also noted that after 13 August 1999, the discharge at Xiehela Station decreased quickly to a value near 350 $m^3 s^{-1}$, which is close to the base flow before the 19 July GLOF.

In 2005, two GLOFs events were also observed (Hagg et al., 2008), but the second peak discharge (1,040 $m^3 s^{-1}$ on 4 August) was smaller than the first one (1,840 $m^3 s^{-1}$ on 15 July) (Figure S3). The change in water level derived from field observations in 2005 was 0.5 m per day, after which a smaller jökulhlaup occurred (Mayr et al., 2014). In this second case, the water supply rate was less than 24 $m^3 s^{-1}$ based on the assumption that the lake area was 4 km^2. However, the 2005 supply rate was similar to those in 2009 and 2010.

Therefore, the supply rate during the 2008 and 1999 GLOFs differed greatly from that during the GLOFs in 2005, 2009, and 2010. Sources other than glacial meltwater and icefall, such as intermediate-term and short-term water storage by glaciers, must have contributed to the flood volumes in 1999 and 2008.

3.4. Uncertainties of the Initial Lake Volume, the Water Supply Rate, and the Flood Volume

The uncertainty of the lake area extraction was about 7% (Xie et al., 2013). The uncertainty of the lake volume derived from the relationship between lake area and volume (combined with the uncertainties in the DEMs)

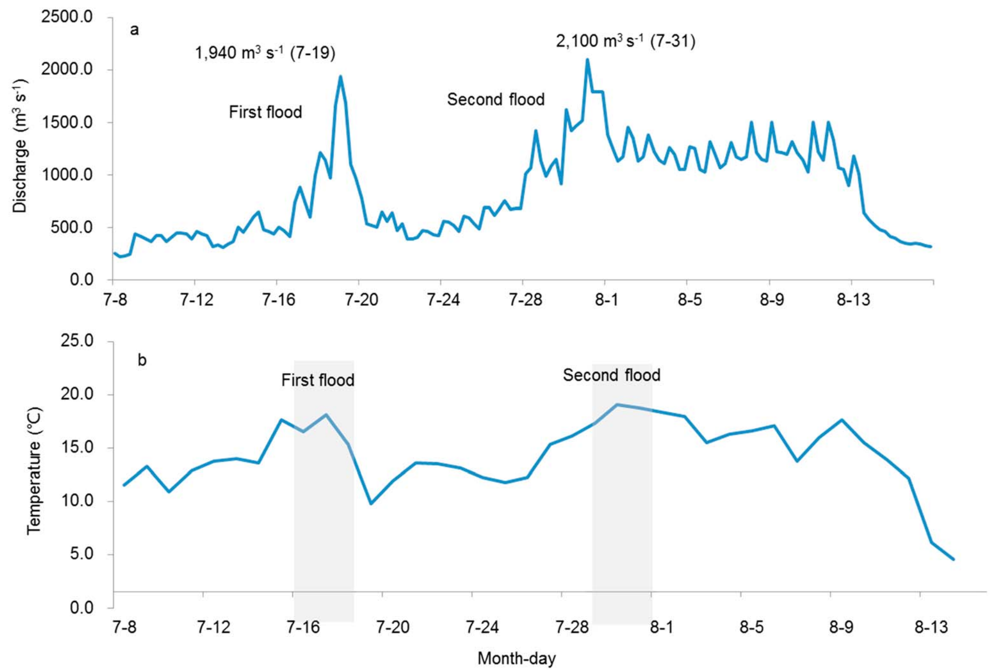

Figure 3. (a) Flooding in 1999 based on records at Xiehela Station, showing two peak floods. (b) Temperature records derived from the NCEP/NCAR reanalysis data set around the times of the two floods.

was about 2%. This, in turn, created an uncertainty of less than 8% in the water supply rate before the GLOFs. The uncertainty in the water supply rate during GLOFs came mainly from flood volume calculated by the graphical separation methods and from the initial lake volume; however, the HJ satellite passes over our study area at 2 day intervals, the images were acquired before the GLOFs. This will lead to estimation of a water supply rate during GLOFs that is lower than the real rate. Unfortunately, the magnitude of this error cannot be estimated based on our current knowledge. The initial lake area and volume in 2008 and 2011 were relatively accurate because the GLOFs occurred very close to when the satellite images were acquired.

4. Discussion and Conclusion

The combination of remotely sensed data of KH-9, SRTM, and SPOT-5/ALOS DEMs provided a good source for estimation of the storage capacity of Lake Merzbacher in 2000 and 2008. Based on the DEMs, we constructed a relationship between the lake's area and volume and used the relationship to derive the lake's water supply rate. In this study, we directly used the change in lake volume to calculate the water supply rate which has the advantage to include the effects of glacial meltwater, precipitation, and calving of ice. Our results showed that the mean water supply rates were 40–60 m^3 s^{-1} with a maximum of 87.3 m^3 s^{-1} due to climate and ice-fall, which is agreement on ~31 to 52 m^3 s^{-1} owing to glacier melting during summer (Mavlyudov, 1995). In addition, we also obtained some large mean supply rates at 200–300 m^3 s^{-1} during GLOFs, such as in 1999, 2008, and 2015.

The GLOFs from Lake Merzbacher were triggered by a gradual increase in the summer air temperature (Ng et al., 2007) that affected melting of the ice lake dam created by the southern Inylchek Glacier (Wortmann et al., 2014). Although there is lack of sufficient precipitation data for a thorough analysis, we were able to obtain precipitation data from the Tianshan Station (78.2°N, 41.9°E, 3614 m asl; Table S2). The precipitation before and after the peak flood were less than 15 mm in all years except 1999. Between the two peaks in 1999, the precipitation was 8.8 mm. The precipitation was about 1 mm during the 2008 GLOF, of which the low amount suggests that the precipitation had little effect on the GLOFs. As a result, we ruled out variability in the water supply rate due to variability in precipitation as a major factor.

The northern Inylchek Glacier surged 3.5 km in late 1996 and early 1997 (Häusler et al., 2011, 2016). Although there were lack of satellite images from that time, a high peak discharge (about 825 $m^3 s^{-1}$) observed at Xiehela Station on 5 December 1996 agreed with the reported surge dates. Regardless of whether the glacier surge triggered the 1996/1997 GLOF, the flood volume (0.284 km^3) was found to be more than the maximum lake volume storage (0.120 km^3). The total precipitation and mean daily temperature were 2 mm and −20.2°C at Tianshan Station in December 1996. This low precipitation suggests that the change in the water supply caused by climatic factors was less important than other factors. In contrast, glacier movement would lead to englacial melting and release of englacial water storage (Bartholomaus et al., 2008; Burgess et al., 2013; Lingle & Fatland, 2003; Mayer et al., 2008). Therefore, the observed supply rate should be resulted from more than meteorological factors (melting due to temperature increases, precipitation) and icefall (calving); it must also have been resulted from changes in englacial water storage.

The key finding from the present study is that the supply rates in 2008 and 2015 (larger than 200 $m^3 s^{-1}$ in both years) differed from those in 2009 and 2012 (less than 70 $m^3 s^{-1}$). The events in 1999 and 2005 were also different in having double peaks in both years. Furthermore, glacier surges in 1996 released more than 0.284 km^3 water, which were recorded by the flood discharges observed at Xiehela Station. Because of the limited availability of remote sensing data, we can only analyze GLOFs in several representative years. Although our hypothesis about the water source is based on relatively limited data, our results suggest the importance of englacial water release during GLOFs. Therefore, we believe that both short-term and intermediate-term storage water contributed to the observed GLOFs from Lake Merzbacher, in addition to the contributions of glacial meltwater and icefall (calving) to certain flood events. However, we need further investigation to verify this finding in future. The irregular frequency of releases of short-term and intermediate-term storage water may explain why the outburst floods are unpredictable. At present, it is hard for us to simulate the volume of the englacial water release when the flood volume also includes this additional form of water release. In addition, we cannot determine the conditions under which the sudden floods are accompanied by a release of englacial water. Future studies are needed to improve these issues.

Based on our results, we can categorize the GLOF events into three general distinct types: case I (singular event-triggered englacial water release), case II (glacier melt due to temperature changes), and case III (englacial water release mixed with glacier melt) in Figure S5. In case I, the flood volume in 1996 resulted from a combination of glacier surges and the release of englacial water storage along with icefall, precipitation, and glacier melting. In case II, for the flood events in 2005, 2009, and 2010, the flood volume observed by remote sensing agreed with observations at Xiehela Station. In this case, the flood volume mainly resulted from melting of the glacier caused by high temperatures. In case III, the flood volumes in 1999, 2008, and 2015 were more complicated to estimate: the response of glacial meltwater to climate change (e.g., temperature rise) is one reason, but the release of short-term and intermediate-term storage water by the glacier was another. Both cases (I and III) included the release of stored englacial water and caused more irregular GLOFs with large flood volumes that are difficult to predict. Therefore, it will be necessary to improve our understanding of the processes that occur within and under the glacier before we can better predict their effects on GLOFs.

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