A Multi-year Analysis of Supraglacial Lake Seasonal Dynamics in the Karakoram

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A Multi-year Analysis of Supraglacial Lake Seasonal Dynamics in the Karakoram

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Abstract

Supraglacial lakes are a key feature of many debris-covered glaciers in the Karakoram region. These lakes are highly dynamic, often forming and draining rapidly on seasonal timescales. However, due to their small size and transient nature, they are largely absent from regional and global glacial lake inventories. In this study, we used Sentinel-1 synthetic aperture radar (SAR) imagery to examine the seasonal (May to September) and interannual (2017 to 2023) dynamics of supraglacial lakes across six glaciers in the Karakoram at scales from 0.001 to 0.50 km^2. Our results show that small (<0.01 km^2) and ephemeral lakes dominate in number, with lake occurrence decreasing sharply as size increases. The lakes had a consistent seasonal pattern, with lake numbers and cumulative area peaking early in the melt season (May or June). Lake formation was concentrated on nearly stagnant glacier surfaces characterized by a debris thickness of less than 0.5 m and a surface slope of less than 9 degrees. This study provides new insights into supraglacial lake dynamics across the Karakoram by quantifying their prevalence, seasonality, and surface controls. These findings are important for evaluating potential downstream hydrologic and hazard impacts and improving our understanding of glacier hydrology and melt processes.

1. Introduction

The Karakoram is characterized by its steep topography, high mountains, and numerous dynamic glaciers (Mölg et al. 2018; Farinotti et al. 2020). This mountain range is home to more than 13,000 glaciers, covering an area of approximately 22,800 km^2, and includes some of the largest glaciers (>50 km long) outside of the polar regions (RGI Consortium 2017; Wendleder et al. 2018; Xie et al. 2023). These glaciers are found at altitudes ranging from 2,300 to 8,600 m above sea level, while most of the ice reserves are concentrated between 4,000 to 5,500 m (Copland et al. 2011; Hewitt 2011; Mölg et al. 2018). The steep mountain walls in the Karakoram are prone to frequent rockfalls and avalanches, which deliver extensive debris that covers the ablation zones of many glaciers in the region (Xie et al. 2023). This thick debris cover insulates the glacier and reduces melt rates, a phenomenon that, along with favorable meteorological conditions, is suggested to be a driving factor of the Karakoram Anomaly (Bisset et al. 2020; Zhu et al. 2024). The Karakoram Anomaly refers to the observed stability or slight mass gain of glaciers in the Karakoram region in contrast to widespread glacier retreat across the rest of the Himalaya (Farinotti et al. 2020).

A key feature of several of Karakoram's debris-covered glaciers is the formation of supraglacial lakes. These lakes develop when meltwater and precipitation accumulate in topographic depressions formed by heterogeneous glacier thinning in the lower and relatively flat areas of the ablation zone (Echelmeyer et al. 1991; Gibson et al. 2017; Yao et al. 2018). Their formation is accelerated by inefficient drainage of meltwater and the collapse of englacial conduits, leading to localized glacier thinning (Sakai et al. 2000; Huo et al. 2021). Supraglacial lakes are dynamic, ranging in size from a few square meters to tens of square kilometers (Miles et al. 2017). Most lakes drain rapidly if they are linked to the drainage network of the glacier, while some can persist for several years (Qiao et al. 2015; Miles et al. 2017; Wendleder et al. 2021). Some supraglacial

ponds and lakes may eventually coalesce and develop into large, moraine-dammed glacial lakes (Richardson and Reynolds 2000; Sakai et al. 2009; Agarwal et al. 2023).

Supraglacial lakes significantly affect glacier melt rates, creating a positive feedback loop between surface ablation and lake formation (Thompson et al. 2016; Miles et al. 2019). Due to their lower surface albedo and enhanced convection compared to thick debris, supraglacial lakes amplify glacier melt, particularly at their margins and bottoms, through efficient heat transfer (Benn et al. 2001; Xin et al. 2012; Zhu et al. 2024). Consequently, the omission of supraglacial lakes and ponds in the parameterization of glacier mass balance models may lead to an underestimation of melt rates (Huo 2021; Zhu et al. 2024). Furthermore, these lakes play a crucial role in glacier hydrology by regulating the storage and drainage of meltwater (Benn and Evans 2014). Their sudden drainage can deliver large volumes of meltwater to the glacier bed, raising basal water pressure, reducing friction, and ultimately accelerating ice flow or triggering glacier surges (Chudley et al. 2019; Wang and Sugiyama 2024). Rapid drainage events can also generate glacial lake outburst floods (GLOFs), or even trigger secondary GLOFs from downstream lakes by rapidly increasing water levels, for example, the Lemthang Tsho GLOF in 2015 (Gurung et al. 2017). GLOFs originating from supraglacial lakes tend to be smaller in magnitude than those from moraine-dammed lakes, however, they occur more frequently due to the seasonal formation and drainage of supraglacial lakes and can cause extensive destruction (Watson et al. 2018; Miles et al. 2018).

A detailed understanding of supraglacial lake evolution is vital for a comprehensive assessment of glacier hydrology and melt dynamics. In the Karakoram, a few studies have examined the long-term evolution and seasonal dynamics of supraglacial lakes (Veettil et al. 2016; Wendleder et al. 2018; Wendleder et al. 2021; Qureshi et al. 2023). However, these studies typically focus on specific glaciers, such as Baltoro and Hispar, or do not include the assessment of seasonal

supraglacial lake dynamics. Many supraglacial lakes are also missing from regional and global glacial lake inventories due to their small sizes and rapidly changing nature. Observation and continuous monitoring of supraglacial lakes and their evolution in the Karakoram-Himalayas is limited by the absence of hydraulic gaging stations and the frequent clouds brought by the Indian Monsoon during summer, when lake formation is most prevalent (Watson et al. 2016; Miles et al. 2018).

This study focuses on a comprehensive multi-year assessment of the seasonal dynamics of supraglacial lakes on six glaciers in the Karakoram region, utilizing Sentinel-1 synthetic aperture radar (SAR) data. SAR collects imagery in all weather conditions, providing a consistent dataset essential for analyzing lake dynamics across extensive spatiotemporal scales (Bovenga 2020; Wangchuk and Bolch 2020). The aim of this research is to evaluate the seasonal evolution of supraglacial lakes, investigate their interannual dynamics, and identify the key factors that influence their formation and seasonal fluctuations. To achieve this, we develop monthly lake datasets from May to September over a seven-year period (2017 to 2023) for six debris-covered glaciers. These datasets are then compared with several ancillary data, such as glacier debris thickness, slope, and velocity, to gain a deeper understanding of the interplay between these factors and supraglacial lake dynamics.

2. Study Area

In this study, we selected six debris-covered glaciers located in the Karakoram Mountains of northern Pakistan (Figure 1). These glaciers were selected based on the occurrence of a considerable number of supraglacial lakes. The lake dynamics analysis was limited to the debris-covered regions within the lower ablation zones of each glacier to minimize potential

complications in mapping the lakes, which could arise from seasonal snow at higher elevations. Our study areas include some of the largest and longest valley glaciers outside the polar regions, such as Baltoro, Batura, and Hispar. A summary of the glacier characteristics, sourced from the RGI Consortium (2017), is provided in Table 1.

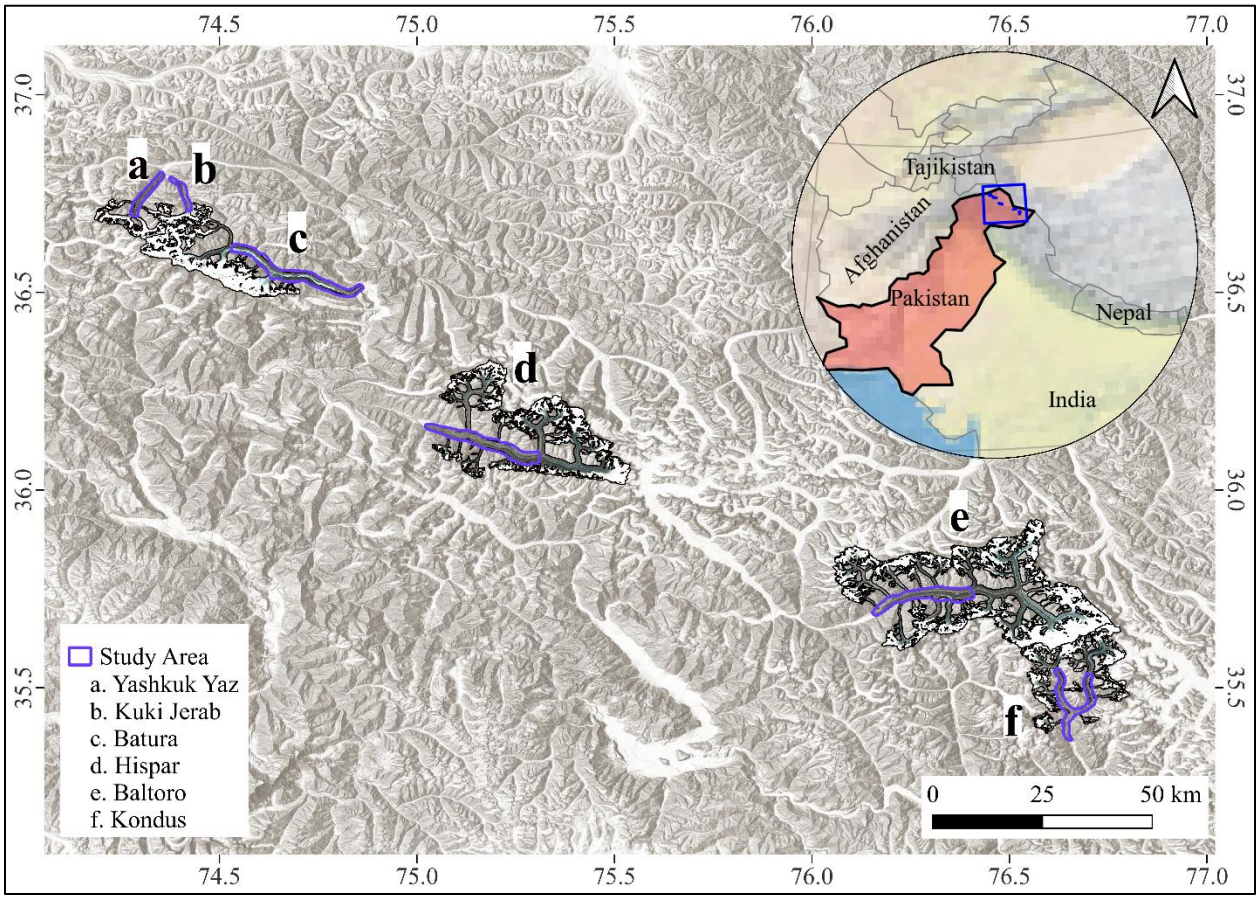


Figure 1: Study areas of the selected glaciers in the Karakoram in northern Pakistan.

Table 1: Characteristics of the six glaciers and the study areas

Glacier	RGI ID	Total Area (km^2)	Study Area (km^2)	Glacier Slope / Study Area Slope (°)	Elevation Range (m)
Yashkuk Yaz	RGI60-14.01670	76.97	22.83	23/12.25	3437-6909
Kuki Jerab	RGI60-14.01964	41.11	13.29	24.3/10.73	3597-6828

Batura	RGI60-14.02150	311.65	83.91	25/9.97	2595-7725
Hispar	RGI60-14.04477	495.65	77.79	23.3/13.17	3110-7794
Baltoro	RGI60-14.06794	809.11	67.52	23.8/11	3385-8569
Kondus	RGI60-14.07239	256.15	55.53	22.8/12.48	3257-7540

The Karakoram exhibits a mid-latitude high-mountain climate that is mostly semi-arid, primarily due to its distance from oceanic moisture sources (Copland et al. 2011; Forsythe et al. 2015; Wendleder et al. 2018). The climate is influenced by three distinct weather systems: the westerlies, the Indian summer monsoon, and the Tibetan Anticyclone (Wake 1989; Hewitt 2005; Bashir et al. 2017). Winter and spring receive most of the precipitation, the majority of which is contributed by the westerlies, while the monsoonal incursions bring extensive cloud cover, precipitation, and higher temperatures during the summer (Archer and Fowler 2004; Quincey et al. 2009; Haq et al. 2023). The wintertime snowfall, driven by the westerlies, sustains the regional snowpack in the Karakoram (Dimri et al. 2015; Javed et al. 2022). The stable anticyclonic weather conditions occasionally weaken, leading to incursions of the Indian monsoon into the Karakoram, which brings heavy precipitation (Wake 1989; Mayer et al. 2006). Air temperature remains sub-zero for most of the year, rising above freezing only during the summer months (June to August) (Reggiani et al. 2017). The microclimatic conditions of the Karakoram region show substantial variation, primarily driven by its wide altitudinal range. The annual mean temperature averages around 2.6 °C, while temperatures in the high mountain zones often remain below freezing throughout the year (Wiltshire 2014; Reggiani et al. 2017; Khan et al. 2020).

3. Methods

3.1 Data

Our primary dataset was derived from Sentinel-1 C-band SAR imagery (5.405 GHz, 5.6 cm), specifically the Ground Range Detected (GRD) collection available in Google Earth Engine (GEE). We used the vertical transmit/vertical receive (VV) polarization and the Interferometric Wide Swath (IW) instrument mode data to delineate supraglacial lakes. Sentinel-2 multispectral imaging (MSI) data was used to create normalized difference water index (NDWI) and normalized difference snow index (NDSI) maps and manually delineated validation datasets. Slope masking and glacier surface slope analysis were performed using digital elevation data from the Shuttle Radar Topography Mission (SRTM) (Farr et al. 2007). The Randolph Glacier Inventory (RGI) glacier outlines were utilized to define the study area polygons (RGI Consortium 2017). Glacier velocity maps and mean glacier velocity time series were created using the ITS_LIVE glacier velocity dataset (Gardner et al. 2022). Additionally, we analyzed debris thickness data from Rounce et al. (2021) to assess debris cover across glaciers.

3.2 Glacial Lake Mapping

The glacial lake mapping process involved three primary steps: (1) data preprocessing and preparation, (2) lake delineation, and (3) accuracy assessment. These steps are summarized below, while a more comprehensive description of the methodology is provided in Khan et al. (2025).

3.2.1 Data Preparation

We created monthly supraglacial lake datasets for the months of May to September from 2017 to 2023. Sentinel-1 GRD imagery in IW mode with VV polarization was imported into GEE and filtered by date and study area. Radiometric distortions in the data were corrected using the gamma

naught normalization approach (Small 2011), while a 3x3 median filter was applied to reduce speckle noise, and a preprocessed SAR dataset was prepared. Further, an NDSI mask was used to filter snow-covered areas, and a slope mask was used to remove regions with slopes greater than 20 degrees, which commonly introduce classification errors due to terrain-induced radar scattering. These preprocessing steps significantly improved computational efficiency and reduced misclassifications caused by wet snow and mountain shadows.

3.2.2 Glacial Lake Delineation

The lake delineation was based on the adaptive thresholding of SAR backscatter. Potential water bodies were initially identified using a lenient SAR backscatter threshold of -12 dB, classifying pixels with backscatter values below this threshold as water. The water mask was vectorized into individual polygons, and key attributes were extracted, including surface area and shape index (perimeter-to-area ratio). We applied a minimum surface area (1,000 m^2) and a shape index (0.3) filter to eliminate smaller and highly irregular-shaped non-lake features. The minimum lake area threshold was chosen to balance mapping accuracy with the retention of essential lake information.

We then applied an adaptive thresholding method based on the Otsu algorithm to reclassify the filtered polygons and obtain the final lake outlines. Manual inspection was conducted to remove false positives, including wet snow patches, glacial ice, and empty crevasses misclassified as lakes. The final lake polygons, along with associated attributes including surface area, mean elevation, and centroid coordinates, were exported as shapefiles for further analysis.

3.2.3 Accuracy Assessment

To evaluate the accuracy of the SAR-based supraglacial lake mapping, we manually delineated 70 lakes using Sentinel-2 MSI false-color composites. This validation dataset included supraglacial

lakes across multiple glaciers and years and served as the reference for validating the lake mapping approach. We assessed the accuracy using mean absolute error (MAE), mean absolute percentage error (MAPE), root mean square error (RMSE), and the coefficient of determination (R^2). These metrics quantify both the magnitude of error and the agreement between SAR-derived and reference lake areas. The MAE and MAPE were obtained using Equations 1 and 2, respectively.

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |Area_{S2} - Area_{S1}| \quad (1)$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n} \left|\frac{Area_{S2} - Area_{S1}}{Area_{S2}}\right| \quad (2)$$

where n is the number of lakes in the validation dataset, $Area_{S1}$ is the area of each lake obtained from the Sentinel-1 imagery, and $Area_{S2}$ is the area obtained using manual delineation from Sentinel-2 optical imagery.

3.3 Seasonal Persistence Analysis of Lake-Covered Areas

We quantified supraglacial lake persistence using a pixel-based approach derived from the monthly lake outlines. For each glacier, all lake polygons from May to September for each year were rasterized onto a common 10 m grid. During rasterization, pixels whose center fell within a lake polygon were assigned a value of 1 (lake-covered) and all other pixels were assigned 0. The five monthly binary rasters (May-September) were then stacked in chronological order, and for each pixel we calculated the maximum length of a consecutive run of lake presence, yielding annual values from 0 to 5 months.

We classified pixel-level lake persistence into three categories based on the maximum consecutive duration: ephemeral (1 month), intermittent (2-3 consecutive months), and persistent (4-5 consecutive months). For each category, lake-covered area was computed by counting the number

of pixels assigned to that class and multiplying by pixel area (100 m^2). We then quantified the relative contribution of each persistence class to the total lake-covered area for each glacier and year.

4. Results

4.1 Supraglacial Lake Mapping Accuracy

The SAR-derived supraglacial lake areas showed excellent agreement with manually delineated lake outlines derived from Sentinel-2 MSI imagery (Figure 2). The validation scatterplot demonstrates a near-one-to-one relationship between the two datasets (R^2 = 0.992; RMSE = 0.004 km^2), indicating that the SAR-based delineation reliably captures the lake area across a wide range of sizes. The overall MAE was 0.003 km^2, and the MAPE was 7.53%, reflecting high mapping accuracy despite the complex surface conditions typical of debris-covered glaciers.

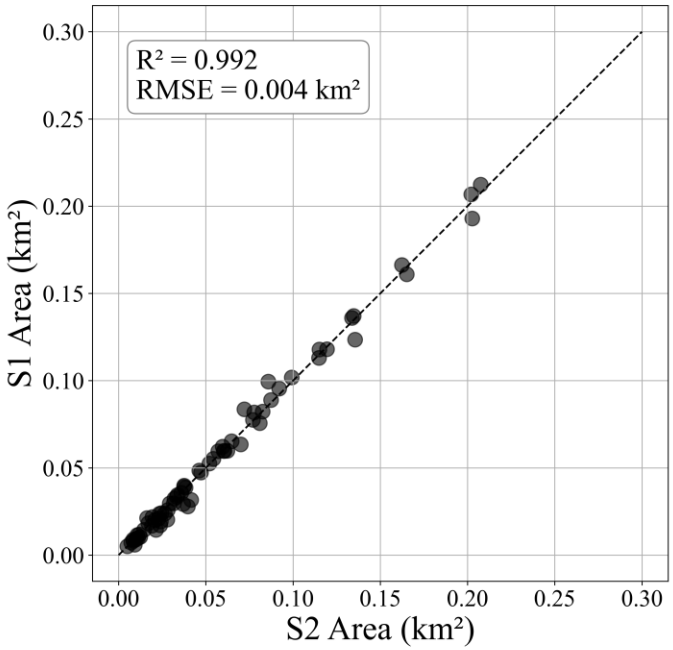


Figure 2: Scatterplot of glacial lake areas derived from Sentinel-1 (S1) SAR and manually digitized Sentinel-2 (S2) imagery. The dashed line is the 1:1 line. The strong agreement (R^2 = 0.992, RMSE = 0.004 km^2) highlights the accuracy of the SAR-based mapping approach.

Comparisons of individual lake outlines (Figure S1) further highlight the strong agreement between the two datasets. In most cases, the SAR-derived boundaries closely matched the optical reference outlines, with only minor differences along lake edges where radar backscatter

transitions gradually into surrounding ice. Larger lakes (>0.02 km^2) exhibited particularly strong consistency because their open water surfaces produce distinct low-backscatter signatures that are easily separable from nearby terrain. Errors were more prominent for very small lakes and those adjacent to wet snow patches. These conditions reduce the contrast between water and surrounding surfaces, making it more challenging to distinguish lakes from thin water-saturated snow or shadowed ice. Nevertheless, these discrepancies were typically small and did not substantially affect overall lake area estimates. Overall, the validation results confirm that the SAR workflow provides a robust and reliable method for supraglacial lake mapping across multiple years and diverse glacier surfaces.

4.2 Supraglacial Lake Number and Area Distribution

Across the six glaciers, supraglacial lake areas ranged from 0.001 km^2 to 0.50 km^2, with very few lakes larger than 0.1 km^2 (Figure 3). The mean number of lakes varied considerably among the glaciers (Table 2). Kuki Jerab had the lowest mean count (33 lakes), whereas Baltoro had the highest (223 lakes). The mean lake area ranged from 0.0028 to 0.0062 km^2, with approximately 70% of the lakes having areas smaller than the mean.

Table 2: *Summary statistics for each glacier, including the overall minimum, maximum, and mean number of lakes for each glacier during the study period and the highest, median, and mean lake area for each glacier. The months of the minimum and maximum lake numbers and maximum area are also shown.*

Glacier	Mean Area (km^2)	Max Lake Area (km^2)	Mean No. of Lakes	Min No. of Lakes	Max No. of Lakes	Mean Cumulative Area (km^2)	% of Total Area
Yashkuk Yaz	0.0039	0.0450 (Sep 2021)	76	38 (Aug 2023)	131 (May 2020)	0.293	1.28
Kuki Jerab	0.0031	0.0250 (May 2021)	33	9 (Sep 2023)	87 (May 2018)	0.112	0.84
Batura	0.0039	0.0610 (Aug 2022)	109	46 (July 2022)	223 (May 2021)	0.440	0.52
Hispar	0.0037	0.3700	177	42	404	0.657	0.85

		(June 2018)		(Sep 2017)	(May 2020)		
Baltoro	0.0062	0.5025 (Sep 2021)	223	114 (July 2022)	440 (May 2019)	1.388	2.05
Kondus	0.0028	0.0680 (June 2020)	78	24 (Aug 2022)	272 (May 2020)	0.251	0.45

Yashkuk Yaz, Kuki Jerab, Batura, and Kondus were dominated by small lakes, typically < 0.07 km^2 (Figure 3a-c and f), while Baltoro and Hispar contained lakes larger than 0.1 km^2 as well (Figure 3d-e). The cumulative lake area reflected these differences. Baltoro showed the highest cumulative lake area (2.11 km^2 in May 2019), followed by Hispar (1.40 km^2 in May 2017), whereas the other glaciers had cumulative lake areas that were consistently below 1 km^2. Lakes covered between 0.5 and 2% of the study area for each glacier.

Seasonal patterns were consistent across all glaciers (Figures 3-4). For each glacier, the peak number of lakes occurred in May or June, while the fewest were between July and September. The cumulative lake area and the number of lakes were correlated, both peaking in May or June and declining as the melt season progressed (Figure 4).

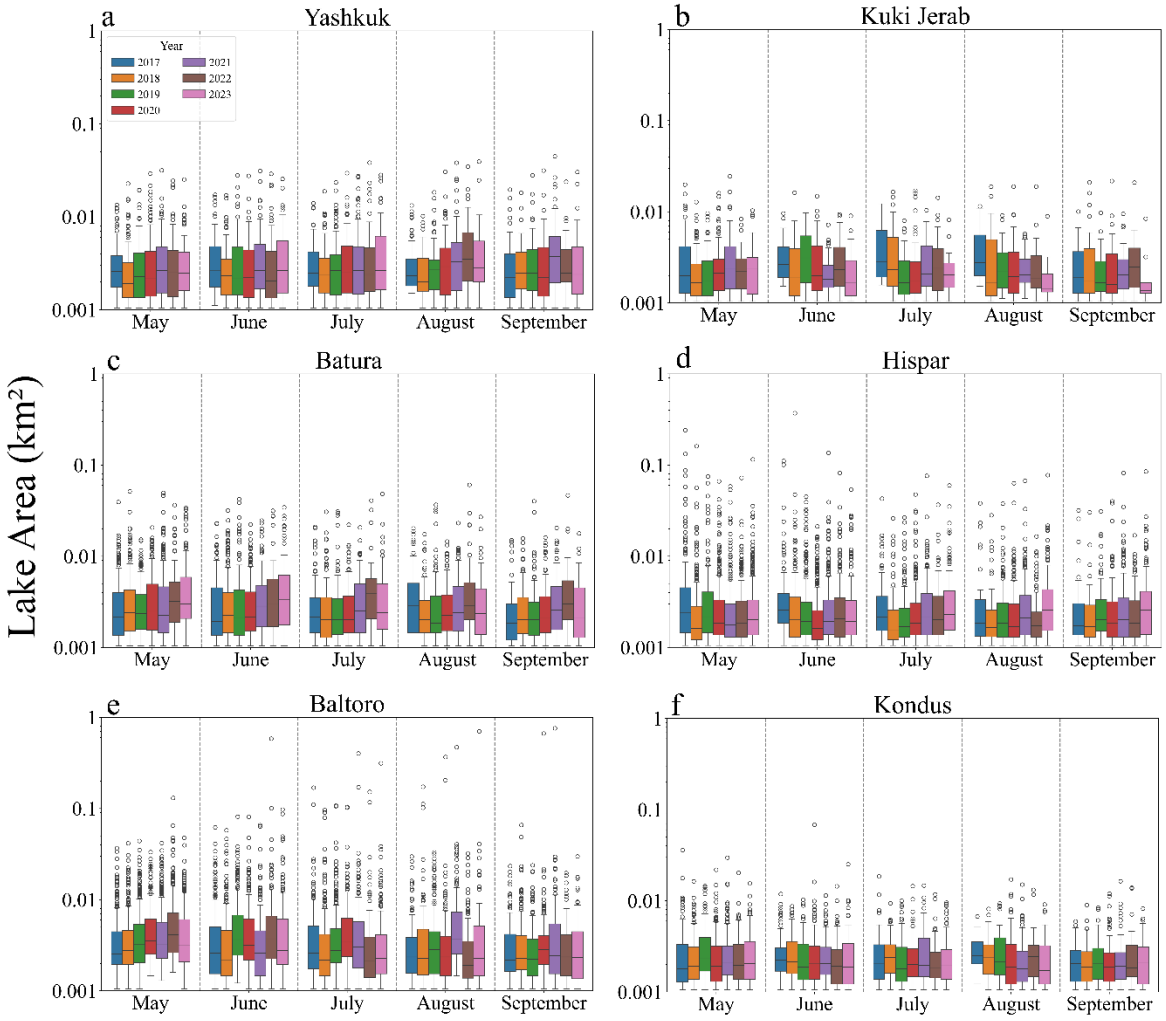


Figure 3: Boxplots showing the distribution of supraglacial lake areas for each glacier. The box represents the interquartile range, the central line marks the median, and points beyond the whiskers indicate outliers. Lake areas are plotted on a logarithmic scale to capture the full range of sizes. To compare the lake area dynamics across multiple years, the datasets are grouped by month; for example, all the May datasets from 2017 to 2023 are grouped together.

Interannual variations were also observed. Yashkuk Yaz, Batura, Hispar, and Baltoro showed a modest increase in median lake area between 2017 and 2023. The most pronounced rise occurred in August from 2018 to 2022 for Yashkuk Yaz (Figure 3a) and from 2020 to 2023 across all months for Batura (Figure 3c). Kuki Jerab showed a small increase in the median lake area in May but had a consistent decline during the peak summer months (Figure 3b), resulting in an overall decreasing trend. The cumulative lake area did not show any notable change for any glacier, except Kuki

Jerab, which had a slightly decreasing trend. Across most glaciers, the highest cumulative lake areas were observed in May 2020 and 2021. In contrast, 2022 and 2023 exhibited lower cumulative lake areas, particularly on the Yashkuk Yaz, Kuki Jerab, Batura, and Kondus glaciers (Figure 4).

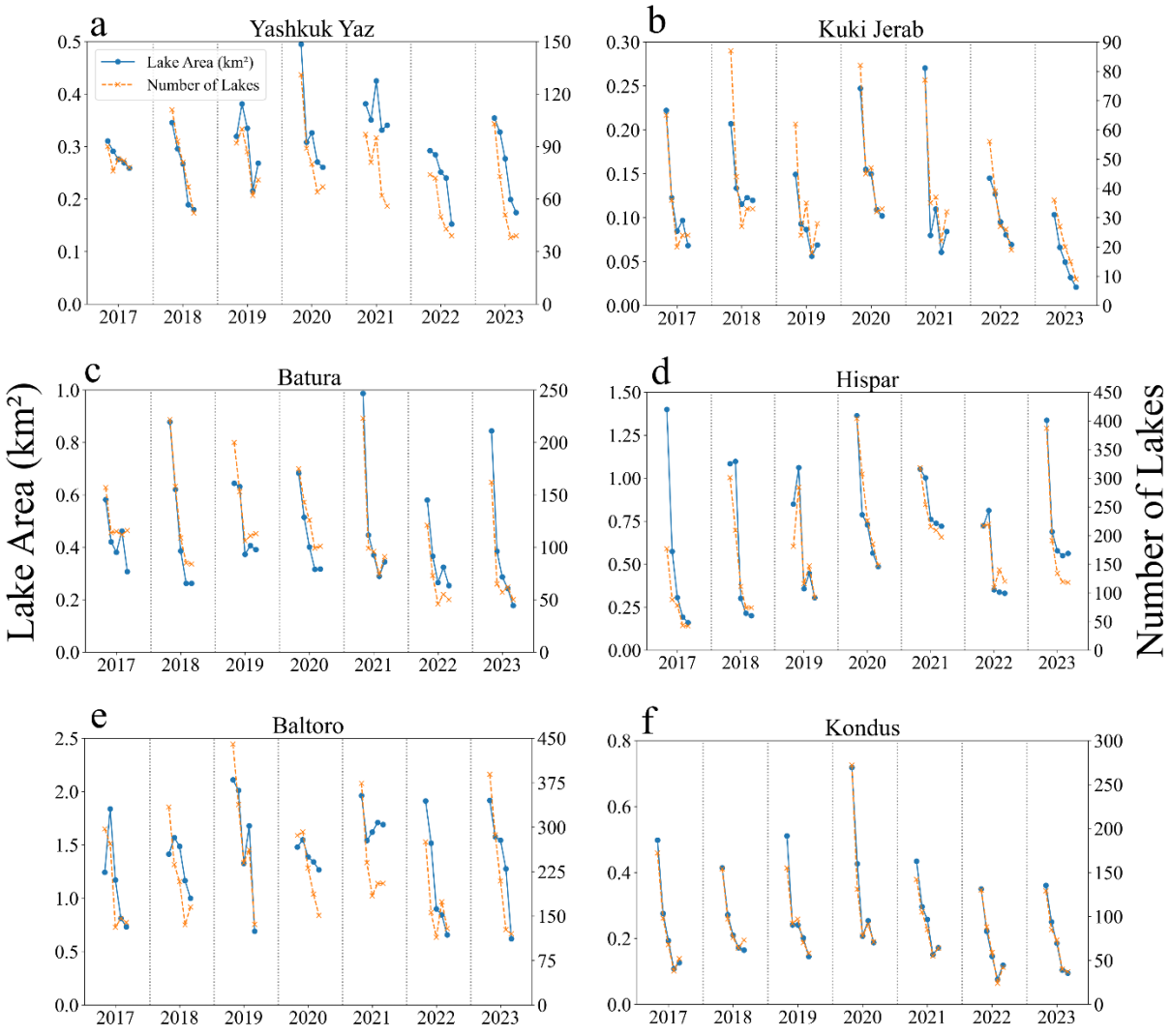


Figure 4: Cumulative monthly lake area and number of lakes from May – September 2017 to 2023 by glacier. The data are plotted as a time series grouped by years to visualize the seasonal evolution of supraglacial lakes, with each dot representing a month, going left to right from May to September. The y-axis scales differ by glacier.

4.3 Seasonal Persistence of Lake-Covered Area

Across all six glaciers, supraglacial lake extent persistence during 2017-2023 was consistently dominated by short-lived inundation of lakes (Figure 5). Ephemeral lake pixels (1 month)

represented the largest fraction of total supraglacial lake area on each glacier and in every year, with values ranging from approximately 44-85% across the six glaciers during the study period. Intermittent lake pixels (2-3 months) consistently formed the second-largest class, contributing roughly 13-40% of total lake-covered area. Persistent lake pixels (4-5 months) were present on all glaciers but remained the smallest category, generally comprising 3-26% of lake area throughout the study period.

Although the cumulative supraglacial lake area varied among glaciers and across years, the proportional distribution among ephemeral, intermittent, and persistent classes remained broadly consistent within each glacier. No glacier exhibited a clear directional trend in persistence class proportions over the seven-year period, and all sites showed recurrent dominance of short-duration presence or expansion for lakes with a considerably smaller, stable presence of multi-month water pixels.

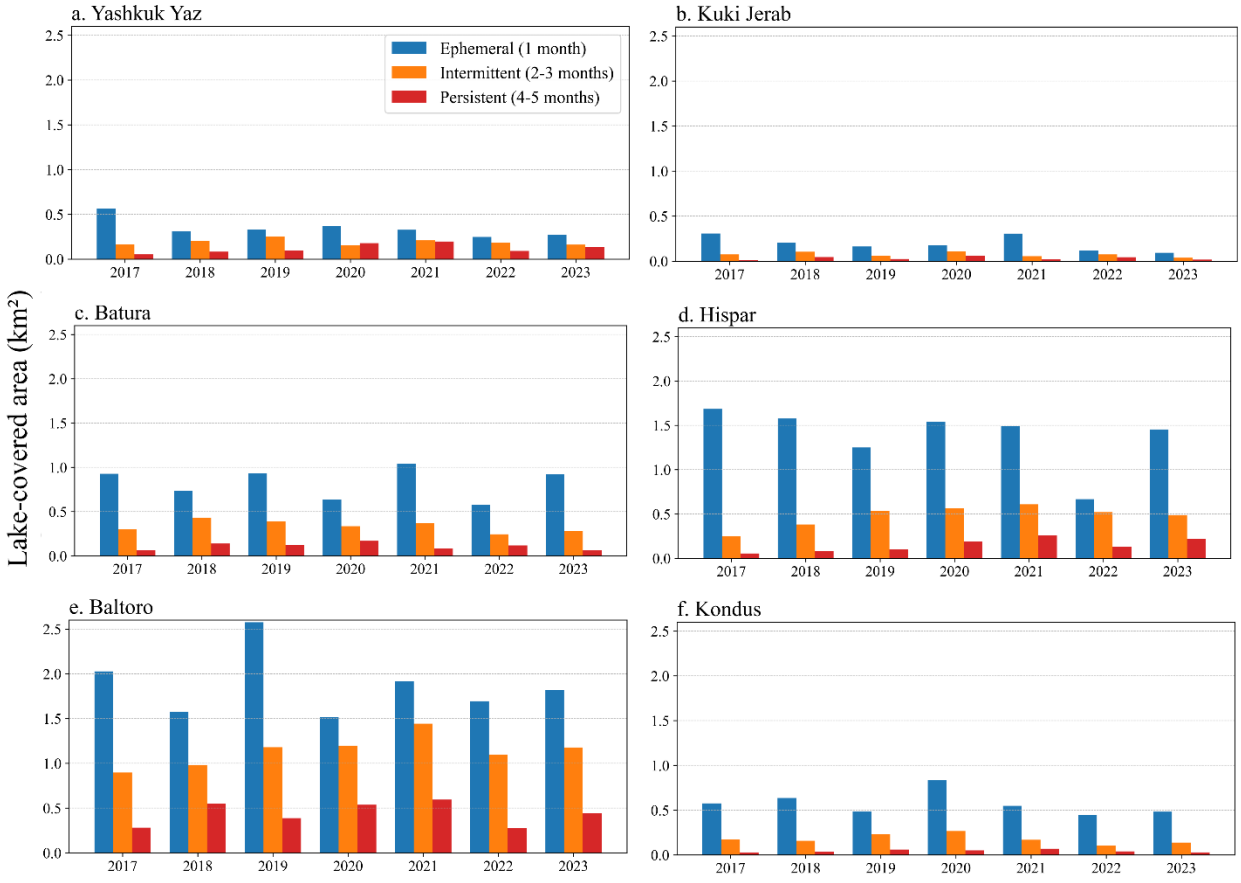
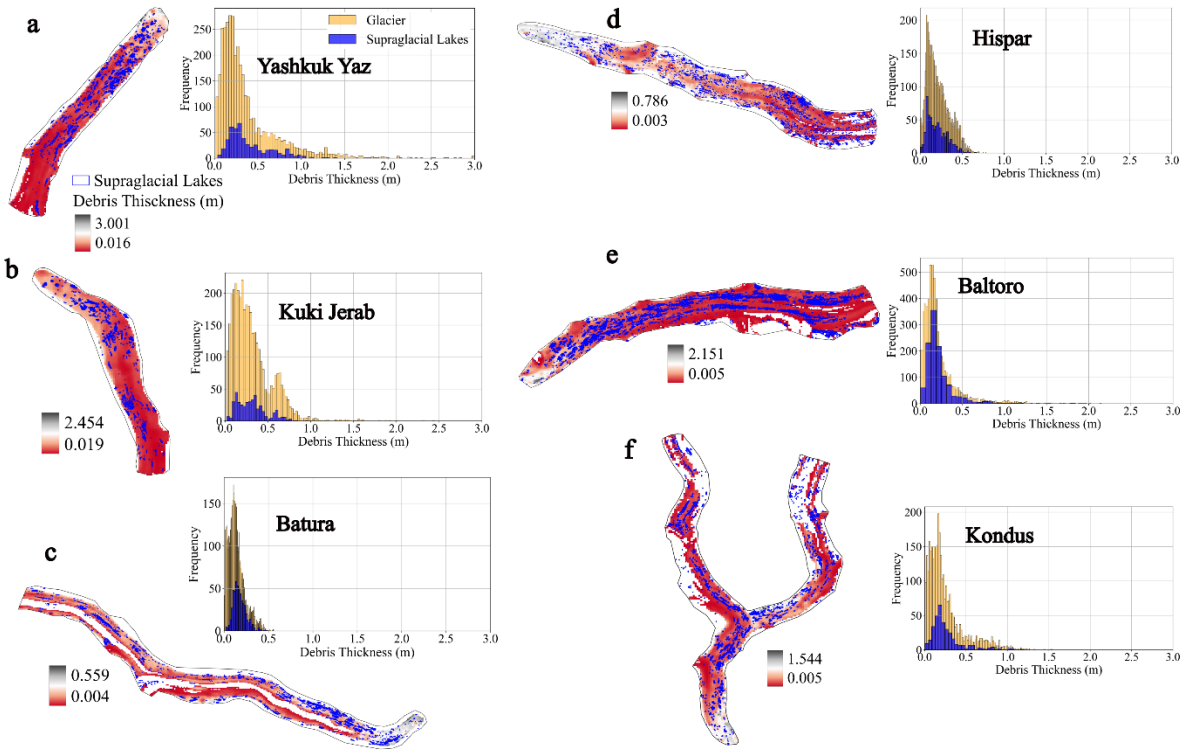


Figure 5. Supraglacial lake-covered area persistence across the six glaciers from 2017-2023. The study areas vary widely across the glaciers (Table 1), leading to considerable differences in the histogram bars. Each panel shows the annual supraglacial lake-covered area classified into ephemeral (1 month), intermittent (2-3 months), and persistent (4-5 months) categories based on monthly lake-presence rasters.

4.4 Glacier Characteristics

We examined glacier debris thickness, surface slope, and velocity to identify drivers of supraglacial lake seasonal dynamics. Supraglacial lake formation predominantly occurred in debris-covered regions (Figure 6). The average debris thickness in the lake-covered areas ranged from 0.17 m (Batura – Figure 6c) to 0.40 m (Yashkuk Yaz – Figure 6a). Although most lakes formed where debris thickness was less than 0.5 m, some lakes persisted in areas with debris as thick as 1.8 m. The thickest debris was observed near the glacier snout, where lake formation was minimal.



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278 *Figure 6: Supraglacial lake datasets (2017-2023) overlayed over the debris thickness data obtained from Rounce et*
279 *al. (2021). The histograms show the debris thickness distribution for the selected glacier area (orange) and the*
280 *supraglacial lake-covered area (blue).*

281 The majority of lakes were in regions with slopes below 9 degrees. Across the six glaciers, the
282 mean slope of supraglacial lake-covered areas ranged from 6.0 to 8.9 degrees, which was 2 to 3
283 degrees flatter than the slopes in areas without lakes.

284 All glaciers exhibited a consistent decrease in surface velocity from May to September, with
285 velocities also declining toward the glacier snouts. In contrast, higher-elevation regions maintained
286 relatively greater velocities throughout the melt season. Among the six glaciers, Batura and Baltoro
287 displayed the highest velocities. Supraglacial lake formation was generally less common in areas
288 with elevated velocities (Figure 7). This relationship was particularly evident on the Batura Glacier
289 (Figure 7c), where the central region, characterized by higher velocities, showed an absence of
290 supraglacial lake development.

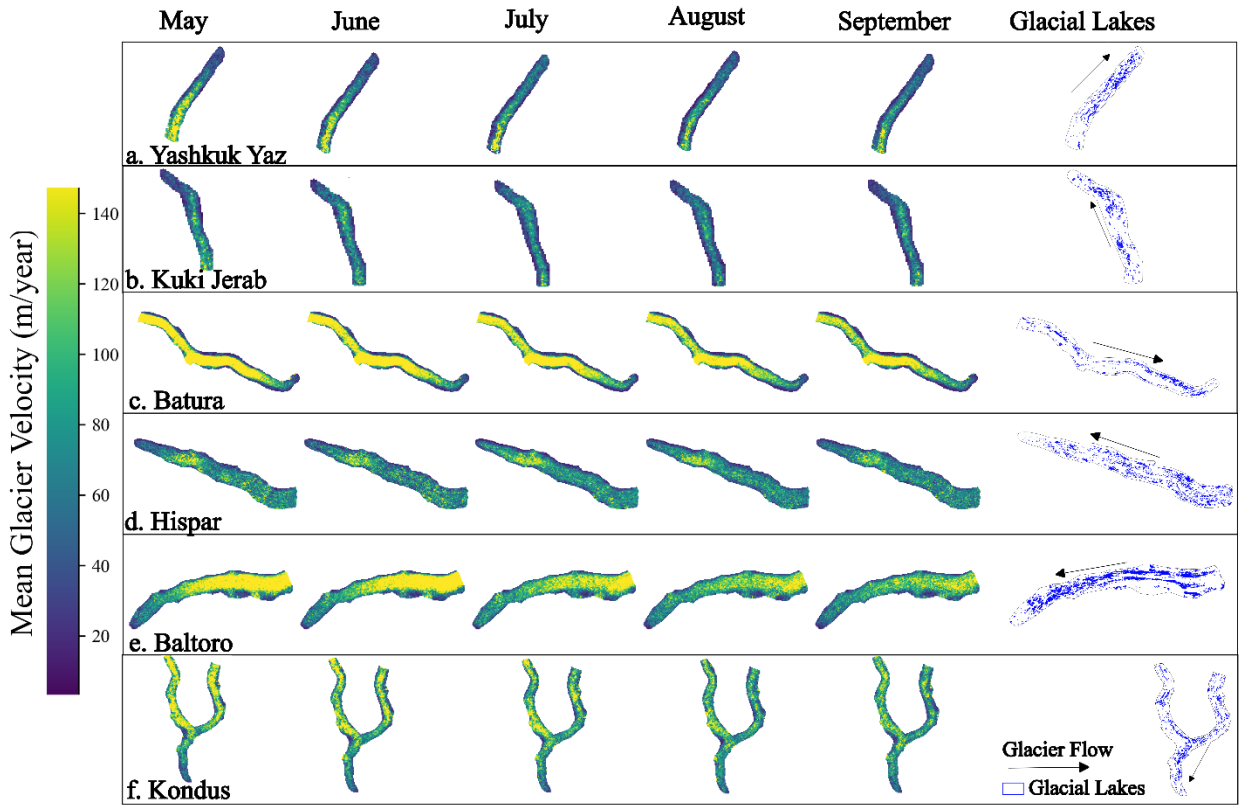
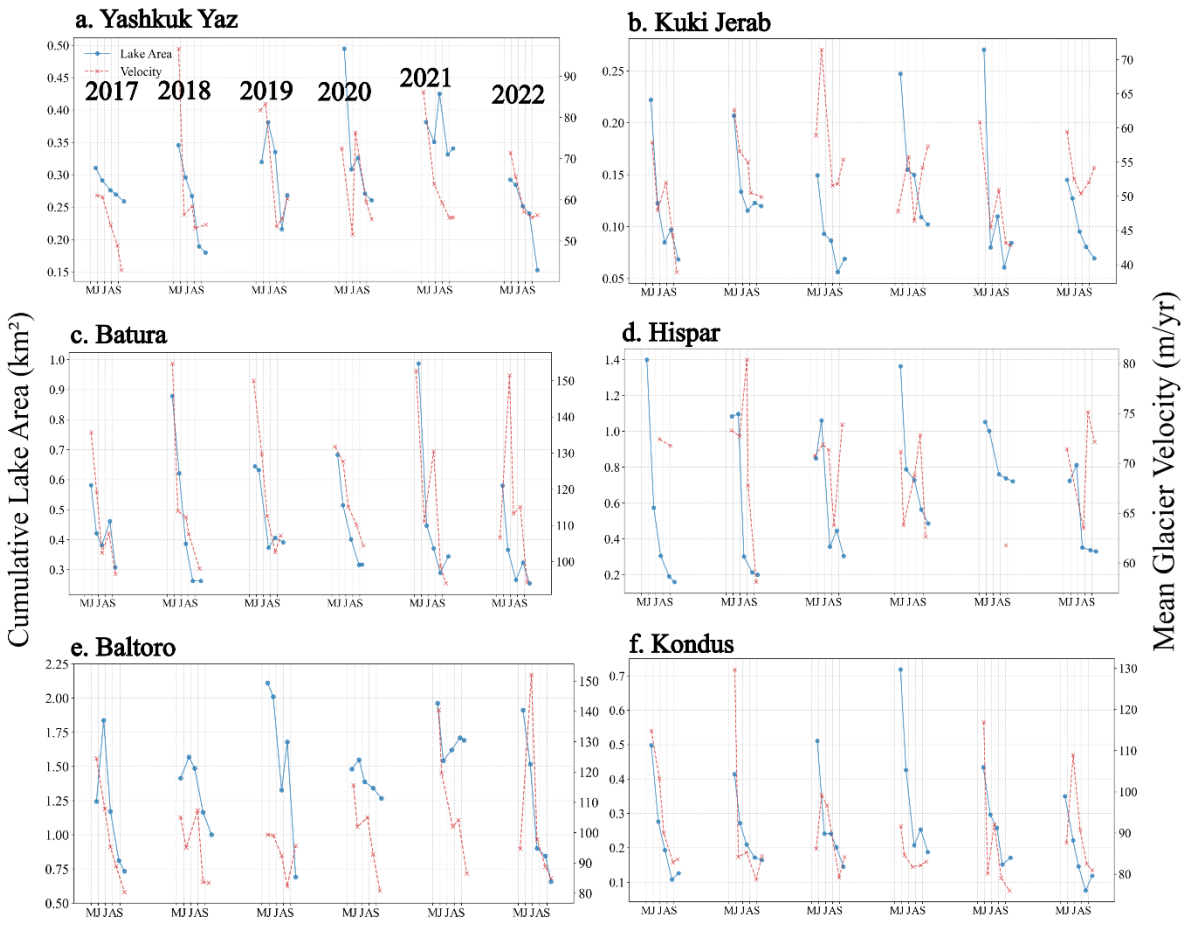


Figure 7: Monthly mean glacier velocity (m/year) maps for the six glaciers from May to September (2017-2022). Each velocity map represents the average glacier velocity for the corresponding month over the study period. The final column on the right shows the combined glacial lake locations from 2017-2022.

Supraglacial lake formation and subsequent drainage can influence glacier dynamics at broader spatial and temporal scales. The time series analysis of cumulative lake area and spatially averaged glacier velocity (Figure 8) shows that periods of high cumulative lake areas (May or June) coincided with elevated glacier velocities. Statistically significant positive linear correlations were observed between cumulative lake area and glacier velocity for Yashkuk Yaz ($p = 0.0031$), Batura ($p = 0.0001$), Baltoro ($p = 0.0459$), and Kondus ($p = 0.0044$). Although Kuki Jerab exhibited an increase in area with increasing velocity, the correlation was not statistically significant ($p = 0.1006$). In contrast, Hispar ($p = 0.8011$) displayed inconsistent relationships between the lake area and glacier velocity.



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305 *Figure 8: Monthly cumulative lake area and spatially averaged glacier velocities (M: May, J: June, J: July, A:*
306 *August, S: September). These two parameters follow a similar seasonal pattern with some variations, suggesting the*
307 *role of supraglacial lake drainage in basal sliding. The y-axis scales vary for the plots.*

308 ## 5. Discussion

309 ### 5.1 Supraglacial Lake Dynamics Comparison with Previous Studies

310 Supraglacial lake mapping is challenging due to the smaller size and dynamic nature of the lakes
311 and complex surroundings (snow, ice, and mountain shadows). As a result, supraglacial lakes are
312 either completely absent from most global and regional glacial lake inventories or only sparsely
313 represented (for example, Wang et al. 2020; Shugar et al. 2020). In our study, we used a SAR-
314 based approach to map supraglacial lakes in the Karakoram. The SAR-based lake mapping

315 facilitated the analysis of seasonal lake dynamics across extensive spatiotemporal scales. Unlike
316 optical imagery, which is often limited by cloud cover and inconsistent availability of useful
317 imagery, the all-weather capability and regular acquisitions of SAR data allowed for the
318 comparison of lake dynamics at uniform temporal intervals.

319 Supraglacial lakes in the Karakoram have been the subject of previous studies. However,
320 comprehensive assessments of seasonal and inter-annual dynamics across multiple glaciers are
321 limited. Wendleder et al. (2018) conducted an analysis of Baltoro's supraglacial lakes from 1991
322 to 2017 using Landsat-8 imagery. Their focus on the long-term evolution of supraglacial lakes
323 provided valuable baseline data. Similarly, Wendleder et al. (2021) used multi-sensor imagery
324 (PlanetScope, Sentinel-2, Sentinel-1, and TerraSAR-X) to assess the seasonal evolution of
325 supraglacial lakes on Baltoro. Qayyum et al. (2020) also mapped Baltoro supraglacial lakes using
326 PlanetScope imagery combined with a deep learning model. The cumulative lake areas obtained
327 in the above studies were slightly higher as compared to our results for Baltoro lakes. These
328 discrepancies were a result of different minimum lake area thresholds and the study area extents.
329 Wendleder et al. (2021) used a threshold of 0.0005 km^2 as opposed to 0.001 km^2 in our study. We
330 mapped the lakes in the lower ablation zone of the main trunk of Baltoro, while these studies
331 considered the whole glacier.

332 The prevalence of small lakes in our study aligns with previous observations of supraglacial lake
333 formation in debris-covered glaciers in various regions in the Karakoram-Himalayas (Mohanty
334 and Maiti 2021; Wendleder et al. 2021; Xu et al. 2023; Zeller et al. 2024). The pronounced
335 seasonality, with peak lake numbers and cumulative area early in the melt season, is also supported
336 by earlier studies in the region (Wendleder et al. 2018; Qayyum et al. 2020; Wendleder et al. 2021).
337 When combining the long-term time series (1991 to 2017) from Wendleder et al. (2018) with our

study, a clear increasing trend in lake numbers and cumulative area from 1991 to 2023 is evident, despite our study covering a smaller region. This suggests there is increasing supraglacial lake formation, potentially linked to broader climatic and glaciological factors. Furthermore, Wendleder et al. (2021) reported an increase in the number and area of Baltoro supraglacial lakes larger than 0.01 km^2, a finding corroborated by our analysis.

Beyond Baltoro, few other studies have focused on supraglacial lakes on the region's other glaciers. Qaisar et al. (2018) conducted a Landsat-based analysis of supraglacial lakes on Hispar Glacier using imagery from 1990, 2000, 2010, 2016, and 2017, with each acquisition captured in a different month. In March 2017, they identified 33 lakes. Qureshi et al. (2023) only found 20 lakes in 2019. These lake numbers differ considerably compared to our study, where the lowest number of lakes was 42 and 92 in September 2017 and 2019, respectively. This discrepancy may be attributed to differences in the minimum lake area thresholds, which were not explicitly reported in the aforementioned studies. Ashraf and Rustam (2020) mapped supraglacial lakes across the northern region of Pakistan, including the six glaciers in our study. They found 378 supraglacial lakes in the Karakoram in 2013, but did not report lakes by glacier. In our study, the average number of supraglacial lakes over the study period for the six glaciers combined was twice that of Ashraf and Rustam (2020).

5.2 Supraglacial Lake Dynamics in the Karakoram

Our findings highlight that small and ephemeral supraglacial lakes (<0.01 km^2) dominate the debris-covered glaciers of the Karakoram. The distinct seasonal patterns of lake formation, expansion, and drainage underscore the dynamic nature of supraglacial lakes. The presence of larger and more unstable lakes at higher elevations in May or June, leading to an early-season peak in lake numbers and cumulative area, supports the idea that seasonal snowmelt plays a key role in

transient lake formation (Arthur et al. 2020). The subsequent decline in lake number and area later in the season can be attributed to the drainage of the transient lakes as meltwater pathways evolve and efficient englacial drainage systems develop (Qiao et al. 2015; Wendleder et al. 2018).

Although lake number and cumulative area generally exhibited a direct correlation, deviations were observed, likely due to the coalescence of smaller lakes into larger ones and the expansion of persistent lakes as the melt season progressed (Leeson et al. 2020; Zeller et al. 2024). This process may explain why some glaciers, for example, Baltoro, experienced an increase in cumulative lake surface area despite an overall decline in the number of lakes.

5.3 Drivers of Supraglacial Lake Formation and Evolution

The pronounced seasonality and fluctuating trends in supraglacial lake dynamics highlight the complex interplay of topographic, glaciological, and meteorological factors in controlling lake formation and persistence (Williamson et al. 2018; Steiner et al. 2019; Wang and Sugiyama 2024). The primary controls on supraglacial lake development are the physical characteristics of the glacier, including debris thickness, glacier velocity, and surface slope, while meteorological conditions play a critical role in their seasonal evolution (Reynolds 2000; Quincey et al. 2007; Dirscherl et al. 2021).

5.3.1 Climatic Drivers

Seasonal temperature fluctuations and precipitation control the timing, extent, and evolution of supraglacial lakes (Qiao et al. 2015; Narama et al. 2017; Wendleder et al. 2021; Dirscherl et al. 2021). As spring temperatures rise, increased meltwater availability facilitates the formation and expansion of these lakes, leading to a peak cumulative lake area during May or June. The Indian summer monsoon further amplifies this process by delivering substantial precipitation between

May and July (Wendleder et al. 2021). Increased delivery of meltwater to the glacier bed through crevasses and englacial conduits raises basal water pressure, which promotes the development of channelized subglacial drainage networks (Narama et al. 2017; Andrews et al. 2018; Wendleder et al. 2024). This enhanced drainage capacity often triggers the rapid drainage of many supraglacial lakes, leading to a reduction in cumulative lake areas despite sustained high surface temperatures. Some persistent lakes expand and reach maximum sizes later in the summer, either through direct meltwater input or through the coalescence of smaller lakes. For example, Baltoro experienced notable lake expansion during the summer of 2021, contributing to an increase in cumulative lake area. Although climatic conditions control the availability of meltwater, the physical characteristics of the glacier surface govern the supraglacial lakes' spatial distribution.

5.3.2 Debris Cover

Supraglacial lake formation was predominantly in debris-covered areas, as opposed to debris-free regions. This suggests that debris is a critical factor in supraglacial lake development. Thick and continuous debris reduces glacier melt rates, while thin and patchy debris enhances the melt by increasing the surface albedo (Minora et al. 2015; Fyffe et al. 2019). Consistent with these observations, our study found no supraglacial lake formation in debris-free regions and reduced formation at glacier snouts, where debris thickness was the highest.

5.3.3 Glacier Surface Slope

In addition to debris, favorable glacier surface slopes and flow velocities are essential for supraglacial lake formation. Gentle slopes and lower surface velocities facilitate meltwater accumulation, thereby promoting supraglacial lake formation (Reynolds 2000; Quincey et al. 2007; Miles et al. 2017; Steiner et al. 2019). Our analysis of the six glaciers revealed that the mean slope of lake-covered areas was two to three degrees flatter than that of non-lake areas,

406 corroborating previous research. However, it should be noted that the SRTM DEMs utilized in our
407 analysis are over a decade old and may not represent the current surface gradients of these dynamic
408 Karakoram glaciers. Despite this limitation, our results reinforce the importance of gentle slopes
409 in facilitating the formation of supraglacial lakes.

410 5.3.4 Glacier Velocity

411 A multifaceted relationship exists between glacier velocity and supraglacial lake dynamics. Lower
412 surface velocities promote supraglacial lake formation by maintaining a stable surface that
413 facilitates meltwater accumulation. Higher velocities and the collapse of englacial and sub-glacial
414 conduits can also create surface depressions for lake formation (Gulley and Benn 2007). High
415 glacier velocities may also destabilize existing lakes through surface deformation (Wendleder et
416 al. 2018). Our findings indicate that supraglacial lakes predominantly form in low-velocity regions,
417 as evidenced by their absence in the high-velocity central areas of the Batura and Baltoro glaciers
418 and in high-velocity patches near the snout of the Hispar glacier (Figure 8).

419 Our analysis revealed that spatially averaged glacier velocities and cumulative lake areas are
420 positively correlated. That higher glacier velocities coincide with periods of increased cumulative
421 lake area suggests that the accumulation and subsequent drainage of supraglacial lakes may
422 contribute to seasonal accelerations in glacier flow, as observed for the Baltoro glacier by
423 Wendleder et al. (2024). The volume and timing of meltwater play a critical role in regulating
424 glacier dynamics; meltwater drainage to the glacier bed enhances basal sliding, resulting in
425 temporary accelerations in glacier flow (Glasser 2013; Togaibekov et al. 2024). This relationship
426 is supported by findings from Chudley et al. (2019), who documented a significant increase in
427 glacier surface velocity during a rapid lake drainage event in Greenland. However, supraglacial
428 lake drainage is not the sole contributor to basal meltwater. Meltwater and rainfall delivered

429 through crevasses and subglacial drainage networks may also induce rapid glacier flows during
430 the summer months (Kraaijenbrink et al. 2016; Benn et al. 2017). Therefore, increased glacier
431 velocities can be observed during periods with fewer supraglacial lakes.

432 6. Conclusion

433 Our study provides a comprehensive assessment of the seasonal and interannual dynamics of
434 supraglacial lakes in the Karakoram and offers insights into the factors governing lake formation,
435 persistence, and drainage. We found that small supraglacial lakes (<0.01 km^2) dominate the
436 Karakoram region. There was pronounced seasonality in supraglacial lake formation and
437 evolution, which was consistent over multiple years and across the glaciers. Peak lake numbers
438 and cumulative areas were observed during May or June, while lake drainage dominated later in
439 the season. This trend suggests that rising temperatures in spring influence the formation and
440 expansion of supraglacial lakes. While lake numbers and cumulative areas generally exhibited a
441 positive correlation, deviations from this relationship were observed, likely due to lake
442 coalescence, expansion of persistent lakes, and variable drainage efficiency. Our results further
443 demonstrate that supraglacial lake-covered area is overwhelmingly dominated by short-lived,
444 ephemeral inundation, with small and transient lakes consistently accounting for the majority of
445 seasonal lake extent, while multi-month persistent lakes represent only a minor fraction across
446 glaciers and years.

447 Our analysis identified surface slope, glacier velocity, debris thickness, and climatic conditions as
448 drivers of supraglacial lake formation and evolution. Regions with gentle slopes, lower glacier
449 velocities, and moderate debris thickness had the most lakes. Temporary glacier flow accelerations
450 during lake drainage periods were also observed. The consistency of these patterns across multiple

glaciers and the comparative analysis with previous studies suggest that these processes also control supraglacial lake dynamics throughout the Karakoram.

This study represents a step forward by quantifying the seasonal dynamics of supraglacial lakes that are largely absent from existing lake inventories. By capturing their consistent seasonal timing, surface controls, and dynamic evolution across multiple glaciers, we provide a more complete picture of glacier surface hydrology in the Karakoram. These findings are important for improving representations of melt processes on debris-covered glaciers, for evaluating the potential for rapid lake drainage and associated hazards, and for assessing how glacier hydrology and downstream water resources may respond to ongoing climate change.

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Data Availability Statement

The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest

472 The authors declare no conflicts of interest. The funders had no role in the design of the study; in
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