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Multiple phases of ice-dammed lake formation and drainage associated with a surge of Shisper Glacier, western Karakoram

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Abstract

Glacier surges can create ice-dammed lakes when the advancing terminus blocks drainage. Such lakes are inherently unstable and can drain abruptly as glacial lake outburst floods (GLOFs), presenting a hazard to downstream populations and infrastructure in high mountain environments. We present satellite image analysis of the evolution of an ice-dammed lake formed by the 2018–20 surge of Shisper Glacier, western Karakoram. Our analysis identifies six phases of lake evolution. A large lake of up to 33.7 ± 9% million m^3 formed in 2018–19, 2019–20, 2020–21 and 2021–22. In each case, the lake began to fill late in the year, reached a maximum size in May, and had completely drained between May and July, typically over 1–2 days. This analysis provides further evidence that GLOF hazards associated with lakes dammed by glacier surges can persist for several years after surge termination.

1. Introduction

Lakes formed at glacier margins in high mountain environments pose a hazard to downstream communities and infrastructure because they can drain abruptly as glacial lake outburst floods (GLOFs) (Taylor and others, 2023). This hazard is substantial because lakes are expanding as glaciers recede (Harrison and others, 2018; Zheng and others, 2021; Zhang and others, 2024). A small population of lakes also form at advancing glacier margins associated with glacier surges, with lakes reported to have formed at 30 surge-type glaciers across High Mountain Asia (HMA) since the early 1800s (Hewitt and Liu, 2010; Bhambri and others, 2019). Surges are a dynamic, cyclical flow instability that affects glaciers in concentrated regional clusters, including several geographical groupings in HMA (Sevestre and Benn, 2015; Guillet and others, 2022; Guo and others, 2023) (Fig. 1a). A typical surge cycle is characterized by an extended (decades to centuries) quiescent period of low flow, glacier thinning and recession in the receiving zone, and mass accumulation in the reservoir zone. This is punctuated by a short (months to years) active surge phase when ice flow increases by several orders of magnitude, mass is rapidly transferred downglacier, and the front can advance (Meier and Post, 1969; Jiskoot, 2011). During the phase of glacier advance, valleys can be blocked off, impeding drainage and forming unstable ice-dammed lakes (Truffer and others, 2021).

There are a number of examples of lakes dammed in this way by glacier surges in HMA, particularly in the Karakoram (Hewitt and Liu, 2010; Bhambri and others, 2019; Bazai and others, 2021; Gao and others, 2021) and the Pamirs (e.g. Truffer and others, 2021; Murodov and others, 2024). The best-studied examples include Khurdopin Glacier (Iturrizaga, 2005; Steiner and others, 2018; Bhambri and others, 2019; Gao and others, 2021; Bazai and others, 2022), Kyagar Glacier (Haemmig and others, 2014; Round and others, 2017; Bhambri and others, 2019; Yin and others, 2019; Li and others, 2023; Zhang and others, 2023) and Shisper (sometimes referred to as Shispare or Shishper) Glacier (Shah and others, 2019; Baig and others, 2020; Bhambri and others, 2020; Rashid and others, 2020; Gao and others, 2021; Khan and others, 2021; Muhammad and others, 2021; Nie and others, 2023; Singh and others, 2023; Bazai and others, 2024) in the Karakoram, and Medvezhiy Glacier in Western Pamir (Truffer and others, 2021; Murodov and others, 2024). These examples share some common characteristics of lake evolution: (1) lakes typically form in steep, narrow side valleys when the drainage is sufficiently impeded by the advancing terminus in the main valley; (2) lakes can form repeatedly in the same place over multiple surge cycles; (3) lakes can form and drain multiple times during a single surge phase, in some cases persisting for several years after surge termination; (4) lakes typically drain in the summer months through subglacial conduits, with drainage events occurring both as abrupt GLOFs or through a gradual lowering of lake level over time; and (5) GLOFs often cause downstream damage and disruption to settlements and infrastructure, particularly the washing away of bridges and roads.

Here, we focus on ice-dammed lake evolution associated with the most recent surge of Shisper Glacier in the Hunza Valley region of Gilgit-Baltistan, western Karakoram (Fig. 1). Based on flow velocities and surface elevation changes, the recent surge was likely underway by April 2018, and by mid-July 2019 the terminus had advanced ~1.5 km (Bhambri and others, 2020). The advancing terminus blocked the meltwater stream from the Muchuhar (sometimes referred to as Mochowar or Mochuwar) Glacier and a lake began to form in

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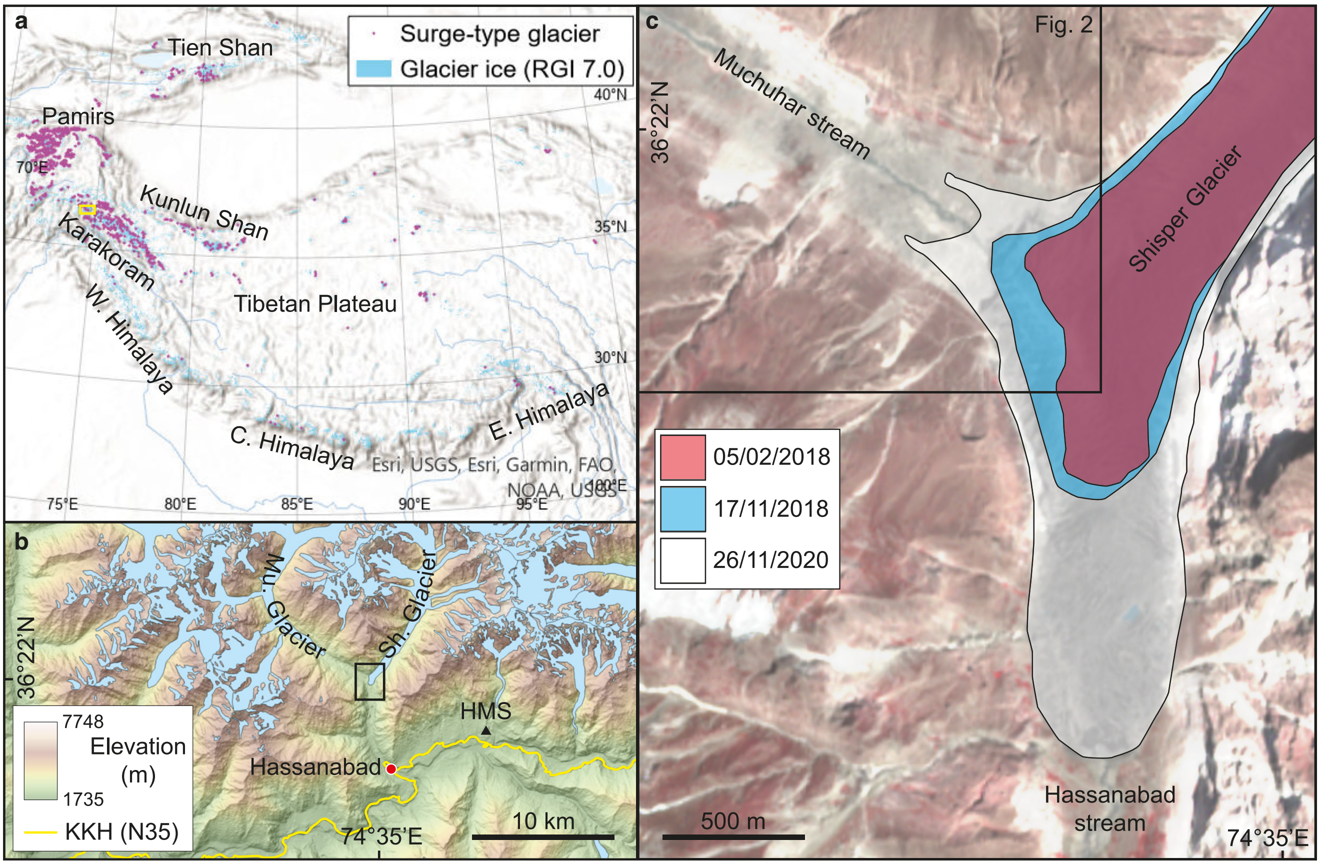

Figure 1. Study area map. (a) Map of High Mountain Asia showing the main surge clusters, including the Karakoram. Surge-type glaciers (in purple) are from Sevestre and Benn (2015) and Guillet and others (2022); non-surge-type glaciers (in blue) are from the Randolph Glacier Inventory (RGI) 7.0. (b) The Hunza Valley region in the Karakoram (yellow rectangle in (a)) showing the location of Shisper Glacier (Sh. Glacier), Muchuhar Glacier (Mu. Glacier), the settlement of Hassanabad, the Hunza meteorological station (HMS) and the Karakoram Highway (KKH (N35)). The background is an ASTER GDEM image and the glaciers (in blue) are from the RGI 7.0. (c) The frontal part of Shisper Glacier in the Hassanabad valley (black rectangle in (b)). The mapped glacier positions show glacier extent at the start of the terminus advance phase of the surge around 5 February 2018 (in red), at the point when the lake first began to form in the Muchuhar valley around 17 November 2018 (in blue), and when the terminus advance ceased around 26 November 2020 (in white). The background is a Sentinel-2 near-infrared false colour image (bands 8, 4 and 3) captured on 14 May 2024. Black rectangle in (c) shows location of Figure 2.

November 2018, expanding to a maximum size of ~0.30 km^2 in May 2019 (Rashid and others, 2020). This lake drained on 22–23 June 2019 and caused some minor damage to downstream infrastructure, including the Karakoram Highway (Fig. 1b). The lake subsequently reformed and reached a size of ~0.25 km^2 before draining on 29 May 2020, again damaging a section of the Karakoram Highway (Muhammad and others, 2021; Singh and others, 2023). The lake also formed in 2020–21 and 2021–22, draining on 7 May 2022 as a GLOF that washed away the Hassanabad bridge on the Karakoram Highway (Nie and others, 2023; Singh and others, 2023).

Shisper Glacier is known to have surged previously in 1973 and 2000–01, but no lakes are thought to have formed during these events (Bhambri and others, 2020). Prior to 1954, the Shisper and Muchuhar glaciers (Fig. 1b) were joined together to form the Hassanabad Glacier, which experienced at least two surges with ~10 km advances in ~1892–93 and ~1904–05 (Mason, 1935; Bhambri and others, 2019, 2020). Both surges were associated with a series of GLOFs (Hewitt and Liu, 2010), suggesting that lakes were probably formed during the terminus advance phase of the surges.

The recent surge that started in 2018 and the associated formation and drainage of a lake in 2019 are very well studied (e.g. Shah and others, 2019; Baig and others, 2020; Bhambri and others, 2020; Rashid and others, 2020; Khan and others, 2021; Muhammad and others, 2021), and we also know that lakes continued to form and drain in the following years (e.g. Muhammad and others, 2021; Nie and others, 2023; Singh and others, 2023; Bazai and others, 2024). In most cases, this previous analysis has primarily focused on calculating maximum lake sizes and the timing and impact of GLOFs. However, locations such as Shisper Glacier, where lakes have repeatedly formed and drained in consecutive years, also present an excellent opportunity to reconstruct a continuous record of lake evolution over multiple years. Such a dataset would provide important information on the inter- and intra-annual dynamics of unstable ice-dammed lakes, including temporal trends in lake initiation, expansion and drainage (e.g. Veh and others, 2023). Here, we explore this using the near-continuous Sentinel-2 satellite image archive to present a comprehensive assessment of multiple years of lake evolution and drainage at Shisper Glacier.

2. Methods

We used the Copernicus Sentinel Hub EO Browser to search through all Sentinel-2 satellite images covering the frontal area of Shisper Glacier from April 2017 until September 2024. Images are captured every 5 d, have a spatial resolution of 10 m and were visualised as near-infrared false colour images (bands 8, 4 and 3). We ignored all images that were too heavily impacted by cloud cover, leaving 225 images in which the glacier terminus and/or ice-dammed lake could be clearly identified. Only ten usable images were available in 2017 (spanning April to December), and there were no sufficiently cloud-free images for

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most of January and February 2019, but there was otherwise an average of three images per month with good visibility of the study area in 2018–24. Lake outlines were mapped manually and surface areas were calculated in ArcGIS Pro. We estimated lake surface area uncertainty following Salerno and others (2012) by using an assumed linear error of ±0.5 pixels (±5 m) in the position of the lake perimeter, whereby surface area error = linear error × perimeter length. We report this as percentage error. To estimate lake volume, we used the ASTER GDEM v3 digital elevation model (DEM; spatial resolution = 30 m) of the pre-lake valley topography and calculated the volume using each individual lake outline. This method effectively takes the maximum elevation that intersects with the lake outline as the shoreline height and uses this alongside the lake area to calculate a volume. We also used this approach to calculate mean and maximum lake depths. We calculated lake volume and depth errors using the vertical std dev. of the ASTER GDEM v3 dataset of ±8 m (Gesch and others, 2016) to represent shoreline height uncertainty, which we present as percentage error. Because multi-year ice-dammed lake expansion and drainage often correlates with seasonal cycles (e.g. Veh and others, 2023), temperature and precipitation data covering the period 2017–23 were acquired from the Hunza meteorological station (36°19′ N, 74°39′ E; 2156 m elevation), located ∼10 km southeast of the Shisper Glacier front (Fig. 1b).

3. Results

Our analysis demonstrates that there have been six separate phases of lake evolution and drainage associated with the recent surge of Shisper Glacier (Figs 2 and 3). Four of these phases created large lakes filling much of the steep and narrow Muchuhar valley, and there were two interim phases of small linear lake formation centred along the Muchuhar Glacier drainage in the valley bottom.

The satellite images show that surging ice had reached the glacier front by early February 2018 and the advancing glacier front had completely blocked the Muchuhar valley by July 2018. A lake first formed at the ice margin by the middle of November 2018 as drainage from Muchuhar Glacier was impeded (Fig. 2a). In this first lake phase, the lake grew steadily in late 2018 and early 2019, reaching a maximum size of 0.29 ± 9% km^2 (18.3 ± 13% million (M) m^3) in late May 2019 (Fig. 3 and Table 1). Although there are few clear Sentinel-2 images in January and February 2019 from which to assess the lake status, both Rashid and others (2020) and Muhammad and others (2021) demonstrated that the lake continued to grow during this period based on Planet and Landsat 8 images, respectively. Surging ice began to splay laterally into the lake at this time, continuing until early May when the ice started to break up into smaller blocks that became distributed throughout the lake. By 20 June 2019, the phase 1 lake had reduced slightly from its maximum size, which was closely followed by a large but steady GLOF on 22–23 June 2019 (Bhambri and others, 2020; Rashid and others, 2020; Muhammad and others, 2021) (Fig. 3). The Muchuhar valley was largely dry and covered by stranded debris-rich ice by the end of July 2019, indicating complete lake drainage and the end of lake phase 1.

The phase 2 lake began to fill almost immediately in early August 2019 (Figs 2b and 3) and grew rapidly in October to December, reaching 0.33 ± 6% km^2 (21.7 ± 12% M m^3) by the end of December 2019. The next available image of 5 February 2020 shows an open lake area of a much-reduced size of 0.04 ± 12% km^2 (1.1 ± 28% M m^3) (Figs 2b and 3) surrounded by stranded debris-rich glacier ice and some thin areas of lake ice cover at the margins, indicating a large but not complete drainage event occurred at some point in early 2020. The lake immediately began to fill rapidly again, reaching 0.32 ± 8% km^2 (21.6 ± 12% M m^3) by the end of May 2020. Distributed ice blocks were again a common characteristic of the lake, which drained on 29 May 2020 (Muhammad and others, 2021). By the middle of June 2020, only a small lake of 0.02 ± 17% km^2 (0.4 ± 38% M m^3) remained (Figs 2b and 3).

Lake phase 3 was a period of restricted lake fluctuations from July to October 2020. A small linear lake centred along the route

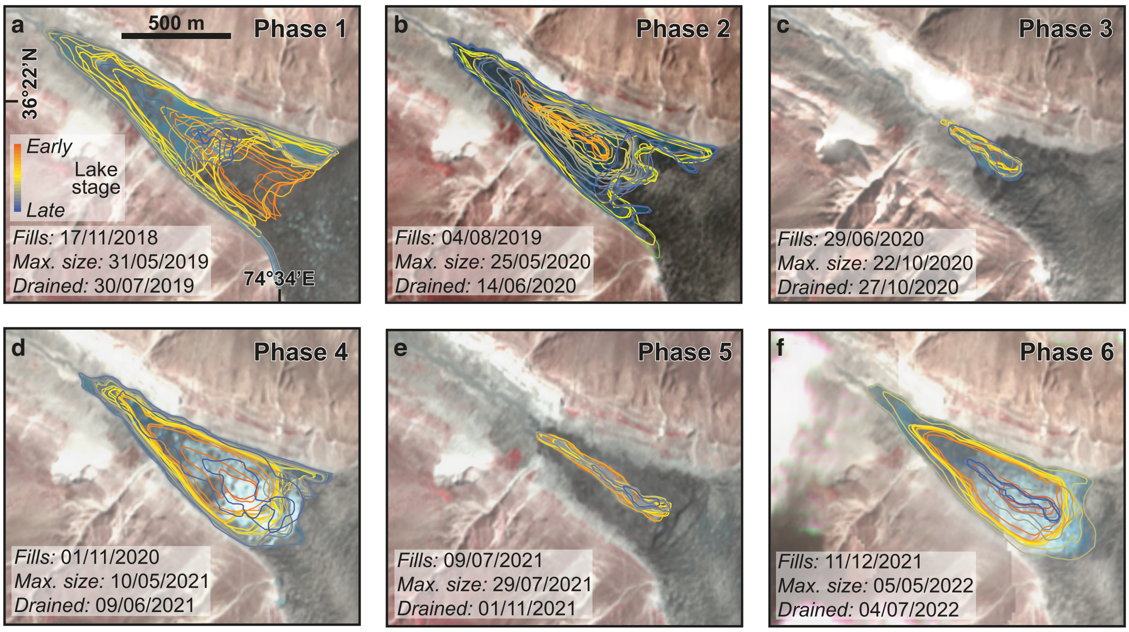

Figure 2. Ice-dammed lake evolution in the Muchuhar valley in 2018–22 mapped from Sentinel-2 images. Six phases of lake filling and drainage are shown in (a) to (f). Each panel shows lake outlines coloured from early to late stages within each phase. The panels also record the dates of the images when lake filling was first identified ('Fills'), when the lake phase reached a maximum size ('Max. size') and when the lake phase was identified to have drained completely ('Drained'). It is important to note that the 'Drained' date is not the exact timing of a GLOF but is the date of the first available image when the lake is observed to have drained completely, signalling the end of a lake phase. The background for each panel is a Sentinel-2 near-infrared false colour image showing the maximum lake size of the phase: (a) 31 May 2019. (b) 25 May 2020. (c) 22 October 2020. (d) 10 May 2021. (e) 29 July 2021. (f) 5 May 2022. See Figure 1c for location.

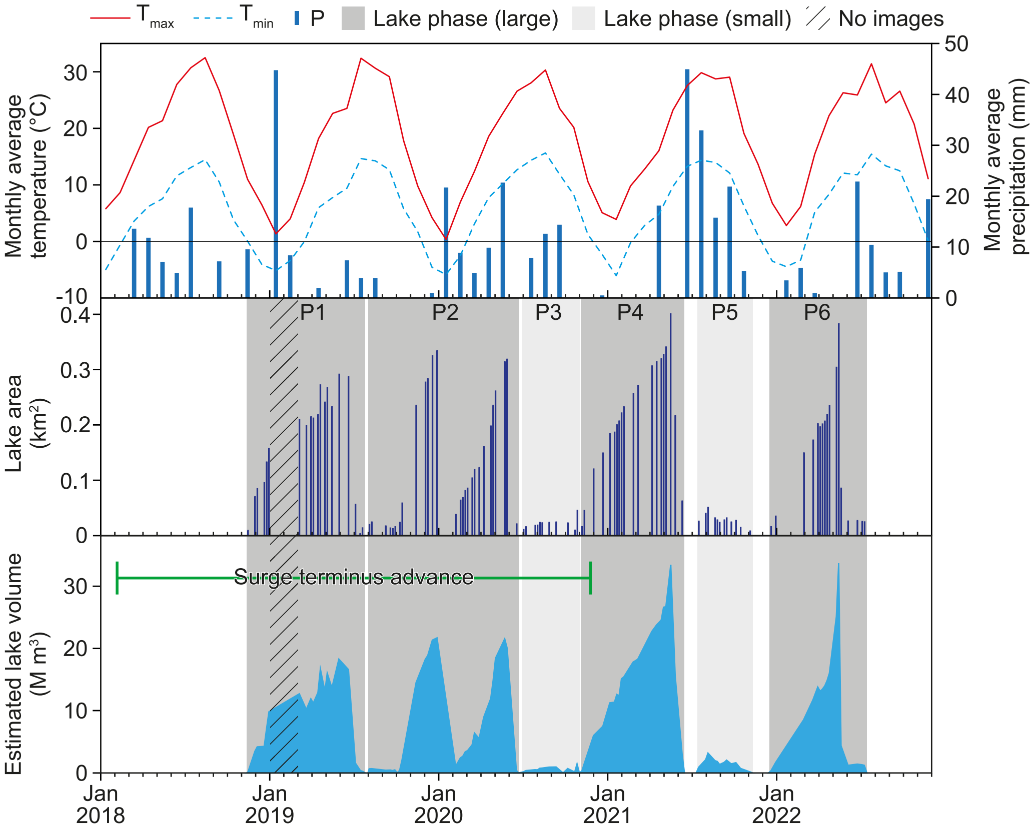

Figure 3. Evolution of lake area (in km^2) and estimated lake volume (in million (M) m^3) plotted against monthly averaged temperature and precipitation from the Hunza meteorological station (see Fig. 1 for station location). Lake phases 1–6 are indicated by the grey shading, with darker shading showing phases that formed a large lake filling the Muchuhar valley, and lighter shading showing phases that only formed a small lake at the ice margin. The bracketed green line shows the period of frontal advance during the surge. T_{max}, maximum temperature; T_{min}, minimum temperature; P, precipitation.

of the Muchuhar Glacier drainage, partially enclosed by debris-covered glacier ice, filled and emptied at least twice, reaching a maximum size of 0.05 ± 11% km^2 (1.4 ± 24% M m^3) before final complete drainage towards the end of October 2020 (Figs 2c and 3).

The fourth lake phase had started to fill by early November 2020, expanding steadily through the end of 2020 and the early months of 2021. The lake area increased abruptly in April and early May to a maximum size of 0.40 ± 4% km^2 (33.5 ± 10% M m^3) by 10 May, before draining to half this size by 20 May and completely in early June 2021 (Figs 2d and 3), again leaving behind a basin choked with stranded ice blocks.

The phase 5 lake represents the second phase of limited lake growth. The lake first formed by early July 2021 within the ice-choked-basin left behind following the previous phase drainage, creating a narrow ribbon lake centred along the Muchuhar Glacier drainage in the valley bottom (Fig. 2e). This lake appears to have been constrained on both sides by debris-covered ice stranded within the basin. The lake reached a maximum size of 0.05 ± 16% km^2 (3.2 ± 13% M m^3) by the end of July, before continuing to fluctuate until complete drainage at the end of October 2021.

The sixth and final lake phase had begun to fill by early December 2021, peaking on 5 May 2022 at 0.38 ± 4% km^2 (33.7 ± 9% M m^3) (Figs 2f and 3). The lake drained on 7 May (Singh and others, 2023) and was 0.09 ± 6% km^2 (4.4 ± 16% M m^3) on 10 May, reducing further to ~0.02 ± 25% km^2 (~1.4 ± 15% M m^3) throughout the remainder of May and into June, before final complete drainage by early July 2022. Following this, no lakes formed up until the end of our analysis on 6 September 2024.

Across the four large lake phases (1, 2, 4 and 6), the average minimum number of days from the onset of lake filling in late autumn/early winter to the lake maximum size in May was 155 days. The average minimum number of days from lake maximum size in May to complete drainage by June/July was 38 days.

Table 1. Dimensions of maximum lake sizes during large lake phases

Lake phase	Date of maximum size	Lake area (km^2)	Estimated lake volume (million (M) m^3)	Mean lake depth (m)	Maximum lake depth (m)
1	31 May 2019	0.29 ± 9%	18.3 ± 13%	64 ± 13%	127 ± 6%
2	25 May 2020	0.32 ± 8%	21.6 ± 12%[a]	70 ± 11%	154 ± 5%
4	10 May 2021	0.40 ± 4%	33.5 ± 10%	84 ± 10%	180 ± 4%
6	5 May 2022	0.38 ± 4%	33.7 ± 9%	89 ± 9%	169 ± 5%

The phase 2 lake maximum size was reached in December 2019 (0.33 ± 6% km^2; 21.7 ± 12% M m^3) before partial drainage occurred, but here we report the (very similar) maximum size in May before final drainage for better comparison with the other phases. The volume marked by [a] indicates that the largest estimated volume did not coincide with the largest lake area – in this case the largest volume was reached on 20 May 2020.

4. Discussion

The regularity of the Sentinel-2 images used in our analysis reveals new details about ice-dammed lake evolution associated with the recent Shisper Glacier surge. Of the six separate phases of lake evolution we identified in the period November 2018 to July 2022, phases 1, 2, 4 and 6 were characterised by large lakes of a similar size (0.29 ± 9%, 0.32 ± 8%, 0.40 ± 4% and 0.38 ± 4% km^2, respectively) that filled most of the initial part of the side valley (Figs 2 and 3). The phase 1 (2018–19) and phase 2 (2019–20) lakes and subsequent drainage as GLOFs have received a lot of attention (e.g. Shah and others, 2019; Baig and others, 2020; Bhambri and others, 2020; Rashid and others, 2020;

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Muhammad and others, 2021), and the phase 4 (2020–21) and phase 6 lake formation and GLOF drainage (2021–22) have also been reported previously (Nie and others, 2023; Singh and others, 2023; Bazai and others, 2024). There were also two phases that did not create large lakes: phases 3 (2020) and 5 (2021), which in both years had begun to fill in June/July and had drained by October/November. We include these as separate phases because they represent periods of relatively stable but fluctuating lake extents, in the case of phase 3 characterised by two instances of complete drainage and refilling, rather than sustained lake growth over a longer time period shown by phases 1, 4 and 6, and in part by phase 2. Hereafter, we focus our discussion primarily on the sequence of the large lake phases (1, 2, 4 and 6), summarised schematically in Figure 4. In particular, we note several shared characteristics with ice-dammed lake evolution associated with surges of the Khurdopin and Kyagar glaciers, also in the Karakoram (e.g. Round and others, 2017; Steiner and others, 2018; Bazai and others, 2022; Zhang and others, 2023). We also compare our observations to long-term trends in episodic ice-dammed lake drainage based on a global dataset (Veh and other, 2023).

Shared characteristics of each of the large lake phases can be identified, indicating common controls on lake evolution (Fig. 4). Rapid lake expansion started by October (phase 2), November (phases 1 and 4) or December (phase 6) (Fig. 4b). Initial lake expansion in late autumn/early winter is consistent with the onset of an inefficient subglacial drainage system, with closed subglacial conduits preventing drainage. Continued lake growth over the winter, when surface water contributions are likely to be severely limited by below 0°C air temperatures (Fig. 3), suggests the lake was receiving some component of subglacial meltwater. This was observed at Khurdopin and Kyagar glaciers, where winter lake expansion was coincident with decelerations in ice flow, indicating a reduction in subglacial water storage and the drainage of subglacial water from the glacier into the lake (Round and others, 2017; Bazai and others, 2022). At Shisper Glacier, a winter deceleration phase was identified from December 2018 to February 2019 (Rashid and others, 2020), indicating reduced ice velocities may have contributed to winter lake expansion.

There was an increase in the rate of filling towards the end of April for all the large lake phases at Shisper Glacier, and the maximum lake size was consistently reached in May (Fig. 4c) in each of 2019 (phase 1), 2020 (phase 2), 2021 (phase 4) and 2022 (phase 6). The late April increase in the rate of lake expansion is coincident with the onset of spring melt. Phase 2 differs from the other three phases because the lake underwent a partial drainage in winter 2019–20, perhaps exploiting pre-existing subglacial conduits opened during the June 2019 drainage, before filling again to a maximum size in May in line with the other phases. This partial drainage was also reported by Muhammad and others (2021), although they placed it between March and April 2020. There does not appear to have been a noticeable rise in river discharge associated with this partial drainage, suggesting it was a gradual event.

The phases 1 and 2 maximum lake size was reached by the end of May, and the phases 4 and 6 maximum lake size was reached in early May. At this stage it is important to note that our lake volume estimations are up to three times larger than those presented in some previous studies. For example, the phase 1 (2019) lake was estimated to have a maximum volume of 18.3 ± 13% $M m^3$, with values of 21.6 ± 12% $M m^3$ for the phase 2 (2020) lake, 33.5 ± 10% $M m^3$ for the phase 4 (2021) lake and 33.7 ± 9% $M m^3$ for the phase 6 (2022) lake (Fig. 3 and Table 1). These contrast to previous volume estimations of ∼5–10 $M m^3$ for the phase 1 (2019) lake, ∼5 $M m^3$ for the phase 2 (2020) lake and ∼6 $M m^3$ for the phase 6 (2022) lake (Rashid and others, 2020; Singh and others, 2023). We suggest that these large discrepancies relate to the different methods used to estimate lake volume. Here, we used a pre-lake DEM to calculate the water volume within the valley based on our mapped lake surface area. By comparison, Rashid and others (2020) and Singh and others (2023) used empirically derived relationships between lake area and mean depth based on a small sample of glacial lakes, including some in the broader HMA region (e.g. Huggel and others, 2002; Cook and Quincey, 2015). To explore this difference, we also used the Huggel and others (2002) empirically derived relationship, and produced estimated maximum lake volumes of 6.0 $M m^3$ (2019), 6.6 $M m^3$ (2020), 9.4 $M m^3$ (2021) and 8.8 $M m^3$ (2022), broadly similar to those of Rashid and others (2020) and Singh

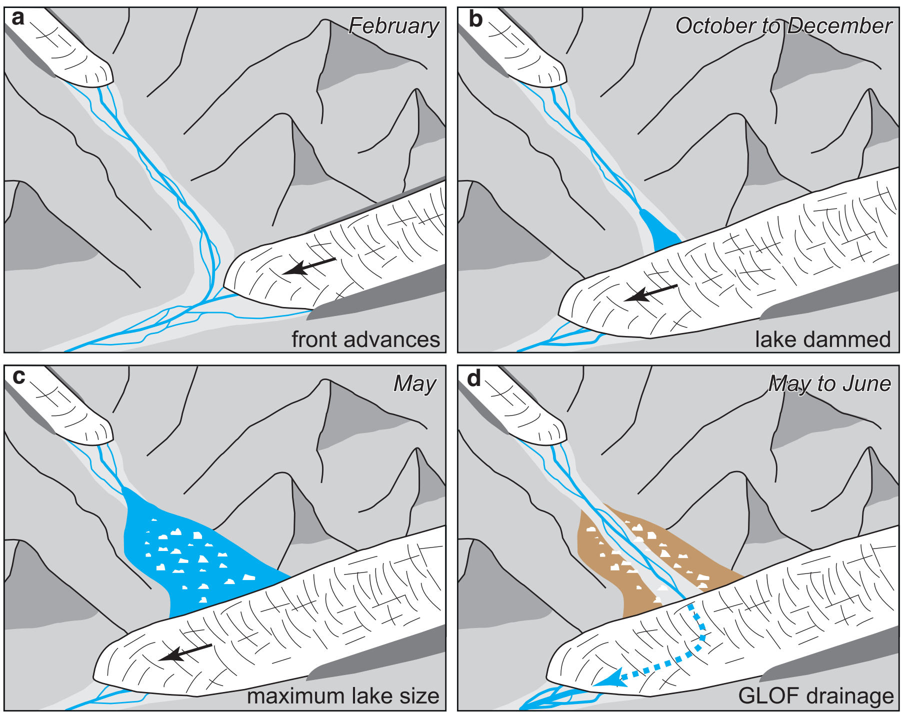

Figure 4. Schematic summary of large lake phase sequence. (a) The glacier begins to advance as surging ice arrives at the front (prior to lake phase 1 only). (b) Muchuhar stream is dammed by the glacier and a lake begins to form. (c) Lake maximum extent is reached in May. (d) The lake drains abruptly in May/June through a subglacial conduit and a GLOF is released into the Hassanabad stream. Steps (b) to (d) are repeated in subsequent large lake phases until a lake no longer forms following the phase 6 GLOF.

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and others (2023) and much lower than our DEM-derived estimates. We offer the following observations that lead us to suggest that DEM-derived volume estimations are most appropriate at this location: (1) the Muchuhar stream is located in a steep and narrow ravine, and thus the lakes that are dammed are very deep. For example, we calculate maximum lake depths of up to 180 ± 4% m, and the mean depths of the large lake phases (Table 1) are all higher than the mean depths reported from a sample of 24 lakes across the wider HMA region (Veh and others, 2020) – although it is also worth noting that this sample of lakes are all moraine-dammed rather than ice-dammed, which can produce lakes with quite different characteristics (Korup and Tweed, 2007). (2) Our estimated lake volumes are similar to those presented by other studies that also used a DEM approach to estimate the Shisper Glacier lake volume in 2019–22 (~17–30 M m^3) (Bhambri and others, 2020; Nie and others, 2023; Bazai and others, 2024), and are also of a similar order to lake volume estimates reported by Round and others (2017) at Kyagar Glacier, where the lake was dammed in a similar steep ravine. The Kyagar Glacier ice-dammed lake was estimated to have a volume of 53 M m^3 in summer 2015 (with a corresponding surface area of ~0.80–0.90 km^2) and 40 M m^3 in summer 2016 (with a corresponding surface area of ~1.0 km^2) (Round and others, 2017; Li and others, 2023). While the Kyagar Glacier lakes had more than twice the surface area of the largest Shisper Glacier lakes, their estimated volumes are less than twice the maximum volume we estimated for the (largest) phase 6 lake, but nearly ten times larger than the volume estimated for the same lake based on an empirically derived area-depth scaling method (Singh and others, 2023). Caution should obviously be applied when comparing different sites and different methods, but we consider our DEM-derived lake volume estimates to be consistent with those at Kyagar Glacier. Together, this implies that some empirically derived area-depth scaling approaches for estimating glacial lake volumes may underestimate ice-dammed lake volumes in steep ravine topography.

Our lake mapping and volume estimations show that the maximum lake size reached during the large lake phases increased during successive years (Fig. 3 and Table 1), even though the phase 1 lake extended further into the Muchuhar valley and had a higher elevation shoreline than the lakes that were dammed in subsequent years (Fig. 2). Successively larger lakes throughout the four years contrast to the global long-term trend for episodically draining ice-dammed lakes, which shows that lakes have on average produced smaller GLOFs over time (Veh and others, 2023). The successively larger lakes at Shisper Glacier can be explained by ice margin dynamics during and following the surge. During phase 1 of lake formation, surging ice splayed into the lake, occupying the deepest part of the valley. By phase 2, the terminus was still advancing further downvalley, but the margin did not extend into the lake by any notable distance. Following surge termination in late 2020, the ice margin blocking the Muchuhar valley continued to narrow towards the centre of the main Hassanabad valley, allowing the lake to expand into the deepest parts of the ravine adjacent to the glacier. Minor variations in the ice margin position adjacent to the deepest part of the lake likely also explain why in some years the maximum lake area does not always coincide with the largest estimated lake volume (Table 1).

GLOFs occurred on 22–23 June in phase 1, on 29 May in phase 2 (Muhammad and others, 2021), by 20 May in phase 4 and on 7 May in phase 6 (Nie and others, 2023; Singh and others, 2023). Complete lake drainage had occurred by the end of July (phase 1), the end of June (phase 2), early June (phase 4) and early July (phase 6). In each case, substantial and complete drainage left behind a lake basin choked with stranded ice blocks (Fig. 4d). Lake drainage in June 2019 took place through melt enlargement of a subglacial conduit that had opened in response to increased meltwater during the higher temperatures of the melt season (Muhammad and others, 2021) (Fig. 3), potentially also related to a period of increased flow velocities (Bhambri and others, 2020; Bazai and others, 2022). We assume similar mechanisms controlled lake drainage in subsequent years, with the successively earlier GLOFs in 2020 (29 May), 2021 (by 20 May) and 2022 (7 May) likely due to exploitation of the pre-existing subglacial conduit that had opened and expanded during the 2019 GLOF. The lake drained 46 days earlier in 2022 (7 May) than in 2019 (22–23 June). This short-term shift in GLOF timing can be compared to long-term trends in episodic ice-dammed lake drainage since 1900, which show that GLOFs on average now occur about 48–102 days earlier in the year in HMA, and about 40 days earlier globally (Veh and others, 2023). Shisper Glacier lake GLOFs in May (2020–22) and June (2019) also occurred earlier in the melt season than the typical northern hemisphere peak in GLOF activity of July and August (Veh and others, 2023).

The formation and drainage of ice-dammed lakes over several years at Shisper Glacier is a clear example of GLOF clustering associated with surging (e.g. Hewitt and Liu, 2010; Bazai and others, 2022, 2024). In particular, our analysis demonstrates that lakes initially formed because of a surge can continue to form and drain even after the surge terminates. This has also been observed at Khurdopin Glacier (Steiner and others, 2018) and Kyagar Glacier (Haemmig and others, 2014; Round and others, 2017; Yin and others, 2019). One key difference we observe is that higher lake volumes at Kyagar Glacier were associated with a thickened terminus and increased ice-dam height during the surge phase, whereas the highest lake volumes at Shisper Glacier occurred following surge termination. The lack of lake formation in 2022–23 and 2023–24 (as of September 2024) indicates that ice-dammed lake phases associated with the surge have ended. This is likely due to a combination of ice-dam thinning in the early quiescent phase, coupled with the re-establishment of an efficient subglacial drainage system characterised by open conduits that prevent a lake from forming (Steiner and others, 2018; Li and others, 2023; Zhang and others, 2023).

5. Conclusions

The 2018–20 Shisper Glacier surge formed an ice-dammed lake in late 2018 that drained in June 2019, damaging downstream infrastructure including part of the Karakoram Highway. We show that the large lake also re-formed and drained in each of 2019–20, 2020–21 and 2021–22, with the final two phases of lake evolution occurring after the surge advance had terminated. In each of these large lake phases, the lake reached a maximum size in May and had drained completely by July. We also identify two intermediate phases of small lake evolution, characterised by fluctuating lake areas that first formed in summer and had drained by autumn in both 2020 and 2021. During large lake phases, the maximum volume of the lake increased in each successive phase, reaching 33.7 ± 9% M m^3 in May 2022. Each large lake phase drained as GLOFs over 1–2 days in May (2020, 2021, 2022) and June (2019), with increased river discharge causing damage to downstream infrastructure. No lake formed in 2022–23 or by the end of our analysis in September 2024, indicating that lake evolution associated with the 2018–20 surge has ended. Shisper Glacier provides additional evidence of the potential hazards posed by the clustering of ice-dammed lake formation and associated GLOFs during glacier surges in the Karakoram, and in particular demonstrates that GLOF hazards can persist for several years after surge termination.

Data. The Sentinel-2 images used in the study were accessed via the Copernicus Sentinel Hub EO Browser (https://apps.sentinel-hub.com/eo-browser). The lake area and volume data are available as GIS files at https://doi.org/10.17029/f65b69a0-180f-470f-b79e-61c71b18e147.

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