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Water storage and drainage of short-lived lakes in the Teskey Range, Central Asia

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Abstract. In the Teskey Range of the Tien Shan (Kyrgyz Republic), four outburst flood disasters from short-lived glacial lakes caused severe damages in the downstream part in 2006, 2008, 2013, and 2014. The short-lived lake grows rapidly and drain within a few months, due to closure and opening of an outlet ice-tunnel in moraine complex at glacier front. The outburst flood of this lake type is a major hazard in this region, it differs from many cases of moraine-dam failure in the eastern Himalaya. To clarify how short-lived lakes store and drain water for short period, we examined its recent changes in water level, area, volume, and discharge with a field survey and satellite data analysis. Korumdu lake appeared and drained within about one month during all summers during 2014–2019 except that in 2016. Water-level data recorded by a data logger and time-lapse camera images show that the lake appeared and expanded suddenly from July to August in 2017–2019. The timing indicates that the lake formed when an outlet ice-tunnel (subsurface channel) drain was blocked by deposition of debris and ice due to ice melting, not by freezing of stored water. Based on calculation of UAV DSMs and water level in 2017, the lake's water volume reached 234,000 m^3 within 29 days, and then the water discharged for 17 days at a maximum rate of 0.66 m^3/s. The small discharge indicates that the diameter of the outlet ice-tunnel was much smaller than those of four short-lived lakes in the same range that caused large drainages (12-27 m^3/s) in 2006, 2008, 2013, and 2014. As the results, the dimensions of the outlet ice-tunnel of short-lived glacial lakes presently are related to the flooding scale. Recent warming temperatures may increase both the size of the tunnels and the basin volumes leading to greater hazard from such lakes in the future. In addition, we investigated the timing of appearance of 160 short-lived glacial lakes in this region using Landsat-7/8, Sentinel-2, and PlanetScope satellite images (2013–2018). We conclude that tunnel closure of 117 lakes was due to deposition of debris and ice during summer. The appearance of a short-lived glacial lake is inevitable in summer when the melting rate is high. The characteristics of this lake type might be shown in another Asian mountain permafrost regions.

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1 Introduction

Compared to the large proglacial lakes in the eastern Himalayas (Ageta et al., 2000; Komori et al., 2004; Bajracharya et al., 2007; Nagai et al., 2017), the northern Tien Shan, Central Asia region instead has many small glacial lakes that are distributed at glacier fronts (Janský et al., 2008; Narama et al., 2010; 2015). Drainage events from these small glacial lakes often produce debris flows and floods. For example, debris flows in 2006, 2008, 2013, 2014, and 2019 in the Teskey Range, northern Tien Shan, caused severe damage including casualties and destroyed bridges, roads, houses, and crops (Narama et al., 2010, 2018; Daiyrov et al., under review). Such short-lived glacial lakes grow rapidly and drain within a few months (Narama et al., 2010, 2018; Daiyrov et al., 2018). In the Tajik Pamir, drainage from a short-lived lake that formed within 2 years resulted in 25 casualties (Mergili et al., 2012). Such lakes drain through an outlet ice-tunnel (subsurface channel) within an ice-cored moraine complex (Popov, 1987), and are also called nonstationary lakes (Erokhin et al., 2017), though this term also includes lakes with a long lifetime. A short-lived lake can be a severe hazard for local residents because it appears suddenly yet can cause large debris flows. The short-lived lakes are a major hazard in this region, and this differs from the outburst which caused by moraine-dam failure in Himalaya and Andes (Costa and Schuster, 1988; Richardson and Reynolds, 2000; Shreshta 2010; Emmer and Cochachin, 2013; Neupane et al.; 2019).

As such glacial lakes drain through an outlet ice-tunnel, the lake can expand rapidly when the outlet ice-tunnel is blocked due to either freezing or deposition of ice and debris (Narama et al., 2010, 2018). Drainage then occurs when the outlet ice-tunnel opens during summer. Some short-lived glacial lakes reappear every year (Daiyrov et al., 2018), which is behavior they share with supraglacial lakes on a debris-covered glacier. Several studies have examined the relationship between supraglacial lakes and englacial conduit on a debris-covered glacier (Benn et al., 2000, 2017; Miles et al., 2016; Watson et al., 2016; Narama et al., 2017), but this relationship has seen little study for glacial lakes.

Short-lived glacial lakes appear at depressions formed due to glacier recession or the subsidence of either an ice-cored moraine complex (Narama et al., 2010, 2018; Daiyrov et al., 2018) or on a depression formed on a surging glacier (Richardson and Reynolds, 2000; Kääb et al., 2004). Narama et al. (2018) showed that such short-lived glacial lakes tend to appear with three geomorphological characteristics: 1) an ice-cored moraine complex (debris landform containing ice), 2) a depression with a water supply on an ice-cored moraine complex or glacier terminus, and 3) the absence of a visible surface outflow channel from the depression, indicating the existence of an outlet ice-tunnel.

Previous studies have argued that the recent expansion of glacial lakes in the Tien Shan is linked to climatic warming and glacier shrinkage (Bolch et al., 2011; Wang et al., 2013; Kapitsa et al., 2017). In addition, Daiyrov et al. (2018) showed that the large variability of glacial lakes was not only related to the local climate condition in the Issyk-Kul Basin, but also to regional geomorphological conditions such as the closure and opening of an outlet ice-tunnel. They also pointed out that ice-cored moraine complexes have developed under mountain permafrost conditions. Ice degradation within such complex results in moraine formation (Iveronova, 1952; Markov, 1955). Surface changes on an ice-cored moraine complex were confirmed in the Jeruy Glacier front between 1979 and 2016 due to ice melting (Daiyrov et al., 2018), and such changes likely affect the outlet ice tunnel and formation of the depressions.

As changes can occur over very large areas and volumes in a short period of time, drainage features and flood scale are extremely unpredictable (Erokhin et al., 2017). Although many short-lived glacial lakes are confirmed in recent years in the northern Tien Shan (Daiyrov et al., 2018), not all short-lived glacial lakes cause large-scale floods. The difference of flood scale remains unclear. A lake's fate depends on whether the dam contains ice (Mergili et al., 2013), and if so, how the outlet ice-tunnel closes and opens. However, the mechanisms of closure and drainage remain also unclear. Such hazards can intensify dramatically and unexpectedly within weeks or even days (Huggel, 2004). In this study, we predict mechanisms of closure and drainage at the Korumdu lake and the reason of different flood scales from shot-lived lakes based on field survey and satellite data analysis. These new knowledges are important for glacier disaster mitigation.

The paper is organized as following. To understand the closure and drainage mechanism of the short-lived lake, we investigated the recent changes in water level, area, volume, and discharge at Korumdu lake based on field survey and satellite data. The Korumdu lake appeared and drained within about one month during all summers in recent years. To clear the reason how the outlet ice-tunnel closes in the Korumdu lake, we examined the surface changes around the Korumdu lake in field survey. To clarify how the other short-lived lakes store and drain water, we investigated the timing of appearance of short-lived lakes for the other lakes in this region were studied in 2015–2019 using Landsat-7/8, Sentinel-2, and PlanetScope satellite images. Finally, we discussed the reason of outlet ice-tunnel closure at Korumdu lake including other lakes, and the relationship between outlet tunnel size and drainage scale including influence of increasing temperature.

2 Study area

The study area is in the northern part of the Teskey Range and near the south shoreline of the Issyk-Kul Basin, Kyrgyz Republic (Fig. 1). The glacier distribution in the western part of the range (3700–4200 m) is lower than the distribution in the eastern part (3800–4500 m). The difference is related to differences in annual precipitation, which is higher in the eastern part than in the western part. For example, during 1998–2007, the average annual precipitation at the Kara-Kujur station (2800 m) of the western part is 255 mm, whereas that at the Tien Shan station (3614 m) of the central part is 378 mm, and that at the Chong-Ashu station (2788 m) of the eastern part is 550 mm (Podrezov and Ryskal, 2019; Fig. 1). Their annual average temperatures are 0.1°C (1961–1988), –6.28°C (1995–2011; Kuzmichenok, 2013), and 0.27°C (1995–2005), respectively. Recent glacier shrinkage has been smaller in the western than the eastern part of the Teskey Range (Aizen et al., 2006; Narama et al., 2006; Kutuzov and Shahgedanova, 2009).

The glacier-moraine zones of the study area in the northern Teskey Range lie at 3200–4000 m (Daiyrov et al., 2018). Within these zones, the ice-cored moraine complex (debris landform including ice) at the glacier front developed during the Little Ice Age (Dikih, 1982; Shatravin, 2007). The moraines include stagnant ice that separated from the glacier terminus during glacier recessions (Iwata, 2005). Four large drainages occurred from short-lived glacial lakes that appeared on the ice-cored moraine

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complex; specifically, from Kashkasuu (2006), west Zyndan (2008), Jeruy (2013), and Karateke (2014) (Narama et al., 2010, 2018).

We ran a field survey at Korumdu lake (41°57′32″ N, 77°13′28″ E) at 3803 m (Figs. 1, 2). The Korumdu catchment forms the largest tributary in the Tong River Basin. The Korumdu glacier occupies an area of 2.35 km^2. The dam of Korumdu lake is an ice-cored moraine complex. The lake has direct contact with the glacier. In addition, we investigated the timing of appearance for 160 short-lived lakes in this region (Fig. 1).

3 Method

3.1 Field observations at Korumdu lake

The field survey at Korumdu lake was run during the summers of 2015–2019 (Figs. 1, 2). The survey involved measuring the water level and water temperature at the lake bottom with a data logger (Hobo U20) at an interval of 1 h since 21 Aug 2015. We also set water-level data loggers (Hobo U20) at lake bottom (water pressure) and ground levels (atmospheric pressure). Water-level logger measurements were corrected to water level (meter) using atmospheric pressure data at the ground. A time-lapse camera (Brinto) was also set with an interval of 1 day.

In addition, we obtained aerial images of Korumdu lake-basin acquired by Phantom-4 (DJI) and JABO H601G (Medix) unmanned aerial vehicles (UAVs) with a mounted camera (Ricoh GR) on 21 Aug 2015, 12 Aug 2016, 6 Aug 2017, 20 July 2018, and 4 Aug 2019. High-resolution orthoimages and digital surface models (DSMs; resolution of 0.2 m) were made using the Pix4D mapper (Pix4D SA) of Structure from Motion (SfM) software with ground control points (GCPs). We obtained the GCPs around the lake using the Trimble GeoExplore 6000 Global Navigation Satellite System (GNSS). The absolute positions were accurate to 30–40 cm at GCPs positions by post-processing with data from the Kyrgyz GNSS reference station. We also investigated the surface changes in an ice-cored moraine complex around the lake by comparing DSMs obtained in 2015 and 2016 on ArcGIS 10.5.

The volume and discharge of the lake in the summers of 2017–2019 were calculated using the daily water level data, UAV DSMs, and time-lapse data on ArcGIS 10.5. The daily volume was calculated based on the 2016 DSM (without water), combined with the DSMs of other years (including amount of glacier recession). We found that the water-level logger measurements agreed with the water levels that were reconstructed from time-lapse camera data based on UAV DSMs. Using the same method, we also reconstructed the water level data between August 4 and 31 based on 10 satellite images from PlanetScope, Landsat-8/Operational Land Imager (OLI), and Sentinel-2 along with UAV DSMs, because we visited at the lake on 4 August 2019. We also investigated the changes in lake area during 2017–2019 using PlanetScope images.

Finally, we examined the climatic and thermal conditions using air and ground temperature data loggers (TR-52i; T&D Co.; resolution accuracy within ± 0.3°C) to log data at 1-hour intervals around the lake. Mean annual air temperature (MAAT) and mean annual ground surface temperature (MAGST) were calculated for 2016–2017.

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3.2 Timing of appearance of short-lived lakes using satellite data

Short-lived glacial lakes were identified using satellite images on ArcGIS 10.5. In particular, 91 images from Landsat-7/Enhanced Thematic Mapper Plus (ETM+, SLC-off) and Landsat-8/OLI, 31 images from Sentinel-2, and 16 images from PlanetScope acquired during 2013–2018. The resolutions of these images are 15 m (pan-sharpened images of Landsat-7/8), 10 m (Sentinel-2), and 3 m (PlanetScope). As a definition of short-lived lake, we use that in Daiyrov et al. (2018), which is based on its seasonal change in area from June to September of each year. Specifically, a short-lived lake is a temporary lake, lasting just one or two years, that appears or doubles in area, then disappears or shrinks within the same year. We counted the number that appeared from June to September each year. In addition, the number was tracked in each given year to examine how it changed from one year to the next. Polygon shapefiles of lakes were extracted manually from the images using ArcGIS 10.3.

4 Results

4.1 Areal variations of Korumdu lake

At the front of the Korumdu glacier lies the Korumdu glacial lake (Fig. 2). It sits in a basin that formed during glacier recession. The basin developed inside an ice-cored moraine complex. Although most of the basin area had been covered by the Korumdu glacier, based on ALOS/AVNIR-2 data taken on 17 September 2007, the UAV ortho-images indicated a basin length of 360 m, a width of 110 m, with total area of 0.062 km^2 in 2019. The basin volume increased from 264,000 m^3 in 2017 to 330,000 in 2019 (Fig. 2) due to retreat of the glacier terminus. In the field, we observed ice ridging and debris sliding on the slope of the basin, indicating that the ice was melting from around the shore, thus increasing the width of the basin.

The lake had no discernable surface drainage channel, but we found an outlet point (Fig. 2). The existence of the outlet shows that lake water flows through an outlet ice-tunnel from the lake. The length of the outlet ice-tunnel is 60 m from the entrance of the basin. Drainage water was observed at the outlet point in 2015, 2017, and 2019, but not 2016 and 2018.

Concerning size changes, in 2015, the lake appeared in July, becoming large on 30 July, then shrank significantly by 21 August (Fig. 3). For 2017–2019, a more complete story of the changes appears in the images in Fig. 4, which are based on PlanetScope satellite data. The images show that the lake appears suddenly at the end of July to the beginning of August and then shrinks and vanishes by the end of August (Fig. 4a–c). Although the timing of lake expansion differs slightly over the years 2017–2019, the lake always appears in summer. These satellite data demonstrate that the lake is a short-lived glacial lake.

The time-lapse on-site images show the same behavior from a different view (Fig. 5). These images also indicate that the lake began to expand from mid-July and reached its maximum level at some time between late July and early August. In contrast, the lake area did not change dynamically in 2016. Based on Landsat-8/OLI data, we also found that the lake appeared in 2014 (May 5, June 27, and September 10). Although these images show rapid drainage, we did not find evidence that the drainage caused flooding during the survey period. According to data in Narama et al. (2018), drainage from Korumdu lake is the flood-wave type in the downstream region because the water stream flows on a gentle slope.

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4.2 Changes in water level, area, volume, and discharge of Korumdu lake

Consider the properties of Korumdu lake from 2017 to 2019. Figure 6 shows the measured water level, lake area and volume, and inflow–outflow discharge. For 2017, we also show the water temperature (Fig. 6a). We also reconstructed the water level data between August 4 and 31 based on 10 satellite images (yellow points in Fig. 6a). We calculated volume and discharge using the water levels and the UAV DSMs.

In 2017, the water level starts increasing from 6 July, reaching a maximum on August 3, and then vanishes on 19 August (Fig. 6a). In the first 29 days, the lake level increases 13 m, the volume reaches 234,000 m^3, and the area reaches 0.36 km^2 (Fig. 6a–c). The resulting rate of volume increase was 8,070 m^3/day. During discharge, 234,000 m3 of water drains in 17 days, with half of the volume draining from 3 to 7 August 2017 (Fig. 6b) resulting in a maximum outflow discharge of 0.66 m^3/s (Fig. 6d). Although the water level increases intermittently before August 3, the outflow is relatively smooth. The lake water temperature averaged about 1°C.

In 2018, the water level peaks three times (Fig. 6a). The first, on 25 July, reaches 3.5 m and a volume of 21,000 m^3 (Fig. 6a,b). The second, the yearly maximum, on 11 August, reaches 6 m and a volume of 53,000 m^3. Finally, the third peak, on 17 August, reaches a level of 5 m and a volume of 39,000 m^3. The maximum discharge occurs after the second peak, reaching 0.32 m^3/s (Fig. 6d). Compared to the case in 2017, the maximum lake level and volume are much smaller in 2018. However, like that in 2017, the inflow rate is also intermittent in 2018. The three peaks indicate that closure of the tunnel occurred several times during the 1-month period.

In 2019, the water level goes up and down until 22 July, when it rises sharply (Fig. 6a). Then the level has a local maximum on 30–31 July, reaching 5 m and a volume of 53,000 m^3, followed by a yearly maximum on 11 August, reaching 6.5 m and 74,000 m^3 (Fig. 6a,b). The maximum discharge occurs right after the second peak, reaching 0.24 m^3/s (Fig. 6d).

Considering all three years, the maximum water level is highest in 2017 (Fig. 6a). Over these years, other differences include the timing of the lake-level increases, the number of peaks, and the maximum water volume. All three years had small discharge rates (maxima of 0.66, 0.32, and 0.24 m^3/s in 2017, 2018, and 2019), consistent with the lack of reported flooding.

Concerning fluctuations, according to the water level data for 2017–2019, the level increased with repeated storage–drainage cycles. In the field, we observed sudden small increases of water level in 2016 and 2017, with the level increasing tens of centimeters within 3 h (Fig. 7). These results indicate that water level fluctuations occurred frequently due to closing and opening of the outlet ice-tunnel.

We observed drainage water at an outlet point in 2015, 2017, and 2019, but not in 2016 and 2018. The reason we argue is due to the relative elevations. The water levels were 3,810 m on 21 Aug 2015, 3,816 m on 6 Aug 2017, and 3,810 m on 4 Aug 2019, all of which are higher than that of the outlet point at the basin. However, we did not observe water drainage in 2016 and 2018 because the water levels were 3,806.5 and 3,807.5 m, respectively (Fig. 8a,c). These results indicate that the entrance of the outlet ice-tunnel at the basin is at approximately 3,807.5 m, water level too low for drainage.

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4.3 Surface changes around Korumdu lake

Over a period of one year, how does the region near the entrance of the outlet ice-tunnel change? To answer this question, we compared UAV orthoimages with DSM data in 2015 and 2016 (Fig. 9). A comparison of Fig. 9a,b shows debris sliding, with horizontal backwasting of an exposed ice ridge by 7 m. The backwasting indicates melting occurred, which is supported by the UAV-derived DSMs in Fig. 9c. In particular, along the profile (a–a′; Fig. 9b) of the landform between 2015 and 2016, the surface elevation decreases by about 5 m. These results indicate that the surface motion and deposition of debris can cause closure of the outlet ice-tunnel during summer.

In the northern part of the Teskey Range, the mountain discontinuous permafrost zone lies above 3,100–3,200 m (Daiyrov et al., 2018). Around Korumdu lake, the mean annual air temperature (MAAT) in 2015–2017 was –4.8°C and the mean annual ground surface temperature (MAGST) in 2015–2019 was –2.9°C. Thus, the buried ice of the ice-cored moraine complex at Korumdu lake is maintained under a permafrost environment. Melting of buried ice causes surface changes including expansion of the lake basin. In addition, melting can lead to closure of an outlet ice-tunnel such as that for a supraglacial lake on a debris-covered glacier (Sakai et al., 2000; Benn et al., 2000; Miles et al., 2016; Watson et al., 2017).

4.4 Comparison to other short-lived lakes in the area

Korumdu lake appeared during July–August and had relatively little drainage, whereas four other short-lived lakes that appeared in May–June caused large drainages and serious damages (Narama et al., 2010, 2018). The different appearance times might reflect different processes causing tunnel closure. To help determine how common these appearance times are, we investigated the timing of appearance of short-lived lakes in the northern part of the Teskey Range from June to September during 2013–2018 using Landsat-7/8, Sentinel-2, and PlanetScope satellite images.

We identified and examined 160 such short-lived lakes during 2013–2018 (the total includes re-appearances of the same lake in different years) in the study area. In Fig. 10, we classify these by month of appearance. The appearance months with the most lakes are June, the snow-melt period, and July, the ice-melt period; specifically, 43 lakes in June and 90 in July. The total numbers and the proportions of the numbers in these two periods varied during the 6 years. This large variability was not directly related to local climate change (Daiyrov et al., 2018).

Concerning re-appearances, 81 lakes appeared only once for 6 years. Of the remaining, 19 appeared twice, 7 appeared 3 times, 2 appeared 4 times, and 2 lakes appeared all 6 years. indicating that tunnel closure occurred with a different month each year. Short-lived lakes that reappear many years likely have a tunnel condition in which closure occurs easily.

5 Discussion

5.1 Cause of outlet ice-tunnel closure at Korumdu lake

In the case of ice tunnel closure, the supraglacial lakes on the debris-covered southern Inylchek Glacier in April–May are likely to appear due to the closure of englacial conduits when stored water freezes (Narama et al., 2017). The closure of englacial conduits on a debris-covered glacier can be due to roof collapses, creep closure, freezing of stored water, or deposition of ice and debris (Gully and Benn, 2009; Narama et al., 2017). Collapse of an outlet ice-tunnel wall in a debris-covered glacier can occur by thermal and mechanical erosion (Sakai et al., 2000; Roberts, 2005; Bjornsson, 2010) or by ice deformation (Clague and O'Connor, 2015).

For comparison, in the study region, the outlet ice-tunnel blockages could be caused by the freezing of stored water during winter or by blockage by collapsing with deposition of mixed debris and ice (Popov, 1987; Narama et al., 2010, 2018). In addition, changes in the ice-cored moraine complex due to subsidence or downwasting might cause a blockage in an outlet ice-tunnel (Daiyrov et al., 2018). The short-lived lakes here that caused the four large drainages (2006, 2008, 2013, and 2014) appeared in May–June and expanded in June–July (Narama et al., 2010, 2018). The timing suggests a closure that is caused by the freezing of stored water during winter or ice-debris deposition (Fig. 11a). We call this the deposition–freezing type. However, no case was reported in which the tunnel condition and water level fluctuations were compared in detail.

In the case of Korumdu lake, the tunnel closed in July–August of every year since 2014 (excluding the case of no expansion in 2016) based on water-level of a data logger and time-lapse camera images. As we observed changes in the basin on the ice-cored moraine complex caused by subsidence or downwasting (Fig. 9), the blockages of the outlet ice-tunnel at its entrance or interior likely was caused by deposition of ice and debris due to thermal erosion. This type of blockage is sketched in Fig. 11b. Further evidence that Korumdu lake forms by the deposition process comes from consideration of water-level fluctuations. The fluctuations of water level, such as spikes, reveal changes in the tunnel condition (Fig. 6d). A sudden blockage of an outlet ice-tunnel can cause a rapid increase in water level within even a few weeks. For Korumdu lake, the water increase was sporadic, indicating that the outlet ice-tunnel was not completely closed, the blockage was temporary, and the size of the ice tunnel is quite small. As a result, lake drainages can also occur any time in summer, depending on how the outlet ice-tunnel responds to the water pressure or thermal erosion.

In 2017, the trend of water volume increase consisted of two parts: 5 to 25 July and 26 July to 3 August (Fig. 6b). The first period had sporadic fluctuations, indicating incomplete closure of the tunnel, but the second period had a smooth increase, indicating complete closure. The lake area reached its maximum value in 2017. This indicates that the period of tunnel closure was longer in 2017 than in 2018 or 2019. Longer closure periods are associated with the formation of larger short-lived lakes (Narama et al., 2018). Thus, the period of closure might be determined by the condition of the tunnel.

Many of the other short-lived lakes that also appear in the ice-melting period are likely to be the deposition–closure type, for the same reasons we applied to Korumdu lake. For example, in Fig. 12, we show surface changes in the outlet ice-tunnel at the Jeruy glacial lake between 2014 and 2016. Ice melting caused large changes and rapid deposition within the outlet ice-tunnel, making closure likely. Thus, the surface condition always changes on an ice-cored moraine complex within the mountain permafrost zone, and the deposition–closure type is the major type in this region. Thus, the appearance of a short-lived glacial lake is inevitable in summer when the melting rate is high. The characteristics of this lake disaster might be shown in another Asian mountain permafrost regions.

5.2 Relationship between outlet tunnel size and drainage scale

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Of the 160 short-lived lakes we identified in 2013–2019, only Jeruy lake (in 2013) and Karateke lake (in 2014) had large drainages. The estimated maximum discharges from Jeruy (182,000 m^3) and Karateke (123,000 m^3) lakes were 14.9 and 11.5 m^3/s, respectively (Narama et al., 2018). These lakes had relatively large outlet tunnels, with Jeruy's cross-section being 4 x 2 m^2 (Fig. 12a,b) and Karateke's about the same or larger (not shown). Earlier, back in 2008, the w-Zyndan lake of 437,000 m^3 had a discharge rate of 27 m^3/s (Narama et al., 2010). Most of the water in these three cases drained over a period of several hours. In contrast, Korumdu lake did not have a large drainage in 2014–2019, and its tunnel cross-section was much smaller than those of Jeruy or Karateke lakes. For example, in 2017, 234,000 m^3 drained from the lake over 17 days, with a maximum discharge rate of 0.66 m^3/s, about 20 times smaller than that of the two large drainages of Jeruy and Karateke.

In addition, with Korumdu lake we observed sudden fluctuations of water level over several hours, which is behavior consistent with closure of a small channel caused by deposition. The relatively small tunnel size of this lake ensured a slower discharge even when it became full (330,000 m^3). During 2017–2019, the lake size was largest in 2017, yet the discharge rates were nearly the same every year. These results show that the lake size and the dimensions of the outlet ice-tunnel are related to the scale of discharge.

However, tunnel dimensions could increase in the future due to thermal erosion, allowing greater discharge rates. Meltwater and increasing temperature can accelerate thermokarst processes (Sakai et al., 2000; Kääb et al., 2001; Miles et al., 2018), enlarging the outlet ice-tunnel. In addition, although basin-size changes depend on the particular glacier landforms, the basin area in the case of Korumdu lake has increased each year due to glacier recession. If this applies to other short-lived glacier lakes in this region, large-scale flooding events during their discharge may increase in the future due to increasing temperature.

6 Conclusion

Our field survey found that Korumdu lake appeared and expanded from July to August and then drained over a period of 2–3 weeks. The lake formed when its outlet ice-tunnel closed, which was due to deposition of debris and ice during summer. Later, the draining process was relatively slow because the outlet ice tunnel was small and the scale of discharge is related to the sizes of the outlet ice-tunnel and the lake volume. We argued that predicting the scale of a drainage requires knowledge of the outlet ice-tunnel dimensions and the lake's depression size. Our research method of combination between water-level data and UAV DSMs could estimate the discharge and the approximate dimensions of the tunnel.

During 2013–2018, satellite data showed this region to have 160 short-lived glacial lakes, many of which had a similar timing of appearance as Korumdu lake. Four lakes that appeared a month earlier had large drainages, the only cases of large drainage in the study. Nevertheless, with a warming climate, any short-lived glacial lake might cause large flooding if the outlet ice tunnel and basin size sufficiently enlarge.

The glacial lake outburst floods (GLOFs) which caused by moraine-dam failure such as Himalaya and Andes are minor cases in this region. Short-lived lakes which caused by closure and opening of an outlet ice-tunnel in moraine complex are a major hazard in this region, because the short-lived lake exists on an ice-cored moraine complex within geomorphological and climate conditions of the mountain permafrost zone. In general, short-lived lakes should be monitored using satellite data and field observations. These new knowledges are useful to understand the phenomena and behavior of the short-lived lakes and consider glacier hazard mitigation in the mountain permafrost regions of Asian high mountains. A threat of the short-lived lakes increases for the residents since 2000s. This hazard case might be major in Asian high mountains in present.

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References

Aizen, V.B., Kuzmichenok, V.A., Surazakov, A.B., and Aizen, E.M.: Glacier changes in the central and northern Tien Shan during the last 140years based on surface and remote-sensing data, Ann. Glaciol., 43, 202–213, 2006.

Ageta, Y., Iwata, S., Yabuki, H., Naito, N., Sakai, A., Narama, C., and Karma.: Expansion of glacier lakes in recent decades in the Bhutan Himalayas, Debris-Covered Glaciers edited by Nakawo, M., Raymond, C.F., Fountain, A., IAHS Publication: Wallingford, UK, 2000, 165–175.

Bajracharya, S.R., Mool, P.K., and Shrestha, B.R.: Impact of Climate Change on Himalayan Glaciers and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan, ICIMOD: Kathmandu, Nepal, 2007.

Benn, D.I., Wiseman, S., and Warren, C.R.: Rapid growth of a supraglacial lake, Ngozumpa Glacier, Khumbu Himal, Nepal, Debris-Covered Glaciers edited by Nakawo, M., Raymond, C.F., Fountain, A., IAHS Publication: Wallingford, UK, 2000, 177–185.

Björnsson, H.: Understanding jökulhlaups: from tale to theory. J. Glaciol., 56(200), 1002–1010, 2010.

Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M., and Blagoveshchensky, V.: Identification of otentially dangerous glacial lakes in the northern Tien Shan. Nat. Hazards, 59, 1691–1714, 2011.

Clague, J.J. and O'Connor, J.E.: Glacier-Related Outburst Floods. In: Snow Ice-Related Hazards, Risks Disasters [Internet]. [place unknown]: Elsevier; [cited 2017 Mar 17]; 487–519. Available from: http://linkinghub.elsevier.com/retrieve/pii/B9780123948496000147, 2015.

Costa, J.E., and Schuster, R.L.: The formation and failure of natural dams. Geol. Soc. Am. Bull., 100, 1054–1068, 1988.

Daiyrov, M., Narama, C., Yamanokuchi, T., Tadono, T., Kääb, A., and Ukita, J.: Regional geomorphological conditions related to recent changes of glacial lakes in the Issyk-Kul basin, northern Tien Shan. Geosciences, 8(3), Art.no. 99, doi:10.3390/geosciences8030099, 2018.

Daiyrov, M., Narama, C., Kääb, A., and Tadono, T.: Formation and outburst of Toguz-Bulak glacial lake in the north part of Teskey Range, Tien Shan, Kyrgyzstan. Under review.

Dikih, A.N.: Regime of modern glaciation of the Central Tien Shan. Academy of Sciences of Kyrgyz SRR. Publisher "Ilim", 526. Frunze, 1982.

Emmer, A., and Cochachin, A.: The causes and mechanisms of moraine-dammed lake failures in the Cordillera Blanca, North American Cordillera, and Himalaya. Acta Universitatis Carolinae, Geographica. 48, 5–15. 2013.

Erokhin, S.A., Zaginaev, V.V., Meleshko, A.A., Ruiz-Villanueva, V., Petrakov, D., Chernomorets, S., Viskhadzhieva, K., Tutubalina, O., and Stoffel, M.: Debris flows triggered from non-stationary glacier lake outbursts: the case of the Teztor Lake complex (Northern Tian Shan, Kyrgyzstan). Landslides. DOI 10.1007/s10346-017-0862-3, 2017.

Gulley, J.D., Benn, D.I., Müller, D., and Luckman, A.: A cut-and-closure origin for englacial conduits in uncrevassed regions of polythermal glaciers, Journal of Glaciology., 55(189), 66-80, https://doi.org/10.3189/002214309788608930, 2009.

Huggel, C.: Assessment of Glacial Hazards based on Remote Sensing and GIS Modeling. Zürich, 2004. ISBN 3 85543 240 6, 2004.

Iveronova, M.U.: The processes of formation of modern moraines in the Tien Shan. In the book: Works of the Tien Shan Physical-Geographic Station. Vol. 2. M. 33-54, Moscow, 1952.

Iwata, S., Kuroda, S., and Kadar, K.: Debris-mantle formation of Wrpute Glacier, the Tien Shan Mountains, China. Bulletin of Glaciological Research, 22, 99-207, 2005.

Janský, B., Šobr, M., Engel, Z., and Yerokhin, S.: High-altitude lake outburst: Tien-Shan case study. In: Dostál P (ed) Evolution of geographical systems and risk processes in the global context. Chapter 7. Charles University in Prague, Faculty of Science. P3K Publishers, Prague, 113 – 127, 2008.

Kääb, A. and Haeberli, W.: Evolution of a high-mountain thermokarst lake in the Swiss Alps, Arct. Antarct. Alp. Res., 33(4), 385–390, 2001.

Kääb, A., Huggel, C., Barbero, S., Chiarle, M., Cordola, M., Epifani, F., Haeberli, W., Mortara, G., Semino, P., Tamburini, A., and Viazzo, G.: Glacier hazards at Belvedere Glacier and the Monte Rosa east face, Italian Alps: Processes and Mitigation, Proceedings Interpraevent 2004, 1, 67–78, 2004.

Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., and Medeu, A.: Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. Nat. Hazards Earth Syst. Sci. 17, 1837–1856, 2017.

Komori, J., Gurung, D.R., Iwata, S., and Yabuki, H.: Variation and lake expansion of Chubda Glacier, Bhutan Himalayas, during the last 35 years. Bull. Glaciol. Res. 21, 49–55, 2004.

Kutuzov, S. and Shahgedanova, M.: Glacier retreat and climatic variability in the eastern Teskey-Alatoo, inner Tien Shan between the middle of the 19th century and beginning of the 21st century, Global Planet. Change, 69, 59–70, 2009.

Kuzmichenok, V.A. Scientific-technical report, Academy of Sciences of the Kyrgyzstan, Bishkek, 61p, 2013.

Markov, K.K.: Essays on Geography Quaternary. M. 346 p, Moscow, 1955.

Mergili, M., Kopf, C., Müllebner, B., and Schneider, J.F.: Changes of the cryosphere and related geohazards in the high-mountain areas of Tajikistan and Austria: A comparison. Geogr. Ann. Ser. A Phys. Geogr. 93, 79–96, 2012.

Mergili, M., Müller, J., and Schneider, J.F.: Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). Glob. Planet. Chang. 107, 13–24, 2013.

Miles, E.S., Willis, I.C., Arnold, N.S., and Steiner, J.: Spatial, seasonal and interannual variability of supraglacial ponds in the Langtang Valley of Nepal, 1999-2013, Journal of Glaciology., 63, 88-105, doi: 10.1017/jog.2016.120, 2016.

Miles, E.S., Willis, I., Buri, P., Steiner, J.F., Arnold, N.S., and Pellicciotti, F.: Surface pond energy absorption across four Himalayan glaciers accounts for 1/8 of total catchment ice loss. Geophysical Research Letters., 10.1029/2018GL079678, 10464-10473, 2018.

Nagai, H., Ukita, J., Narama, C., Fujita, K., Sakai, A., Tadono, T., Yamanokuchi, T., and Tomiyama, N.: Evaluating the Scale and Potential of GLOF in the Bhutan Himalayas Using a Satellite-Based Integral Glacier–Glacial Lake Inventory. Geosciences, 7(3), 2017.

Narama, C., Shimamura, Y., Nakayama, D., and Abdrakhmatov, K.: Recent changes of glacier coverage in the western Terskey-Alatoo Range, Kyrgyz Republic, using Corona and Landsat. Ann. Glaciol. 43, 223–229, 2006.

Narama, C., Duishonakunov, M., Kääb, A., Daiyrov, M., and Abdrakhmatov, K.: The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan. Nat. Hazards Earth Syst. Sci. 10, 647–659, 2010.

Narama, C., Daiyrov, M., Kazehare, S., Yamamoto, M., and Tadono T.: Glacier lake inventory of the northern Tien Shan – Kyrgyz, Kungoy, and Teskey Ala-Too Ranges. Report of Mountain Research Group of Niigata University, Niigata, Japan, Niigata Printing, 2015.

Narama, C., Daiyrov, M., Tadono, T., Yamamoto, M., Kääb, A., Morita, R., and Ukita, J.: Seasonal drainage of supraglacial lakes on debris-covered glaciers in the Tien Shan Mountains, Central Asia. Geomorphology, 286, 133–142, 2017.

Narama, C., Daiyrov, M., Duishonakunov, M., Tadono, T., Hayato, S., Kääb, A., Ukita, J., and Abdrakhmatov, K.: Large

https://doi.org/10.5194/nhess-2020-252
Preprint. Discussion started: 23 October 2020

Natural Hazards and Earth System Sciences
Open Access
Discussions

drainage from short-lived glacial lakes in the Teskey Range, Tien Shan Mountains, Central Asia. Nat. Hazards Earth Syst. Sci. 18, https://doi.org/10.5194/nhess-18-1-2018, 2018.

Neupane, R., Chen, H., and Cao, C.: Review of moraine dam failure mechanism. Geomatics, Natural Hazards and Risk, 10, 1948-1966, 2019.

Podrezov, O.A. and Ryskal', M.O.: Validation of precipitation data of multi satellite tmpa model for the Kyrgyzstan mountainous TERRITORY // Geographical bulletin. №1(48). P. 63–74. doi 10.17072/2079-7877-20189-1-63-74, 2019.

Popov, N.V.: Outburst glacial mudflows and their prevention in the mountains of Northern Tien Shan. Data Glaciol. Stud. 59, 188–193, 1987. (In Russian)

Sakai, A., Takeuchi, N., Fujita, K., and Nakawo, M.: Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas. Debris-Covered Glaciers edited by Nakawo, M., Raymond, C.F., Fountain, A., IAHS Publication: Wallingford, UK, 2000; 119–130, 2000.

Richardson, S. D. and Reynolds, J. M.: An overview of glacial hazards in the Himalayas, Quatern. Int., 65/66, 31–47, 2000.

Roberts, M.J.: Jökulhlaups: a reassessment of floodwater flow through glaciers. Rev. Geophys., 43(1), RG1002. (10.1029/2003RG000147, 2005.

Shreshta, B.B.: Glacial Lake Outburst due to Moraine Dam Failure by Seepage and Overtopping with Impact of Climate Change. Annuals of Disas. Prev. Res., 53B, Inst., Kyoto Univ., 2010.

Shatravin, V.I.: Reconstruction of glaciation in the Pleistocene and Holocene based on new method, in: Climate, Glaciers, Lakes of Tien-Shan: travel in the past, edited by: Romanovsky, V. V., The Institute of Water Problems and Hydropower, Bishkek, 26–46, 2007. (in Russian)

Wang, X., Ding, Y., Liu, S., Jiang, L., Wu, K., Jiang, Z., and Guo, W.: Changes of glacial lakes and implications in Tian Shan, Central Asia, based on remote sensing data from 1990 to 2010. Environ. Res. Lett. 8, 1–11, 2013.

Watson, C.S., Quincey, D.J., Smith, M.W., Carrivick, J.L., Rowan, A.V., and James, M.R.: Quantifying ice cliff evolution with mult-temporal point clouds on the debris-covered Khumbu Glacier, Nepal. Journal of Glaciology, 63, 823-837, https://doi: 10.1017/jog.2017.47, 2017.

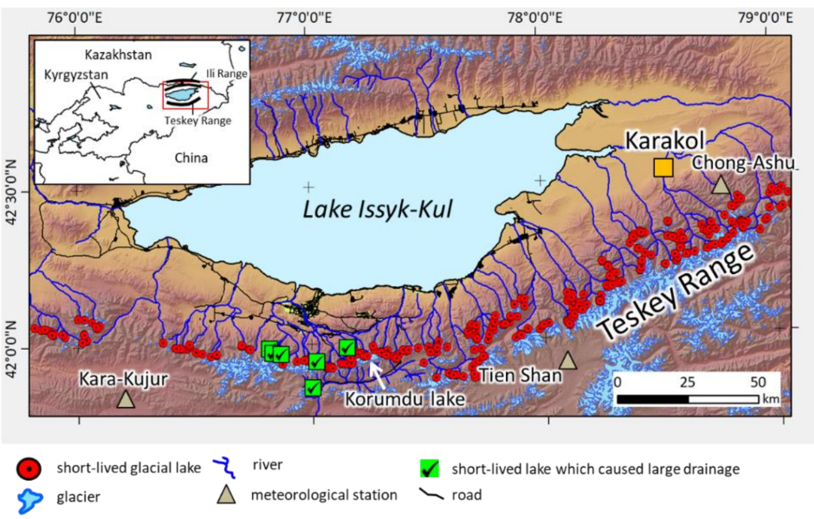

Figure 1: Study area in the northern part of the Teskey Range located on the south shoreline of Issyk-Kul Lake, Kyrgyz Republic. Red circles are short-lived glacial lakes that appeared in 2013–2018. Green squares with checks are short-lived lakes that have caused large drainages since the 1970s. The shaded relief map was created using SRTM DEM.

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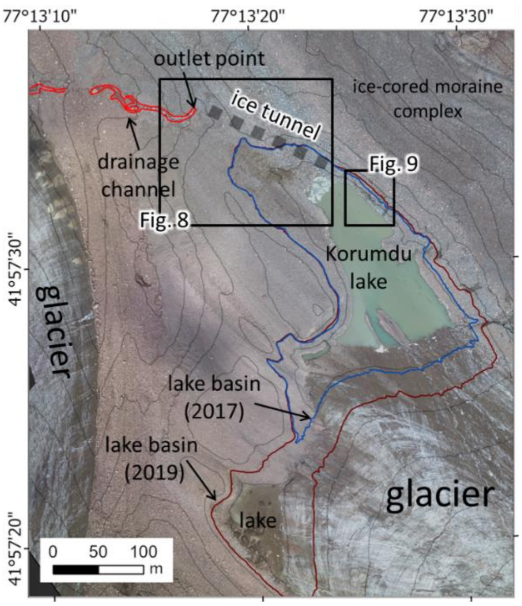

Figure 2: Geomorphological map of the Korumdu glacier front. The location of the glacier is shown in Fig. 1. Orthoimages were acquired by our UAV imagery in 2019. Contour spacing is 10 m.

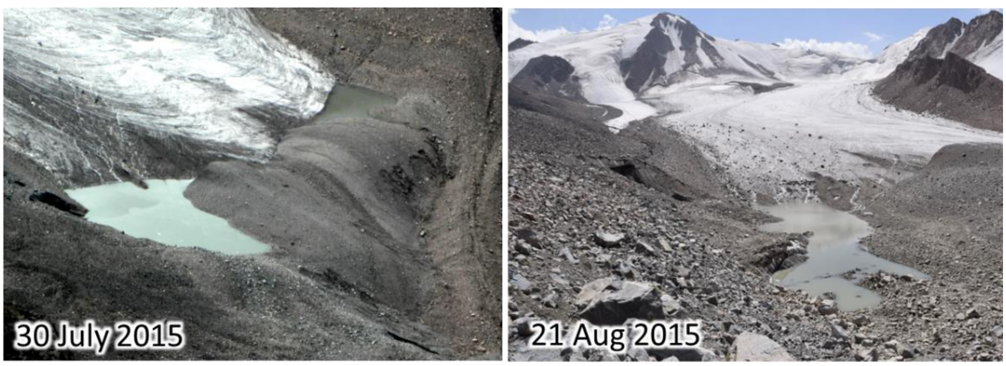

Figure 3: Korumdu glacial lake on 30 July 2015 (from a helicopter) and 21 August 2015 (from field observation).

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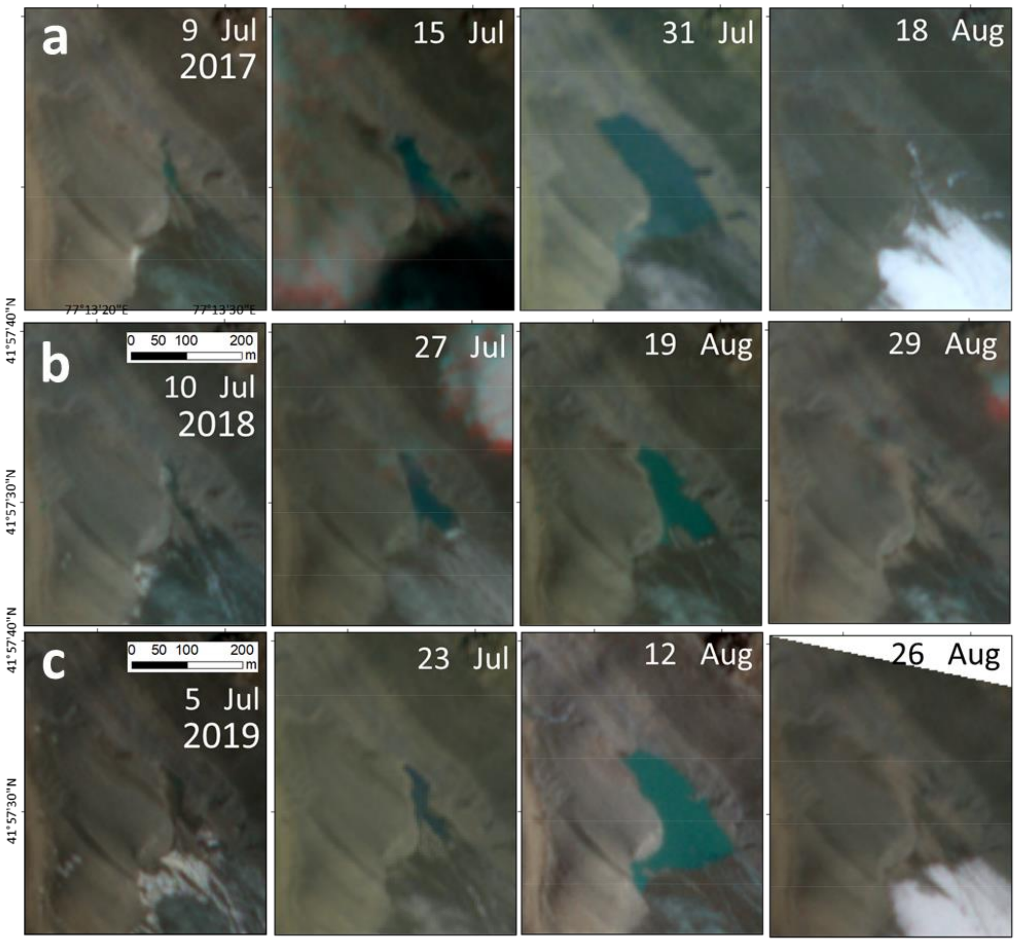

Figure 4: Time sequence of satellite images (PlanetScope) of the Korumdu lake area during 2017–2019.

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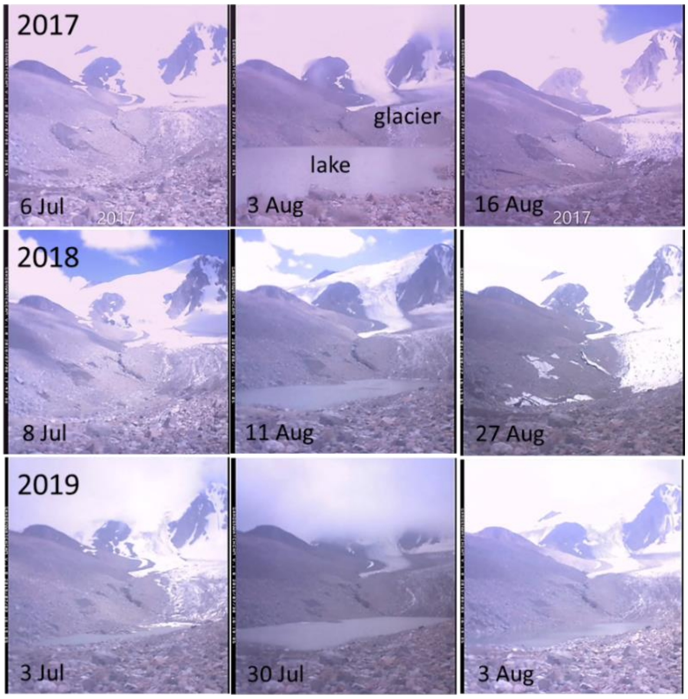
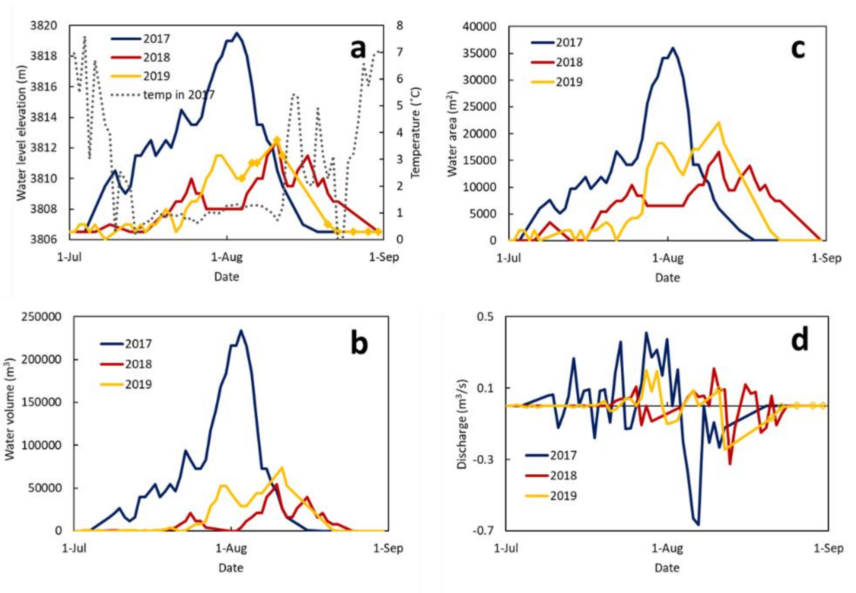


Figure 5: Time sequence of ground camera images of the Korumdu lake area during 2017–2019.



425 Figure 6: Yearly Korumdu lake properties 2017–2019. (a) Water level (left) and temperature in 2017 (right). (b) Lake volume. (c) Water surface area. (d) Inflow–outflow discharge. These data derived from 2017 to 2019 based on water-level logger (Hobo U20) data, UAV DSMs, time-lapse camera, and PlanetScope satellite images.

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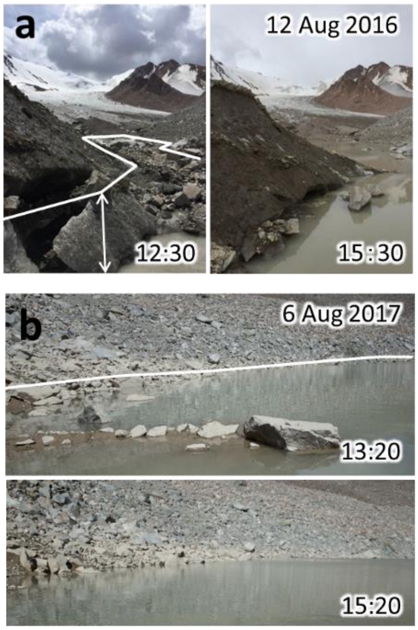

Figure 7: Two examples of a sudden small increase in water level. (a) On 12 August 2016. (b) Same as (a) except 3 hours later. (c) On 6 August 2017. (d) Same as (c) except 2 hours later. Images taken in the field.

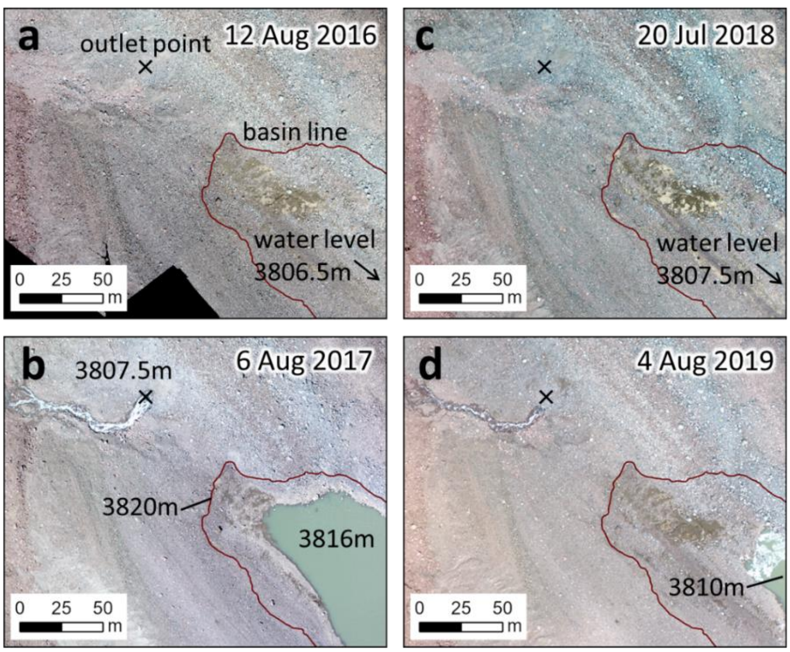

Figure 8: One-day drainage from Korumdu lake. (a) On 12 Aug. 2016. (b) On 6 Aug. 2017. (c) On 20 Jul. 2018. (d) On 4 Aug. 2019. Orthoimages are from our UAV imagery.

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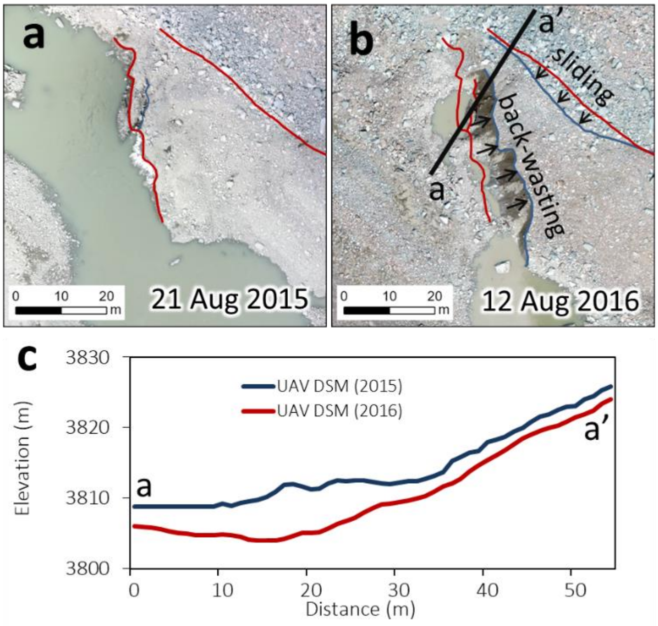


Figure 9: Surface features and elevation profiles of the debris landform at the entrance of the outlet ice-tunnel based on UAV ortho-image. (a) On 21 Aug. 2015. Left red line shows the position of the exposed ice edge line of the debris surface before the ice-cliff underwent backwasting and melting. Right red line shows the deposition line of boulders on the slope. (b) Same as (a) except 12 Aug. 2016. The blue lines show the new positions after one year. (c) Elevation profile of the surface along line a–a′ in (b).

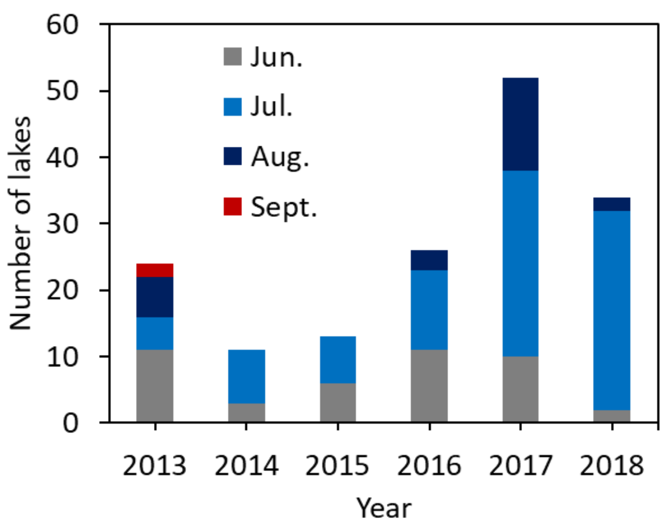
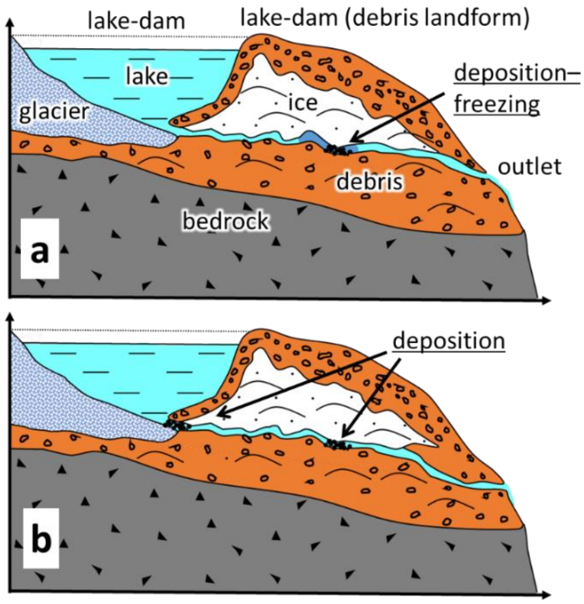


Figure 10: Total number of short-lived lakes in the months of June–September during 2013–2018 in the northern part of the Teskey Range.



445 Figure 11: The two types of ice-tunnel closure in the region. Sketches show cross-sections through a glacier, lake basin, and ice-cored moraine complex in the case of a short-lived lake (based on Popov, 1987). (a) Deposition–freezing type of closure that appears when an outlet ice-tunnel is blocked due to the freezing of storage water or deposition of debris and ice. (b) Deposition–closure type that appears when an outlet ice-tunnel at the entrance or interior is blocked due to deposition of debris and ice by thermal erosion (ice melting).

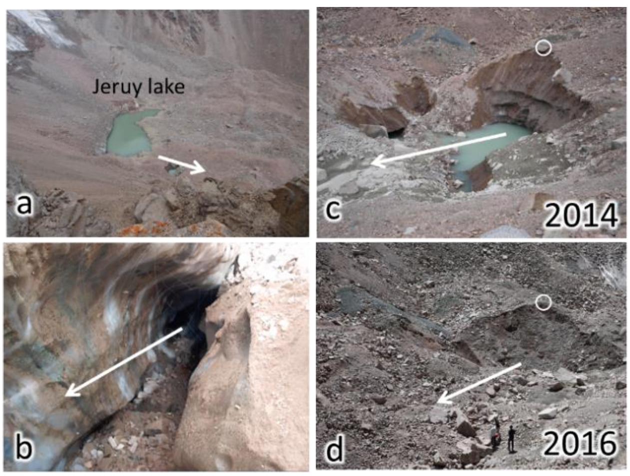


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Figure 12: Basin and outlet ice-tunnel of Jeruy lake, which drained in 15 August 2013. (a) Lake basin of Jeruy lake on 9 August 2014. White arrow shows the direction of drainage flow. (b) Outlet Ice-tunnel for the drainage channel on 9 Aug 2014. (c) The outlet ice-tunnel area on 9 August 2014. White circle in (c) and (d) shows the same location. (d) Same as (c) except on 9 August 2016.