Formation, evolution and drainage of short-lived glacial lakes in permafrost environments of the northern 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 in 2006, 2008, 2013, and 2014 caused severe damages in the downstream part. Short-lived glacial lakes grow rapidly and drain within a few months, due to closure and opening of an outlet ice-tunnel in an ice-cored moraine complex at the glacier front. In addition to these factors, summer meltwater from the glacier can cause rapid growth. Outburst floods of this lake type are a major hazard in this region and differ from the moraine-dam failures common to the eastern Himalaya. To clarify how short-lived glacial lakes store and drain water over short periods, we use results from a field survey and satellite data to analyse the water level, area, volume, and discharge of Korumdu lake (2014–2019) as well as satellite data to monitor the appearance of 160 other short-lived lakes (2013–2018). Except in 2016, Korumdu lake appeared and drained within about one month during all the summers. 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 of lake appearance indicates that the lake formed when an outlet ice-tunnel (subsurface channel) drainage was blocked by depositions of ice-debris mixture due to ice melting, not by freezing of stored water. For 2017, we used unmanned aerial vehicle (UAV)-derived digital surface models (DSMs) and water levels, finding that the lake's 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. This discharge rate is more than 20 times smaller than those found earlier (2006–2014) for four short-lived lakes in the region. We argue that this large variation in rates is due to variation in the dimensions of the outlet ice tunnels. For the 160 other short-lived glacial lakes, we argue that 117 formed mainly due to tunnel closure from deposition of ice ice-debris mixture, though increased glacial melt also likey contributed. In the Teskey Range, the appearance of short-lived glacial lakes on the moraine complexes at glacier fronts is inevitable in summer when the melting rate is high. Similar behaviour of short-lived lakes may occur in other mountain regions of Central Asia, such as the Tien Shan and Pamir mountains, wherever ice-cored moraine complexes exist within mountain permafrost zone. Moreover, warming temperatures may increase both tunnel size and lake-basin size (lake volume) leading to increased hazard potential from such lakes in the future.

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), glaciers in the northern Tien Shan (Central Asia) tend to have small glacial lakes near their termini (Janský et al., 2008; Narama et al., 2010a; 2015). Drainage events from these lakes often produce hazardous debris flows and floods. For example, debris flows in 2006, 2008, 2013, 2014, and 2019 in the Teskey Range of the northern Tien Shan caused severe damage (including casualties) and destroyed bridges, roads, houses, and crops (Narama et al., 2010a, 2018; Daiyrov et al., 2020).

Some of these small lakes are called short-lived as they grow rapidly and drain within a few months (Narama et al., 2010a, 2018; Daiyrov et al., 2018). Such short-lived lakes appear in depressions of ice-cored moraine complexes at glacier fronts. The lakes drain through an outlet ice-tunnel (subsurface channel) within the moraine complex (Popov, 1987; Narama et al., 2010a; 2018). Some authors call them nonstationary lakes (Erokhin et al., 2017), though this term also includes lakes with a long lifetime. Most short-lived glacial lake fill periodically and within one year, though some may develop for 2–3 years before draining. The latter type can be more dangerous; for example, in the Tajik Pamir, drainage from a short-lived glacial lake that formed within 2 years resulted in 25 casualties (Mergili et al., 2012). In northern Tien Shan, short-lived glacial lakes can be a severe hazard for local residents because they appears suddenly yet can cause large debris flows. Such an outburst (outburst mechanism and damage potential) differs from those that are caused by moraine-dam failure in the Himalaya and Andes (Costa and Schuster, 1988; Richardson and Reynolds, 2000; Shreshta 2010; Emmer and Cochachin, 2013; Neupane et al.; 2019). In those cases, a mass-movement trigger is the main cause of dam failures of the glacial lakes in the Himalayas and Andes (Emmer and Cochachin, 2013; Neupane et al.; 2019).

Short-lived glacial lakes that are dammed by partially frozen moraine material (ice-cored moraine complex) drain through a subsurface outlet ice-tunnel. These lakes can expand rapidly when the outlet ice-tunnel is blocked due to either freezing of stored water or depositions of ice and debris (Narama et al., 2010a, 2018). Drainage then occurs when the outlet ice-tunnel opens during summer. Some of these short-lived glacial lakes reappear every year (Daiyrov et al., 2018), which is behavior they share with supraglacial lakes. Several studies reported the formation and drainage supraglacial lakes are related to connectivity of englacial conduits on a debris-covered glacier (Benn et al., 2000, 2017; Miles et al., 2016; Watson et al., 2016; Narama et al., 2017). However, the variations of the short-lived glacial lakes arise from their ice-tunnel opening and closing as well as the increase in glacial melt during summer (Daiyrov et al., 2020).

Short-lived glacial lakes appear at depressions that can be created when glacier recedes, when an ice-cored moraine complex subsides (Narama et al., 2010a, 2018; Daiyrov et al., 2018), and on a surging glacier (Richardson and Reynolds, 2000; Kääb et al., 2004). Narama et al. (2018) showed that such short-lived glacial lakes typically form where the following three conditions exist: 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. The last condition indicates that the moraine complex has an outlet ice-tunnel to drain lake water.

The number and area of glacial lakes in the Tien Shan has recently increased, a trend that 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 in the number and distribution of glacial lake types in the Issyk-Kul Basin is not only related to the local climate conditions, but also to above three conditions in the glacier forefield as described above.

Many short-lived glacial lakes have been observed in the northern Tien Shan in recent years (Daiyrov et al., 2018). They can change over large areas and volumes in a short period of time, making their drainage features and discharge rates unpredictable (Erokhin et al., 2017), but not all short-lived glacial lakes cause large-scale floods. A short-lived 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 lake formation and drainage remain unclear. Hazards from an abruptly changing glacial-lake discharge can intensify dramatically and unexpectedly within weeks or even days (Huggel, 2004).

In this study, we investigate formation and drainage mechanisms of Korumdu lake in the Teskey Range, Tien Shan (Kyrgyz Republic) and the reason for different flood discharge (rates) from short-lived lakes based on field survey and satellite data analysis. To clarify how the other short-lived lakes in the Teskey Range store and drain water, we investigate their timing of appearance during summer months between 2013 and 2018 using Landsat-7/8, Sentinel-2, and PlanetScope satellite images. Finally, we discuss the causes of outlet ice-tunnel closure for Korumdu lake and other lakes of the same type in the study area. We also examine the relationship between outlet tunnel size and lake drainage rate. Findings from our study are relevant for glacier-related hazard mitigation.

2 Study area

The study area is situated in the northern part of the Teskey Range, south of Lake Issyk-Kul (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) due to the annual precipitation being 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 was 255 mm, whereas at the Tien Shan station (3614 m) of the central part it was 378 mm, and at the Chong-Ashu station (2788 m) of the eastern part it was 550 mm (Podrezov and Ryskal, 2019; Fig. 1). Mean annual air temperature was 0.1°C (1961–1988) for Kara-Kujur, –6.28°C (1995–2011; Kuzmichenok, 2013) for Tien Shan, and 0.27°C (1995–2005) for Chong-Ashu. The western part of the range had less glacier shrinkage than that in the eastern part (Aizen et al., 2006; Narama et al., 2006; Kutuzov and Shahgedanova, 2009).

In this area, the four large drainage events of Kashkasuu (2006), western Zyndan (2008), Jeruy (2013), and Karateke (2014) recently occurred from short-lived glacial lakes that formed on ice-cored moraine complexes (debris landforms including ice) (Narama et al., 2010a; 2018). The ice-cored moraine complexes here lie at 3200–4000 m (Daiyrov et al., 2018) at the glacier fronts that developed during the Little Ice Age (Dikih, 1982; Shatravin, 2007; Narama et al., 2010b) due to ice and debris stagnated by several glacier advances during the glacier shrinkage process (Iwata et al., 2005).

We ran a field survey at Korumdu lake at 3806 m (Figs. 1, 2). The Korumdu catchment is source to the largest tributary in the Tong River Basin, and according to a Sentinel-2 satellite image in 2019, Korumdu glacier occupies an area of 2.35 km^2. At

the front of the Korumdu glacier lies Korumdu glacial lake (Fig. 2). The dam of this lake is an ice-cored moraine complex. The lake developed in a depression that formed during the retreat of the glacier and retains direct contact with the glacier. We selected this lake for research because (i) the lake is a short-lived type that appears every year, (ii) it is easy to access, and (iii) this lake is located in the Tong region where four large outburst floods occurred in the past. 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. In addition, we investigated the timing of appearance for 160 short-lived lakes in the northern Teskey Range during 2013–2018 (Fig. 1) using Landsat-7/8, Sentinel-2, and PlanetScope satellite images (Supplemental Table 1).

3 Methods

3.1 Field observations at Korumdu lake

The field survey at Korumdu lake (Figs. 1, 2) was run during the summers of 2015–2019. We installed water level and water temperature data loggers (Hobo U20) at lake bottom and ground surface on the moraine to collect measurements once per hour since 21 August 2015. Water level logger measurements (water pressure data) at lake bottom were converted to the water level (meter) using atmospheric pressure data at the adjacent ground surface on the moraine. A time-lapse camera (Brinto) was installed as well and took one oblique image of the area per day.

In addition, we obtained aerial images of the lake basin acquired by Phantom-4 (DJI) and JABO H601G (Medix) unmanned aerial vehicles (UAVs) with a mounted camera (Ricoh GR) on 21 August 2015, 12 Aug 2016, 6 August 2017, 20 July 2018, and 4 August 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 and ground control points (GCPs). We collected the GCPs around the lake using a Trimble GeoExplore 6000 Global Navigation Satellite System (GNSS). The absolute positions of GCPs were corrected during post-processing using data from the Kyrgyz GNSS reference station and had an accuracy of 30–40 cm. Surface elevation changes of the moraine complex surrounding the lake were computed in ArcGIS 10.5 by comparing UAV-derived DSMs from 2015 and 2016.

The daily volume and discharge of the lake during the summers of 2017–2019 were calculated using the daily water level data and the 2017–2019 UAV-derived DSMs combined with the 2016 UAV-derived DSM (without water) in ArcGIS 10.5. For the water volume at the lake bottom, we used the 2016 DSM because the 2017–2019 DSMs had water at the lake bottom. In addition, we investigated whether satellite remote sensing data could replace an in situ water level logger data to calculate lake water levels using the combined DSMs. We found that the water level logger measurements agreed with the derived water levels based on satellite data and combined UAV-derived DSMs. For example, we confirmed the position of the water level by comparing a UAV orthorectify image and satellite data on 1-m counter lines extracted by the combined UAV-derived DSMs. Finally, we obtained the water level and water area from satellite data. Using this method, we 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 because we do not have water level data after our last visit on 4 August 2019. We also investigated the changes in lake area during 2017–2019 by comparing lake polygons that had been digitized manually using PlanetScope images.

Finally, we examined the meteorological and thermal conditions using air and ground temperature data loggers (TR-52i; T&D; accuracy ± 0.3°C) to log data at 1-hour intervals around the lake (Fig. 2). Mean annual air temperature (MAAT) between 2015 and 2017 and mean annual ground surface temperature (MAGST) during in 2015–2019 were calculated.

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

Short-lived glacial lakes in the northern Teskey Range were identified in ArcGIS 10.5 using satellite images (Landsat-7/Enhanced Thematic Mapper Plus (ETM+, SLC-off), Landsat-8/OLI), acquired during 2013–2018 (Supplemental Table 1). We used the definition by Daiyrov et al. (2018) for short-lived lakes, which is based on seasonal changes in lake area over the summer months of each year. Specifically, a short-lived lake is a temporary lake, lasting just one or two years, that suddenly appears or increases substantially in area, then disappears or shrinks within the same year. We counted the number of lakes that appeared from June to September each year. In addition, the number of lakes was tracked in each given year to examine how it changed from one year to the next. Polygon shapefiles of lakes were digitized manually from the images using ArcGIS 10.5.

4 Results

4.1 Areal variability of Korumdu lake

ALOS/AVNIR-2 data taken on 17 September 2007 indicated that most of the lake basin had been covered by Korumdu glacier . Thus, the lake basin developed in a depression that formed during the retreat of the glacier. The UAV ortho-images in 2019 indicated a basin length of 360 m, a width of 110 m, with a total area of 0.062 km^2. The lake basin volume increased from 264,000 to 330,000 m^3 from 2017 to 2019 (Fig. 2) due to retreat of the glacier terminus. In the field, we observed ice ridging and debris sliding on the basin's slope, indicating that the ice was melting around the shore, thus increasing the basin's width. The lake had no discernable surface drainage channel, but we found an outlet point where meltwater from the lake emerges from a subsurface ice-tunnel within the ice-cored moraine complex that connects to the lake (Fig. 2). The length of the outlet ice-tunnel is 60 m from the entrance of the lake basin. During the fieldwork, we observed melt draining at the outlet point on 30 July 2015, 6 August 2017, and 4 August 2019, but not in 12 August 2016 and 20 July 2018.

Concerning lake size changes, in 2015, the lake appeared sometime before 30 July, then shrank significantly by 21 August (Fig. 3). In 2016, according to the water level data and on-site time-lapse camera images, the lake area did not appear. For 2017–2019, we had more images of the area and thus a more precise sequence of changes in lake size is shown with a sequence of PlanetScope satellite images in Fig. 4. 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. 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

160 maximum size at some time between late July and early August. In addition, we checked Landsat-8/OLI data in 2014, finding that the lake existed on 5 May, 27 June, and 10 September in 2014. Thus, the satellite data demonstrate that the lake is a short-lived glacial lake.

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

165 Consider the trends in Korumdu lake during the three summers of 2017–2019. For 2017, Fig. 6a shows the water level increasing from 6 July, reaching a maximum on 3 August, and then the lake is empty on 19 August. Within 29 days, the water level increases 13 m, the area reaches 0.36 km^2 (Fig. 6b), and the volume reaches 234,000 m^3 (Fig. 6c). The resulting rate of lake volume increase was 8,070 m^3 per day. During the emptying of the lake, 234,000 m^3 of water drain in 17 days, with half of the volume draining from 3 to 7 August 2017 (Fig. 6c), resulting in a maximum net outflow discharge of 0.66 m^3/s (Fig.

170 6d). Although the water level increases intermittently before 3 August, the net outflow is relatively smooth. The lake water temperature averages about 1°C (Fig. 6a). The temperature fluctuates more when the lake is shallower because the heating of shallower water by solar irradiance is stronger than cooling from inflowing ice meltwater.

The same figures show the cases for 2018 and 2019. In 2018, the water level peaks three times, though reaches only about half that of 2017 (Fig. 6a). The first peak, on 25 July, occurs with a lake depth of 3.5 m and a volume of 21,000 m^3 (Fig. 6a, c).

175 The second, and maximum peak, occurs on 11 August with a lake depth of 6 m and a volume of 53,000 m^3. The third peak occurs on 17 August with a lake depth of 5 m and a volume of 39,000 m^3. The maximum net discharge occurs after the second peak, reaching 0.32 m^3/s (Fig. 6d). Similar to 2017, the net inflow rate also clearly varies over time in 2018. The three peaks in water level, area, and volume indicate that closure of the ice-tunnel occurred several times during a one-month period.

In 2019, the lake water level rises and falls before 22 July, when it rises sharply (Fig. 6a). Then, the water level shows a local

180 maximum around 30–31 July, reaching a lake depth of 5 m and a volume of 53,000 m^3. The 2019 maximum level occurs on 11 August, with a lake depth of 6.5 m and a corresponding volume of 74,000 m^3 (Fig. 6a, c). The maximum discharge occurs right after the second peak, reaching 0.24 m^3/s (Fig. 6d).

Over all three years, the highest water level is in 2017 (Fig. 6a). In general, each year had a different timing of lake-level increase, number of peaks, and maximum water volume. All three years had relatively small net discharge rates (maxima of

185 0.66, 0.32, and 0.24 m^3/s in 2017, 2018, and 2019), which is consistent with the absence of reported flooding.

During each of these years, the lake level rose and fell several times, indicating repeated storage-drainage cycles. In the field, we observed sudden small increases in water level in 2016 and 2017, with the lake 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.

190 During the fieldwork, we observed lake water draining out an outlet point in 2015, 2017, and 2019, but not in 2016 and 2018. We argue that this might be due to the difference in relative elevations between the lake level and the outlet ice-tunnel entrance. In particular, the water levels were at 3,810 m a.s.l on 21 August 2015, 3,816 m a.s.l on 6 August 2017, and 3,810 m a.s.l on 4 August 2019, thus the water levels were higher than the outlet ice-tunnel entrance at approximately 3,807.5 m a.s.l. In 2016

and 2018, lake water levels were at 3,806.5 m a.s.l and 3,807.5 m a.s.l, respectively, thus the water levels were lower than the outlet ice-tunnel entrance at approximately 3,807.5 m a.s.l (Fig. 8a, c). Therefore, we observed no drainage at the outlet point of the ice-tunnel in 2016 and 2018 during our visit.

4.3 Surface elevation changes around Korumdu lake

Between 2015 and 2016, debris sliding and horizontal backwasting around the lake exposed up to 7 m of an ice ridge (Fig. 9). The backwasting indicates that melting of debris-covered ice occurred, which is supported by comparing the UAV-derived DSMs from both years (Fig. 9c). For instance, along the cross-sectional profile a–a' in Fig. 9b, the surface elevation decreased by about 5 m (Fig. 9c). These results are consistent with closure in the outlet ice-tunnel during being duet to surface motion and ice-debris deposition. During our fieldwork in 2016, we observed the entrance of an ice-tunnel and water flow to its entrance. After two or three hours, the lake level increased (Fig. 7), consistent with the cause being closure of the ice-tunnel.

In the northern part of the Teskey Range, the discontinuous mountain permafrost zone lies above 3,100–3,200 m a.s.l (Daiyrov et al., 2018). Around Korumdu lake (3,806 m a.s.l), the mean annual air temperature (MAAT) during 2015–2017 was –4.8°C and the mean annual ground surface temperature (MAGST) during 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, expansion and deposition (closure) in the outlet ice-tunnel.

4.4 Comparison to other short-lived glacial lakes of the Teskey Range

To help determine when other short-lived glacial lakes form, we used satellite images during 2013–2018 to identify and examined 160 such short-lived glacial lakes in the northern Teskey Range. A classification of these lakes by month of appearance is shown in Fig. 10. Most lakes appeared in June (43 lakes) during the snow-melt period, and in July (90 lakes) during the ice-melt period. The total numbers and the proportions of the numbers for these two periods varied during the 6 years. Such variability has been argued to be related to geomorphological conditions such as drainage through ice tunnel inside of ice-cored moraine complex (Daiyrov et al., 2018).

Concerning reappearances, 81 lakes appeared only once during six years. Of the remaining, 19 lakes appeared twice, 7 lakes appeared three times, 2 lakes appeared four times, and 2 lakes appeared all 6 years. These results are consistent with tunnel closure being the main cause of formation. Short-lived glacial lakes that reappear during many years likely has an environment that either favors tunnel closure and hence lake formation or an increase in meltwater from glacier during summer (Daiyrov et al., 2020).

5 Discussion

5.1 Causes of outlet ice-tunnel closure in the northern Teskey Range

We first consider four previously studied short-lived lakes in the area. The Kashkasuu, western Zyndan, Jeruy, and Karateke lakes appeared in May–June and expanded in area until June–July, then all had relatively large drainage events leading to

serious damages (Narama et al., 2010a, 2018). This timing of lake appearance suggests an ice-tunnel closure that is caused by the freezing of stored water during winter or deposition of ice-debris mixture as sketched in Fig. 11a (Popov, 1987; Narama et al., 2010a, 2018). We call this the deposition–freezing type of ice-tunnel closure.

In contrast, Korumdu lake appeared during July–August (except in 2016) and produced relatively little drainage during emptying. This different appearance time might reflect a different formation process. As we observed subsidence and downwasting changing the lake basin (Fig. 9), the blockages of the outlet ice-tunnel at its entrance or interior were likely caused by deposition of ice-debris mixture from thermal erosion. This type of blockage (deposition-closure type) is sketched in Fig. 11b. The water level fluctuations supports this mechanism. The fluctuations of lake water level and discharge spikes reveal changes in the ice-tunnel morphology (Fig. 6d). A sudden blockage of an outlet ice-tunnel can cause a rapid increase in water level within a few weeks. Also, the water level 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 small. As a result, lake drainages can occur any time in summer, depending on how the outlet ice-tunnel responds to changes in water pressure or deposition of ice-debris mixture through melting processes.

In the northern Teskey Range, the Toguz-Bulak glacial lake appeared in June and disappeared in September every year from 2010 through 2019 due to the inflow of glacier meltwater (Daiyrov et al., 2020). This lake has a surface drainage channel from the lake, but its incoming glacial runoff controls its behaviour, such as its area. Thus, in addition to the closure of deposition, the lake-area changes during summer is also likely influenced by changes in the rate of incoming meltwater.

In 2017, there were two trends in lake water volume (Fig. 6b). The first period (5–25 July) involved sporadic fluctuations superimposed on an increase in water volume, indicating incomplete closure of the ice-tunnel. Then, in the second period of 26 July to 3 August, the volume continuously and rapidly increases, indicating complete closure of the ice-tunnel. Hence, we argue that the main factor of these rapid lake-area changes is tunnel closure. The lake area reached its maximum in 2017. This indicates that the tunnel closure was longer in 2017 than in 2018 or 2019. Longer periods of tunnel closure are associated with the formation of larger short-lived glacial lakes (Narama et al., 2018). Thus, the period of closure is likely determined by the morphology of the ice-tunnel and deposition condition of tunnel-closure point.

Many of the other short-lived glacial lakes in the northern Teskey Range, observed via satellite imagery, are likely to belong to the deposition-closure type as well. However, some likely have a larger influence from the water balance between drainage and storage, related to increasing glacial meltwater and tunnel size. Consider Jeruy glacial lake between 2014 and 2016 (Fig. 12). Ice melting caused distinct changes and rapid deposition within the outlet ice-tunnel, which likely led to tunnel closure. Thus, morphology and surface characteristics of an ice-cored moraine complex within the mountain permafrost zone are prone to frequent changes, and the deposition–closure type is likely the main type for the short-lived glacial lakes in the northern Teskey Range. If the deposition–closure processes occur in summer when the melting rate is high, the formation of a short-lived glacial lake is highly likely.

5.2 Relationship between outlet tunnel size and lake drainage

Of the 160 short-lived lakes we identified in 2013–2018, only Jeruy lake (in 2013) and Karateke lake (in 2014) showed considerable drainage. 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 one at Jeruy, as

265 well as one at Karateke, having a cross-section of about 8 m^2 (Fig. 12a,b). Earlier, in 2008, the w-Zyndan lake (437,000 m^3) emptied at the higher discharge rate of 27 m^3/s (Narama et al., 2010a). Most of the water in these three cases drained over a period of several hours. In contrast, Korumdu lake did not show such high drainage rates during 2014–2019, draining at a maximum rate of 0.66 m^3/s in 2017, taking 17 days to drain 234,000 m^3, and its tunnel cross-section was much smaller than those at Jeruy or Karateke lakes.

270 In addition, Korumdu lake exhibited sudden fluctuations of water level over several hours, which we argued was related to closure of the small outlet ice-tunnel caused by deposition of and blockage by debris. The relatively small tunnel size of this lake resulted in slower lake discharge even when lake volume reached its maximum (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, at least for Korumdu lake, the dimensions of the outlet ice-tunnel were the dominant factor controlling lake discharge rates.

275 However, tunnel dimensions could increase in the future due to thermal erosion, allowing greater discharge rates. Meltwater and increasing temperature can accelerate thermokarst processes enlarging the outlet ice-tunnel (Sakai et al., 2000; Kääb et al., 2001; Miles et al., 2018). In addition, although lake basin size changes on ice-cored moraine complexes depend on the details of the thermal erosion, the basin area of Korumdu lake has increased each year due to glacier retreat. If these apply to other short-lived glacier lakes in the Teskey Range, large-scale flooding events during their discharge may become more frequent

280 in the future due to increasing temperature.

6 Conclusions

From our field survey, we 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 we argued was due to deposition of ice-debris mixture

285 during summer. The lake drainage was always relatively slow. We argue that predicting drainage rates requires knowing the dimensions of the outlet ice-tunnel and the size of the lake basin. By combining water level data and UAV-derived DSMs from consecutive years, we were able to estimate daily lake discharge and approximate the tunnel dimensions at much less than 8 m^2. Four lakes that appeared a month earlier (May–June) showed drainage rates were significantly higher compared to Kromudu lake. Based on satellite images from 2013–2018, 160 short-lived glacial lakes were detected in the northern Teskey

290 Range, many of which had a similar timing of appearance as Korumdu lake with average 27% forming in June, average 73% in July–September. This result shows the deposition–closure type is likely the main type for the short-lived glacial lakes in the northern Teskey Range.

Although short-lived glacial lakes in the northern Teskey Range rarely flood via moraine-dam failure, they are nevertheless can be a major flood hazard. Moreover, the warming climate may result in larger outlet ice-tunnels and lake basin sizes that

295 could cause large flood events. Therefore, short-lived lakes should be monitored using satellite data and field observations to

better understand their characteristics and behaviour. Such monitoring may help mitigate glacier-related hazards in permafrost zones of high-mountain areas of Central Asia.

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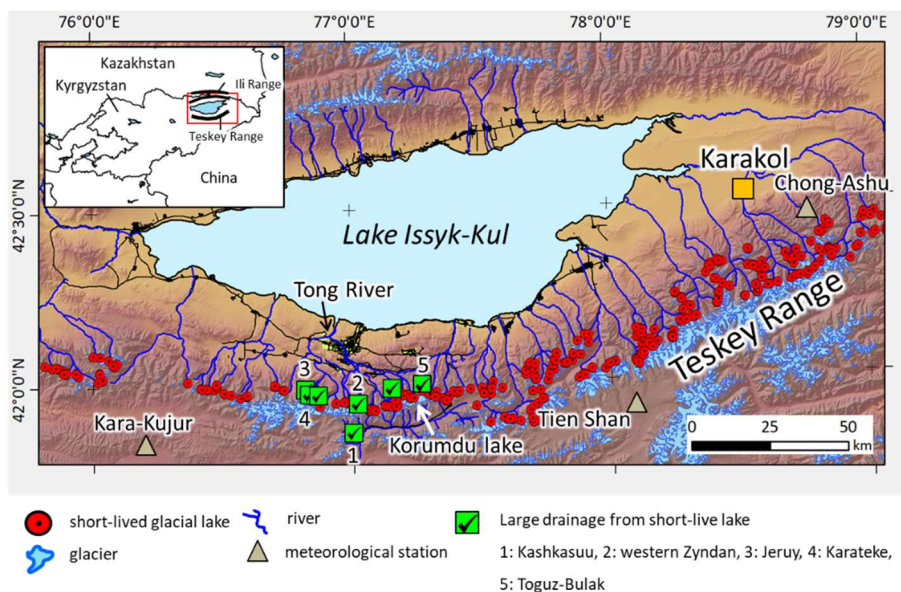


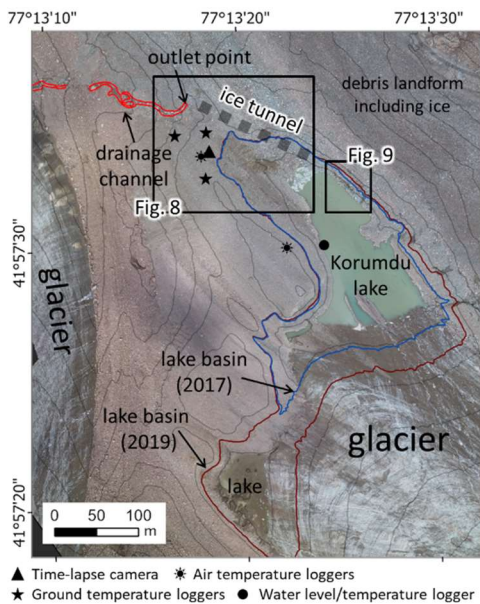
Figure 1: Study area in the northern part of the Teskey Range located on the south of Lake Issyk-Kul, Kyrgyz Republic. Red circles indicate locations of short-lived glacial lakes that appeared in 2013–2018. Green squares with checks show short-lived glacial lakes that have caused large drainage events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

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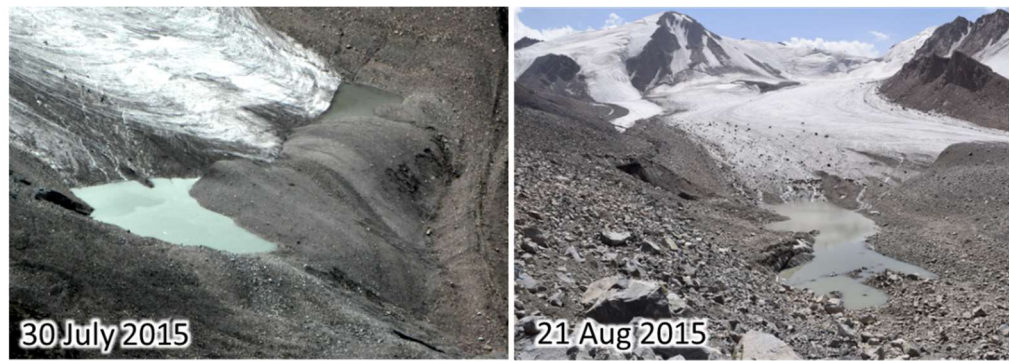
Figure 2: Overview of the Korumdu glacier front. The location of the glacier is shown in Fig. 1. Orthoimages were acquired by our UAV imagery in 2019. Contour spacing is 10 m.

415 Figure 3: Korumdu glacial lake on 30 July 2015 (from a helicopter) and 21 August 2015 (from field observation). The width at the lake middle is about 85 m (left image) and 40 m (right).

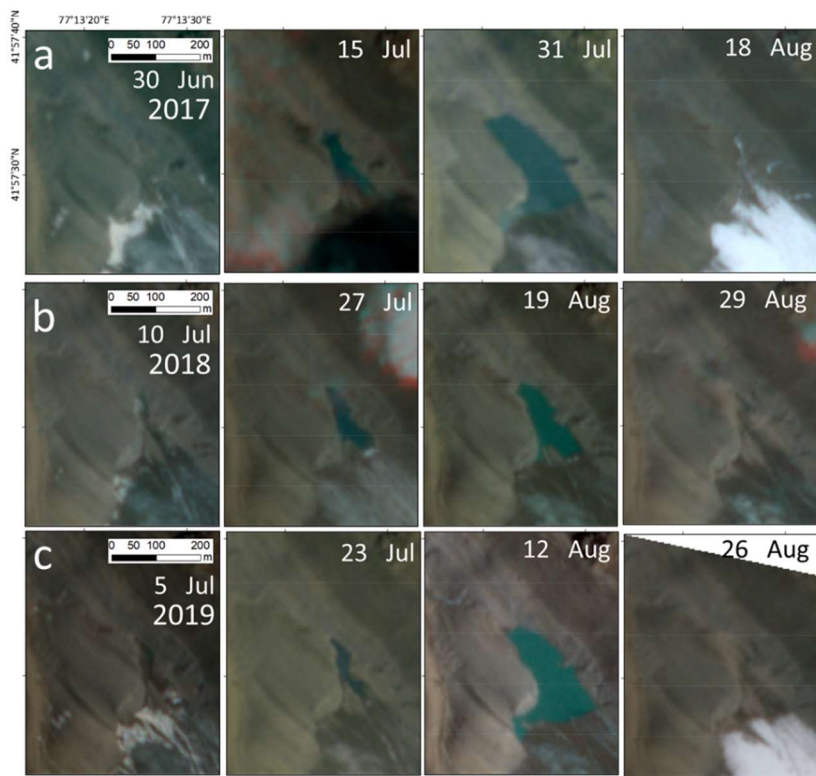



Figure 4: Time sequence of satellite images (PlanetScope) of Korumdu lake in (a) 2017, (b) 2018, and (c) 2019.

420 Figure 5: Korumdu lake during 2017–2019 from on time-lapse camera images acquired in the field.

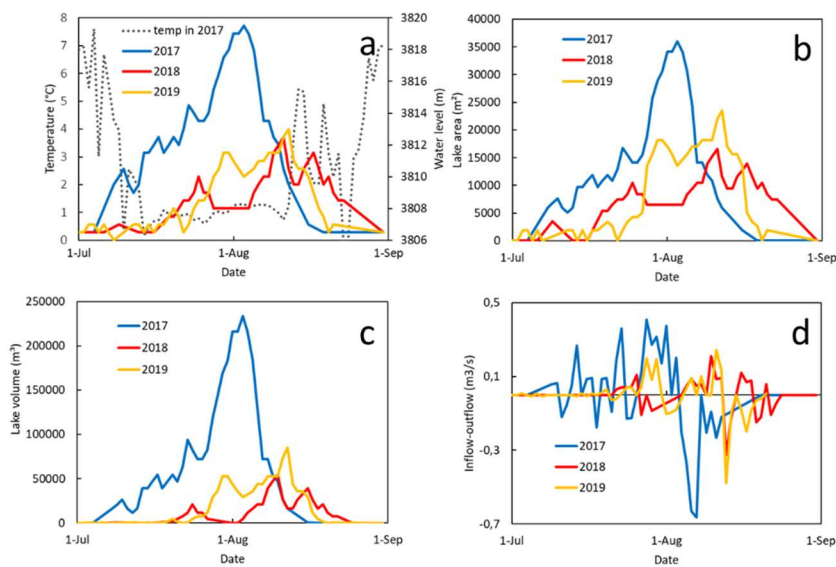



Figure 6: Water levels of Korumdu lake in 2017–2019. (a) and air/water temperature in 2017. (b) Lake volume. (c) Lake surface area. (d) Inflow–outflow rate. Data based on water level logger data, UAV-derived DSMs, time-lapse camera images, 425 and PlanetScope satellite images.

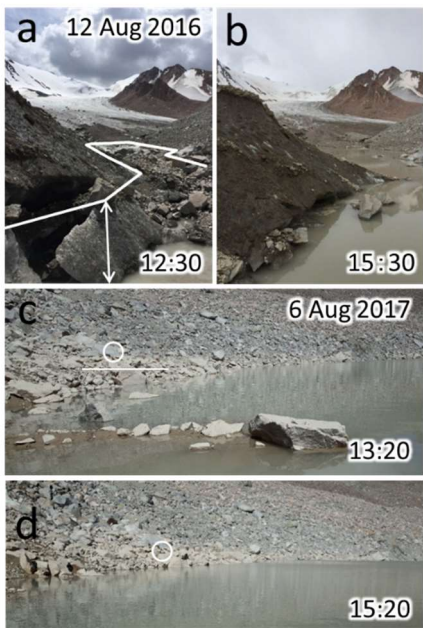
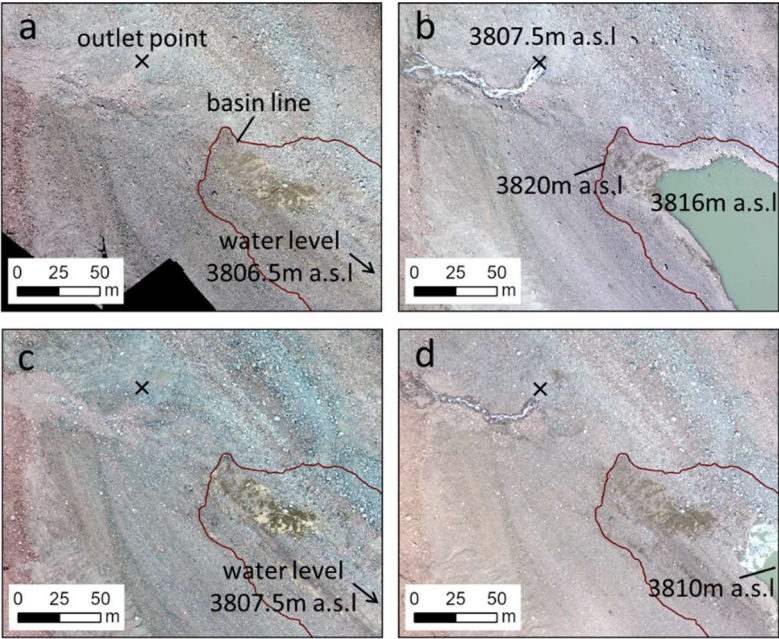



Figure 7: Two examples of a sudden small increase in water level of Korumdu lake. (a) On 12 August 2016. (b) Same as (a) except 3 hours later. (c) On 6 August 2017. (d) Same as (c) except 2 hours later. Images taken in the field.

430   Figure 8: One-day drainage events from Korumdu lake on the listed dates. (a) On 12 August 2016. (b) On 6 August 2017. (c) On 20 July 2018. (d) On 4 August 2019. Images from UAV surveys.

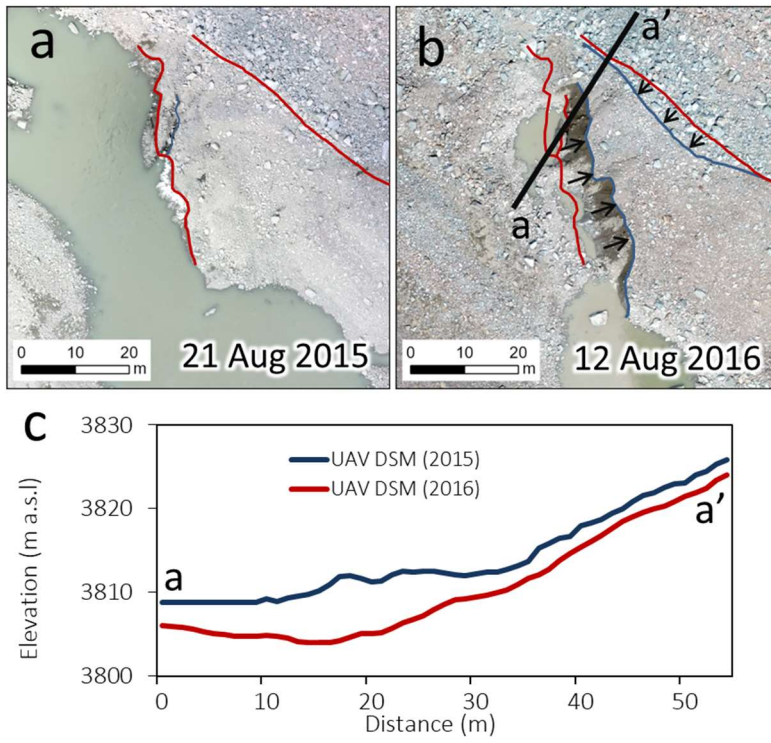



Figure 9: Surface features and elevation profiles of the debris-covered stagnant ice at the entrance of the outlet ice-tunnel based on UAV orthoimages. (a) On 21 August 2015. Left red line shows the position of the exposed ice edge of the debris surface before the ice-cliff underwent backwasting and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

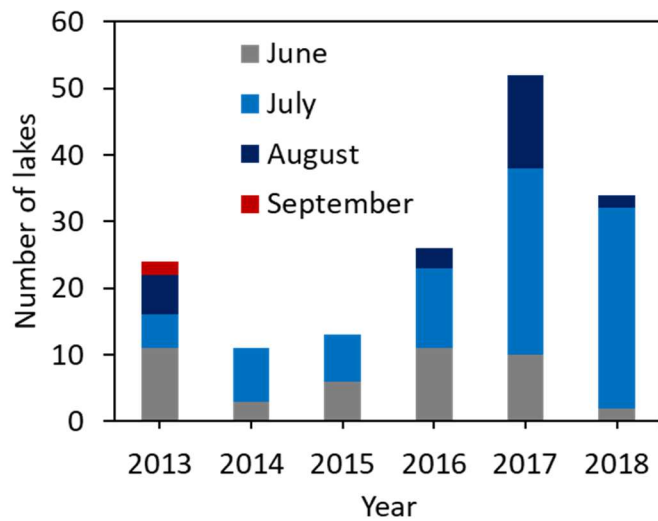



Figure 10: Total number of short-lived lakes in the months of June–September during 2013–2018 in the northern part of the Teskey Range derived by Landsat-7/8, Sentinel-2, and PlanetScope satellite images.

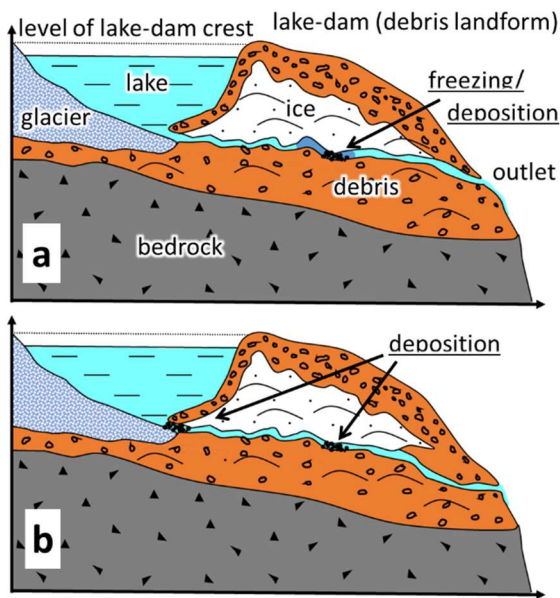



Figure 11: The two types of ice-tunnel closure occurring in the northern Teskey Range. Sketches show cross-sections through a glacier, lake basin, and ice-cored moraine complex in the case of a short-lived lake (based on Popov, 1987). (a) Deposition–freezing type of closure in case of an outlet ice-tunnel being blocked by freezing of storage water or deposition of debris and ice. Dark blue in the tunnel is frozen. (b) Deposition–closure type of closure in case of an outlet ice-tunnel being blocked by deposition of debris and ice by thermal erosion (ice melt).

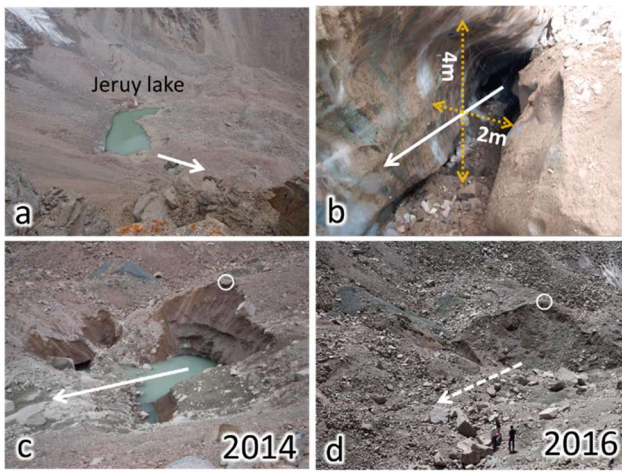



Figure 12: Basin and outlet ice-tunnel of Jeruy lake, which drained on 15 August 2013. (a) Lake basin of Jeruy glacial lake on 9 August 2014. The white arrow shows the direction of lake drainage. (b) Insight into the outlet ice-tunnel on 9 Aug 2014. (c) The outlet ice-tunnel area on 9 August 2014. The white circles in (c) and (d) show the same location. (d) Same as (c) except on 9 August 2016.

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475 Supplemental Table 1: Satellite images source dates

Landsat-7 and 8

ID	Satellite	Acquisition date	Resolution (m)	Lake
1	Landsat-8/OLI	12-Jun-13	15 (pan)	other short-lived glacial lakes
2	Landsat-8/OLI	19-Jun-13	15 (pan)	other short-lived glacial lakes
3	Landsat-8/OLI	5-Jul-13	15 (pan)	other short-lived glacial lakes
4	Landsat-8/OLI	28-Jul-13	15 (pan)	other short-lived glacial lakes
5	Landsat-7 ETM+/SLC-off	29-Jul-13	15 (pan)	other short-lived glacial lakes
6	Landsat-8/OLI	30-Jul-13	15 (pan)	other short-lived glacial lakes
7	Landsat-8/OLI	6-Aug-13	15 (pan)	other short-lived glacial lakes
8	Landsat-8/OLI	15-Aug-13	15 (pan)	other short-lived glacial lakes
9	Landsat-8/OLI	29-Aug-13	15 (pan)	other short-lived glacial lakes
10	Landsat-8/OLI	31-Aug-13	15 (pan)	other short-lived glacial lakes
11	Landsat-8/OLI	1-Sep-13	15 (pan)	other short-lived glacial lakes
12	Landsat-8/OLI	7-Sep-13	15 (pan)	other short-lived glacial lakes
13	Landsat-7 ETM+/SLC-off	8-Sep-13	15 (pan)	other short-lived glacial lakes
14	Landsat-8/OLI	23-Sep-13	15 (pan)	other short-lived glacial lakes
15	Landsat-7 ETM+/SLC-off	24-Sep-13	15 (pan)	other short-lived glacial lakes
16	Landsat-7 ETM+/SLC-off	1-Oct-13	15 (pan)	other short-lived glacial lakes
17	Landsat-8/OLI	9-Oct-13	15 (pan)	other short-lived glacial lakes
18	Landsat-7 ETM+/SLC-off	10-Oct-13	15 (pan)	other short-lived glacial lakes
19	Landsat-8/OLI	5-May-14	15 (pan)	other short-lived glacial lakes
20	Landsat-7 ETM+/SLC-off	29-May-14	15 (pan)	other short-lived glacial lakes
21	Landsat-7 ETM+/SLC-off	14-Jun-14	15 (pan)	other short-lived glacial lakes
22	Landsat-8/OLI	15-Jun-14	15 (pan)	other short-lived glacial lakes
23	Landsat-8/OLI	27-Jun-14	15 (pan)	other short-lived glacial lakes
24	Landsat-7 ETM+/SLC-off	30-Jun-14	15 (pan)	other short-lived glacial lakes
25	Landsat-8/OLI	1-Jul-14	15 (pan)	other short-lived glacial lakes
26	Landsat-8/OLI	8-Jul-14	15 (pan)	other short-lived glacial lakes
27	Landsat-7 ETM+/SLC-off	9-Jul-14	15 (pan)	other short-lived glacial lakes
28	Landsat-7 ETM+/SLC-off	16-Jul-14	15 (pan)	other short-lived glacial lakes
29	Landsat-7 ETM+/SLC-off	25-Jul-14	15 (pan)	other short-lived glacial lakes
30	Landsat-7 ETM+/SLC-off	1-Aug-14	15 (pan)	other short-lived glacial lakes
31	Landsat-8/OLI	2-Aug-14	15 (pan)	other short-lived glacial lakes
32	Landsat-7 ETM+/SLC-off	10-Aug-14	15 (pan)	other short-lived glacial lakes
33	Landsat-8/OLI	25-Aug-14	15 (pan)	other short-lived glacial lakes
34	Landsat-8/OLI	1-Sep-14	15 (pan)	other short-lived glacial lakes
35	Landsat-7 ETM+/SLC-off	2-Sep-14	15 (pan)	other short-lived glacial lakes
36	Landsat-8/OLI	3-Sep-14	15 (pan)	other short-lived glacial lakes
37	Landsat-8/OLI	10-Sep-14	15 (pan)	other short-lived glacial lakes
38	Landsat-7 ETM+/SLC-off	18-Sep-14	15 (pan)	other short-lived glacial lakes
39	Landsat-8/OLI	19-Sep-14	15 (pan)	other short-lived glacial lakes
40	Landsat-8/OLI	26-Sep-14	15 (pan)	other short-lived glacial lakes
41	Landsat-7 ETM+/SLC-off	17-Jun-15	15 (pan)	other short-lived glacial lakes
42	Landsat-8/OLI	18-Jun-15	15 (pan)	other short-lived glacial lakes
43	Landsat-8/OLI	2-Jul-15	15 (pan)	other short-lived glacial lakes
44	Landsat-7 ETM+/SLC-off	3-Jul-15	15 (pan)	other short-lived glacial lakes
45	Landsat-8/OLI	4-Jul-15	15 (pan)	other short-lived glacial lakes
46	Landsat-8/OLI	11-Jul-15	15 (pan)	other short-lived glacial lakes
47	Landsat-7 ETM+/SLC-off	12-Jul-15	15 (pan)	other short-lived glacial lakes
48	Landsat-8/OLI	18-Jul-15	15 (pan)	other short-lived glacial lakes
49	Landsat-8/OLI	30-Jul-15	15 (pan)	other short-lived glacial lakes
50	Landsat-8/OLI	12-Aug-15	15 (pan)	other short-lived glacial lakes
51	Landsat-8/OLI	19-Aug-15	15 (pan)	other short-lived glacial lakes
52	Landsat-7 ETM+/SLC-off	20-Aug-15	15 (pan)	other short-lived glacial lakes
53	Landsat-8/OLI	21-Aug-15	15 (pan)	other short-lived glacial lakes
54	Landsat-8/OLI	4-Sep-15	15 (pan)	other short-lived glacial lakes
55	Landsat-7 ETM+/SLC-off	5-Sep-15	15 (pan)	other short-lived glacial lakes
56	Landsat-8/OLI	6-Sep-15	15 (pan)	other short-lived glacial lakes
57	Landsat-8/OLI	13-Sep-15	15 (pan)	other short-lived glacial lakes
58	Landsat-8/OLI	29-Sep-15	15 (pan)	other short-lived glacial lakes
59	Landsat-8/OLI	8-Oct-15	15 (pan)	other short-lived glacial lakes
60	Landsat-7 ETM+/SLC-off	10-Jun-16	15 (pan)	other short-lived glacial lakes
61	Landsat-8/OLI	11-Jun-16	15 (pan)	other short-lived glacial lakes
62	Landsat-7 ETM+/SLC-off	26-Jun-16	15 (pan)	other short-lived glacial lakes
63	Landsat-8/OLI	20-Jun-16	15 (pan)	other short-lived glacial lakes
64	Landsat-7 ETM+/SLC-off	12-Jul-16	15 (pan)	other short-lived glacial lakes
65	Landsat-8/OLI	13-Jul-16	15 (pan)	other short-lived glacial lakes
66	Landsat-8/OLI	20-Jul-16	15 (pan)	other short-lived glacial lakes
67	Landsat-7 ETM+/SLC-off	21-Jul-16	15 (pan)	other short-lived glacial lakes
68	Landsat-8/OLI	22-Jul-16	15 (pan)	other short-lived glacial lakes
69	Landsat-8/OLI	29-Jul-16	15 (pan)	other short-lived glacial lakes
70	Landsat-7 ETM+/SLC-off	30-Jul-16	15 (pan)	other short-lived glacial lakes
71	Landsat-8/OLI	29-Jul-16	15 (pan)	other short-lived glacial lakes
72	Landsat-8/OLI	7-Aug-16	15 (pan)	other short-lived glacial lakes
73	Landsat-7 ETM+/SLC-off	13-Aug-16	15 (pan)	other short-lived glacial lakes
74	Landsat-8/OLI	14-Aug-16	15 (pan)	other short-lived glacial lakes
75	Landsat-8/OLI	21-Aug-16	15 (pan)	other short-lived glacial lakes
76	Landsat-7 ETM+/SLC-off	22-Aug-16	15 (pan)	other short-lived glacial lakes
77	Landsat-8/OLI	23-Aug-16	15 (pan)	other short-lived glacial lakes
78	Landsat-7 ETM+/SLC-off	7-Sep-16	15 (pan)	other short-lived glacial lakes
79	Landsat-8/OLI	8-Sep-16	15 (pan)	other short-lived glacial lakes
80	Landsat-7 ETM+/SLC-off	14-Sep-16	15 (pan)	other short-lived glacial lakes
81	Landsat-8/OLI	15-Sep-16	15 (pan)	other short-lived glacial lakes
82	Landsat-8/OLI	22-Sep-16	15 (pan)	other short-lived glacial lakes
83	Landsat-7 ETM+/SLC-off	23-Sep-16	15 (pan)	other short-lived glacial lakes
84	Landsat-8/OLI	24-Sep-16	15 (pan)	other short-lived glacial lakes
85	Landsat-8/OLI	14-Jun-17	15 (pan)	other short-lived glacial lakes
86	Landsat-8/OLI	30-Jun-17	15 (pan)	other short-lived glacial lakes
87	Landsat-8/OLI	1-Jul-17	15 (pan)	other short-lived glacial lakes
88	Landsat-8/OLI	7-Jul-17	15 (pan)	other short-lived glacial lakes
89	Landsat-8/OLI	9-Jul-17	15 (pan)	other short-lived glacial lakes
90	Landsat-8/OLI	16-Jul-17	15 (pan)	other short-lived glacial lakes
91	Landsat-8/OLI	25-Jul-17	15 (pan)	other short-lived glacial lakes
92	Landsat-8/OLI	25-Jul-17	15 (pan)	other short-lived glacial lakes
93	Landsat-8/OLI	1-Aug-17	15 (pan)	other short-lived glacial lakes
94	Landsat-8/OLI	8-Aug-17	15 (pan)	other short-lived glacial lakes
95	Landsat-8/OLI	10-Aug-17	15 (pan)	other short-lived glacial lakes
96	Landsat-8/OLI	26-Aug-17	15 (pan)	other short-lived glacial lakes
97	Landsat-8/OLI	2-Sep-17	15 (pan)	other short-lived glacial lakes
98	Landsat-7 ETM+/SLC-off	17-Sep-17	15 (pan)	other short-lived glacial lakes
99	Landsat-8/OLI	11-Oct-17	15 (pan)	other short-lived glacial lakes
100	Landsat-8/OLI	25-Jun-18	15 (pan)	other short-lived glacial lakes
101	Landsat-8/OLI	10-Jul-18	15 (pan)	other short-lived glacial lakes
102	Landsat-8/OLI	19-Jul-18	15 (pan)	other short-lived glacial lakes
103	Landsat-8/OLI	19-Jul-18	15 (pan)	other short-lived glacial lakes
104	Landsat-8/OLI	5-Sep-19	15 (pan)	other short-lived glacial lakes
105	Landsat-8/OLI	7-Aug-19	15 (pan)	other short-lived glacial lakes

Sentinel-2

ID	Satellite	Acquisition date	Resolution (m)	Lake
1	Sentinel-2	10-Jun-16	10	other short-lived glacial lakes
2	Sentinel-2	30-Jun-16	10	other short-lived glacial lakes
3	Sentinel-2	17-Jul-16	10	other short-lived glacial lakes
4	Sentinel-2	9-Aug-16	10	other short-lived glacial lakes
5	Sentinel-2	29-Aug-16	10	other short-lived glacial lakes
6	Sentinel-2	18-Sep-16	10	other short-lived glacial lakes
7	Sentinel-2	8-Oct-16	10	other short-lived glacial lakes
8	Sentinel-2	12-Jun-17	10	other short-lived glacial lakes
9	Sentinel-2	12-Jun-17	10	other short-lived glacial lakes
10	Sentinel-2	12-Jun-17	10	other short-lived glacial lakes
11	Sentinel-2	12-Jun-17	10	other short-lived glacial lakes
12	Sentinel-2	15-Jun-17	10	other short-lived glacial lakes
13	Sentinel-2	17-Jun-17	10	other short-lived glacial lakes
14	Sentinel-2	21-Jun-17	10	other short-lived glacial lakes
15	Sentinel-2	30-Jun-17	10	other short-lived glacial lakes
16	Sentinel-2	2-Jul-17	10	other short-lived glacial lakes
17	Sentinel-2	7-Jul-17	10	other short-lived glacial lakes
18	Sentinel-2	7-Jul-17	10	other short-lived glacial lakes
19	Sentinel-2	7-Jul-17	10	other short-lived glacial lakes
20	Sentinel-2	9-Jul-17	10	other short-lived glacial lakes
21	Sentinel-2	20-Jul-17	10	other short-lived glacial lakes
22	Sentinel-2	22-Jul-17	10	other short-lived glacial lakes
23	Sentinel-2	27-Jul-17	10	other short-lived glacial lakes
24	Sentinel-2	27-Jul-17	10	other short-lived glacial lakes
25	Sentinel-2	27-Jul-17	10	other short-lived glacial lakes
26	Sentinel-2	27-Jul-17	10	other short-lived glacial lakes
27	Sentinel-2	27-Jul-17	10	other short-lived glacial lakes
28	Sentinel-2	9-Aug-17	10	other short-lived glacial lakes
29	Sentinel-2	14-Aug-17	10	other short-lived glacial lakes
30	Sentinel-2	29-Aug-17	10	other short-lived glacial lakes
31	Sentinel-2	29-Aug-17	10	other short-lived glacial lakes
32	Sentinel-2	31-Aug-17	10	other short-lived glacial lakes
33	Sentinel-2	31-Aug-17	10	other short-lived glacial lakes
34	Sentinel-2	31-Aug-17	10	other short-lived glacial lakes
35	Sentinel-2	31-Aug-17	10	other short-lived glacial lakes
36	Sentinel-2	18-Sep-17	10	other short-lived glacial lakes
37	Sentinel-2	20-Sep-17	10	other short-lived glacial lakes
38	Sentinel-2	20-Sep-17	10	other short-lived glacial lakes
39	Sentinel-2	20-Sep-17	10	other short-lived glacial lakes
40	Sentinel-2	20-Sep-17	10	other short-lived glacial lakes
41	Sentinel-2	23-Sep-17	10	other short-lived glacial lakes
42	Sentinel-2	10-Oct-17	10	other short-lived glacial lakes
43	Sentinel-2	10-Jun-18	10	other short-lived glacial lakes
44	Sentinel-2	17-Jun-18	10	other short-lived glacial lakes
45	Sentinel-2	22-Jun-18	10	other short-lived glacial lakes
46	Sentinel-2	22-Jun-18	10	other short-lived glacial lakes
47	Sentinel-2	27-Jun-18	10	other short-lived glacial lakes
48	Sentinel-2	27-Jun-18	10	other short-lived glacial lakes
49	Sentinel-2	27-Jun-18	10	other short-lived glacial lakes
50	Sentinel-2	30-Jun-18	10	other short-lived glacial lakes
51	Sentinel-2	7-Jul-18	10	other short-lived glacial lakes
52	Sentinel-2	7-Jul-18	10	other short-lived glacial lakes
53	Sentinel-2	7-Jul-18	10	other short-lived glacial lakes
54	Sentinel-2	10-Jul-18	10	other short-lived glacial lakes
55	Sentinel-2	22-Jul-18	10	other short-lived glacial lakes
56	Sentinel-2	25-Jul-18	10	other short-lived glacial lakes
57	Sentinel-2	25-Jul-18	10	other short-lived glacial lakes
58	Sentinel-2	27-Jul-18	10	other short-lived glacial lakes
59	Sentinel-2	27-Jul-18	10	other short-lived glacial lakes
60	Sentinel-2	30-Jul-18	10	other short-lived glacial lakes
61	Sentinel-2	30-Jul-18	10	other short-lived glacial lakes
62	Sentinel-2	1-Aug-18	10	other short-lived glacial lakes
63	Sentinel-2	1-Aug-18	10	other short-lived glacial lakes
64	Sentinel-2	1-Aug-18	10	other short-lived glacial lakes
65	Sentinel-2	1-Aug-18	10	other short-lived glacial lakes
66	Sentinel-2	1-Aug-18	10	other short-lived glacial lakes
67	Sentinel-2	4-Aug-18	10	other short-lived glacial lakes
68	Sentinel-2	4-Aug-18	10	other short-lived glacial lakes
69	Sentinel-2	4-Aug-18	10	other short-lived glacial lakes
70	Sentinel-2	9-Aug-18	10	other short-lived glacial lakes
71	Sentinel-2	11-Aug-18	10	other short-lived glacial lakes
72	Sentinel-2	11-Aug-18	10	other short-lived glacial lakes
73	Sentinel-2	11-Aug-18	10	other short-lived glacial lakes
74	Sentinel-2	11-Aug-18	10	other short-lived glacial lakes
75	Sentinel-2	14-Aug-18	10	other short-lived glacial lakes
76	Sentinel-2	14-Aug-18	10	other short-lived glacial lakes
77	Sentinel-2	14-Aug-18	10	other short-lived glacial lakes
78	Sentinel-2	16-Aug-18	10	other short-lived glacial lakes
79	Sentinel-2	16-Aug-18	10	other short-lived glacial lakes
80	Sentinel-2	16-Aug-18	10	other short-lived glacial lakes
81	Sentinel-2	16-Aug-18	10	other short-lived glacial lakes
82	Sentinel-2	20-Aug-18	10	other short-lived glacial lakes
83	Sentinel-2	29-Aug-18	10	other short-lived glacial lakes
84	Sentinel-2	31-Aug-18	10	other short-lived glacial lakes
85	Sentinel-2	31-Aug-18	10	other short-lived glacial lakes
86	Sentinel-2	31-Aug-18	10	other short-lived glacial lakes
87	Sentinel-2	31-Aug-18	10	other short-lived glacial lakes
88	Sentinel-2	3-Sep-18	10	other short-lived glacial lakes
89	Sentinel-2	5-Sep-18	10	other short-lived glacial lakes
90	Sentinel-2	5-Sep-18	10	other short-lived glacial lakes
91	Sentinel-2	5-Sep-18	10	other short-lived glacial lakes
92	Sentinel-2	8-Sep-18	10	other short-lived glacial lakes
93	Sentinel-2	8-Sep-18	10	other short-lived glacial lakes
94	Sentinel-2	13-Sep-18	10	other short-lived glacial lakes
95	Sentinel-2	30-Sep-18	10	other short-lived glacial lakes
96	Sentinel-2	30-Sep-18	10	other short-lived glacial lakes
97	Sentinel-2	27-Jun-19	10	other short-lived glacial lakes
98	Sentinel-2	27-Jun-19	10	other short-lived glacial lakes
99	Sentinel-2	27-Jun-19	10	other short-lived glacial lakes
100	Sentinel-2	30-Jun-19	10	other short-lived glacial lakes
101	Sentinel-2	5-Jul-19	10	other short-lived glacial lakes
102	Sentinel-2	12-Jul-19	10	other short-lived glacial lakes
103	Sentinel-2	15-Jul-19	10	other short-lived glacial lakes
104	Sentinel-2	30-Jul-19	10	other short-lived glacial lakes
105	Sentinel-2	1-Aug-19	10	other short-lived glacial lakes
106	Sentinel-2	4-Aug-19	10	other short-lived glacial lakes
107	Sentinel-2	4-Aug-19	10	other short-lived glacial lakes
108	Sentinel-2	9-Aug-19	10	other short-lived glacial lakes
109	Sentinel-2	11-Aug-19	10	other short-lived glacial lakes
110	Sentinel-2	11-Aug-19	10	other short-lived glacial lakes
111	Sentinel-2	11-Aug-19	10	other short-lived glacial lakes
112	Sentinel-2	11-Aug-19	10	other short-lived glacial lakes
113	Sentinel-2	29-Aug-19	10	other short-lived glacial lakes
114	Sentinel-2	29-Aug-19	10	other short-lived glacial lakes
115	Sentinel-2	31-Aug-19	10	other short-lived glacial lakes
116	Sentinel-2	31-Aug-19	10	other short-lived glacial lakes
117	Sentinel-2	31-Aug-19	10	other short-lived glacial lakes
118	Sentinel-2	3-Sep-19	10	other short-lived glacial lakes
119	Sentinel-2	3-Sep-19	10	other short-lived glacial lakes
120	Sentinel-2	23-Sep-19	10	other short-lived glacial lakes
121	Sentinel-2	23-Sep-19	10	other short-lived glacial lakes
122	Sentinel-2	25-Sep-19	10	other short-lived glacial lakes
123	Sentinel-2	25-Sep-19	10	other short-lived glacial lakes
124	Sentinel-2	25-Sep-19	10	other short-lived glacial lakes

PlanetScope

ID	Satellite	Acquisition date	Resolution (m)	lake basin extraction
1	Planet Scope	28-Jul-13	3	analysis short-lived glacial lakes
2	Planet Scope	18-Aug-13	3	analysis short-lived glacial lakes
3	Planet Scope	27-Jun-14	3	analysis short-lived glacial lakes
4	Planet Scope	30-Jun-17	3	Korumdu lake
5	Planet Scope	15-Jul-17	3	Korumdu lake
6	Planet Scope	31-Jul-17	3	Korumdu lake
7	Planet Scope	18-Aug-17	3	Korumdu lake
8	Planet Scope	10-Jul-18	3	Korumdu lake
9	Planet Scope	27-Jul-18	3	Korumdu lake
10	Planet Scope	19-Aug-18	3	Korumdu lake
11	Planet Scope	23-Aug-18	3	Korumdu lake
12	Planet Scope	29-Aug-18	3	Korumdu lake
13	Planet Scope	30-Aug-18	3	Korumdu lake
14	Planet Scope	5-Jul-19	3	Korumdu lake
15	Planet Scope	23-Jul-19	3	Korumdu lake
16	Planet Scope	8-Aug-19	3	Korumdu lake
17	Planet Scope	12-Aug-19	3	Korumdu lake
18	Planet Scope	26-Aug-19	3	Korumdu lake

ALOS/AVNIR-2

ID	Satellite	Acquisition date	Resolution (m)	Used for…
1	ALOS/AVNIR-2	2007/9/17	2.5	lake basin extraction