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ARTICLE

Draining and filling of ice-dammed lakes at the terminus of surge-type Dań Zhùr (Donjek) Glacier, Yukon, Canada

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Abstract: Recent surges of Dań Zhùr (Donjek) Glacier have formed lakes at the glacier terminus that have drained catastrophically, resulting in hazards to people and infrastructure downstream. Here we use air photos and satellite imagery to describe lake formation, and the timing of filling and draining, since the 1930s. Between the 1930s and late 1980s, lakes were typically small (<0.6 km²), took many years to form after a surge event, and drained slowly as they were displaced by the glacier advancing in the next surge. However, since 1993, the lakes have become larger (>1 km²) and drain rapidly through or under the glacier by breaking a terminal ice dam. For the past two surges, since 2001, the lakes formed during or immediately after a surge in an increasingly larger basin between the Neoglacial maximum moraine and an increasingly smaller maximum terminus extent. Most recently, the 2012–2014 surge created a lake that drained in summer 2017, refilled, and drained again in both summer 2018 and summer 2019. The 2019 lake was 2.2 km², the largest on record, and drained entirely within 2 days. While a lake is unlikely to form again before the next expected surge in the mid-2020s, future surges of Dań Zhùr Glacier are still likely to create terminal lakes, necessitating continued monitoring for surge activity and lake formation.

Key words: glacier surge, remote sensing, glacier lake outburst flood, Yukon, St. Elias Mountains.

Résumé : Les surges récentes du glacier Dań Zhùr (Donjek) ont formé des lacs au front du glacier qui se sont vidangés de manière catastrophique, posant un danger pour les humains et les infrastructures en aval. Nous utilisons des photographies aériennes et l'imagerie satellitaire pour décrire la formation des lacs et le moment de leur remplissage et de leur vidange depuis les années 1930. Entre cette décennie et la fin des années 1980, les lacs étaient typiquement petits (<0,6 km²), prenaient de nombreuses années à se former après un épisode de surge et se vidangeaient lentement au fil de leur déplacement par l'avancée du glacier durant la surge subséquente. Depuis 1993, les lacs sont cependant plus grands (>1 km²) et se vidangent rapidement à travers ou sous le glacier en brisant une obturation glaciaire frontale. Pour les deux dernières surges, depuis 2001, les lacs se sont formés durant ou immédiatement après une surge dans un bassin de plus en plus grand entre la moraine du maximum néoglaciaire et l'étendue maximum de plus en plus restreinte du front. La surge la plus récente de 2012–2014 a entraîné la formation d'un lac qui s'est vidangé à l'été 2017, puis s'est rempli et vidangé à nouveau aux étés 2018 et 2019. Le lac de 2019 faisait 2,2 km², soit le plus grand lac observé, et s'est complètement vidangé en deux jours. S'il est peu probable qu'un autre lac se forme avant la prochaine surge prévue au milieu de la décennie 2020, les surges futures du glacier Dań Zhùr sont toujours susceptibles de créer des lacs frontaux, nécessitant ainsi une surveillance continue de l'activité de surge et de la formation de lacs. [Traduit par la Rédaction]

Mots-clés : surge glaciaire, télédétection, débâcle de lac glaciaire, Yukon, St. Elias Mountains.

Introduction

Glacier-dammed lakes pose a threat to downstream infrastructure and communities because glacial lake outburst floods can occur rapidly with little or no warning. Surge-type glaciers pose a unique set of hazards because they periodically advance and retreat, providing a mechanism for the regular damming and drainage of such lakes. Surge-type glaciers have two phases, a quiescent phase, typically lasting approximately 10–100 years, when the glacier velocity is very slow, and an active phase, typically lasting approximately 1–10 years, during which time the glacier advances (Meier and Post 1969). During their advance, surge-type glaciers can block rivers and form terminal or ice marginal lakes, which typically become unstable in the ensuing months and years as the stagnant ice melts. Depending on the volume and discharge of the lake when it drains, these transient water bodies can cause downstream damage (Bhambri et al. 2019).

Both Alaska–Yukon and Karakoram have high concentrations of ice-dammed lakes (Hewitt 1982) and surge-type glaciers (Sevestre and Benn 2015). Bhambri et al. (2019) identified 146 ice dams and outburst floods that have occurred in the Karakoram since 1533, resulting in at least 30 major disasters. These floods have caused damage to downstream infrastructure including roads, bridges, and agricultural terraces (Hewitt and Liu 2010), as much as 1200 km from the source (Bhambri et al. 2019).

The St. Elias Mountains also have surge-type glacier-dammed lakes, although fewer than the Karakoram. Post and Mayo (1971) identified and mapped 750 glacier-dammed lakes or former lakes in southeastern Alaska, south-central Alaska, and southwestern Yukon, although most of these do not form as a result of surging. The most famous lake formed by a glacier surge occurred at the terminus of Náłúdäy (Lowell) Glacier, which blocked the Alsek River repeatedly over a century ago (Clague and Rampton 1982). The resulting lake, Neoglacial Lake Alsek, was over 100 km long

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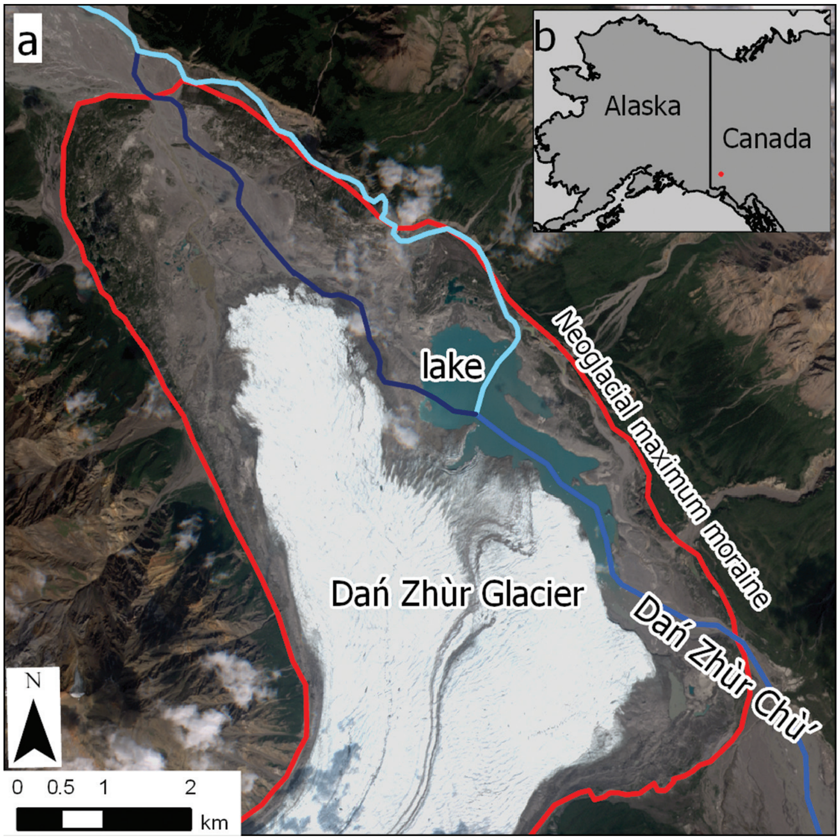
Fig. 1. (*a*) Terminus of Dań Zhùr Glacier as seen on 5 July 2019 (Sentinel-2). Recent Dań Zhùr Chù' (medium blue) paths are shown when the lake is full (moraine path; light blue) and when the lake is empty and an ice canyon is present (dark blue). The dry river bed to the southeast is where Dań Zhùr Chù' flowed at a more advanced position before the 1990s. The Neoglacial maximum moraine (red) wraps around the terminus of Dań Zhùr Glacier. Sentinel-2 image is supplied courtesy of the U.S. Geological Survey. (*b*) Inset map showing study location (red dot). Data source: Natural Earth version 4.1.0 (www.naturalearthdata.com). [Colour online.]



and 200 m deep at its maximum and flooded the present-day town site of Haines Junction (Bevington and Copland 2014). When this dam broke, a flash flood killed Yakutat Tlingit people camped downstream at the junction of the Tatshenshini and Alsek rivers (Cruikshank 1981). The 1965–1968 surge of Steele Glacier formed a small lake, which produced minor outburst floods into Dań Zhùr Chù' (Donjek River) valley without any significant damage (Collins and Clarke 1977; Clarke 1982). Surges of other glaciers in the region could form an ice dam at their termini (Post and Mayo 1971), including Black Rapids and Tweedsmuir glaciers, which could dam the Delta and Alsek rivers, respectively, although no recent blockages have been observed.

We describe the timing and mechanisms of lake formation and drainage at the terminus of Dań Zhùr Glacier since the 1930s in relation to repeated surges of the glacier. Although there has been previous modelling of the potential for glacial lake outburst floods caused by this ice body (Clarke and Mathews 1981), there have been no studies of recent events.

Study region

Dań Zhùr Glacier (61.21°N, 139.51°W; Fig. 1) is located in the St. Elias Mountains, Yukon, Canada. We use the original Southern Tutchone name here, Dań Zhùr Glacier, instead of the name used in recent scientific literature, Donjek Glacier. Similarly, we use Dań Zhùr Chù' instead of Donjek River.

Dań Zhùr Glacier is part of Kluane First Nation traditional territory, which is used for hunting and fishing, as well as Kluane National Park and Reserve, which brings rafters and hikers to Dań Zhùr Chù' valley. The Alaska Highway is located 56 km downstream from the glacier terminus, where a bridge has crossed the river since the 1940s; it was most recently replaced in 2008. The status of temporary lakes above these subsistence and recreational lands, and an important transportation artery, is therefore of concern to users of the valley. Dań Zhùr Chù' headwaters are located on and around Kluane Glacier, 24 km upstream from Dań Zhùr Glacier.

During Neoglacial (Little Ice Age) times, Dań Zhùr Glacier was more extensive than it is today. Radiocarbon dating of spruce logs embedded in end moraines indicates that this advance occurred 280–340 years ago, with ring counts of trees growing on the moraines indicating that Dań Zhùr Glacier was retreating before 1825 (Porter and Denton 1967). This moraine was later mapped by Johnson (1972), who referred to it as the "maximum Neoglacial terminal moraine" and "Neoglacial maximum moraine". This moraine plays an important role in causing the damming of Dań Zhùr Chù', and we refer to it as the Neoglacial maximum moraine throughout this paper. Its extent is mapped in Fig. 1.

Dań Zhùr Glacier has a long history of surging, dating back at least hundreds of years in Oral Traditions (Cruikshank 1981), and to the 1930s in scientific records (Kochtitzky et al. 2019). Geomorphic evidence suggests that Dań Zhùr Chù' has been dammed, causing lake formation, at least four times since 1270, and most recently drained between 1810 and 1840 (Perchanok 1980). We refer to lake formation prior to 1840 as Neoglacial Lake Dań Zhùr to distinguish these events from the recent lakes we describe here.

Dań Zhùr Glacier has undergone eight surge events since the 1930s, or approximately one surge every 12 years (Abe et al. 2016;

Table 1. Description of air photos used in this study.

Photo ID	Date	Source	Tie points	RMSE of georectification
wb0516	14 August 1937	Washburn/UAF	n/a	n/a
A11002-274	24 July 1947	RCAF	8	114 m
A15434-179	10 August 1956	RCAF	8	92.0 m
PHColl734.YD24	1961	Post/UW	n/a	n/a
PHColl734.YD32	25 August 1968	Post/UW	n/a	n/a
PHColl734.YD37	27 August 1969	Post/UW	n/a	n/a
A24758-088	27 July 1977	RCAF	8	67.1 m
A24952-022 to 25	3 July 1978	RCAF	8	21.0 m

Note: UAF, University of Alaska Fairbanks; UW, University of Washington; RCAF, Royal Canadian Air Force; RMSE, root mean square error.

Kochtitzky et al. 2019), causing the glacier to temporarily advance, at times partially blocking Dań Zhùr Chù'. During a surge, mass is transported downglacier towards Dań Zhùr Chù', causing the glacier terminus to increase in area by ~2 km², although each successive surge has been less extensive due to a long-term negative surface mass balance (Larsen et al. 2015; Kochtitzky et al. 2019). Dań Zhùr Glacier most recently surged from summer 2012 to winter 2013–2014.

Modelling by Clarke and Mathews (1981), using hypsometric data mapped from 1956 stereo air photography, suggested that a full blockage of Dań Zhùr Chù', such as the pre-1840 blockage, could create a 12.3 km² lake with a maximum depth of 60 m and volume of 0.234 km³. A sudden release of such a lake, as likely occurred with Neoglacial Lake Dań Zhùr, would result in a modeled maximum peak discharge of 5968 $m^3 \cdot s^{-1}$, which could be devastating for infrastructure downstream. However, such a large lake has not formed recently as surges have not been voluminous enough to completely block Dań Zhùr Chù' since the early 1800s (Kochtitzky et al. 2019).

Methods

Air photos

Air photos provide snapshots of conditions at the glacier terminus in summers between 1937 and 1978. The earliest photo, taken by Bradford Washburn on 14 August 1937, was acquired from the Alaska and Polar Regions Collections and Archives at the Elmer E. Rasmuson Library at the University of Alaska Fairbanks (Table 1). Photos taken by Austin Post between 1961 and 1969 were acquired from the University of Washington Special Collections. Because the Washburn and Post photos are oblique, we did not georectify them, although we did compare the extent of lakes visible in them with georectified nadir images to produce area estimates.

Other photos were taken by the Royal Canadian Air Force in 1947, 1956, 1977, and 1978. These nadir pointing photos were taken from the underside of an aircraft and were acquired from the Yukon Energy, Mines, and Resources Library in Whitehorse, Yukon. We georectified these photos in ArcGIS 10.5 with a maximum positional uncertainty of 114 m (Table 1) using eight tie points to a 0.49 m resolution WorldView-2 image from 2 September 2012.

Satellite imagery

To provide a continuous (at least annual) record of lake filling and draining since 1973, we reviewed >3000 Earth-observing optical satellite images with a 30 m minimum horizontal resolution of the terminus of Dań Zhùr Glacier. To examine the early part of the satellite archive, we downloaded images from the United States Geological Survey Earth Explorer website (https://earthexplorer.usgs.gov/), including 8 Landsat-1 scenes from 1973–1977, 12 Landsat-2 scenes from 1975–1980, 3 Landsat-3 scenes from 1978–1980, and 4 Landsat-4 scenes from 1982–1985. We used Descartes Labs software version 0.27.0 to visualize the lake area in 10 Landsat-4 scenes from 1988, 479 Landsat-5 scenes from 1984–2011, 124 Landsat-7 scenes from 2016–2019, 229 Landsat-8 scenes from 2016–2019, and 725 Sentinel-2 scenes from 2015–2019. Early images from some satellite sensors were missing from the Descartes platform, so for these we used the Google Earth Engine Digitization Tool (Lea 2018) to visually examine 736 Landsat-7 scenes from 1999–2016, 365 Landsat-8 scenes from 2013–2016, and 287 Sentinel-1 scenes from 2014–2019. We additionally examined 639 scenes from the Planet Labs image archive (3–4 m resolution) from 2016–2019 to further constrain event timing (Planet Team 2017).

Images were analyzed for the presence or absence of standing water (i.e., lake) at the glacier terminus using the normalized difference water index (NDWI) to aid in visual interpretation of false colour images:

$$\text{NDWI} = (\text{Green} - \text{NIR})/(\text{Green} + \text{NIR}) \quad (1)$$

where Green and NIR are the green and near infrared bands, respectively, from the Landsat and Sentinel-2 satellites. After visual inspection of each image, we manually digitized the lake for area calculations. All area calculations were performed in a UTM 7N WGS84 projection. In this paper, we show images that are important for lake analysis; all figures show a false colour image when possible and useful. Our analysis focuses on the largest, most significant lake area changes that provide insight into lake formation and drainage to improve hazard forecasting. Small transient lake changes also occurred throughout the years, likely due to weather and associated changes in melt and river discharge, and are not described further.

Error analysis

Although we use imagery from a variety of sources, lakes smaller than 0.05 km² are difficult to quantify and are not described here beyond their presence. Practically speaking, these lakes are not hazardous due to their small volume. We used methods described by Haritashya et al. (2018) and Krumwiede et al. (2014) to determine uncertainty in lake area. Assuming our outlines are within half a pixel of the "true" lake outline, we find a maximum uncertainty of 0.17 km² for the largest lake observed, or 7.7%. However, this study is focused on comparing the relative size of lakes over time, which has much less uncertainty. As such, we used eq. 22.3 in Krumwiede et al. (2014) to quantify the precision of our observations and find that our precision of lake area outlines is 2.5%. This number is more appropriate to use as the uncertainty in this study as we focus on understanding the relative changes in lake size over time.

Results

Surge events occurred on Dań Zhùr Glacier in ~1935, ~1947, late 1950s, ~1969, 1977–1980, 1988–1990, 2000–2002, and 2012–2014 (Kochtitzky et al. 2019). We frame our results around these surge events because changes in the glacier terminus position provide the primary driver for lake formation and drainage. With-

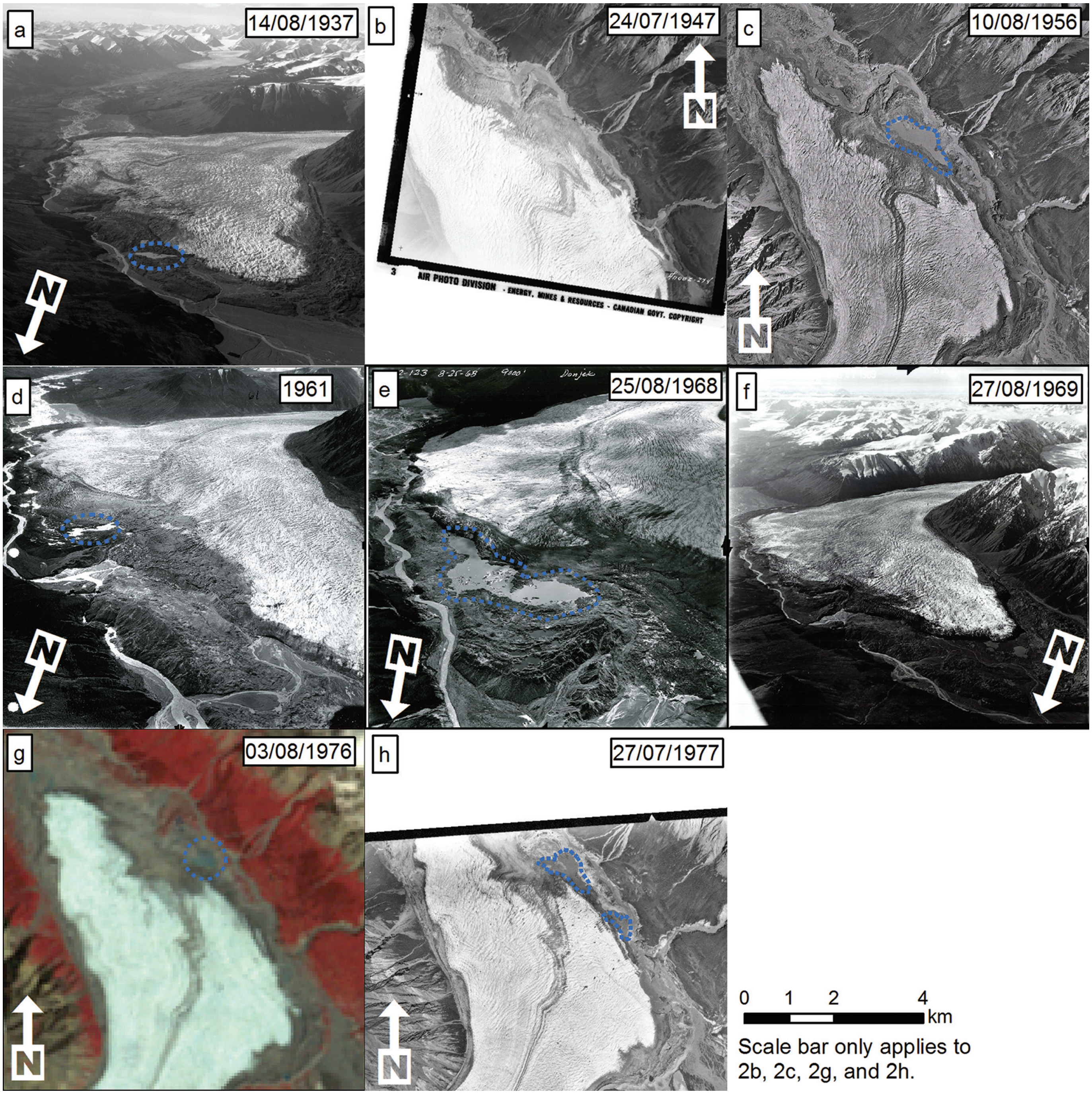


Fig. 2. Air photos of Dań Zhùr Glacier: (*a*) 14 August 1937, taken by Bradford Washburn; (*b*) 24 July 1947, RCAF (A11002-274); (*c*) 10 August 1956, RCAF (A15434-179); (*d*) 1961, taken by Austin Post; (*e*) 25 August 1968, taken by Austin Post; (*f*) 27 August 1969, taken by Austin Post; (*g*) 3 August 1976, Landsat 2; (*h*) 27 July 1977, RCAF (A24758-088). Blue dashed outlines indicate lakes discussed in text. RCAF photographs courtesy of the Yukon Energy, Mines, and Resources Library. Austin Post photographs courtesy of Special Collections, University of Washington Libraries (PHColl734.YD24, PHColl734.YD32, PHColl734.YD37). Bradford Washburn photograph (WB0516) from the Bradford Washburn Photograph Collection at the Archives of the University of Alaska Fairbanks. [Colour online.]

out these periodic advances, lakes would not form at the terminus of Dań Zhùr Glacier.

Prior to 1977–1980 surge event

In the early- to mid-20th century, surges of Dań Zhùr Glacier were not large enough to block the Dań Zhùr Chù', but were sufficient enough to fill the Dań Zhùr Chù' valley such that it was difficult for large (>0.5 km^2) lakes to form. Whereas data are sparse prior to the satellite era, air photos provide snapshots of Dań Zhùr's history. The first known air photo of the glacier from 1937 shows what might be a small lake of <0.2 km^2 within the Neoglacial maximum moraine (Fig. 2*a*). A 24 July 1947 air photo shows Dań Zhùr Glacier just after a surge event without any lake (Fig. 2*b*). Although Dań Zhùr Chù' was pushed to the north side of the valley, the glacier did not dam the river at this time. This photo shows the most advanced position of Dań Zhùr Glacier captured in the historical record and indicates that the glacier has never completely blocked water flow through Dań Zhùr Chù' valley since at least the 1940s, as almost every surge has been less extensive than the last since the 1930s. The exception to this pattern is the 1978 surge when the terminus extended as much as 200 m further than the 1969 surge, although Dań Zhùr Chù' was not dammed during this event.

By the mid-1950s, Dań Zhùr Glacier had retreated from its late 1940s surge extent (Kochtitzky et al. 2019), which allowed a 0.27 km² lake to form in the newly created basin adjacent to the terminus (Fig. 2*c*). However, the lake did not appear to be fed by the river, with the river remaining outside the moraine created by the ~1947 surge. This lake was nearly gone by 1961 (Fig. 2*d*), after a late 1950s surge (Kochtitzky et al. 2019) presumably displaced it.

By 1968, the glacier had retreated, allowing a <0.6 km² lake to form in the new space (Fig. 2*e*). In ~1969, Dań Zhùr Glacier surged and again displaced this lake (Fig. 2*f*). During the ensuing quiescent phase, the glacier retreated, allowing the ice-marginal lake to form again. Landsat 1 and 2 images show a lake forming in 1976, although the extent is poorly constrained due to the 60 m resolution (Fig. 2*g*). The lake increased in size until 1977, when air photos show two lakes with a combined area of 0.58 km² along the glacier margin (Figs. 2*h* and 3). There was also a third 0.26 km² lake, or widening of the river, to the southeast of this lake.

1977–1980 surge event and subsequent quiescent phase

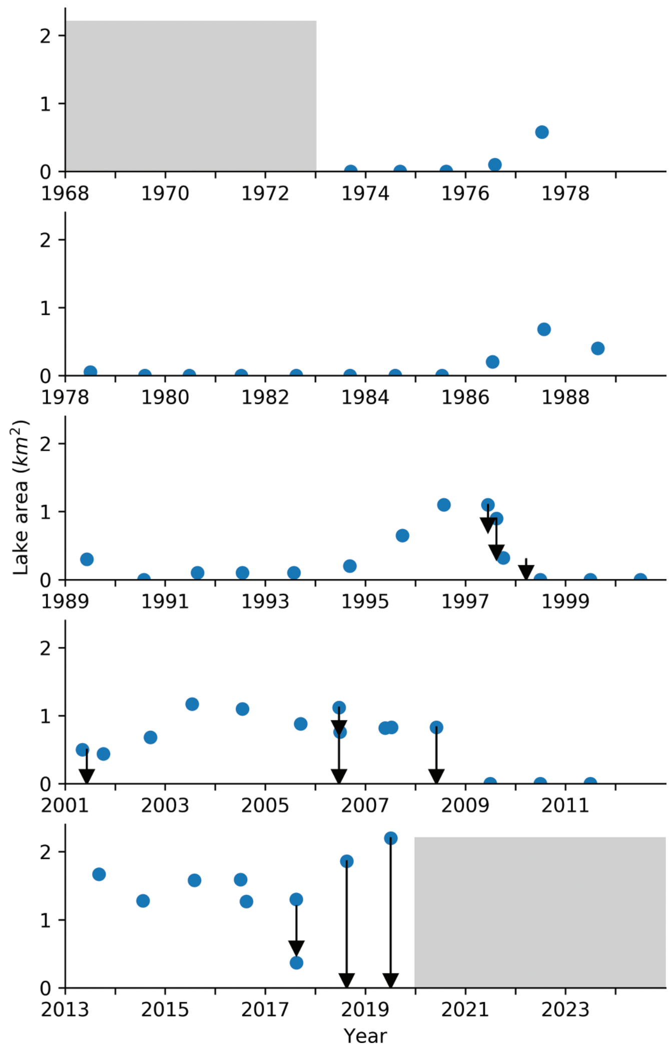
The advance of Dań Zhùr Glacier due to the 1977–1980 surge pushed out the lakes that formed at the terminus before the surge began and replaced them with glacier ice (Figs. 3 and 4*a*). By 1978, only a few small pools of water were left, totaling <0.05 km² (Fig. 5*a*). By July 1986, a small 0.2 km² lake had formed at the terminus in the space left by the stagnant, melting ice (Fig. 5*b*). A 0.33 km² ice marginal lake may have also been present along the southern terminus in 1986, although the extent to which this was just a widening of the river is unclear. The next surge began in summer 1988 (Kochtitzky et al. 2019), but the lake changed minimally from 1986 to 1989 (Fig. 5*c*).

1988–1990 surge event and subsequent quiescent phase

Dań Zhùr Glacier surged for 1.97–2.15 years between 1988 and 1990 (Kochtitzky et al. 2019), again displacing the lakes at the terminus (Fig. 3). In 1989, the lake was nearly gone (Fig. 6*a*) and, by July 1990, had entirely drained (Fig. 6*b*). The glacier terminus remained without a substantial lake until the summer of 1993, with only small lakes of <0.1 km² present on the Neoglacial maximum moraine (Fig. 6*c*). A basin appeared between 13 August and 14 September 1993 (Fig. 6*d*) that seems to have been formed by Dań Zhùr Chù' being rerouted beneath the eastern glacier terminus without forming a lake, although the exact mechanism is not understood. By summer 1994, a 0.18 km² lake had formed within that basin (Fig. 6*e*). By summer 1995, two similarly sized lakes grew to the southeast (Fig. 6*f*), to create a total lake area of 0.65 km², with these lakes remaining in 1996. By May 1997, a new lake had reappeared to the north (Figs. 4*b* and 6*g*), raising the total lake area to 1.1 km². However, between 30 June and 15 August 1997, the northern lake drained (Fig. 6*h*), leaving behind the now larger southern lake at 0.90 km². During fall 1997, the northern part of the southern lake drained, leaving 0.32 km² of lakes to the southeast (Fig. 6*i*).

In spring 1998, the remaining portion of these lakes drained as they became part of Dań Zhùr Chù', with the river rerouting under the glacier terminus in a subglacial channel (Fig. 7*a*). Subsequently, the ice roof over the subglacial channel partially collapsed, creating a sinuous ice canyon (Fig. 7*b*). By 28 September 1998, the channel roof had collapsed along the length of the glacier terminus and fully exposed the river to the atmosphere (Fig. 7*c*). This >4 km long ice canyon prevented lakes forming in either 1999 or 2000 (Fig. 3), before the next surge event, as it allowed water to easily drain from the glacier terminus.

Fig. 3. Lake area by surge cycle; arrows indicate partial or full lake drainage (shown by arrow length). Subplots start with the first full year after a surge has initiated and show total lake area for the ensuing quiescent phase. Grey areas indicate time periods for which data are not available. Lake area observation precision is ~2.5% or less than the size of the plotted point. [Colour online.]



2000–2002 surge event and subsequent quiescent phase

During winter 2000–2001, the initial surge of Dań Zhùr Glacier was sufficient to block the river and form five small lakes totaling 0.50 km² at the terminus (Fig. 8*a*). However, these lakes emptied, except for the far southern lake, between 8 June and 3 July 2001 (Figs. 3 and 8*b*; Table 2). By the beginning of September 2001, Dań Zhùr Glacier had again advanced far enough that a dam was remade near the northern part of the terminus, which started increasing in size again (Fig. 8*c*). By October 2001, the lake was 0.44 km² with an additional 0.22 km² lake to the southeast (Fig. 8*d*). During the 2002 melt season, the lake area continued to increase, reaching 0.68 km² by September 2002 (Fig. 8*e*). The lakes continued to grow during the 2003 melt season, reaching 1.17 km² in July 2003 (Fig. 8*f*), although it is difficult to distinguish between the river and a lake in some locations. That fall, both lakes decreased in size, but the lakes persisted throughout 2004, 2005, and 2006 without draining.

On 23 June 2006, the total lake area was 1.12 km² (Fig. 9*a*); however, by 30 June 2006, the northern lake had drained, leaving behind the now 0.76 km² southern lake (Fig. 9*b*). Between 30 June and 2 August 2006, the southern lake also drained (Table 2), likely

Fig. 4. Maximum glacier extent, minimum glacier extent, and largest lake area for each of the past four surge-quiescent cycles: (*a*) 1979–1988, (*b*) 1990–2000, (*c*) 2002–2012, (*d*) since 2014. (*e*) Inset map showing location of Figs. 4*a*–4*d*. The maximum surge extent observed in the historical record in 1947 is shown for reference in Figs. 4*a*–4*d*. Areas where the minimum quiescent extent is downglacier (north) of a lake indicates areas of glacier advance after lake drainage and before the next surge. Blue outlines indicate the maximum lake extent observed before the next surge occurs. Landsat images supplied courtesy of the U.S. Geological Survey. [Colour online.]

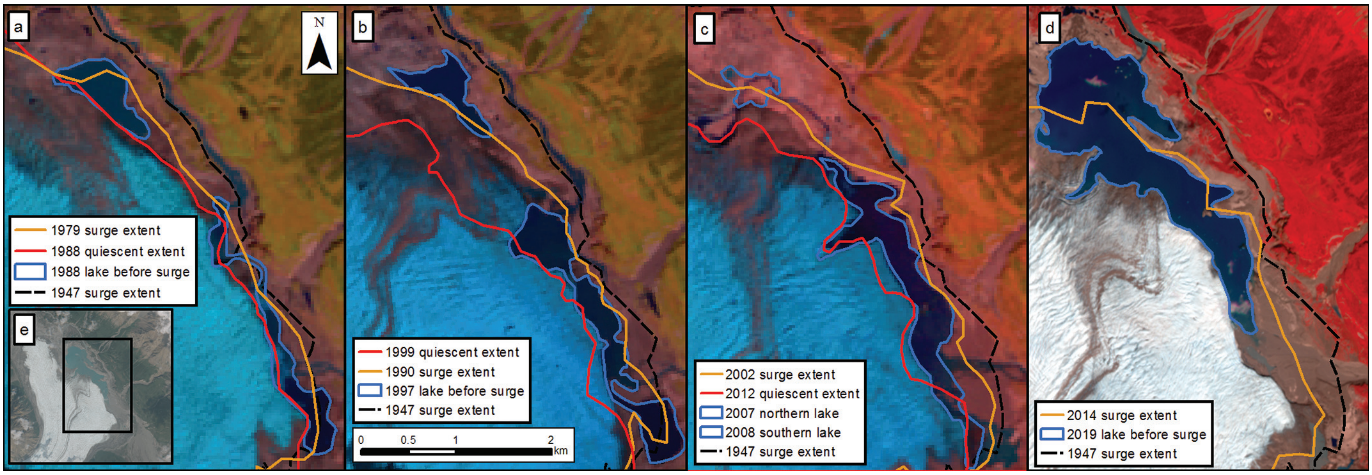
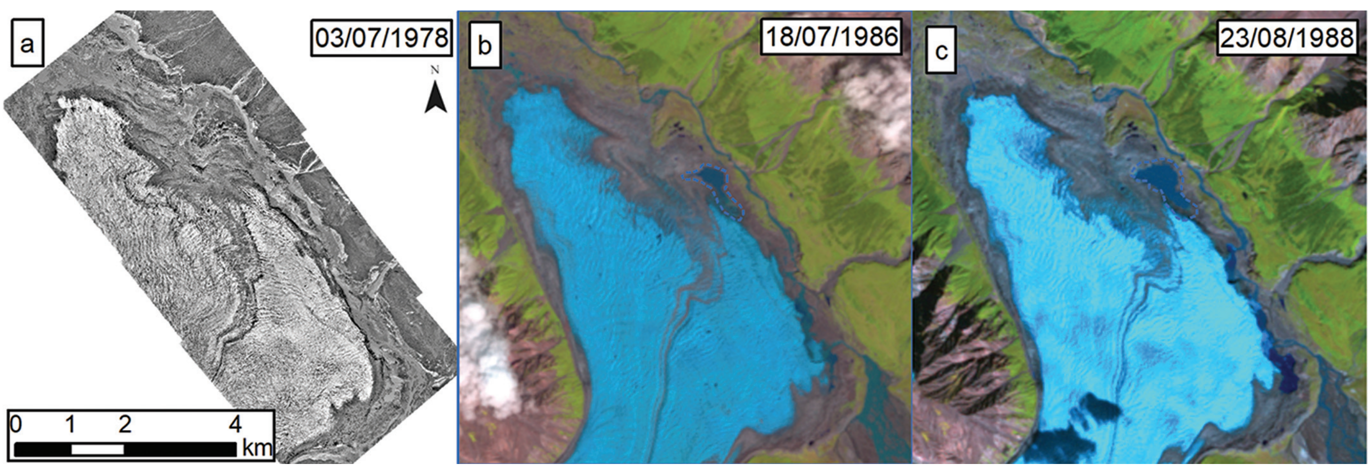


Fig. 5. Lakes in relation to the 1977–1979 surge event: (*a*) 3 July 1978, RCAF (A24952–22 to 25) from the Yukon Energy, Mines, and Resources Library in Whitehorse, Yukon; (*b*) 18 July 1986, Landsat 5; (*c*) 23 August 1988, Landsat 5. Blue dashed outlines indicate lakes discussed in the text. RCAF photographs courtesy of the Yukon Energy, Mines, and Resources Library. Landsat images supplied courtesy of the U.S. Geological Survey. [Colour online.]



subglacially through a rupture in the glacier close to the location of the start of the 1998 ice canyon. On 9 August 2006, the rupture was <60 m across, but had grown to be up to 150 m wide and 660 m long that fall as the river was rerouted under the glacier (Fig. 9*c*).

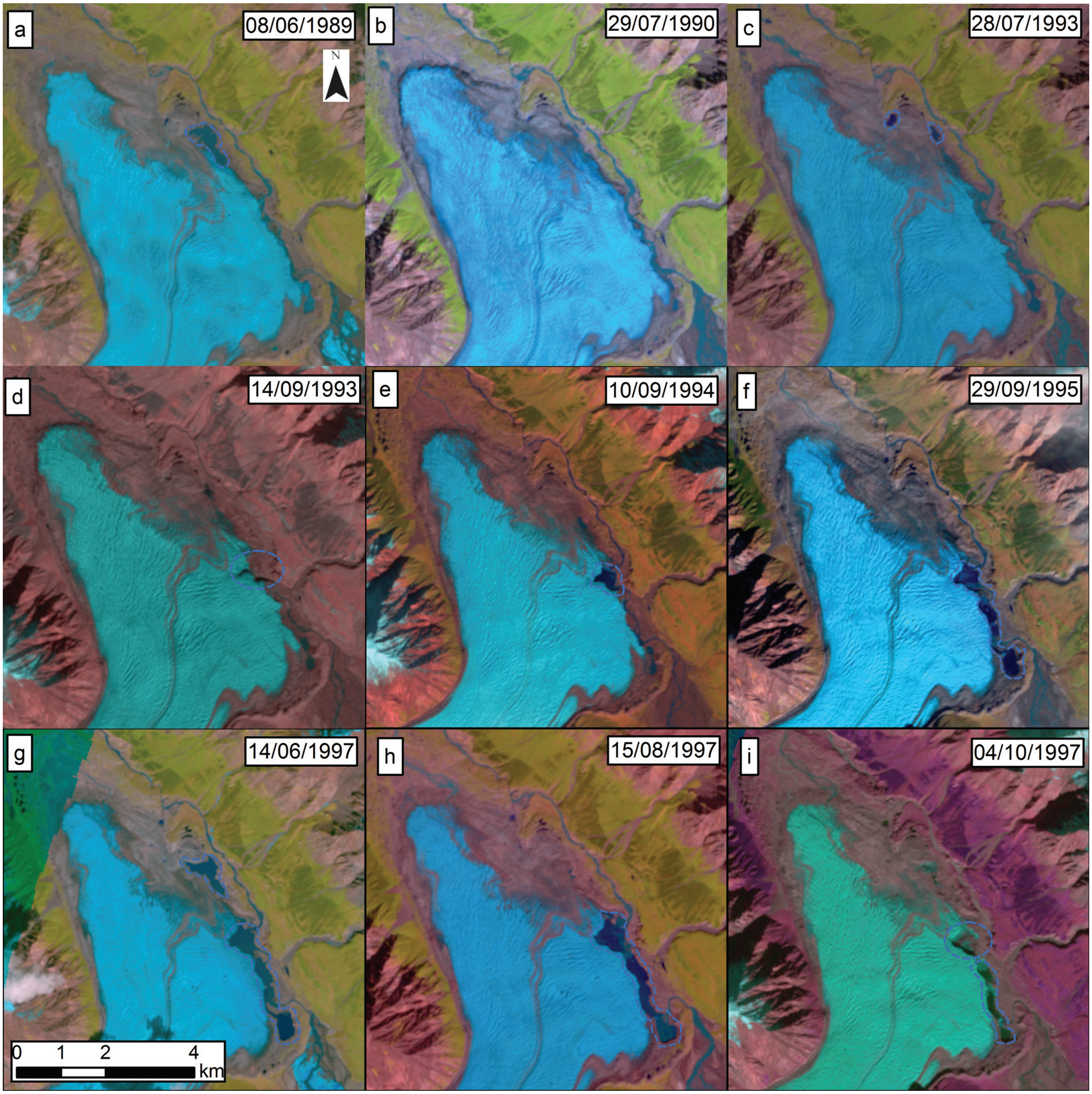
During winter 2006–2007, the glacier motion closed off the subglacial river channel, enabling the southern lake to re-establish before 25 May 2007 (Fig. 9*d*). At the same time, a 0.15 km^2 northern lake formed again (Fig. 9*d*). However, the northern lake did not last long, as it drained between 4 July and 10 July 2007, leaving just a 0.82 km^2 southern lake for the remainder of the year (Fig. 9*e*). The 0.82 km^2 southern lake lasted into early 2008 but drained between 3 June and 28 July 2008 (Table 2; Fig. 4*c*), rerouting the river along the terminus of the glacier instead of reoccupying the subglacial channel (Fig. 9*f*). After this, the river continued flowing along the terminus, and no lakes formed again until the next surge event (Fig. 3).

After the 2012–2014 surge event

The 2012–2014 surge once again dammed Dań Zhùr Chù' and formed lakes. During the winter of 2012–2013, lakes formed in the same northern and southern positions as in previous surges and grew in size to reach a maximum total area of 1.67 km^2 at the end of the 2013 melt season (Fig. 10*a*). The lakes persisted through 2014, 2015, and 2016 (Figs. 3, 11), when the northern and southern lakes connected between 4 July (Fig. 10*b*) and 16 August 2016 (Fig. 10*c*). This lake level dropped, indicating that the southern lake surface was at a higher elevation than the northern lake, and reduced the total lake area to 1.27 km^2 by 16 August 2016. The lake remained in this configuration throughout the winter, growing slightly to 1.3 km^2 by 15 August 2017 (Fig. 10*d*). By the next day, it had almost completely drained (Fig. 10*e*; Table 2), although 0.37 km^2 of water remained in the basin for the remainder of the year.

The lake refilled between November 2017 and January 2018 and had grown to 1.86 km^2 on 18 August 2018 (Fig. 10*f*). Between 19 August and 21 August 2018, the lake drained with the river flowing out under the glacier (Fig. 10*g*; Table 2). Between November 2018 and January 2019, the lake once again refilled. By 5 July 2019, the lake had reached an area of 2.2 km^2, the largest area

Fig. 6. Lakes after the 1988–1990 surge event: (*a*) 8 June 1989, Landsat 5; (*b*) 29 July 1990, Landsat 5; (*c*) 28 July 1993, Landsat 5; (*d*) 14 September 1993, Landsat 5; (*e*) 10 September 1994, Landsat 5; (*f*) 29 September 1995, Landsat 5; (*g*) 14 June 1997, Landsat 5; (*h*) 15 August 1997, Landsat 5; (*i*) 4 October 1997, Landsat 5. Blue dashed outlines indicate features discussed in the text. Landsat images supplied courtesy of the U.S. Geological Survey. [Colour online.]



recorded (Fig. 10*h*), but then drained between 11 July and 14 July (Table 2; Fig. 4*d*). A Sentinel-1 scene taken at 20:02:48 local time (UTC −7) on 13 July 2019 shows a partially drained lake and a Planet Scope scene taken at 13:11:09 local time (UTC −7) shows an empty lake on 14 July, indicating this was the day of the drainage event. The next optical image of the drained lake bed was 27 July 2019 (Fig. 10*i*). When the 2019 lake drained, it created another ice canyon through the glacier, which Dań Zhùr Chù' now occupies (Fig. 10*i*).

Discussion

Clarke and Mathews (1981) hypothesized that a 12.3 km² lake could form at the terminus of Dań Zhùr Glacier if a surge blocked the entire river valley, but no lake of this size has been observed in the air photo record or otherwise described since 1825. Instead, due to continually less extensive surges since the 1930s (Abe et al. 2016; Kochtitzky et al. 2019), lakes of increasing size have been forming at the terminus due to partial damming of Dań Zhùr Chù' and flooding of a basin created as the glacier retreated after surge

Fig. 7. Ice canyon before the 2000–2002 surge event: (*a*) 1 June 1998, Landsat 5; (*b*) 17 July 1998, Landsat 5; (*c*) 28 September 1998, Landsat 5. Blue dashed outlines indicate ice canyon discussed in the text. Images supplied courtesy of the U.S. Geological Survey. [Colour online.]

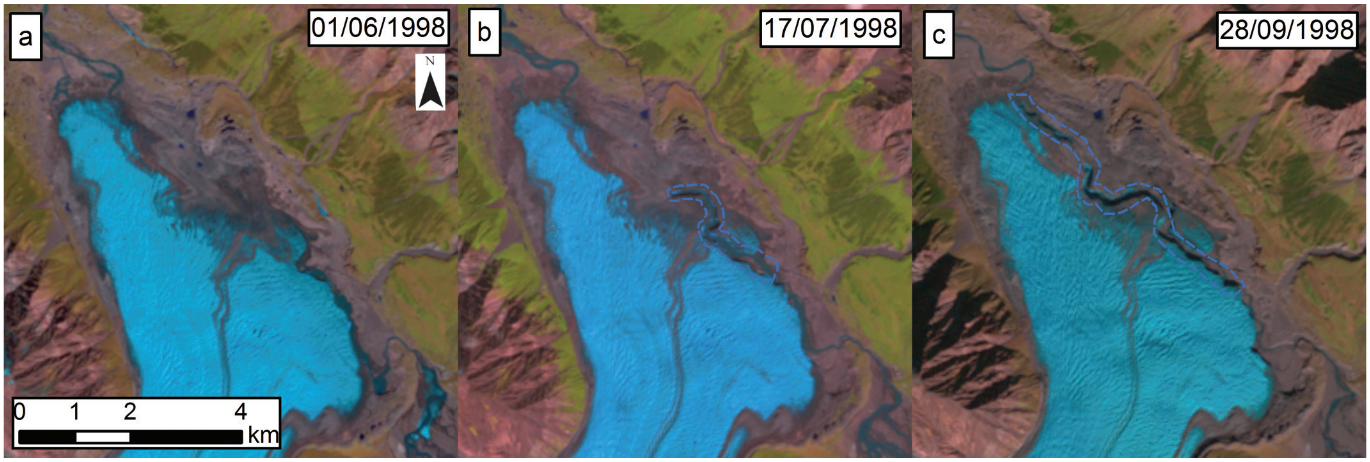
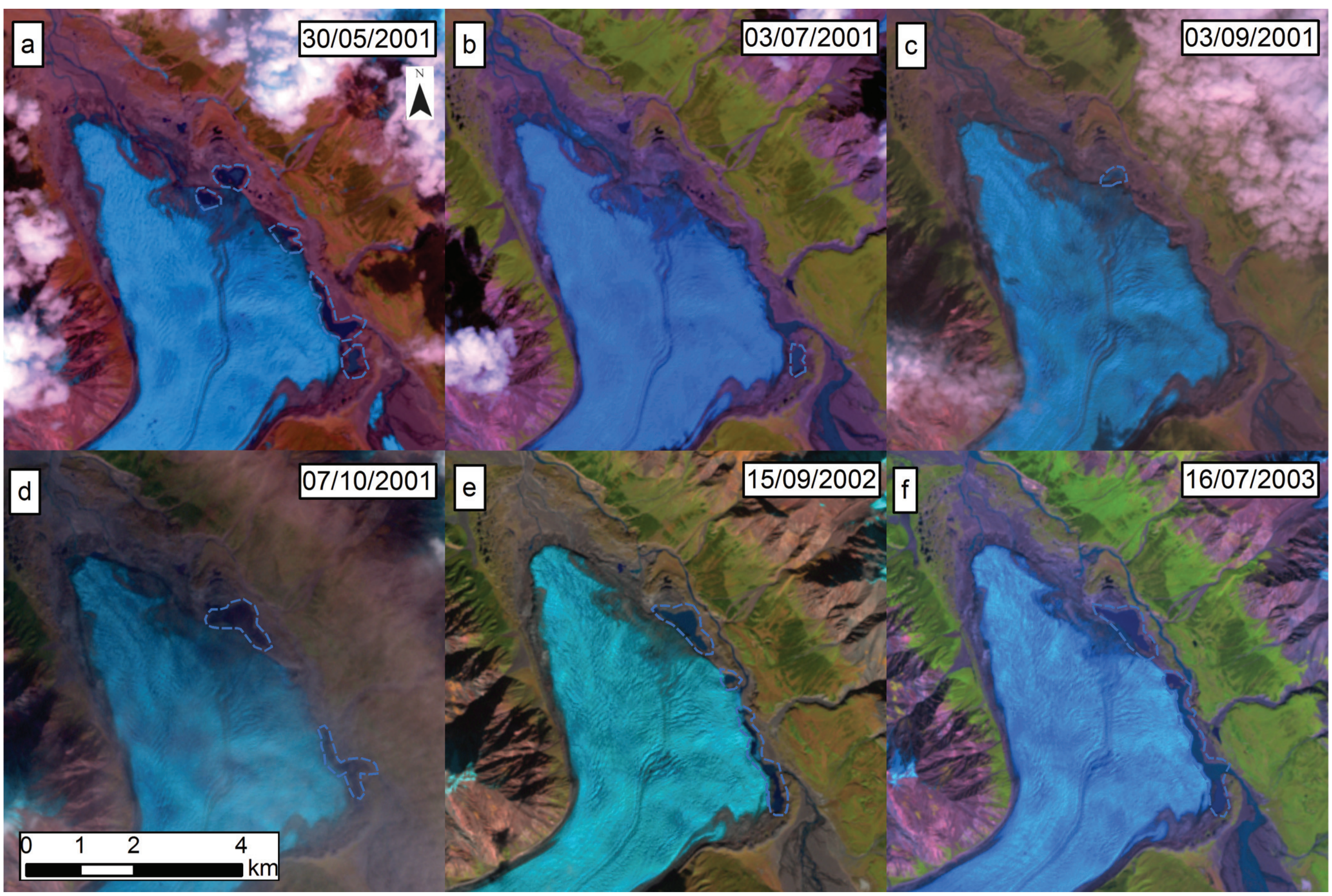


Fig. 8. Lakes immediately following the 2000–2002 surge event: (*a*) 30 May 2001, Landsat 7; (*b*) 3 July 2001, Landsat 7; (*c*) 3 September 2001, Landsat 7; (*d*) 7 October 2001, Landsat 7; (*e*) 15 September 2002, Landsat 7; (*f*) 16 July 2003, Landsat 7. Blue dashed outlines indicate features discussed in the text. Images supplied courtesy of the U.S. Geological Survey. [Colour online.]



events. While much smaller in size than the hypothesized 12.3 km² Neoglacial Lake Dań Zhùr, the drainage of these recent lakes is still potentially hazardous for downstream recreational activities. A news story by the Canadian Broadcasting Corporation described the hazards from the 2019 lake drainage event from high water and sedimentation in the Dań Zhùr Chù' valley, including on the hiking trail and at a seasonal residence (McColl 2019).

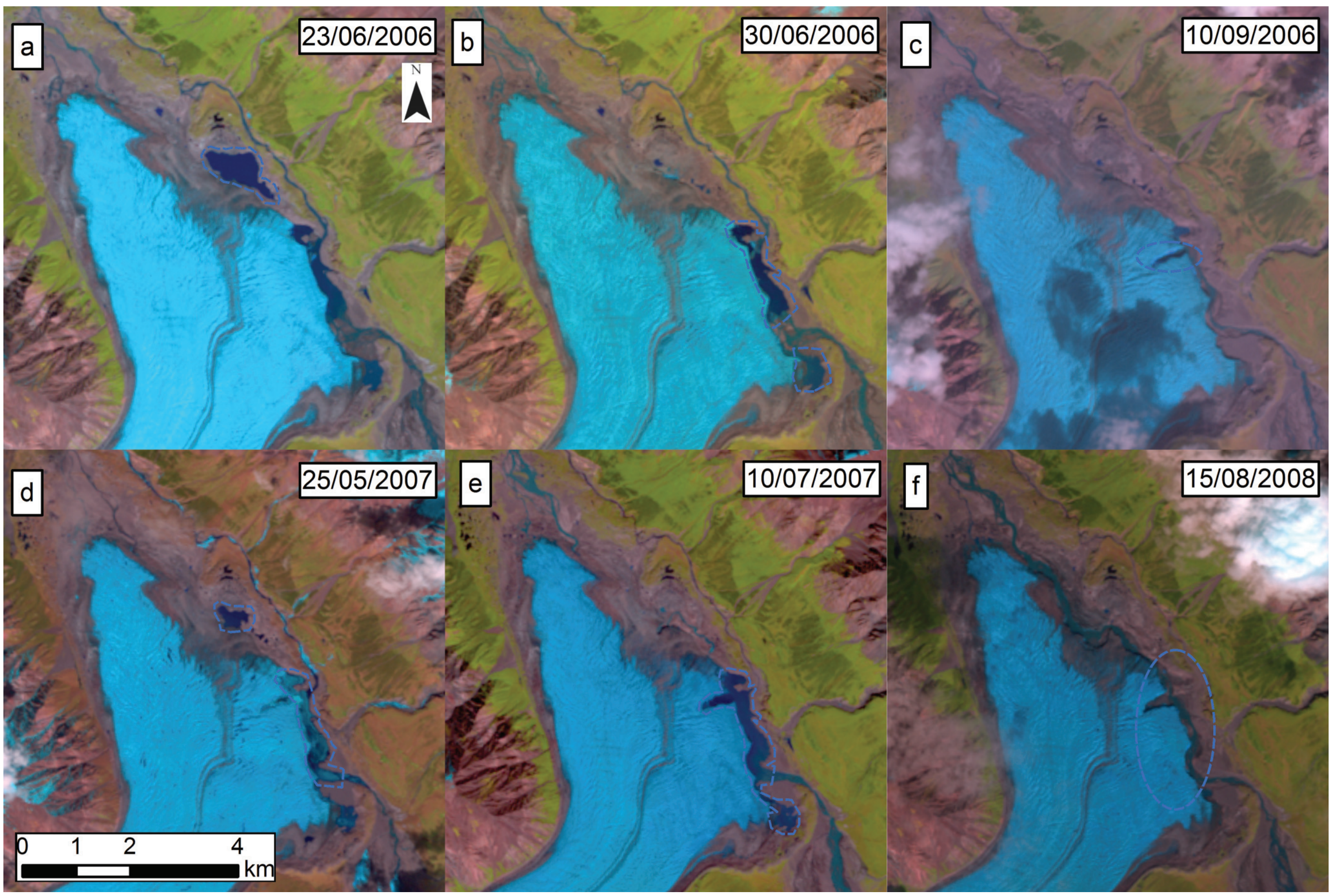
The details of Dań Zhùr lake formation and drainage have evolved over time as changes in terminus geometry have altered the ways in which the glacier and river interact. Lakes before the late-1980s surge of Dań Zhùr Glacier were formed during the quiescent phase, as the glacier retreated and allowed meltwater to pool at the terminus. These lakes were relatively small (<0.6 km²), only formed after >6 years of quiescence, and did not appear to

Table 2. Timing of lake formation and drainage at Dań Zhùr Glacier for lakes >0.5 km².

Time lake formed	Period lake drained	Lake age	Lake size (km²)
Summer 1994	Three events from 30 June 1997 to 20 March 1998	3–3.5 years	1.1*
Winter 2000–2001	8 June to 2 July 2001	6–8 months	0.50
Summer 2001	23 June to 2 August 2006	5 years	0.76
Winter 2006–2007	3 June to 28 July 2008	18–20 months	0.82
Winter 2012–2013	15–16 August 2017	4.5 years	1.30
Winter 2017–2018	19–21 August 2018	8–10 months	1.86
Winter 2018–2019	11–14 July 2019	7–9 months	2.20

*The entire lake did not drain at once; the largest event in 1997 reduced lake area by 0.58 km².

Fig. 9. Lakes after the 2000–2002 surge event: (*a*) 23 June 2006, Landsat 5; (*b*) 30 June 2006, Landsat 5; (*c*) 10 September 2006, Landsat 7; (*d*) 25 May 2007, Landsat 5; (*e*) 10 July 2007, Landsat 5; (*f*) 15 August 2008, Landsat 5. Blue dashed outlines indicate lakes discussed in the text. Landsat images are supplied courtesy of the U.S. Geological Survey. [Colour online.]

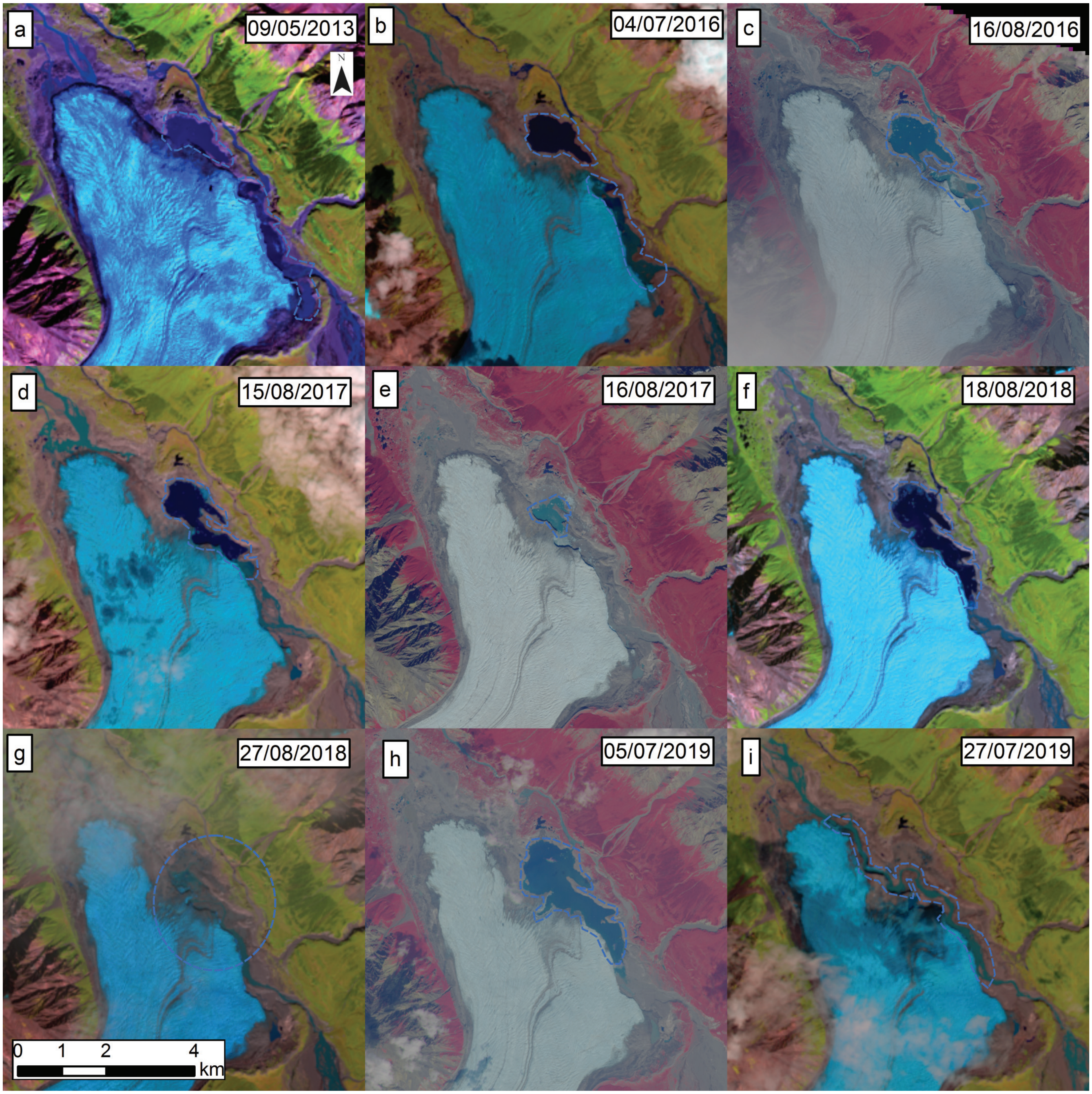


drain rapidly (Fig. 3). Rather, their drainage was driven by the next surge of the glacier, which gradually closed the basin space available for lake formation (e.g., the 1988–1990 surge displaced the lakes formed near the end of the quiescent period after the 1977–1979 surge; Figs. 5, 6*a*, 6*b*). During this period, Dań Zhùr Chù' remained on the outside of the Neoglacial maximum moraine and did not appear to interact with the lakes.

A significant change in the characteristics of the terminal lakes began in the 1990s. After the 1988–1990 surge, it took >5 years of quiescence for significant lakes to form, as in previous surge cycles, but once they started forming, they became much larger (>1.0 km²) than in any previously observed period and started undergoing rapid drainage events (Fig. 3). This was a period when Dań Zhùr Chù' started flowing inside the Neoglacial maximum moraine, including in 1993 when it was routed beneath the glacier for the first time (Fig. 6*d*). The lakes since 1993 have typically drained rapidly either beneath or through the glacier terminus as an ice dam was breached and (or) a subglacial channel was opened, including through an impressive >4 km long ice canyon in 1998 (Fig. 7*c*).

The 1990s marked an inflection point, as after this time lakes formed during and immediately after the active surge phase for the first time, as seen after the 2000–2002 and 2012–2014 surges (Figs. 3, 9, 10, 11). This has occurred due to the convergence of two factors: (1) the creation of an increasingly large basin between the glacier terminus and the Neoglacial maximum moraine, because the maximum extent of each recent surge has been smaller than the last; (2) sufficient advance to still create an ice dam. As Dań Zhùr Glacier has continued its long-term retreat, the lake basin

Fig. 10. Lakes after the 2012–2014 surge event: (*a*) 9 May 2013, Landsat 8; (*b*) 4 July 2016, Landsat 8; (*c*) 15 August 2016, Sentinel-2A; (*d*) 15 August 2017, Landsat 8; (*e*) 16 August 2017, Sentinel-2B; (*f*) 18 August 2018, Landsat 8; (*g*) 27 August 2018, Landsat 8; (*h*) 5 July 2019, Sentinel 2A; (*i*) 27 July 2019, Landsat 8. Blue dashed outlines indicate features discussed in the text. Landsat and Sentinel images are supplied courtesy of the U.S. Geological Survey. [Colour online.]



has continued to grow, creating ever larger lakes. In 2016, the northern and southern lakes at the terminus joined to become one for the first time. Subsequent lakes in 2017, 2018, and 2019 were all connected, with 2019 hosting the largest lake ever observed (Fig. 10*h*).

The recent lakes at Dań Zhùr Glacier appear to be unique in comparison with those that have formed elsewhere in the St. Elias Mountains. At Náłúdäy (Lowell) Glacier, glacier-dammed lakes and associated glacial lake outburst floods have not occurred since the late 1800s, when previously more extensive surges of the glacier blocked the entire valley and created Neoglacial Lake Alsek (Clague and Rampton 1982). Hazard Lake, formed by an advance of Steele Glacier (Collins and Clarke 1977; Clarke 1982), does not occur at the terminus but rather several kilometres upglacier and drains via subglacial channels. Dań Zhùr Glacier is unique because it has produced more terminal lakes than elsewhere in this region over the past 50+ years. The lakes are also larger and draining more frequently with time.

Globally, fewer glacial lake outburst floods have occurred in the last few decades than around 1930 (Harrison et al. 2018). Harrison

Fig. 11. Oblique air photo of Dań Zhùr Glacier from 13 July 2014, showing two ice-marginal lakes at the end of the 2012–2014 surge formed in the basin between the Neoglacial maximum moraine (to the right) and glacier terminus (to the left). Photograph taken by Luke Copland. [Colour online.]

et al. (2018) suggest this is due to a delayed response in outburst floods to post-Little Ice Age warming, and they hypothesize that outburst flood frequency will increase in the coming decades due to current warming. We observe the opposite trend at Dań Zhùr Glacier, where current warming has set up a glacier geometry that is conducive to present-day ice dam formation and outburst floods, but in the longer term we expect ice-dammed lakes to stop forming once the glacier retreats up the valley. To our knowledge, Dań Zhùr Glacier is unique in having formed large ice-dammed lakes during the Neoglacial Maximum (i.e., Little Ice Age) up to ~1840, then undergoing a period of no ice-dammed lakes during the second half of the 19th century and first half of the 20th century, before reverting to the ability to host increasingly larger lakes over the past ~50 years.

Questions still remain about the dynamics of lakes at the terminus of Dań Zhùr Glacier, mostly concerning subglacial processes. Lakes have always drained during summer months, often through a channel beneath the terminus (Figs. 6*d*, 6*i*, 7*a*, 9*c*, 9*f*, 10*e*, and 10*g*), although how and why this channel forms are presently unclear. In some years, such as in 2019, it appears that a subaerial channel is derived from the subglacial channel when the overlying ice has melted sufficiently and collapsed the glacier roof above.

We can make some predictions about the future of Dań Zhùr lakes and associated glacial lake outburst floods. In the medium term, Dań Zhùr Glacier is likely to surge again by the mid-2020s, creating another lake (or set of lakes) at the glacier terminus. If recent trends continue, this lake will drain and refill multiple times as it grows over a period of several years. Ultimately, the maximum total lake area is likely to be greater than the 2.2 km^2 observed in 2019, due to the formation of an increasingly larger basin between the progressively smaller maximum surge extent and Neoglacial maximum moraines. These lakes are likely to form during and immediately after the surge and be held back by an ice dam that could catastrophically release and result in rapid loss of the lake volume. This could damage downstream areas, including traditional and recreational lands and infrastructure such as the Alaska Highway. In the longer term, lakes will finally stop forming at the terminus of Dań Zhùr Glacier once maximum surge extents are insufficient to create an ice dam, similar to the present situation at Nàłùdäy Glacier. However, given the dynamic nature of the Dań Zhùr Glacier terminus, accurately predicting when this will take place is challenging.

Conclusions

Lakes ranging from <0.1 to 12.3 km^2 have formed in Dań Zhùr Chù' valley since at least 1270 (Perchanok 1980). While a 12.3 km^2 or similar size lake has not been present in the valley since the early 1800s, recent lakes as large as 2.2 km^2 have formed at the terminus in a basin between the Neoglacial maximum moraine and the glacier front. Between the 1930s and 1990s, the lakes were relatively small in size, took many years to form after a surge event, and were displaced by subsequent surges. However, since the 2000–2002 surge, lakes that formed during and immediately after a surge have become larger in size and drain rapidly through an ice channel. Since the 1990s, a dense satellite image record indicates that lakes always fill in winter, typically between November and January, and always empty during summer, typically between June and September, although not necessarily within the same year. This is important as summer months bring more people to Dań Zhùr Chù' valley, and thus increase the risk from outburst floods.

Significant questions remain about the future evolution of Dań Zhùr lakes. In the current climate regime, it is extremely unlikely that Dań Zhùr Glacier will reach the northern side of Dań Zhùr valley, even during a surge, due to a persistent negative mass balance. Thus, a complete blockage of the valley and subsequent formation of a large (>10 km^2) lake hypothesized by Clarke and Mathews (1981) is very unlikely. It is also unlikely that a lake will form before the next surge event as there is currently a large canyon cut through the glacier terminus, allowing Dań Zhùr Chù' to flow unimpeded through the glacier. However, it is important to continue monitoring Dań Zhùr Glacier for the next surge event, anticipated in the early to mid-2020s, as rapid lake drainage is likely to pose a hazard for 4–6 years after a surge. The next surge event is likely to produce at least one lake larger than 2.2 km^2, which would again be of concern to public safety in the Dań Zhùr Chù' valley.

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