Supplementary Information

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

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Supplementary figures

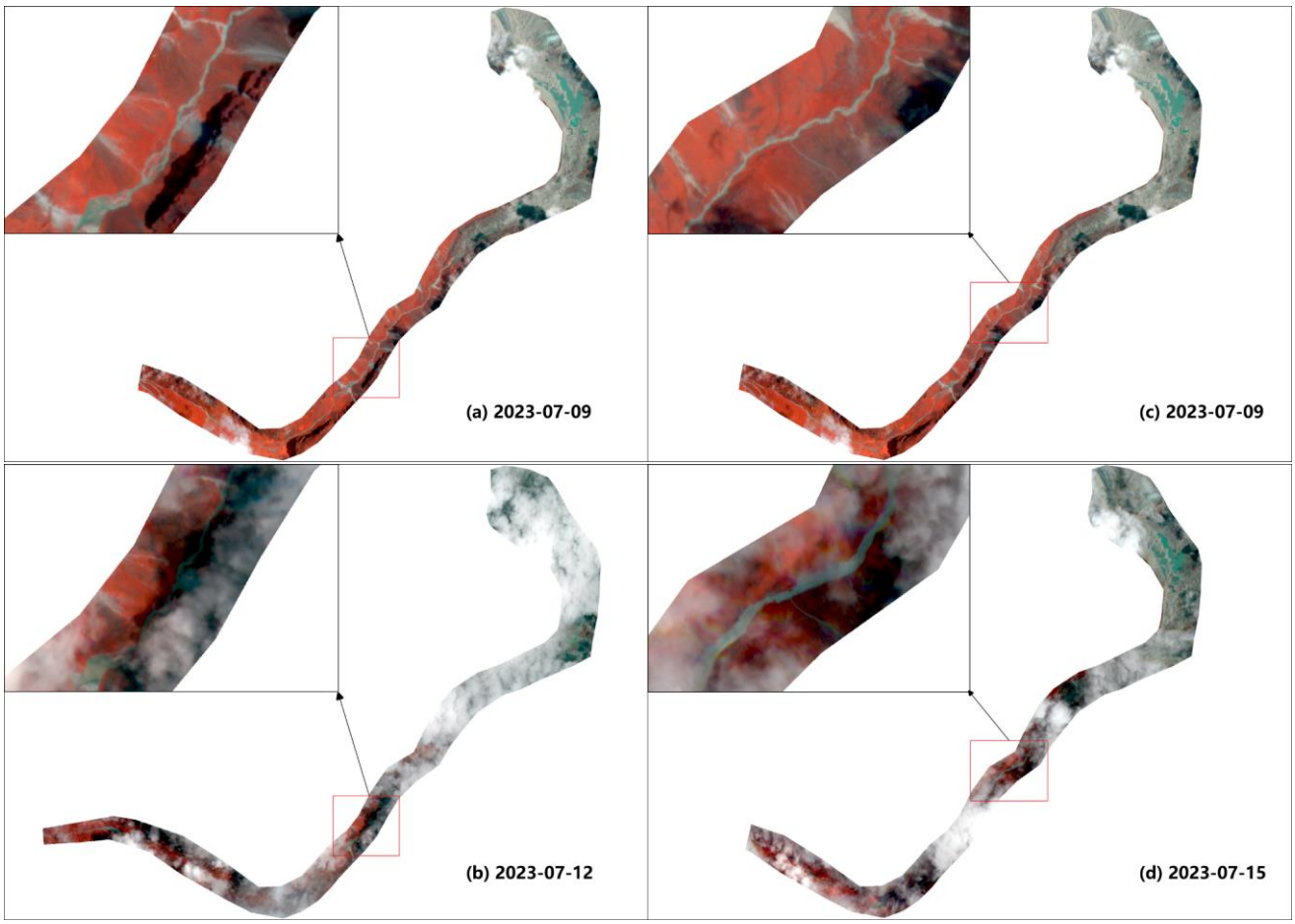

Figure S1. PlanetScope constraints on the 2023 drainage timing from outlet and downstream-channel morphology. PlanetScope false-colour images show the glacier outlet and downstream channel before and after the July 2023 drainage event. Red boxes indicate the outlet/channel reaches used for visual interpretation. Imagery from 9 July and the partially cloud-affected 12 July scene does not show clear

post-drainage channel modification, whereas outlet modification and downstream-channel widening are evident by 15 July. These observations constrain the 2023 event to between the 12 and 15 July PlanetScope acquisitions, although the exact occurrence time remains unresolved. PlanetScope imagery © 2023–2026 Planet Labs PBC.

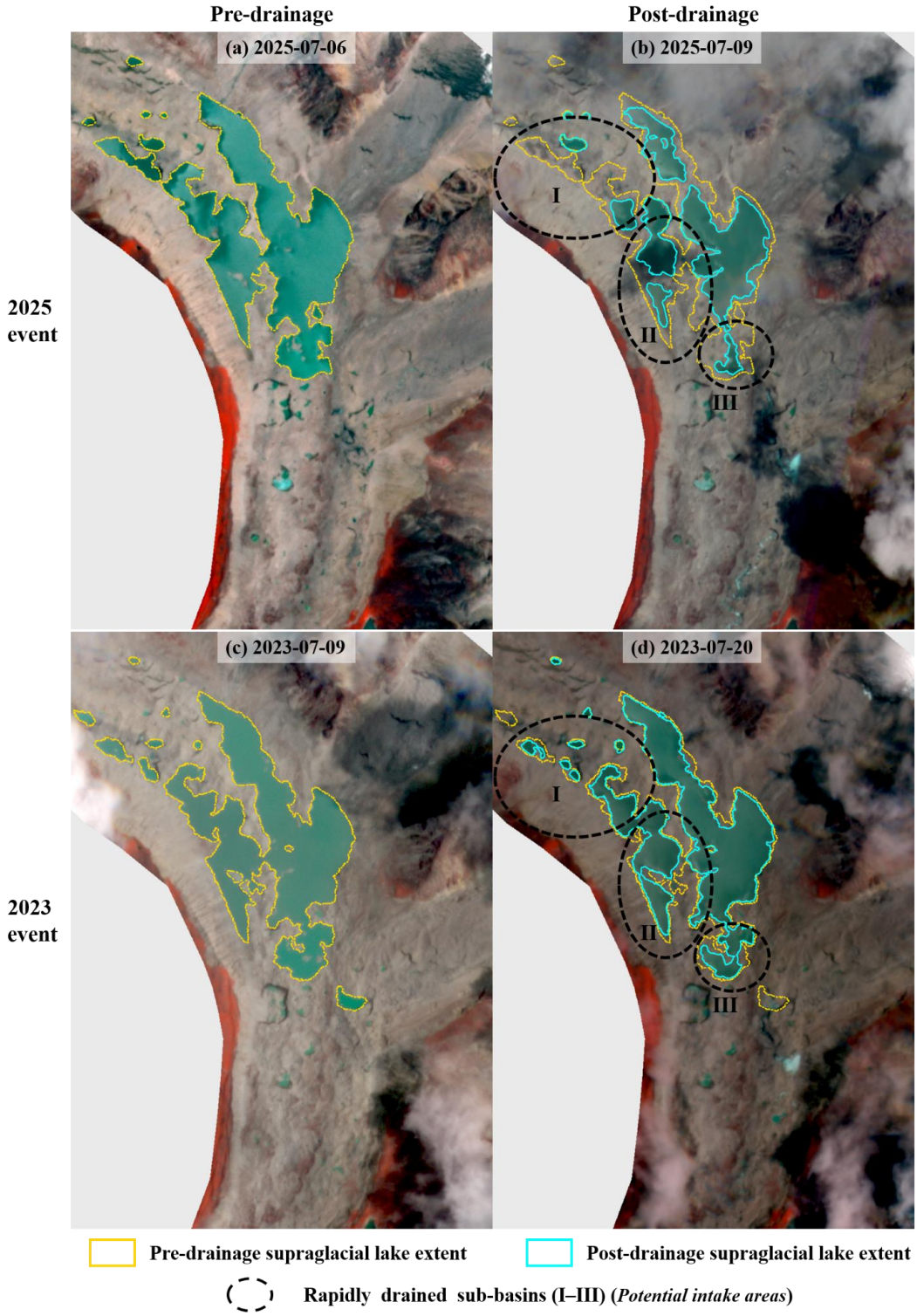

Figure S2. Spatially heterogeneous drainage and residual-water patterns in the 2023 and 2025 events. Pre- and post-drainage lake outlines show the spatial distribution of lake-area reduction and residual water. Yellow outlines indicate the pre-drainage supraglacial lake extents extracted from PlanetScope imagery, and cyan outlines indicate the post-drainage residual water extents. The marked zones I, II, and III indicate distinct image-derived drainage behaviours, including areas that were nearly emptied and areas that remained partially water-covered after drainage. The figure supports the interpretation that Purepu behaved as a compound supraglacial lake system rather than a single simple lake basin. PlanetScope imagery © 2023–2026 Planet Labs PBC.

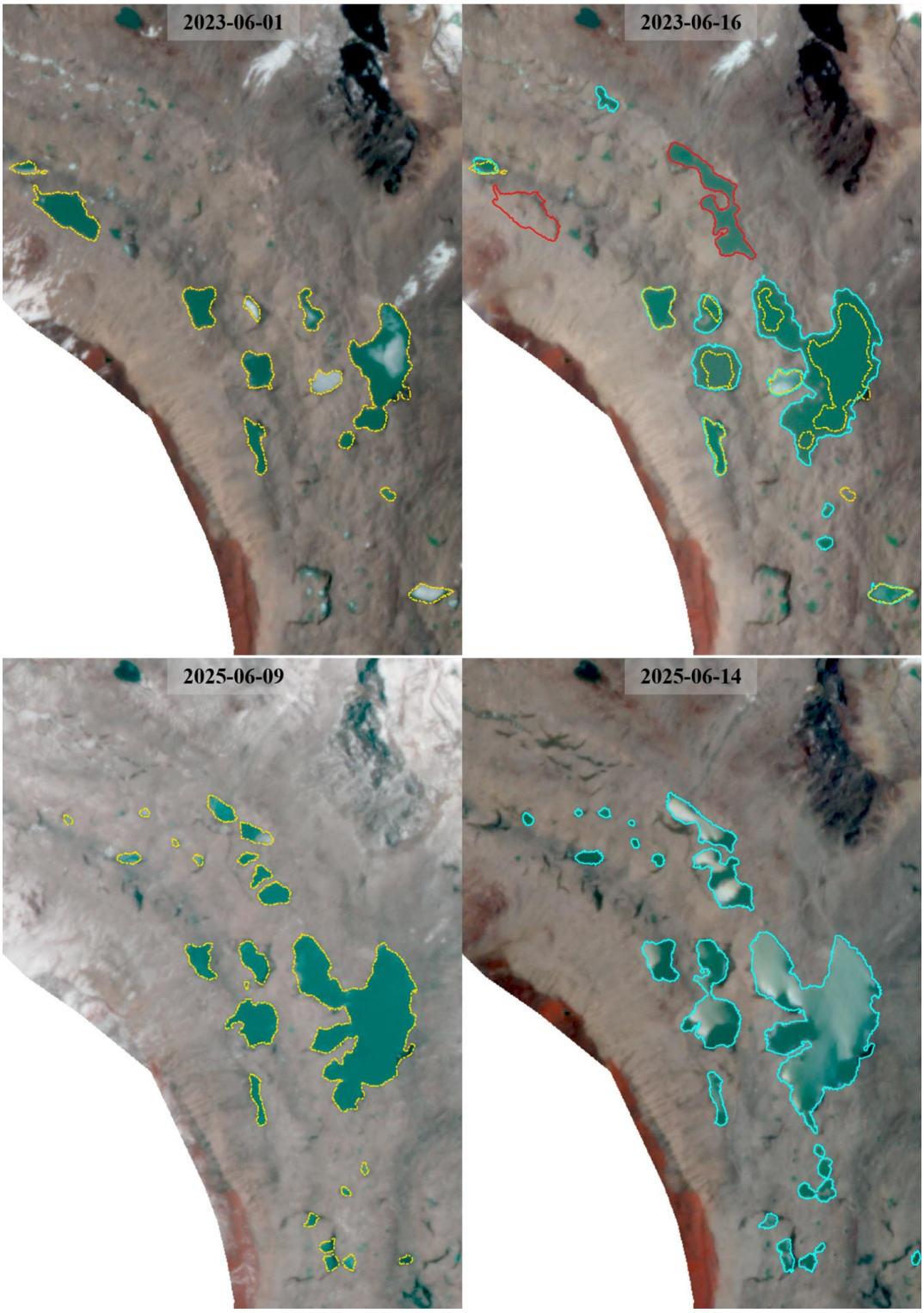

Figure S3. Early-season supraglacial pond evolution before the 2023 and 2025 drainage events. PlanetScope false-colour images compare early melt-season pond evolution. In 2023, images acquired on 1 and 16 June show pond disappearance, new pond formation, and pond expansion, indicating active early-season lake reorganization before the July drainage event. In 2025, images acquired on 9 and 14 June show mainly pond expansion, enlargement, and increasing connection between pond clusters, without clear evidence of pond disappearance comparable to 2023. Yellow and cyan outlines denote earlier and later lake boundaries, respectively; red outlines highlight ponds that disappeared or changed markedly in the 2023 sequence. PlanetScope imagery © 2023–2026 Planet Labs PBC.

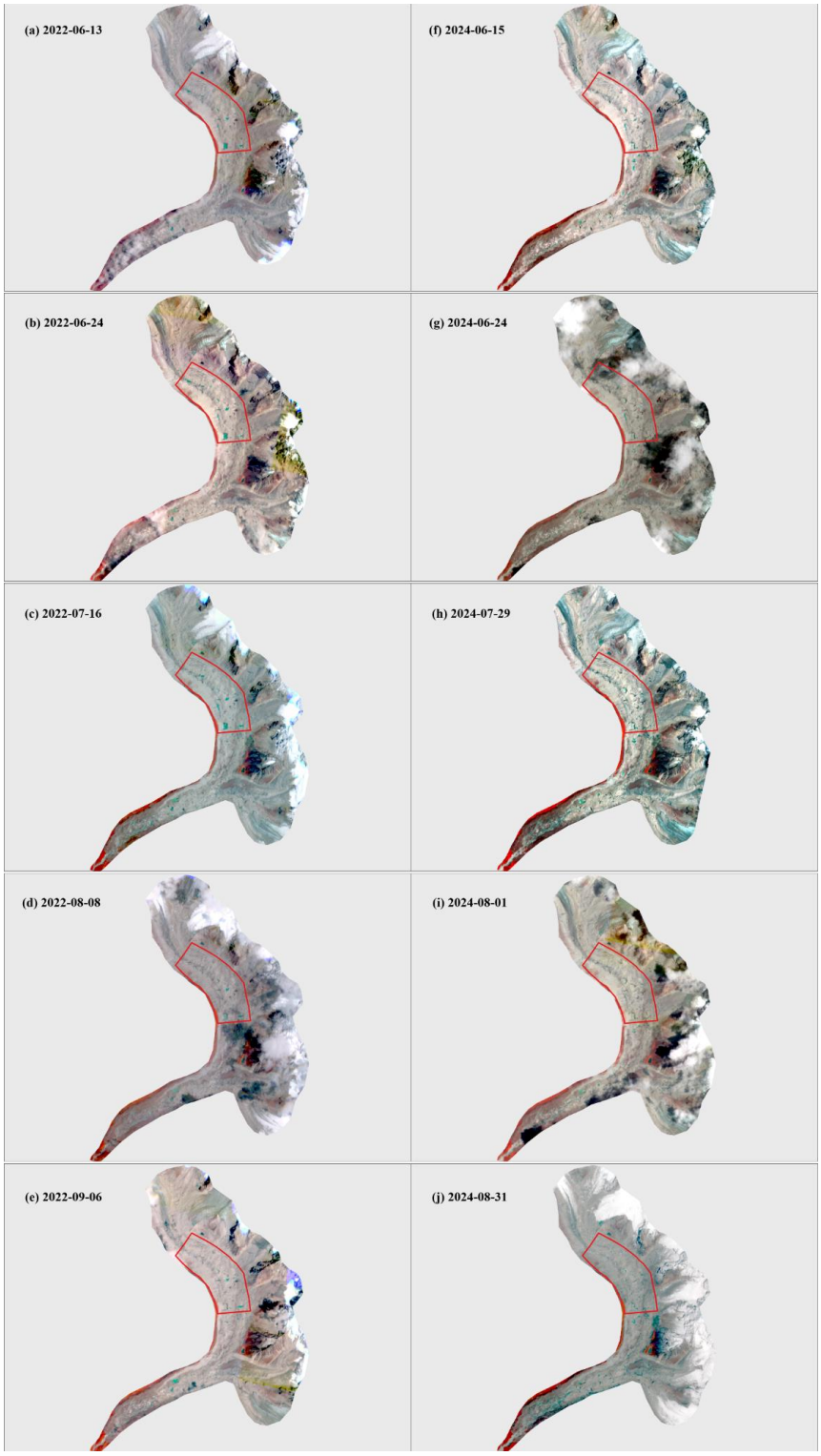

Figure S4. Non-event-year supraglacial lake conditions in 2022 and 2024. PlanetScope false-colour images show the main lake-forming zone during the 2022 and 2024 melt seasons. Red polygons mark the zone where the large supraglacial lake system developed in the 2023 and 2025 event years. In contrast to the event years, no large and persistent supraglacial lake developed in this zone during the displayed 2022 and 2024 observations, indicating strong interannual variability in lake formation. PlanetScope imagery © 2023–2026 Planet Labs PBC.

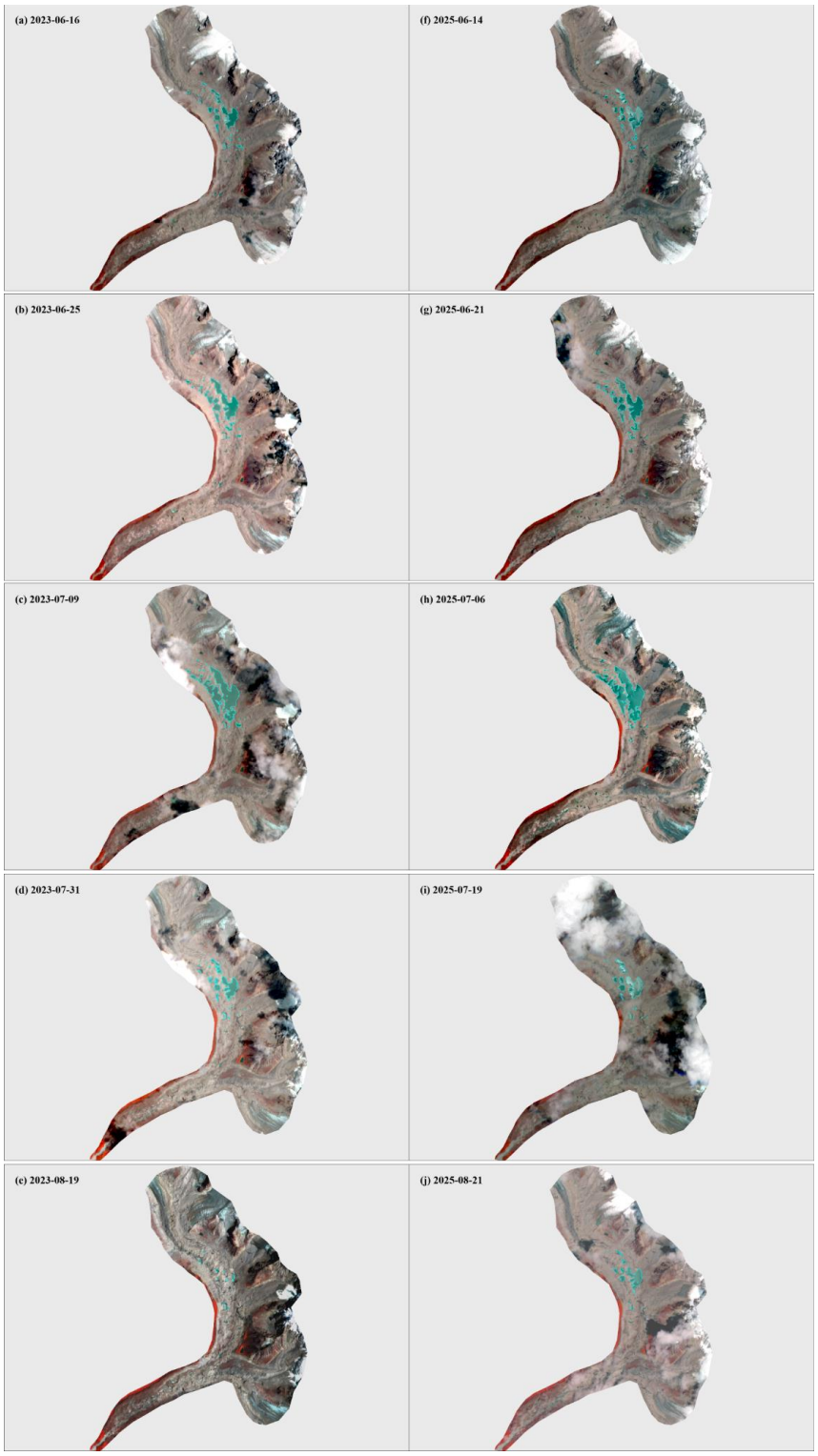

Figure S5. Melt-season evolution of the Purepu supraglacial lake system in the 2023 and 2025 event years. PlanetScope false-colour images show the development of the lake system from mid-June to late August in 2023 and 2025. The 2023 sequence shows lake expansion before the mid-July satellite-inferred drainage event and subsequent reduction to small residual ponds. The 2025 sequence shows rapid expansion before the reported 8 July GLOF, followed by incomplete drainage and persistent residual water. This figure provides satellite-derived spatial evidence for the distribution of supraglacial lakes and post-event residual water, supporting the lake-area time series and the interpretation of drainage states. PlanetScope imagery © 2023–2026 Planet Labs PBC.

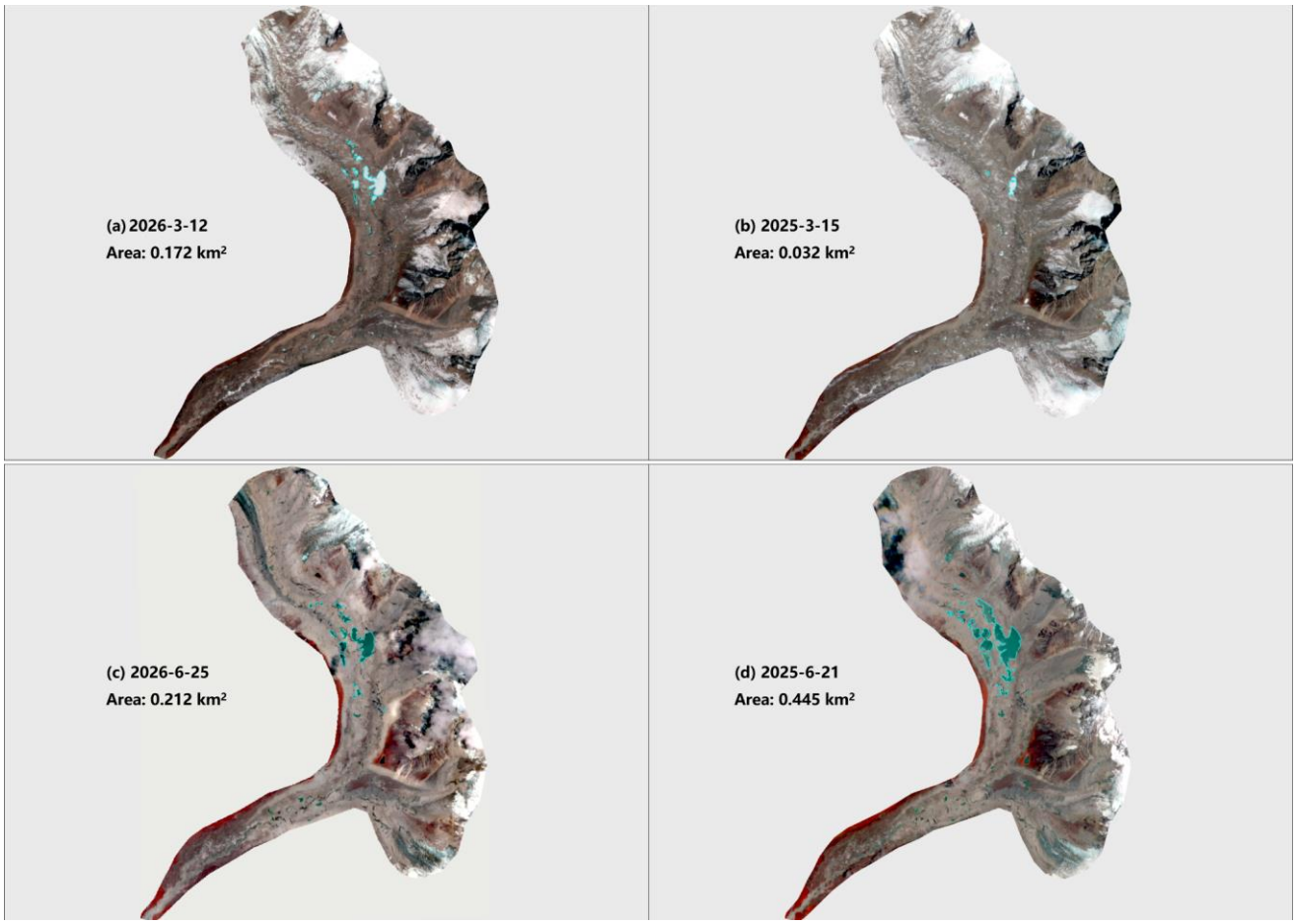

Figure S6. Residual-water persistence after the 2025 GLOF and early melt-season lake state in 2026. Panels compare the lake system in spring and early melt-season observations in 2025 and 2026. The mapped area on 12 March 2026 was 0.172 km2, much larger than the 0.032 km2 mapped on 15 March 2025, indicating residual water persisted through winter after the incomplete 2025 drainage. The 25 June 2026 area was 0.212 km2, lower than the 0.445 km2 mapped on 21 June 2025. The 25 June 2026 panel is based on Sentinel-2 imagery and should be interpreted as a monitoring-scale estimate rather than a directly equivalent PlanetScope measurement. PlanetScope imagery © 2023–2026 Planet Labs PBC.

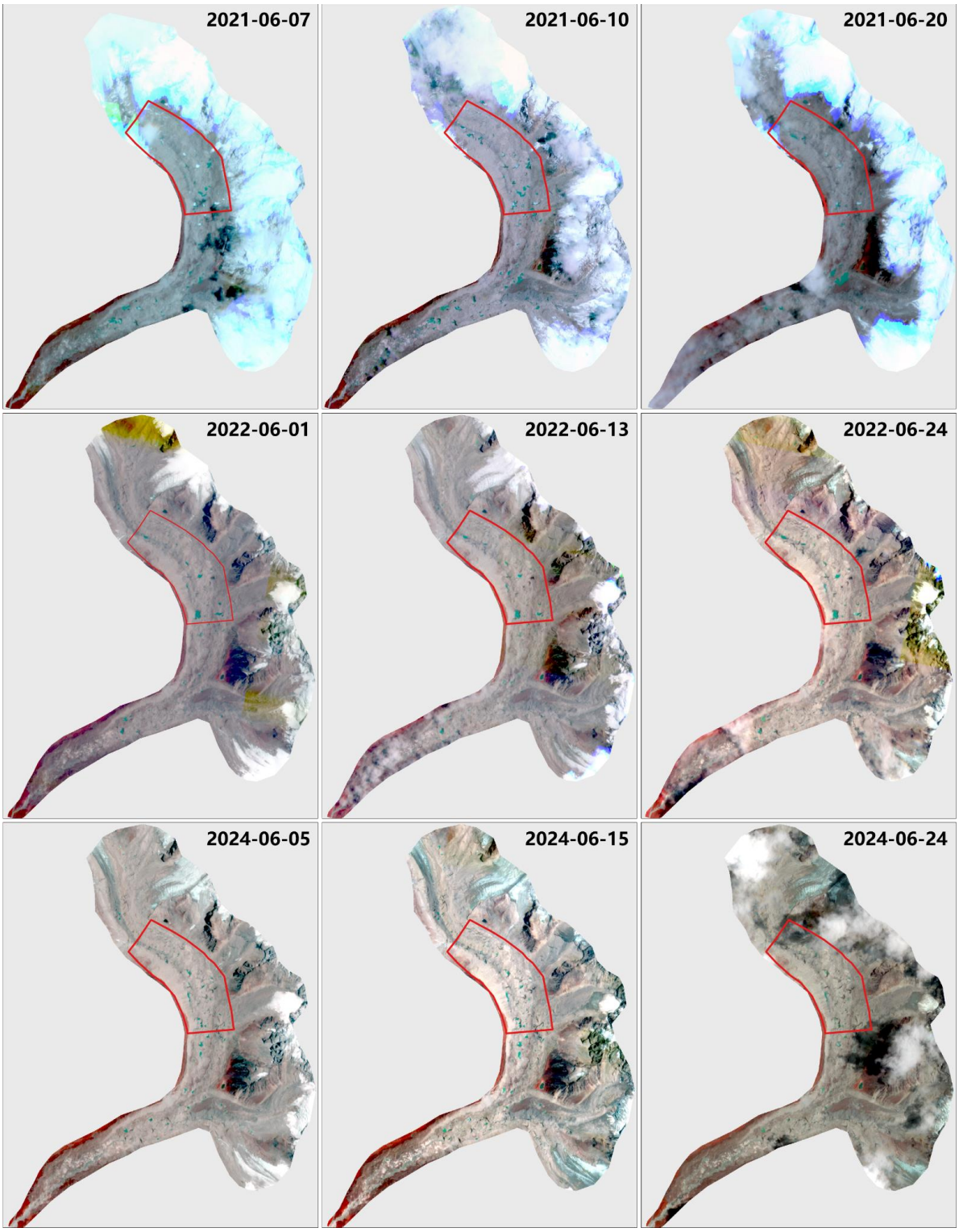

Figure S7. Satellite evidence for weak supraglacial lake development during June in non-event years 2021, 2022, and 2024. PlanetScope false-colour images show the main lake-forming zone during June in non-event years. Red polygons indicate the main lake-forming zone used for comparison. In the available June satellite imagery from 2021, 2022, and 2024, the main lake-forming zone was dominated by scattered small ponds, and no large connected supraglacial lake system was observed. This provides a non-event reference for interpreting event-year lake expansion. PlanetScope imagery © 2023–2026 Planet Labs PBC.

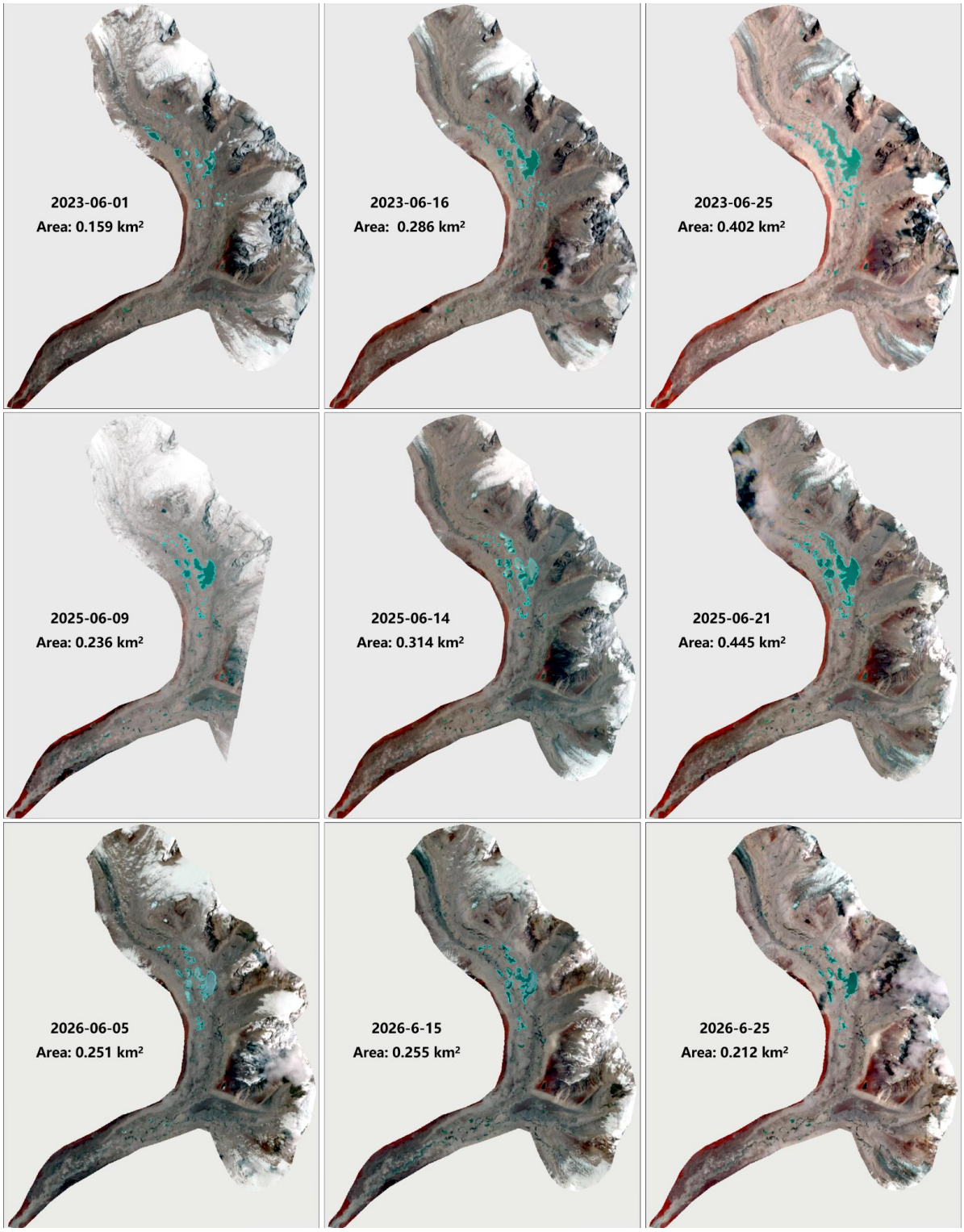

Figure S8. Satellite evidence for pronounced supraglacial lake development during June in the 2023 and 2025 event years and the 2026 monitoring year. PlanetScope imagery from 2023 and 2025 shows pronounced June supraglacial lake development before the July drainage events, while the 2026 Sentinel-2 image provides a post-2025 monitoring comparison of residual water and renewed lake development. In 2023 and 2025, the lake system expanded rapidly through June before July drainage, reaching larger and more connected states. In 2026, the lake area remained larger than in non-event years but below the late-June 2025 pre-GLOF state. The lake state observed on 25 June 2026 indicates that intensive monitoring should be conducted in early July to reduce downstream risk from a potential 2025-like GLOF event. PlanetScope imagery © 2023–2026 Planet Labs PBC.

Supplementary tables

Tab. S1. Satellite image inventory used for lake mapping, event timing constraints, and figure preparation. The table lists the satellite images used in the study, including acquisition date and time, sensor, product type, cloud conditions, ground control, spatial resolution, viewing geometry, and figure or analysis reference. PlanetScope imagery provides the primary basis for lake mapping and event reconstruction, while Sentinel-1, Sentinel-2, and Landsat observations were used where available for timing checks or monitoring context.

No.	satellite_id	Acquisition date	Acquisition time UTC	Product type	Sensor	cloud_percent	ground_control	gsd	pixel_resolution	shadow_percent	sun_elevation	view_angle	visible_percent	Figure/analysis reference
1	222f	2021-06-07	04:18:15	PSScene	PSB.SD	45	TRUE	3.8	3	3	63.1	3.9	55	Figure S7
2	105c	2021-06-10	04:43:06	PSScene	PSB.SD	22	TRUE	4.6	3	1	68.3	1	78	Figure S7
3	2223	2021-06-20	04:08:45	PSScene	PSB.SD	39	FALSE	3.8	3	1	60.6	2.9	61	Figure S7
4	2458	2022-06-01	04:04:24	PSScene	PSB.SD	0	TRUE	4	3	0	59.5	5	100	Figure S7
5	2420	2022-06-13	04:00:58	PSScene	PSB.SD	10	TRUE	4	3	4	58.6	5	90	Figure S4, Figure S7
6	2420	2022-06-13	04:01:01	PSScene	PSB.SD	19	TRUE	4	3	5	58.6	5	81	Figure S4, Figure S7
7	2439	2022-06-24	04:01:19	PSScene	PSB.SD	18	TRUE	3.9	3	4	58.8	3.2	82	Figure S4, Figure S7
8	2439	2022-06-24	04:01:21	PSScene	PSB.SD	36	TRUE	3.9	3	8	58.8	3.2	64	Figure S4, Figure S7
9	2479	2022-07-16	04:31:17	PSScene	PSB.SD	10	TRUE	4	3	1	64.2	4.9	90	Figure S4
10	2438	2022-07-16	04:33:14	PSScene	PSB.SD	5	TRUE	4	3	1	64.2	1.1	95	Figure S4
11	2438	2022-07-16	04:33:16	PSScene	PSB.SD	0	TRUE	4	3	0	64.2	1	100	Figure S4
12	249b	2022-08-08	04:35:16	PSScene	PSB.SD	33	TRUE	4	3	1	61.8	5	67	Figure S4
13	249b	2022-08-08	04:35:18	PSScene	PSB.SD	21	TRUE	4	3	3	61.8	5	79	Figure S4
14	2480	2022-09-06	04:32:35	PSScene	PSB.SD	15	TRUE	3.9	3	1	57.3	1	85	Figure S4
15	2486	2023-03-03	04:35:35	PSScene	PSB.SD	0	TRUE	3.8	3	1	45.1	1.1	100	Figure 3
16	2486	2023-03-03	04:35:37	PSScene	PSB.SD	0	TRUE	3.8	3	1	45.2	1.1	100	Figure 3
17	24c5	2023-03-27	04:04:38	PSScene	PSB.SD	0	TRUE	4	3	1	48	0.1	100	Figure 3
18	24c5	2023-03-27	04:04:41	PSScene	PSB.SD	0	TRUE	4	3	0	48.1	0.1	100	Figure 3
19	24a8	2023-04-08	04:04:51	PSScene	PSB.SD	0	TRUE	3.9	3	0	51.7	0.9	100	Figure 3
20	24a8	2023-04-08	04:04:54	PSScene	PSB.SD	0	TRUE	4	3	0	51.8	0.9	100	Figure 3
21	2262	2023-04-28	04:22:56	PSScene	PSB.SD	0	TRUE	3.4	3	0	60.6	2.9	100	Figure 3
22	2262	2023-04-28	04:22:58	PSScene	PSB.SD	0	TRUE	3.4	3	0	60.6	2.9	100	Figure 3
23	24d0	2023-05-14	04:05:15	PSScene	PSB.SD	0	TRUE	3.8	3	0	59	0.8	100	Figure 3
24	24d0	2023-05-14	04:05:17	PSScene	PSB.SD	0	TRUE	3.8	3	0	59	0.7	100	Figure 3
25	24bc	2023-05-25	04:03:37	PSScene	PSB.SD	32	TRUE	3.8	3	1	59.8	3.2	68	Figure 3
26	24bc	2023-05-25	04:03:39	PSScene	PSB.SD	45	TRUE	3.9	3	2	59.8	3.2	55	Figure 3
27	24c4	2023-06-01	04:05:48	PSScene	PSB.SD	0	TRUE	3.9	3	0	59.9	1.2	100	Figure 3, Figure S3, Figure S8
28	24a9	2023-06-16	04:04:53	PSScene	PSB.SD	1	TRUE	3.9	3	0	59.7	0.7	99	Figure 3, Figure S3, Figure S5, Figure S8
29	24a9	2023-06-16	04:04:56	PSScene	PSB.SD	3	TRUE	3.9	3	0	59.7	0.7	97	Figure 3, Figure S3, Figure S5, Figure S8
30	242e	2023-06-25	04:02:41	PSScene	PSB.SD	0	TRUE	4	3	0	59.3	4.9	100	Figure 3, Figure S2, Figure S8
31	24ce	2023-07-09	04:04:47	PSScene	PSB.SD	13	TRUE	3.9	3	2	58.5	0.8	87	Figure 2, Figure 3, Figure S1, Figure S2, Figure S5

32	24b0	2023-07-12	04:03:57	PSScene	PSB.SD	86	TRUE	3.9	3	0	58.4	5	14	Figure S1
33	24b0	2023-07-12	04:04:00	PSScene	PSB.SD	88	TRUE	3.9	3	1	58.3	4.9	12	Figure S1
34	2465	2023-07-15	04:04:21	PSScene	PSB.SD	49	TRUE	3.7	3	1	57.6	5	51	Figure S1
35	2465	2023-07-15	04:04:23	PSScene	PSB.SD	95	TRUE	3.7	3	1	57.6	5	5	Figure S1
36	2490	2023-07-20	04:42:53	PSScene	PSB.SD	18	TRUE	3.6	3	2	65.5	5	82	Figure 2, Figure 3, Figure S5, Figure S2
37	2486	2023-07-31	04:41:49	PSScene	PSB.SD	14	TRUE	3.6	3	2	64.5	0.4	86	Figure 3, Figure S5
38	2459	2023-08-19	03:59:07	PSScene	PSB.SD	5	TRUE	3.6	3	1	53.8	4.9	95	Figure 2, Figure 3, Figure S5
39	24a8	2023-08-19	04:04:11	PSScene	PSB.SD	1	TRUE	3.8	3	0	55	4.6	99	Figure 2, Figure 3, Figure S5
40	24b5	2023-09-28	04:05:46	PSScene	PSB.SD	7	TRUE	3.9	3	3	48	3.2	93	Figure 3
41	24b5	2023-09-28	04:05:49	PSScene	PSB.SD	12	TRUE	3.9	3	5	48	3.1	88	Figure 3
42	241e	2023-12-30	04:10:21	PSScene	PSB.SD	1	TRUE	3.5	3	0	30	4.9	99	Figure 3
43	241e	2023-12-30	04:10:23	PSScene	PSB.SD	0	TRUE	3.4	3	0	30.1	5	100	Figure 3
44	24ce	2024-06-05	04:13:10	PSScene	PSB.SD	6	TRUE	3.7	3	1	62.1	5	94	Figure S7
45	2423	2024-06-15	04:22:48	PSScene	PSB.SD	0	TRUE	3.1	3	0	63.5	3.1	100	Figure S4, Figure S7
46	2440	2024-06-24	04:30:24	PSScene	PSB.SD	32	TRUE	3.1	3	9	64.6	4.9	68	Figure S4, Figure S7
47	2416	2024-07-29	05:04:32	PSScene	PSB.SD	1	TRUE	3.3	3	0	69.5	3	99	Figure S4
48	2416	2024-07-29	05:04:34	PSScene	PSB.SD	0	TRUE	3.3	3	0	69.5	3.1	100	Figure S4
49	2430	2024-08-01	04:31:57	PSScene	PSB.SD	39	TRUE	3.1	3	2	62.6	3.5	61	Figure S4
50	2430	2024-08-01	04:31:59	PSScene	PSB.SD	47	TRUE	3.1	3	2	62.6	3.5	53	Figure S4
51	24fd	2024-08-31	05:05:38	PSScene	PSB.SD	4	TRUE	3.8	3	0	63.9	1.9	96	Figure S4
52	24fd	2024-08-31	05:05:40	PSScene	PSB.SD	7	TRUE	3.8	3	1	64	1.9	93	Figure S4
53	24da	2025-03-06	05:14:52	PSScene	PSB.SD	0	TRUE	3.7	3	0	51.5	5	100	Figure 3
54	24f9	2025-03-15	05:15:09	PSScene	PSB.SD	0	TRUE	3.6	3	0	55.3	1.5	100	Figure S6
55	24ee	2025-03-26	05:12:11	PSScene	PSB.SD	0	TRUE	3.7	3	0	59.2	4.1	100	Figure 3
56	2409	2025-04-01	05:15:16	PSScene	PSB.SD	0	TRUE	3.8	3	0	61.3	5	100	Figure 3
57	251e	2025-04-01	05:23:45	PSScene	PSB.SD	0	TRUE	3.9	3	0	62.7	1.5	100	Figure 3
58	2409	2025-04-25	05:14:00	PSScene	PSB.SD	0	TRUE	3.7	3	0	69.3	0.2	100	Figure 3
59	2409	2025-04-25	05:14:02	PSScene	PSB.SD	0	TRUE	3.7	3	0	69.4	0.2	100	Figure 3
60	2515	2025-05-15	05:12:49	PSScene	PSB.SD	2	TRUE	3.7	3	0	73.4	2.9	98	Figure 3
61	2515	2025-05-15	05:12:51	PSScene	PSB.SD	5	TRUE	3.7	3	0	73.4	2.9	95	Figure 3
62	251d	2025-05-25	05:14:55	PSScene	PSB.SD	0	TRUE	3.7	3	0	74.6	1.4	100	Figure 3
63	252e	2025-06-09	05:25:00	PSScene	PSB.SD	0	TRUE	3.8	3	0	77	0.6	100	Figure 3, Figure S3, Figure S8
64	252e	2025-06-09	05:25:03	PSScene	PSB.SD	0	TRUE	3.8	3	0	77.1	0.6	100	Figure 3, Figure S3, Figure S8
65	24ee	2025-06-14	05:20:26	PSScene	PSB.SD	0	TRUE	3.6	3	0	75.9	4.9	100	Figure 3, Figure S3, Figure S8
66	24ee	2025-06-14	05:20:28	PSScene	PSB.SD	3	TRUE	3.6	3	0	75.9	4.9	97	Figure 3, Figure S3, Figure S8
67	2507	2025-06-21	05:16:35	PSScene	PSB.SD	6	TRUE	3.6	3	0	75.3	2	94	Figure 3, Figure S5, Figure S6, Figure S8
68	2507	2025-06-21	05:16:37	PSScene	PSB.SD	8	TRUE	3.6	3	0	75.4	2	92	Figure 3, Figure S5, Figure S6, Figure S8

69	2522	2025-07-06	05:23:11	PSScene	PSB.SD	0	TRUE	3.8	3	0	75.7	1	100	Figure 2, Figure 3, Figure S2, Figure S5
70	2417	2025-07-09	04:54:15	PSScene	PSB.SD	80	TRUE	3	3	1	69	3.2	20	Figure 2, Figure 3, Figure S2
71	2540	2025-07-19	05:27:08	PSScene	PSB.SD	74	TRUE	3.8	3	2	74.7	5	26	Figure 3, Figure S5
72	2540	2025-07-19	05:27:11	PSScene	PSB.SD	48	TRUE	3.8	3	3	74.8	5	52	Figure 3, Figure S5
73	24aa	2025-08-21	05:30:46	PSScene	PSB.SD	11	TRUE	3.3	3	0	70.1	1.4	89	Figure 2, Figure 3, Figure S2
74	2534	2025-09-23	05:26:17	PSScene	PSB.SD	0	TRUE	3.8	3	0	59.5	1.1	100	Figure 2, Figure 3
75	2534	2025-09-23	05:26:19	PSScene	PSB.SD	0	TRUE	3.8	3	0	59.6	1.1	100	Figure 2, Figure 3
76	2549	2025-09-23	05:26:52	PSScene	PSB.SD	51	TRUE	3.8	3	0	59.4	5	49	Figure 2, Figure 3
77	2549	2025-09-23	05:26:54	PSScene	PSB.SD	14	TRUE	3.8	3	2	59.5	5	86	Figure 2, Figure 3
78	2549	2025-09-23	05:26:57	PSScene	PSB.SD	0	TRUE	3.8	3	1	59.6	5	100	Figure 2, Figure 3
79	251a	2025-12-30	05:25:13	PSScene	PSB.SD	0	TRUE	3.5	3	3	36.8	1.2	100	Figure 2, Figure 3
80	24f7	2025-12-30	05:26:44	PSScene	PSB.SD	0	TRUE	3.5	3	0	36.9	3.1	100	Figure 2, Figure 3
81	24fe	2026-03-12	05:24:56	PSScene	PSB.SD	0	TRUE	3.7	3	0	55.1	4.7	100	Figure 2, Figure S6

Table S2. Lake-area time series of the Purepu supraglacial lake system. The table reports mapped lake areas and associated uncertainties for the 2023 and 2025 event years and selected monitoring observations. It provides the source data for the seasonal lake-area evolution (Figure 3 (a)) and area-based drainage-completeness calculations (Figure 3 (b)).

date	lake_area_km2	note
2023-03-03	0.04 ± 0.005	pre-drainage
2023-03-27	0.043 ± 0.008	pre-drainage
2023-04-08	0.045 ± 0.009	pre-drainage
2023-04-28	0.063 ± 0.006	pre-drainage
2023-05-14	0.077 ± 0.008	pre-drainage
2023-05-25	0.09 ± 0.01	pre-drainage
2023-06-01	0.159 ± 0.012	pre-drainage
2023-06-16	0.286 ± 0.022	pre-drainage
2023-06-25	0.402 ± 0.035	pre-drainage
2023-07-09	0.701 ± 0.146	pre-drainage
2023-07-20	0.53 ± 0.071	post-drainage
2023-07-31	0.256 ± 0.028	post-drainage
2023-08-19	0.025 ± 0.001	near-complete drainage
2023-09-28	0.015 ± 0.001	near-complete drainage
2023-12-30	0.013 ± 0.001	near-complete drainage
2025-03-06	0.033 ± 0.016	pre-drainage
2025-03-26	0.046 ± 0.013	pre-drainage
2025-04-01	0.059 ± 0.009	pre-drainage
2025-04-25	0.093 ± 0.011	pre-drainage
2025-05-15	0.121 ± 0.012	pre-drainage
2025-05-25	0.188 ± 0.023	pre-drainage
2025-06-09	0.236 ± 0.031	pre-drainage
2025-06-14	0.314 ± 0.039	pre-drainage
2025-06-21	0.445 ± 0.053	pre-drainage
2025-07-06	0.717 ± 0.164	pre-drainage
2025-07-09	0.376 ± 0.042	post-drainage
2025-07-19	0.3 ± 0.044	post-drainage
2025-08-21	0.196 ± 0.03	residual water
2025-09-23	0.206 ± 0.042	residual water
2025-12-30	0.16 ± 0.0345	residual water

Table S3. DEM-constrained lake-volume-loss estimates for the 2023 and 2025 drainage events. The table reports pre- and post-event reference images and DEM-constrained lake-volume-loss components. Volume loss is summarized for fully drained and partially drained residual-water states. These values are first-order DEM-constrained lake-volume losses and should not be interpreted as field-measured flood volumes or discharge.

Item	2025 event	2023 event
Pre-event image time (Beijing time)	2025-07-06 13:23:11	2023-07-09 12:04:47
Post-event image time (Beijing time)	2025-07-09 12:54:15	2023-07-15 12:04:21
Volume loss from fully drained ponds (m3)	7,283.813	103,124.531
Volume loss from partially drained ponds (m3)	3,545,000.906	763,744.313
Total estimated drainage volume (m3)	3,552,284.719	866,868.844
Ratio relative to 2023	4.1	1