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Brief communication: Repeated supraglacial lake drainage from the Purepu Glacier system, central Himalaya

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Abstract. We report repeated drainage from the Purepu supraglacial lake system in the central Himalaya using high-resolution satellite imagery. A satellite-inferred 2023 drainage event is constrained to 12-15 July, whereas a reported GLOF occurred early on 8 July 2025. Both followed lake expansion to ~0.70-0.72 km², but DEM-constrained lake-volume loss increased from 0.87×10^6 m³ in 2023 to 3.55×10^6 m³ in 2025. The 2025 event remained incomplete, and flood-volume reconstruction suggests additional englacial or subglacial contributions cannot be excluded. Residual water persisted into 2026, supporting high-frequency monitoring in early July 2026.

1 Introduction

Supraglacial ponds and lakes are dynamic components of debris-covered glacier systems. On Himalayan debris-covered glacier tongues, irregular surface topography, differential ablation, ice cliffs, and local depressions favour the formation of ponded water, which can expand, coalesce, reorganize, or drain over short timescales (Benn et al., 2012; Watson et al., 2016). Although many glacial lake outburst flood (GLOF) studies have focused on moraine-dammed or proglacial lakes, supraglacial lakes can also produce rapid drainage and downstream impacts. A documented outburst from a supraglacial lake system on Changri Shar Glacier in the Everest region showed that a lake may fill and drain within a single melt season and that such events can be reconstructed using high-resolution satellite imagery (Miles et al., 2018). More broadly, glacial lakes have expanded globally in recent decades, increasing the importance of monitoring lake development and drainage in glacierized mountain regions (Shugar et al., 2020).

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

Despite this growing attention, repeated drainage from the same supraglacial lake system remains poorly documented. This gap is important for three reasons. First, a drainage event may be recorded as a disaster only when it produces visible downstream damage or is reported by local authorities; otherwise, it may remain detectable only from satellite imagery. Reported GLOF records are known to be affected by geographic and temporal reporting biases (Veh et al., 2022), even though global GLOF databases increasingly integrate literature, reports, and satellite-based evidence (Lützow et al., 2023). Second, when no disaster report is available, event timing depends on satellite acquisition frequency, cloud conditions, and image usability. This is especially problematic during the Himalayan monsoon season, when short-lived drainage events can occur between available optical images. Third, lake-area loss alone does not fully describe drainage behavior. Area-based drainage completeness, DEM-constrained lake-volume loss, and residual water persistence are needed to distinguish near-complete drainage from incomplete drainage and to evaluate whether a lake system returns to a low-storage state after an event.

Here we address these gaps using the Purepu supraglacial lake system in the central Himalaya, where a reported GLOF occurred in July 2025 and an earlier 2023 drainage event can be independently reconstructed from satellite imagery. Specifically, we reconstruct the 2023 and 2025 drainage events, distinguish the satellite-inferred 2023 event from the reported 2025 GLOF, and constrain their timing using PlanetScope imagery and auxiliary public satellite observations. We then quantify seasonal lake-area evolution, area-based drainage completeness, and DEM-constrained lake-volume loss, and use non-event years and post-2025 residual water observations to discuss monitoring implications. By comparing the reported 2025 GLOF with the satellite-inferred 2023 drainage event under a consistent remote-sensing framework, this Brief Communication highlights contrasts in drainage completeness, lake-volume loss, and post-event water persistence, and their implications for targeted monitoring.

2 Study area and data

2.1 Study area

The Purepu Glacier system is located in the central Himalaya near the China-Nepal border. The supraglacial lake system examined in this study developed on the debris-covered tongue of Purepu Glacier. Floodwater from this glacier system can drain downstream through a steep transboundary valley toward Rasuwagadhi, where the Rasuwagadhi Friendship Bridge and the Rasuwagadhi Hydropower Project are located. The distance from the supraglacial lake system to the Rasuwagadhi Friendship Bridge is approximately 31 km, forming a direct source-to-impact pathway from the glacier surface to downstream infrastructure (Fig. 1).

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

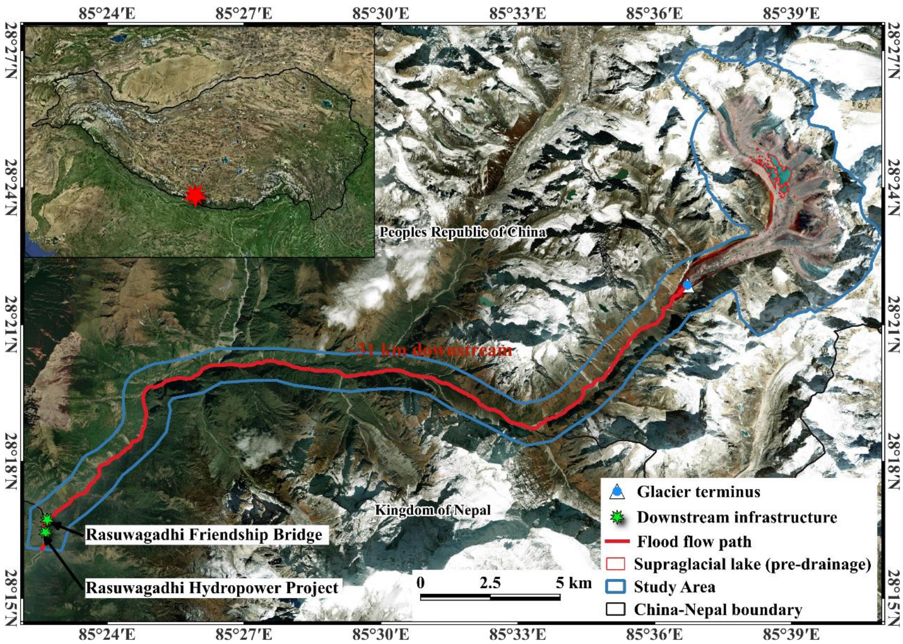

Figure 1: Study area and downstream flood path. The figure shows the location of the Purepu Glacier system in the central Himalaya, the mapped pre-drainage supraglacial lake system, the glacier terminus, the downstream flood flow path, and exposed infrastructure including the Rasuwagadhi Friendship Bridge and the Rasuwagadhi Hydropower Project. Background imagery: Esri World Imagery Wayback (Sources: Esri, Maxar, Earthstar Geographics, and the GIS User Community) and Jilin-1 Global Map (© Chang Guang Satellite Technology Co., Ltd.).

2.2 Satellite imagery, DEM, and event-report data

High-resolution PlanetScope surface reflectance imagery was used as the primary dataset for reconstructing supraglacial lake evolution and drainage because it provides the spatial and temporal detail required to identify small ponds, lake-boundary changes, outlet modification, and short-lived drainage-related features on the debris-covered glacier surface (Planet Team, 2026). PlanetScope imagery was used for lake mapping, pre- and post-drainage comparison, and event reconstruction. Sentinel-1, Sentinel-2, and Landsat 8/9 observations were used as auxiliary satellite observations to check whether the timing of the satellite-inferred 2023 drainage event could be further constrained. One Sentinel-2 image acquired on 25 June 2026 was also used as a recent monitoring-scale observation of the post-2025 lake state. Because this observation has a coarser spatial resolution than PlanetScope imagery, the corresponding lake area is interpreted cautiously as a monitoring-scale estimate.

We used the 8 m High Mountain Asia DEM mosaic as an auxiliary topographic dataset for first-order DEM-constrained lake-volume loss estimation (Shean, 2017). The DEM was used only to provide topographic constraints on pre- and post-drainage lake volumes. Because the DEM is not contemporaneous with the 2023 and 2025 drainage events, the resulting volume estimates are interpreted as DEM-constrained approximations rather than direct measurements of lake volume, flood discharge, or lake-bed geometry.

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

Public event reports, including DPNet-Nepal situation reports, were used to support the timing and downstream-impact context of the reported 2025 GLOF (DPNet-Nepal, 2025). No disaster report was used to date the 2023 event, which is treated in this study as a satellite-inferred drainage or GLOF-like event. The full satellite image inventory, including acquisition date, acquisition time, sensor, product type, cloud conditions, spatial resolution, viewing geometry, and figure or analysis use, is provided in Table S1.

3 Methods

3.1 Lake mapping and area uncertainty

Supraglacial lake outlines were mapped using a combined spectral-thresholding and manual interpretation workflow. For well-developed June-July lakes, we first calculated the Normalized Difference Water Index (NDWI; McFeeters, 1996):

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

Scene-specific NDWI thresholds were then applied to generate initial water masks. These masks were visually checked against false-colour imagery and manually refined to correct classification errors associated with debris-covered ice, shadows, clouds, snow, turbid water, and mixed pixels. For small ponds, early-spring and winter scenes, snow- or ice-covered water, and partially frozen ponds, NDWI-based extraction was less reliable; in these cases, lake boundaries were mapped mainly by manual visual interpretation. All mapped polygons were checked in a projected coordinate system, and lake area was calculated from the final polygon geometry. Area uncertainty was estimated using a ±1pixel boundary uncertainty around each mapped lake outline. The resulting lake-area time series and uncertainties are reported in Table S2.

3.2 Area-based drainage completeness

To compare the drainage outcome of the two events, we calculated drainage completeness as the normalized reduction in lake area relative to the pre-drainage reference area:

$$C = 1 - \frac{A_t}{A_{pre}} \quad (2)$$

where A_{pre} is the mapped pre-drainage lake area and A_t is the lake area at a later observation date. A value close to 1 indicates near-complete lake-area loss relative to the pre-drainage area, whereas lower values indicate incomplete area loss and persistent residual water. This area-based metric was used to compare post-event lake evolution between 2023 and 2025 and should not be interpreted as volume-based drainage completeness.

3.3 DEM-constrained lake-volume loss estimation

Pre- and post-drainage lake volumes were estimated using a first-order DEM-constrained approach, and lake-volume loss was calculated from their difference. Pre- and post-drainage lake polygons were overlaid on the 8 m High Mountain Asia DEM. For each lake and date, a water-level proxy was derived

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

from surrounding DEM elevations, from which water depth and volume within the mapped boundary were calculated.

A fixed 16 m inward and outward shoreline buffer was applied to all lakes and dates. The median DEM elevation within this buffer was used as the water-level proxy (z_{lake}). Water depth for each DEM pixel within the lake polygon was calculated as the positive difference between the water-level proxy and the DEM elevation:

$$h = \max(z_{lake} - z_{DEM}, 0) \quad (3)$$

Negative depths were set to zero. Lake volume was obtained by summing positive depths over lake pixels and multiplying by the DEM pixel area (64 m²). This procedure was applied consistently to both pre- and post-drainage polygons. Pre- and post-drainage lakes were matched using unique identifiers and spatial correspondence. Lake-volume loss for each lake was calculated as:

$$\Delta V = V_{pre} - V_{post} \quad (4)$$

and event-scale loss was obtained by summing ΔV across matched lakes. Lakes were classified as fully or partially drained based on post-event residual water. This classification was used only to summarize volume components in Table S3 and Fig. 3c and does not imply different estimation methods.

The approach assumes that the lake basins were dry or at low water levels at the time represented by the DEM. Because the DEM is not contemporaneous with the 2023 and 2025 events and no field measurements of lake depth, bed geometry, discharge, or drainage channels are available, ΔV values should be interpreted as internally consistent, first-order DEM-constrained estimates. They do not represent direct measurements of downstream flood volume or discharge. No formal sensitivity analysis of buffer width was performed; thus, the fixed 16 m buffer ensures methodological consistency between events rather than providing uncertainty-bounded estimates.

4 Results and discussion

4.1 Repeated drainage evidence and satellite-constrained event timing

High-resolution optical imagery shows two rapid drainage events from the Purepu supraglacial lake system in July 2023 and July 2025 (Fig. 2). In 2023, PlanetScope imagery acquired on 9 July shows a well-developed supraglacial lake system before drainage. The 20 July image shows a fragmented post-drainage lake configuration with markedly reduced water extent, while the 19 August image shows only small residual ponds, indicating that the 2023 event evolved toward near-complete drainage later in the melt season. A recent remote-sensing reconstruction also identified a 2023 outburst from the Purepu supraglacial lake system (Zhang et al., 2026). Because no contemporaneous disaster report is available, we treat the event here as a satellite-inferred drainage or GLOF-like event and constrain its timing solely from satellite observations.

Because cloud cover affected part of the lake area during the critical period, the 2023 timing constraint relies not only on lake-area change but also on outlet and downstream-channel morphology. The imagery shows no clear post-drainage channel modification on 9 and 12 July, whereas outlet scour

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

and channel widening are evident by 15 July (Fig. S1). Complete cloud cover in the PlanetScope imagery on 13 July and the absence of usable PlanetScope observations on 14 July create an observation gap. Public Sentinel-1, Sentinel-2, and Landsat 8/9 observations were also examined, but acquisition gaps, cloud contamination, and limited usable coverage prevented further narrowing of the event timing. The 2023 drainage is therefore constrained to between the 12 and 15 July PlanetScope acquisitions, but the exact occurrence time remains unresolved. Because the lake-forming zone was partly obscured by cloud on 15 July, a cloud-free PlanetScope image acquired on 20 July is used in Fig. 2 to illustrate the post-drainage lake morphology.

In 2025, the lake system was again well developed immediately before drainage, as shown by the 6 July PlanetScope image. The 9 July image shows a marked spatial reduction of the lake system after the reported 8 July GLOF. Unlike the 2023 event, however, the lake system did not drain completely in 2025. Residual water remained visible on 21 August, 23 September, and 30 December 2025, and was still detectable on 12 March 2026. Thus, Figure 2 provides direct spatial evidence for repeated drainage from the same supraglacial lake system, while also showing contrasting post-event states: near-complete drainage after the 2023 event and persistent residual water after the 2025 event. The 2025 event is treated as a reported GLOF because disaster reports indicate that it occurred in the early morning of 8 July 2025, and this timing is consistent with the pre- and post-event PlanetScope observations.

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

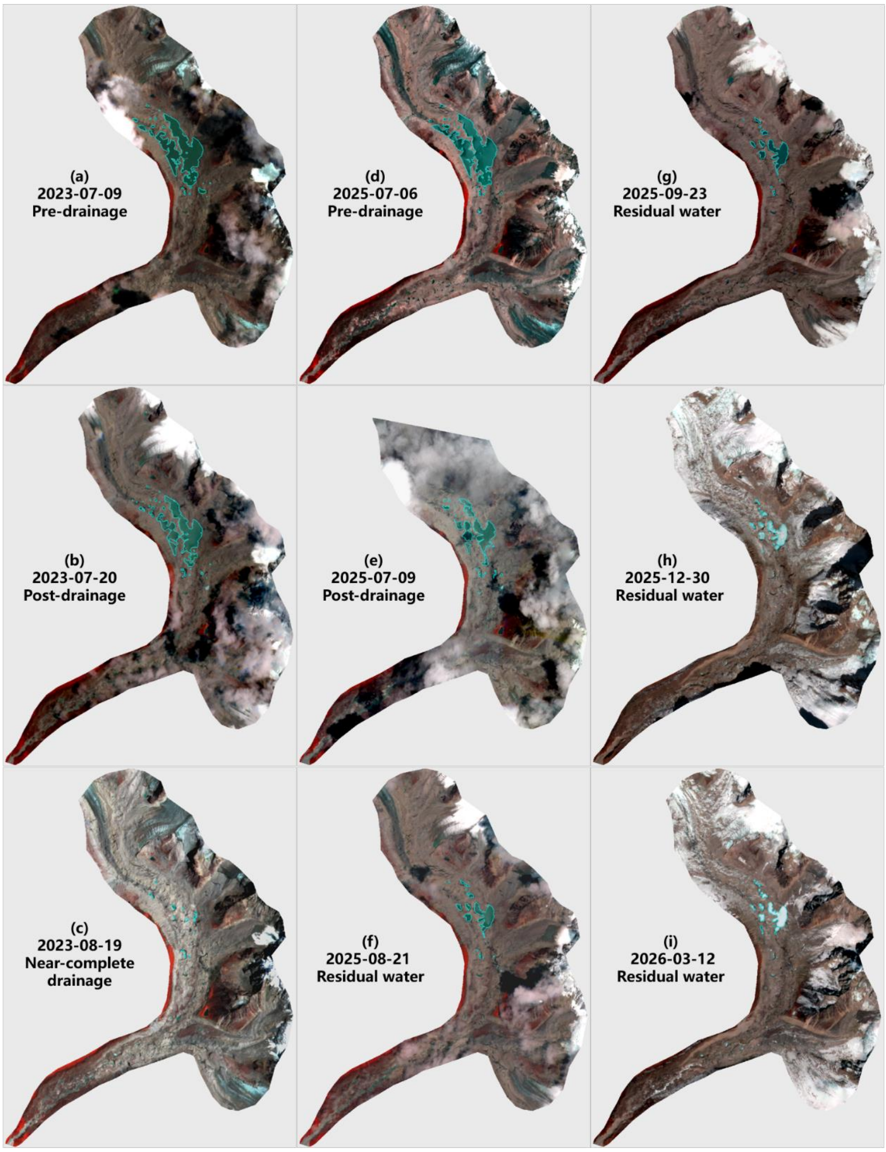

Figure 2. Key high-resolution optical images of the 2023 and 2025 drainage events. The figure compares pre- and post-drainage conditions of the Purepu supraglacial lake system in 2023 and 2025, showing repeated lake drainage, near-complete drainage after the 2023 event, and persistent residual water after the 2025 event. PlanetScope imagery © 2023–2026 Planet Labs PBC.

4.2 Contrasting drainage outcomes and possible drainage-system controls

Although the 2023 and 2025 events occurred after comparable seasonal lake expansion, their drainage outcomes differed strongly (Fig. 3). Pre-drainage lake area reached 0.701 ± 0.146 km² in 2023 and 0.717 ± 0.164 km² in 2025 (Fig. 3a; Table S2). These similar extents should not be interpreted as a

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

deterministic drainage threshold; rather, both events followed rapid early-melt-season expansion to a comparable total lake extent.

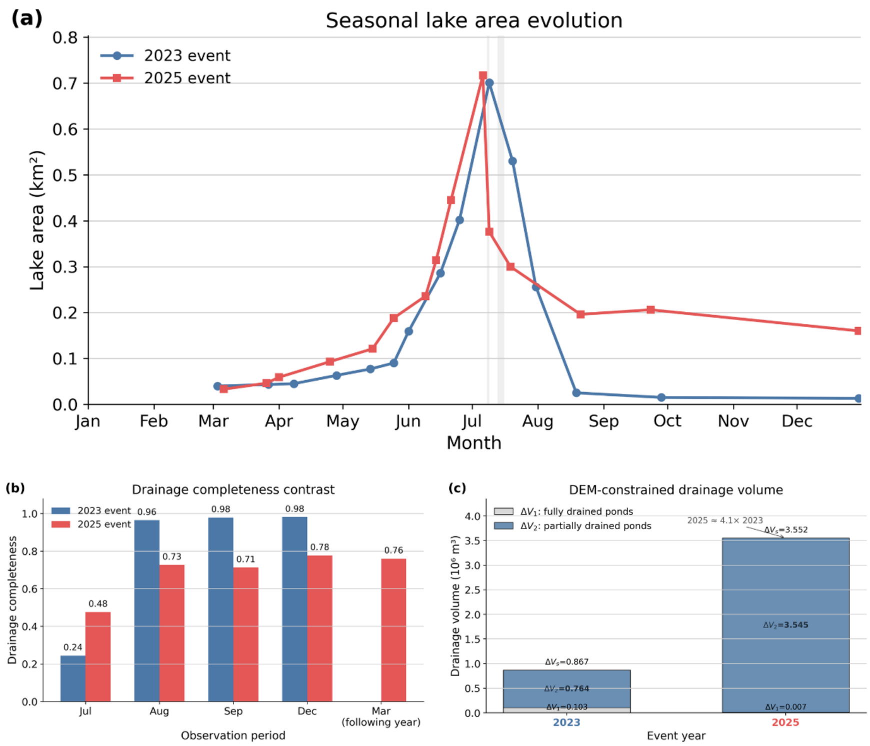

Figure 3. Lake-area evolution, area-based drainage completeness, and DEM-constrained lake-volume loss. (a) Seasonal lake-area evolution in 2023 and 2025. (b) Drainage completeness calculated relative to the pre-drainage lake area. (c) DEM-constrained lake-volume loss components for the 2023 and 2025 events, separated into fully drained and partially drained pond components.

The 2023 event evolved toward near-complete drainage, with area-based drainage completeness reaching approximately 0.96-0.98 by late August to September (Fig. 3b). In contrast, the 2025 event remained incomplete, with completeness of approximately 0.71-0.78 during later observations and about 0.76 by March 2026. DEM-constrained lake-volume loss was 0.867 × 10^6 m^3 in 2023 and 3.552 × 10^6 m^3 in 2025, indicating an approximately 4-fold greater loss in 2025 (Fig. 3c; Table S3). Most of the 2025 loss came from partially drained pond clusters, leaving substantial residual water. An independent bathymetric reconstruction estimated that approximately 7.22 × 10^6 m^3 of water was released during the 2025 Purepu GLOF (Zhang et al., 2026). Because the two estimates use different topographic datasets and volume-reconstruction approaches, they are not directly equivalent. The discrepancy underscores that our ΔV is an internally consistent, first-order metric for event comparison rather than a direct estimate of flood volume.

Beyond methodological differences in volume reconstruction, changes in mapped supraglacial lake storage may not fully close the event-scale water budget. Li et al. (2025) reported a discrepancy between the estimated supraglacial lake outburst volume and monitored downstream flood magnitude and

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

proposed englacial water storage and channel-material entrainment as possible contributing processes. Transient water storage in englacial and subglacial systems is documented in other glacier settings, and such reservoirs can drain abruptly (Livingstone et al., 2022; Ogier et al., 2025; Bowling et al., 2025). Rapid release of water stored within or beneath Purepu Glacier therefore cannot be excluded as an additional contribution to the 2025 flood, although such subsurface storage is not directly detectable in the available satellite imagery.

The mapped drainage pattern also shows strong spatial heterogeneity within the compound lake system. Pre- and post-drainage outlines in Fig. S2 show distinct zones of lake-area loss, consistent with spatially heterogeneous drainage rather than uniform evacuation through a single lake-scale pathway. Some pond clusters were nearly emptied, whereas others retained residual water, indicating spatial differences in drainage efficiency and hydraulic connectivity. This pattern is consistent with a compound supraglacial lake system comprising multiple pond clusters and surface depressions, in which drainage pathways and pond connectivity vary spatially. Total lake area alone may therefore be insufficient to explain drainage magnitude or completeness.

Early-season imagery further suggests differences in drainage-system preconditioning. Between 1 and 16 June 2023, several ponds disappeared while others appeared or expanded (Fig. S3), indicating lake reorganization, local drainage, and evolving hydrological connectivity before the main July event. In contrast, the 2025 sequence from 9 to 14 June was dominated by pond expansion and increasing connectivity, with no comparable pond disappearance. The 2023 system may therefore have undergone earlier local drainage, whereas water storage continued to increase in 2025. Similar behavior has been observed on debris-covered Himalayan glaciers, where perched ponds interact with evolving englacial drainage systems (Benn et al., 2017; Miles et al., 2017a). Such connectivity could also modify hydraulic connections to transient englacial or subglacial water storage, although this cannot be resolved from satellite imagery. Within the mapped lake system, the smaller 2023 lake-volume loss may partly reflect earlier drainage-system development or partial lake drainage, whereas the larger but incomplete 2025 event involved greater water-level lowering across an expanded and partially connected pond system.

Together, these observations suggest that similar pre-drainage lake extents can lead to contrasting drainage outcomes depending on pond connectivity, drainage-system state, and possible contributions from transient subsurface water storage.

4.3 Implications for repeated supraglacial lake drainage monitoring

The Purepu case shows strong interannual variability in supraglacial lake development. In 2022 and 2024, large and persistent lakes did not develop in the main lake-forming zone (Fig. S4). In contrast, the event years 2023 and 2025 showed rapid melt-season expansion followed by July drainage (Fig. S5). Repeated drainage therefore does not imply annual drainage. Instead, the system appears episodic, switching between low-storage non-event states and high-storage drainage-prone states. This behavior is consistent with previous observations that supraglacial ponds on debris-covered Himalayan glaciers can vary strongly over seasonal and interannual timescales (Watson et al., 2016; Miles et al., 2017b).

The incomplete 2025 drainage left residual water that persisted into the following year. The mapped lake area on 12 March 2026 was 0.172 km², compared with only 0.032 km² on 15 March 2025, indicating

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

that the lake system did not return to the low-storage spring condition observed prior to the July 2025 GLOF event (Fig. S6). However, the 25 June 2026 lake area was 0.212 ± 0.032 km², which remained below the 0.445 ± 0.053 km² mapped on 21 June 2025. Because the 25 June 2026 observation is based on Sentinel-2 imagery, whereas the other Fig. S6 panels are based on PlanetScope imagery, it should be interpreted as a monitoring-scale estimate rather than a directly comparable high-resolution area measurement. The 2026 observation therefore supports continued monitoring.

The need for continued monitoring is further supported by multi-year mid- to late-June imagery from 2021-2026 (Fig. S7 and S8). In the non-event years 2021, 2022, and 2024, the main lake-forming zone remained dominated by scattered small ponds and did not develop a large, connected supraglacial lake system. In contrast, the event years 2023 and 2025 both showed rapid expansion during June, with the lake system reaching a much larger and more connected state before July drainage. The 2026 imagery shows a more developed supraglacial lake system than in the non-event years but a less extensive lake state than the late-June 2025 pre-GLOF condition. The lake state observed in June 2026 strengthens the case for high-frequency monitoring during early July, especially given the downstream exposure of the Rasuwagadhi Friendship Bridge and hydropower infrastructure. Continued high-frequency monitoring is therefore important for supporting timely risk communication between downstream stakeholders.

More broadly, the 2025 event confirms that the Purepu supraglacial lake system can generate damaging downstream GLOF impacts, whereas the 2023 event shows that similar drainage can occur without being captured in disaster reports. This is consistent with the broader challenge that GLOF records depend on uneven combinations of field evidence, local reports, literature, and satellite observations (Veh et al., 2022; Lützow et al., 2023). For the Purepu supraglacial lake system, monitoring should begin no later than late June and continue through mid-July, when event-year lake expansion intensified before drainage. This monitoring emphasis is consistent with recent field and remote-sensing evidence from the 2025 Purepu GLOF, which identified rapid lake growth, persistence into early July, and drainage configuration as key monitoring considerations and emphasized coordinated transboundary monitoring and early-warning protocols (Zhang et al., 2026). High-frequency optical imagery is essential for detecting short-lived changes, and SAR observations should be used where cloud cover limits optical interpretation.

5 Conclusions

We identify repeated drainage from the Purepu supraglacial lake system, including a satellite-inferred drainage or GLOF-like event in July 2023 and a reported GLOF in the early morning of 8 July 2025. PlanetScope imagery constrains the 2023 event to 12-15 July, whereas the 2025 timing is independently supported by disaster reports and pre- and post-event satellite observations.

Both events followed lake expansion to approximately 0.70-0.72 km², but this similarity should not be interpreted as a deterministic drainage threshold. Their drainage outcomes differed markedly: the 2023 lake system evolved toward near-complete area loss, whereas DEM-constrained lake-volume loss was approximately 4 times greater in 2025 and the lake system remained incompletely drained, leaving persistent residual water.

https://doi.org/10.5194/egusphere-2026-4065
Preprint. Discussion started: 12 August 2026

Total lake area alone is therefore insufficient to characterize drainage behavior in the compound Purepu lake system. Area-based drainage completeness and DEM-constrained lake-volume loss, together with residual-water persistence and spatial pond connectivity, provide complementary evidence. Early-season imagery suggests different drainage-system states before the two events, while independent flood-volume estimates indicate that changes in mapped supraglacial lake storage may not fully explain the 2025 flood magnitude. An additional contribution from englacial or subglacial water storage cannot be excluded.

Multi-year June imagery indicates episodic lake development: large connected lakes were absent in the non-event years 2021, 2022, and 2024, whereas rapid June expansion preceded the 2023 and 2025 drainage events. In 2026, residual water persisted and June imagery showed a more developed lake system than in the non-event years, but a less extensive state than in late June 2025. These observations support continued high-frequency monitoring. At Purepu, monitoring should continue through mid-July, using high-resolution optical imagery where possible and SAR observations when cloud cover limits optical interpretation.

Code and Data availability

PlanetScope surface reflectance imagery used in this study is commercial satellite imagery provided by Planet Labs PBC. These data are subject to Planet licensing restrictions and cannot be redistributed by the authors. The acquisition dates, acquisition times, sensors, product types, cloud conditions, spatial resolutions, viewing geometries, and uses of the PlanetScope scenes analysed in this study are listed in Table S1. The 8 m High Mountain Asia DEM mosaic used for DEM-constrained lake-volume loss estimation is publicly available from the NASA National Snow and Ice Data Center Distributed Active Archive Center under DOI: 10.5067/KXOVQ9L172S2. Sentinel-1 and Sentinel-2 data used to examine event timing and recent lake conditions are freely available from the Copernicus Data Space Ecosystem. Landsat 8/9 observations used as auxiliary timing constraints are freely available from the U.S. Geological Survey through Earth Explorer. The derived lake-area time series, area uncertainties, and DEM-constrained lake-volume loss estimates used in this study are provided in Tables S2 and S3. The supplementary figures document the satellite-image evidence used for event timing, spatial drainage interpretation, residual-water persistence, and multi-year June monitoring comparisons.

Supplement link

The link to the supplement will be included by Copernicus, if applicable.

Author contributions

QX: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, and Writing original draft. SK and WD: Supervision, Funding acquisition, Review and Editing. WW, ZH, XH, BC, and BX: Review and Editing.

https://doi.org/10.5194/egusphere-2026-4065
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Competing interests

The authors declare that they have no conflict of interest

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Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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