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Erosion-driven shrinkage of recently glacier-detached lakes signals a proglacial-to-paraglacial transition across the Third Pole

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Abstract

Glacier retreat drives the expansion of glacier-contact lakes until topographic constraints trigger their detachment from parent glaciers. While the expansion phase is well-documented, the post-detachment evolution and its driving mechanisms remain poorly understood, limiting future glacier-related water resource and hazard assessments. Here, we investigated the spatio-temporal evolution of recently glacier-detached lakes across the Third Pole from 1990 to 2023 by combining multi-temporal lake inventories, climate and glacier mass-balance datasets, glacier runoff simulations, and geomorphic proxies for erosion and sediment supply. We identified 882 glacier-contact lakes that became detached during the study period, accounting for 29% of the 3024 glacier-contact lakes mapped in 2023. Contrary to the widely documented expansion of glacier-contact lakes, detached lakes decreased in total area from 45.11 ± 0.02 to 42.63 ± 0.02 km², corresponding to an estimated water-volume loss of ~0.04 Gt, despite an increase in modeled glacier runoff of ~0.37 Gt. Moraine-dammed lakes accounted for the larger absolute area loss, whereas bedrock-dammed lakes showed greater relative shrinkage. Shrinking detached lakes exhibited a median proglacial erosion potential about two times higher than non-shrinking lakes and preferentially occurred in areas with higher abrasion potential, suggesting an important role of proglacial erosion and sediment infilling in post-detachment lake shrinkage. These results indicate that detached lake evolution cannot be explained by meltwater supply alone. Instead, glacier detachment may mark a shift from meltwater-dominated lake expansion toward sediment-influenced lake shrinkage, reflecting an ongoing proglacial-to-paraglacial transition in high mountain glacial lake systems. Accounting for this transition can improve future assessments of glacial lake evolution, alpine water storage, and GLOF-related hazards under continued glacier retreat.

Key words: Glacier-detached lakes, lake shrinkage, driving mechanisms, proglacial erosion

1. Introduction

Global warming is profoundly changing the glaciers and hydrological systems in alpine regions (Yao et al., 2022), accelerating glacier wastage (Brun et al., 2017; Hugonnet et al., 2021; Larocca et al., 2023; Yang et al., 2023) and impacting glacial lake evolution (Carrivick and Quincey, 2014; Carrivick et al., 2022; Shugar et al., 2020). The Third Pole region (TPR), including the Tibetan Plateau and surrounding mountains and often referred to as High Mountain Asia, hosts the largest glacier cover outside the polar regions and has experienced rapid expansion of glacier-contact lakes driven by glacier retreat and melt (Zhang et al., 2023a; Zhang et al., 2023b). Glacier-contact lakes exert a significant influence on both upstream glacier dynamics and downstream human settlements due to their direct connection with their parent glaciers (Carrivick and Tweed, 2013; Carrivick and Tweed, 2021; Emmer et al., 2015; Peng et al., 2023). Glacier-contact lakes are observed at the termini of glaciers that are experiencing greater mass loss compared to those without such lakes (Carrivick et al., 2020; Sutherland et al., 2020), particularly in the Himalaya (King et al., 2019; Maurer et al., 2019; Zhang et al., 2023a).

Detachment of glacier-contact lakes from their parent glaciers, which is a consequence of ongoing glacier terminus recession, represents a critical transition in their evolution and associated hazard potential. As glaciers recede out of their glacier-contact lakes, the lakes transition from directly contacting the glacier to becoming detached (non-glacier-contact) lakes (Emmer et al., 2020; Zhang et al., 2024). While detached glacier lakes are typically still connected to the subaerial meltwater stream, as glaciers continue to retreat or eventually disappear, the glacier meltwater contribution to the lake may decline depending on local catchment hydrology (Emmer et al., 2015). Furthermore, the transition from lake-terminating to land-terminating glaciers also alters the dynamics and recession rate of the glacier front (Mallalieu et al., 2021; Scofield et al., 2024). Lake-driven thermal and mechanical processes, including thermal undercutting, buoyancy-driven calving, and elevated basal water pressure, can enhance glacier retreat, but these effects largely cease once a glacier-contact lake detaches from its parent glacier (Carrivick et al., 2020). Finally, GLOF hazard is likely to change during and after the lake detachment process. While direct exposure to ice avalanches and rockfalls increases the susceptibility to glacial lake outburst floods (GLOFs) (Emmer, 2017; Emmer, 2024b), this influence changes after detachment. For instance, GLOF susceptibility to calving glacier fronts will decrease but whether the overall GLOF hazard will be reduced depends on local conditions and geomorphic dynamics in the catchment. The probability of ice avalanches into the lakes may temporarily increase during glacier recession but then decrease with further distance to the lakes (Emmer et al., 2015; King

et al., 2019).

Detachment of glacier-contact lakes can be regarded as part of a transition from proglacial to paraglacial conditions (Tweed and Carrivick, 2015). The term 'paraglacial' was first introduced to describe the time-period during which alluvial fans developed following glacier retreat in the mountains of southern British Columbia, Canada (Ryder, 1971a; Ryder, 1971b). This concept was later broadened to describe landscape-scale sediment-system adjustment following glacier retreat, during which abundant glacial sediment can be rapidly reworked by fluvial and debris-flow processes over millennial timescales (Brardinoni et al., 2018; Church and Ryder, 1972). Paraglacial refers to a transitional phase during which landscapes progressively shift to a non-glacial state following intense glacial disturbance (Slaymaker, 2009; Slaymaker, 2011). In this phase, erosion, sediment supply, and the instability of recently deglaciated terrain become key drivers of glacial lake evolution.

Coincident with accelerating glacier melt, landscape instability as manifest in erosion and sedimentation processes is intensifying in alpine environments, particularly around the glacial lakes (Carrivick and Heckmann, 2017; Carrivick and Tweed, 2021), affecting lake evolution and downstream ecosystems (Hosmann et al., 2025; Li et al., 2020; Li et al., 2021a; Wilkes et al., 2023). While alpine erosion is driven by a combination of natural and anthropogenic forces (Zhang et al., 2025; Zhang et al., 2022), natural processes remain dominant in most high-altitude, relatively remote regions where human activities exert limited influence. Detached lakes undergo distinct environmental transformations compared with glacier-contact lakes (Hardmeier et al., 2024). In general, glacier-dominated sediment input gradually decreases as glaciers lose mass and retreat up-valley (Carrivick and Tweed, 2013; Carrivick and Tweed, 2021), owing to the exposure, unstable proglacial terrain that becomes an increasingly important source of material after direct glacial influence ceases (Delaney et al., 2018), or as glacier meltwater discharge diminishes, or as glacier meltwater stream power declines with distance from a glacier. Sediment discharge from the glacierized catchment is increasingly influenced by materials derived from the surrounding landscape, including those resulting from weathering processes and mass wasting events (Delaney et al., 2024). These shifts may have a profound effect on the evolution of recently detached lakes, making the response of the lake area to climatic and environmental changes more complex (Steffen et al., 2022). Understanding the characteristics of erosion and sedimentation processes in recently detached lakes, and their quantitative relationship to changes in lake area, is therefore of paramount scientific importance for the prediction of future trends in glacial lake evolution and the assessment of associated environmental risks.

Glacially-derived sediment, along with material transported by glacial meltwater, aeolian, and hillslope

processes, is deposited in glacial lakes (Carrivick and Tweed, 2021). Sediment transport fluxes may peak between 2100 and 2200 as cryospheric degradation continues in cold mountain regions (Zhang et al., 2022). This period may also see a shift from meltwater-dominated to rainfall-dominated sediment transport regimes. The timing of this transition is controlled by regional deglaciation rates, meltwater volume, rainfall intensity, and interactions between landforms and erosional processes (Carrivick et al., 2018a; Carrivick et al., 2018b; Carrivick and Rushmer, 2018; Mancini et al., 2025). Within glacial lakes, sedimentation is influenced by multiple factors, significantly determined by whether the lake's drainage is endorheic or exorheic. Endorheic lakes exhibit high sediment retention, while exorheic lakes allow for partial sediment export.

With accelerating glacier retreat under climate change, the dynamic evolution of glacial lakes has become a critical focus of high mountain research. These lakes are a direct manifestation of glacier–hydrological interaction and pose potential risks of GLOFs. Some previous studies have begun to focus on the key transformation processes of glacial lakes, especially the evolution of glacier-contact lakes to recently detached lakes (Emmer et al., 2020; Sato et al., 2022; Scofield et al., 2024). Recent global assessments have improved our understanding of glacial lake expansion, water storage, and heterogeneous lake changes under glacier retreat, showing widespread increases in lake number, area, and volume at regional to global scales (Shugar et al., 2020; Zhang et al., 2024). Regional studies have further highlighted the importance of lake type, dam type, and topological position in explaining glacial lake evolution, including transitions from proglacial to detached states in areas such as the Cordillera Blanca and southeastern Tibet (Peng et al., 2024; Rick et al., 2022). In parallel, emerging work on future glacial lake storage and sedimentation has shown that sediment infilling can influence lake lifespan and storage capacity, especially for small and newly formed lakes (Steffen et al., 2022; Veh et al., 2026). However, these studies have generally focused on overall lake expansion, lake-type inventories, future lake formation, or hazard potential, rather than systematically quantifying the observed post-detachment trajectories of recently detached lakes and disentangling their relationships with climatic, glaciological, hydrological, and geomorphic factors.

Despite these advances, significant knowledge gaps persist in documenting the occurrence of glacier-contact lake detachment and quantifying the characteristics of their subsequent evolution. As glaciers continue to retreat, the number and area of glacier-contact lakes that become detached glacier-contact lakes is still unclear in the TPR. There is also a lack of systematic research on the evolutionary trajectory of glacial lakes following detachment from glaciers: continued expansion, stabilization or gradual shrinkage. Current predictions of future glacial lake evolution and risks often do not take into account the effects of glacial lake

detachment from glaciers, which limits the accurate prediction of future glacial lake dynamics and associated risks. Therefore, it is essential to quantitatively characterize the spatiotemporal evolution of recently detached lakes and their linkages with climatic, glaciological and geomorphic processes including temperature, precipitation, glacier mass balance, erosion, and sedimentation, in order to provide first-order insights into the drivers of lake evolution within the proglacial-to-paraglacial transition, and to support a more informed understanding of future changes in the alpine cryosphere and related hazards. Building on the proglacial-to-paraglacial transition framework, we formulated three working hypotheses. First, ongoing glacier retreat has increased the occurrence of lake detachment, leading to an accelerating transition from glacier-contact to recently glacier-detached states across the TPR. Second, after detachment, lake evolution is not necessarily characterized by continued expansion. Instead, reduced direct glacier influence and increasing sediment delivery from newly exposed terrain may promote lake shrinkage. Third, if post-detachment shrinkage reflects increasing paraglacial geomorphic adjustment, shrinking lakes should show stronger associations with erosion- and sediment-related geomorphic proxies than with climatic variables, glacier mass balance, or modeled glacier runoff alone.

This study systematically and quantitatively analyzed the spatiotemporal distribution, regional patterns, detachment dynamics, and post-detachment evolution of newly detached glacial lakes in the TPR from 1990 to 2023. By quantifying the relationships between lake shrinkage and climatic (temperature, precipitation), glaciological (glacier mass balance), and geomorphic processes (erosion and sedimentation) factors, this study aims to explore the potential drivers of the spatiotemporal evolution of detached glacial lakes. We further project glacier runoff changes under future climate scenarios to evaluate their contribution to hydrological inputs to glacial lakes. This study provides an improved understanding of high-mountain glacial lake dynamics within the proglacial-to-paraglacial transition, which inform future efforts in GLOF hazard assessment and water resource management under ongoing climate change (Figure 1).

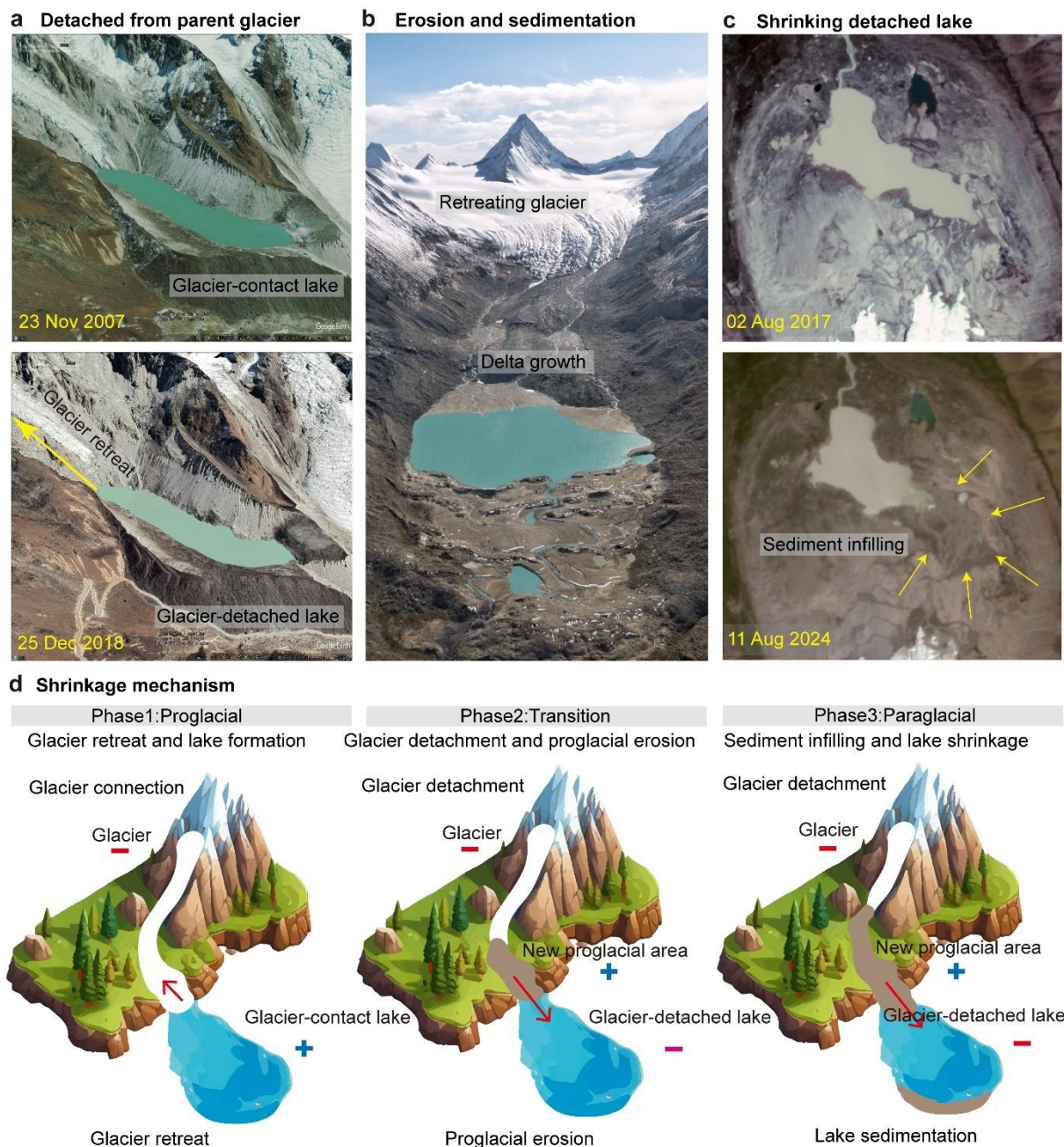


Figure 1. Evolution and shrinkage mechanisms of recently glacier-detached lakes. a) A typical example of a glacier-contact lake detaching from its parent glacier (27.82°N, 87.75°E). On 23 Nov 2007, the glacier was still directly connected to the lake. By 25 Dec 2018, the glacier retreated significantly, and the lake completely detached from it. b) A glacier-detached lake experiencing ongoing proglacial erosion and sedimentation, with visible sediment deposits accumulating in the lake basin (29.82°N, 84.69°E). c) A shrinking glacier-detached lake (33.98°N, 89.21°E). The lake area significantly decreased from 2017 to 2024 due to sediment infilling. Yellow arrows indicate visible sediment/depositional features where shown. d) Conceptual model illustrating the shrinkage mechanism of glacier-detached lakes. A typical evolutionary path in which glaciers retreat initially forms a glacier-contact lake. Continued retreat leads to glacier detachment and the exposure of a new proglacial area, where intense erosion occurs. The resulting sediment is gradually deposited into the lake, leading to infilling and shrinkage.

2. Materials and Methods

2.1. Study Area

The Third Pole region (TPR), with the Tibetan Plateau as its core and surrounding mountain ranges (Figure 2), often referred to as the "Asia Water Tower", is a highly sensitive area in the context of global climate change and plays an important role in regional hydrological regulation (Immerzeel et al., 2020; Qiu, 2008; Yao et al., 2012). Extending from the Pamir Plateau and the Hindu Kush in the west, to the Hengduan Mountains in the east, the Tianshan Mountains in the north, and the Himalaya in the south, this region spans an area of over 5 million km² and has an average altitude exceeding 4,000 m a.s.l. Due to its unique geographical location and high-altitude characteristics, glacial lake in the TPR is particularly responsive to climate change. Rapid changes of the glacial lake profoundly impact regional water security, with far-reaching consequences for the survival and development of billions of people downstream (Immerzeel et al., 2020). Rising intensities and frequencies of warm extremes ($0.37^{\circ}\text{C decade}^{-1}/2.4\% \text{ decade}^{-1}$) (Yang et al., 2022) are occurring concurrently with increasing precipitation amount and intensity, which is becoming more erratic spatiotemporally (Li et al., 2021b). These dual climatic shifts may influence glacial lake stability and their sedimentary environments. Rising temperature has expedited glacier melting and permafrost degradation, directly affecting the formation, expansion and evolution of glacial lakes.

As the largest ice storage area on Earth after the Arctic and Antarctica, TPR encompassing the world's largest mountain glacier concentration, with approximately 131,762 glaciers covering ~99,468 km² (RGI 7.0 Consortium, 2023), is experiencing rapid change with significant implications for glacial lake evolution. From 2000 to 2023, this region experienced substantial mass loss of glaciers (~23.1 Gt/yr) (Zemp et al., 2025). These changes directly influence the formation, evolution, and eventual fate of glacial lakes, particularly those undergoing detachment and subsequent sedimentation. Glacier retreat alters regional hydrology and the risk of GLOFs, relevant to the stability of detached glacial lakes. The TPR is also the source of ten major Asian rivers including the Yangtze, Yellow, Mekong, and Indus, provides water resources for over 1.3 billion people (Immerzeel et al., 2010). While increased glacier melt initially enhances runoff, long-term retreat reduces meltwater contributions, impacting downstream water security and highlighting the importance of understanding glacial lake contributions to regional water budgets (Huss and Hock, 2018). These interconnected cryospheric changes underscore the complex environmental context for the detachment lakes and sedimentation process within the TPR.

2.2. Extraction and classification of detached glacial lakes

In this study, we use the term “recently glacier-detached lakes” to refer specifically to lakes that were formerly in direct contact with a parent glacier but lost this direct contact during the observation period from 1990 to 2023. This term therefore describes a time-bound transition captured by our multi-temporal inventory, rather than all lakes that may have detached from glaciers over longer geomorphic timescales. For brevity, these lakes are hereafter referred to as “glacier-detached lakes” or “detached lakes”. To classify lake–glacier connectivity, we distinguished three lake types: supraglacial lakes, glacier-contact lakes, and glacier-fed non-glacier-contact lakes. Supraglacial lakes are located on glacier surfaces, most commonly within debris-covered areas and generally concentrated near glacier termini, rather than being widely distributed up-glacier as reported in Alaska (Rick et al., 2022). Glacier-contact lakes are situated at glacier termini and remain in direct contact with glacier ice. Glacier-fed non-glacier-contact lakes are no longer in direct contact with glacier ice but still receive meltwater input from upstream glaciers. (Figure S1).

This classification was primarily used to identify lakes that became detached during the study period. Specifically, if a lake was classified as glacier-contact in an earlier inventory but as glacier-fed non-glacier-contact in a later inventory, it was counted as a recently glacier-detached lake. For example, a lake that was glacier-contact in 1990 but glacier-fed non-glacier-contact in 2000 was identified as having detached during the 1990–2000 period. Lake–glacier connectivity was assessed from multi-temporal inventories compiled for approximately 1990, 2000, 2010, and 2023. Detachment was therefore identified at the scale of inventory intervals rather than exact years: lakes that changed from glacier-contact to glacier-fed non-glacier-contact between two inventory dates were interpreted as having detached during that interval. This approach captures persistent lake–glacier decoupling, but may not resolve short-lived or rapid connectivity changes within individual inventory intervals. Lakes that were already glacier-fed non-glacier-contact lakes in the earliest available inventory were not counted as recently glacier-detached lakes, even though some of them may have originated from earlier proglacial lakes over longer geomorphic timescales. These pre-existing non-glacier-contact lakes were excluded from the quantitative analysis of detachment rates, post-detachment area change, and associated drivers, because their detachment timing, pre-detachment area, and immediate post-detachment evolution could not be consistently reconstructed from the available datasets. Therefore, our inventory should be interpreted as representing recent detachment events captured between 1990 and 2023, rather than the complete population of lakes that may have detached from glaciers over longer timescales.

This study partitions lakes that become detached from their parent glacier within the TPR into Himalaya

and extra-Himalayan subsets(Figure S2). For the Himalaya, glacial lake outlines for circa 1990, 2000, and 2010 were obtained from the dataset provided by Zhang et al. (2023a). For the extra-Himalayan subset in circa 1990, 2000, and 2010, and for the entire TPR in 2023, detached glacial lakes were automatically extracted from Landsat imagery using the deep learning framework developed by Tang et al. (2024). This framework employed a three-stage workflow: preprocessing Landsat imagery to enhance glacial lake features, predicting lake boundaries using a DeepLabv3+ model with a MobileNetV3 backbone, and refining predictions through thresholding and vectorization to create polygonal lake outlines(Tang et al., 2024). Manual correction using high-resolution Google Earth imagery as a reference involved removing ~10% of the false positives, including misclassified glaciers, rivers, shadows, and bare land(Tang et al., 2024). High-resolution Google Earth imagery was used as supplementary evidence where coverage was available, but the classification was based primarily on the Landsat inventories to maintain consistency across the TPR. Manual correction was completed by one experienced operator and independently checked by another. Detachment timing was determined at the scale of inventory intervals rather than exact years. A lake was interpreted as having detached during a given interval if it was classified as glacier-contact in the earlier inventory and glacier-fed non-glacier-contact in the later inventory. This approach captures persistent lake–glacier decoupling, but may not resolve short-lived or rapid connectivity changes within individual inventory intervals.

This study classified supraglacial, glacier-contact, and glacier-fed non-glacier-contact lakes based on their spatial relationships with glaciers. The classification was carried out through visual interpretation of multi-temporal Landsat imagery to assess lake–glacier connections, rather than by delineating glacier boundaries directly. In the inventory, lakes that were not in direct contact with glaciers but still received glacier meltwater input and were located within a 10 km buffer of glacier extents were classified as glacier-fed non-glacier-contact lakes. The 10 km buffer was used as a search window to identify potential glacier-related lakes and to exclude lakes unlikely to be influenced by glaciers, rather than as the sole criterion for determining whether a lake was glacier-fed. The final classification was based on visual interpretation of lake–glacier connectivity, including the spatial relationship between lakes and glacier termini and evidence of meltwater connection from multi-temporal satellite imagery. For glacier-contact lakes, direct contact between the lake margin and glacier ice or the glacier terminus was required. For glacier-fed non-glacier-contact lakes, we required clear separation from glacier ice together with geomorphic or hydrological evidence of continued meltwater connection, such as visible meltwater channels or an upstream glacierized catchment. Ambiguous cases were checked using multiple Landsat scenes from the same inventory period where available, to reduce the

influence of seasonal snow, shadows, debris-covered ice, variable water level, and transient meltwater channels. High-resolution Google Earth imagery was used as supplementary reference where coverage was available, especially for narrow glacier–lake connections and complex glacier-margin settings. However, the final classification was based primarily on Landsat inventories to maintain consistency across the full TPR and across inventory periods.

This study specifically focuses on recently glacier-detached lakes, defined as lakes that were glacier-contact in an earlier inventory but subsequently lost direct glacier contact and transitioned into glacier-fed non-glacier-contact lakes during the observation period. These recently glacier-detached lakes are the subject of our analysis. The recently glacier-detached glacial lakes were categorized by their dam types (moraine or bedrock) following established classifications (Emmer et al., 2020; Rick et al., 2022; Zhang et al., 2023a) (Figure S1). Importantly, ice-dammed lakes were excluded from this study to ensure consistency and reliability of datasets due to their inherent instability and complex drainage dynamics, which can lead to rapid and unpredictable changes in lake area. The dataset was compiled by an expert over the course of one year, ensuring high accuracy and consistency, and was independently reviewed by another expert for additional validation. These efforts make the glacier-detached glacial lakes dataset provide a robust foundation for subsequent statistical analyses and investigations into the dynamics, drivers, and potential consequences of glacial lake evolution in the context of climate change. The dataset was compiled by one experienced operator and independently checked by another operator to improve consistency in lake-boundary delineation and lake–glacier connectivity classification.

2.3. Compilation of shrinking glacial lake inventory

In this study, we systematically screened and analyzed shrinking glacial lakes to explore their shrinkage characteristics and the driving factors behind them. Based on the extracted glacial lake boundaries, the area of each glacial lake in different phases was calculated. By comparing the area of the same glacial lake between two periods, lakes showing area reduction were first identified as potential shrinking detached lakes. To reduce the influence of seasonal fluctuations and image-related delineation errors, we introduced an area-change threshold of 0.0054 km² (Wang et al., 2020). This threshold corresponds to the typical inter-annual variability in glacial lake area measurements observed using Landsat imagery, accounting for image resolution (30 m) and the inherent delineation uncertainty. It effectively distinguishes long-term lake area changes from short-term noise or seasonal effects. Lakes with $\Delta A \leq 0.0054 \text{ km}^2$ were treated as having no robust area change,

whereas lakes with area reduction exceeding this threshold were retained as candidate shrinking lakes. Candidate lakes were further verified by side-by-side visual inspection of co-registered and color-enhanced multi-temporal Landsat imagery displayed at the same spatial scale. Only lakes showing persistent and visually clear area reduction were recorded as confirmed shrinking lakes. Those without persistent shrinkage were removed from the shrinking inventory and assigned to the non-shrinking group for subsequent statistical analyses. Lakes affected by documented GLOF events were excluded prior to the area-change analysis using the GLOF dataset (Shrestha et al., 2023).

For each confirmed shrinking glacial lake, several key attributes were recorded: a unique identifier (*ID*), longitude and latitude, detachment period, dam type, lake distribution region, pre-detachment area (A_1), area shrinkage ratio (ω), and median surrounding slope. Detachment periods were determined from multi-temporal Landsat imagery. Dam type (moraine or bedrock) was identified via visual interpretation of high-resolution Google Earth imagery, combined with DEM data. The MERIT DEM is a hydrologically conditioned and bias-reduced global elevation dataset representing terrain around 2000 at 3 arc-second (~90 m) resolution (http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_DEM) (Yamazaki et al., 2017). We used MERIT DEM because it provides spatially consistent, void-filled, and bias-reduced topographic information across the entire TPR, which is important for regional-scale comparisons among thousands of lakes. Glacial lakes were assigned to subregions based on the Randolph Glacier Inventory (RGI 7.0 Consortium, 2023). Pre-detachment area (A_1) represents the lake area during the proglacial stage, immediately prior to detachment. Area shrinkage was calculated as $\Delta A = A_1 - A_2$, where A_1 is the pre-detachment area and A_2 is the post-detachment area. The area shrinkage ratio (ω) was then calculated as $\omega = (\Delta A / A_1) \times 100\%$.

To further quantify the relative level of shrinkage, confirmed shrinking detached lakes were categorized into four levels based on ω : Level 0 (< 5%, minimal change); Level 1 (5%–25%, mild shrinkage); Level 2 (25%–50%, moderate shrinkage); and Level 3 ($\geq$ 50%, extreme shrinkage). Median terrain slope around each lake, derived from the MERIT DEM (http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_DEM), was also calculated as a potential factor influencing lake stability and shrinkage processes.

2.4. Statistical analysis of potential drivers of lake shrinkage

To assess potential drivers of lake shrinkage, we used the lake area dataset compiled as described above, in which lake boundaries were delineated from multi-temporal Landsat imagery and shrinkage was quantified as the difference between pre- and post-detachment areas. Recently detached lakes were classified as either

shrinking or non-shrinking. The study period (1990–2023) was divided into three decadal periods: 1990–2000 (Period 1), 2000–2010 (Period 2), and 2010–2023 (Period 3). Monthly temperature and precipitation data were obtained from the Third Pole Meteorological Forcing Dataset (TPMFD, <https://doi.org/10.11888/Atmos.tpd.300398>) and the Third Pole High-resolution Precipitation dataset (TPHiPr, <https://doi.org/10.11888/Atmos.tpd.272763>) respectively, spanning 1990–2020 to assess potential climatic drivers of lake area change (Jiang et al., 2023). Linear trend analysis was employed to evaluate temperature and precipitation changes. Linear trends in temperature and precipitation time series for each lake were determined using least squares regression. Resulting slopes represent the rate of change, with associated *p*-values indicating statistical significance. Annual mean temperature and precipitation were calculated by averaging monthly data. Interannual variability was quantified as the difference between consecutive years for both temperature and precipitation.

Long-term glacier mass balance from Hugonnet et al. (2021) for the period 2000–2020 was used to quantify the water contribution of glacier mass loss to the recently detached lakes. Glacier mass-balance data for glaciers feeding shrinking and non-shrinking lakes were extracted and analyzed separately. Comparisons of glacier mass balance between these two groups were conducted to explore the relationship between lake-area change and glacier mass balance.

The sedimentation process of glacier-contact lakes was quantified according to three main components identified by Steffen et al. (2022): abrasion, proglacial erosion, and headwall erosion. Subglacial abrasion, driven by the interaction between basal ice and bedrock, results in the smoothing and grinding of the underlying bedrock. Increased ice thickness enhances basal pressure and frictional forces, while steeper slopes generally correlate with higher ice flow velocities, promoting sediment-bedrock interaction and thus increased abrasion. Following Steffen et al. (2022), we estimated a glacier-specific subglacial abrasion index as the product of normalized glacier thickness (Millan et al., 2022) and local slope:

$$SAI = \left(\frac{h - h_{min}}{h_{max} - h_{min}} \right) \times \left(\frac{\alpha - S_{min}}{S_{max} - S_{min}} \right) \quad (1)$$

where, *SAI* is the subglacial abrasion index; *T* is the local glacier thickness (Millan et al., 2022); *h_{min}* and *h_{max}* are the minimum and maximum glacier thickness values used for normalization; *S* is the slope derived from the MERITDEM; *S_{min}* and *S_{max}* are the minimum and maximum slope values used for normalization. Both thickness and slope are normalized to a 0–1 scale. Higher *SAI* indicates more intense subglacial abrasion.

Proglacial erosion refers to erosive processes occurring within the deglaciated zone. In this study, the

deglaciated zone was operationally defined using a circular buffer approach to normalize glaciers of different shapes. This zone is defined as the non-glaciated area within a specified buffer radius of both the glacier and its associated lake, delineated by the intersection of these two buffer zones. This intersection serves to isolate the deglaciated area immediately surrounding the lake, excluding distal deglaciated regions not directly influenced by the lake. Glacier area (A_g) and thickness (h) were referenced to the year 2000 (consistent with the MERIT DEM and Millan et al. (Millan et al., 2022)), and the temporal expansion of the proglacial zone during 1990–2023 was approximated using the thinning rate ($\frac{dh}{dt}$). The buffer radius, which accounts for potential expansion due to glacier thinning over the study period, was calculated as follows:

$$R_{proglacial} = \frac{R_g \times (h + \frac{dh}{dt} * N)}{h} \quad (2)$$

$$R_g = \sqrt{\frac{A_g}{\pi}} \quad (3)$$

where, $R_{proglacial}$ is the radius of the proglacial area. R_g is the glacier radius. h is the glacier thickness. dh/dt is the annual average elevation change. N is the number of years in the study period. A_g is the glacier area. π is the mathematical constant pi. This formulation of $R_{proglacial}$ accounts for the potential expansion of the proglacial area due to glacier thinning (ΔE) over the study period (N). This equivalent-radius formulation provides a standardized approximation for irregular glacier geometries and ensures comparability across thousands of lakes.

The circular buffer is an approximation that enables consistent comparison across a large regional dataset. It does not fully reproduce irregular glacier outlines, valley confinement, drainage routing, or local moraine and headwall morphology. The resulting proglacial and headwall zones should be interpreted as standardized zones of potential influence rather than exact geomorphic process domains.

PEI was developed to quantify the erosive potential within the deglaciated zone. This index was calculated as the product of the normalized deglaciated area and the normalized slope within that zone, both derived from a DEM. Steeper slopes and larger deglaciated areas generally correlate with increased meltwater flow, greater glacier-bedrock contact, and enhanced erosive potential. Higher PEI values indicate higher potential for proglacial erosion.

$$PEI = \left(\frac{A - A_{min}}{A_{max} - A_{min}} \right) \times \left(\frac{S - S_{min}}{S_{max} - S_{min}} \right) \quad (4)$$

where, PEI is the proglacial erosion index; A is the area of the deglaciated zone; A_{min} and A_{max} are the minimum and maximum area used for normalization; S is the mean slope of the deglaciated zone. S_{min} and S_{max} are the minimum and maximum slopes used for normalization. Both area and slope are normalized to a 0-1 scale.

Headwall erosion refers to processes occurring within the non-glaciated area above the median elevation and within a specified buffer radius upslope of the glacier feeding the associated glacier-contact lake. For consistency, this buffer radius ($R_{headwall}$) was set equal to the proglacial radius ($R_{proglacial}$), providing a standardized scale of influence for both upslope (headwall) and downslope (proglacial) processes. Headwall zones were delineated from non-glaciated terrain upslope of the glacier-lake system, using the same temporal reference (1990–2023).

A headwall erosion index (HEI) was calculated to quantify the potential for erosive processes within the cirque headwall. This index is defined as the product of the normalized headwall area and the square of the normalized headwall slope, acknowledging the potentially non-linear influence of slope on erosion processes. Higher HEI indicates a greater potential for headwall erosion.

$$HEI = \left(\frac{A_h - A_{min}}{A_{max} - A_{min}} \right) \times \left(\frac{S_h - S_{min}}{S_{max} - S_{min}} \right)^2 \quad (5)$$

where, A_h is the headwall area; A_{min} and A_{max} are the minimum and maximum headwall areas used for normalization; S_h is the mean slope of the cirque wall; S_{min} and S_{max} are the minimum and maximum slopes used for normalization.

Because SAI, PEI, and HEI are normalized indices, they provide dimensionless measures of relative erosional or sediment-supply potential and should not be interpreted as direct estimates of sediment flux, erosion rate, or deposited sediment volume. Their value lies in comparing relative conditions among shrinking and non-shrinking lakes at regional scale. And the process attribution at individual lakes requires bathymetry, sediment budgets, or field-based measurements.

2.5. Mann-Whitney U test

This study uses the nonparametric statistical method Mann-Whitney U test, also known as Wilcoxon rank sum test (Dronova et al., 2021; Mann and Whitney, 1947; Wilcoxon, 1992), to evaluate the distribution differences between shrinking and non-shrinking glacial lakes in terms of temperature change, precipitation change,

glacial mass balance, and sedimentation process. This method combines and sorts the two sets of data, calculates the rank sum of each sample in the combined data, obtains the rank sum of each group of samples, and then obtains the U statistic, which reflects the difference in the distribution position of the two groups of samples.

$$U = \min(R_1 - \frac{n_1(n_1 + 1)}{2}, R_2 - \frac{n_2(n_2 + 1)}{2}) \quad (6)$$

where n_1 and n_2 are the sample sizes of the two groups of samples, R_1 and R_2 are the sum of the ranks of the corresponding groups.

The p -value was calculated based on the U statistic for hypothesis testing. The p -value represents the probability of observing the current data or more extreme data under the premise that the null hypothesis (that is, there is no difference in the corresponding characteristics of the two groups of glacial lakes) is established. If the p -value is less than the significance level (usually 0.05), it can be considered that the two groups of data have significant differences, otherwise it is considered that the two groups of data come from the same distribution. This method does not depend on the specific distribution of the data, so it has important applications when dealing with small sample sizes or uneven data distribution.

The Mann-Whitney U test evaluates whether individual variables differ between shrinking and non-shrinking groups, but it does not establish causality or account for interactions among drivers. We therefore interpret significant differences as statistical associations and use them as evidence for plausible mechanisms.

$$z = \frac{U - \frac{n_1 n_2}{2}}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}} \quad (7)$$

$$p = 2 \times P(Z > |z|) \quad (8)$$

where $P(Z > |z|)$ represents the probability of observing a Z -score greater than Z in magnitude under the standard normal distribution.

2.6. Estimation of water-volume changes in recently glacier-detached lakes

To quantify water-volume changes associated with the post-detachment evolution of glacial lakes, we converted lake area to volume using an empirical area–volume scaling relationship. Because direct

bathymetric measurements of glacial lakes remain sparse across the TPR, we compiled 140 published bathymetric measurements from glacial lakes in TPR, including lake area, measured volume, dam type, lake–glacier connection status, survey year and data source (Table S4). Because the bathymetric dataset is dominated by moraine-dammed lakes and contains only one bedrock-dammed lake, the available measurements were pooled to fit a single TPR-wide area–volume relationship. Separate dam-type-specific relationships were not fitted due to the insufficient number of bedrock-dammed lake measurements.

Following the power-law form used in previous Himalayan glacial lake studies(Zhang et al., 2023a), we fitted an empirical relationship between measured lake area and volume(Figure S3):

$$V = 42.57A^{1.414} \quad (9)$$

where V represents the lake volume (10^6 m^3) and A represents the lake area (km^2). The fitted parameters, model performance statistics are provided in Table S2.

In this study, recently glacier-detached lake, its area A_1 before detachment from the glacier and its area A_2 after detachment from the glacier are obtained, and the corresponding volumes V_1 and V_2 are calculated by substituting them into the above empirical formulas. The net volume lost is expressed as:

$$\Delta V = V_1 - V_2 \quad (10)$$

where ΔV is the net water-volume change after lake detachment (10^6 m^3). The total net water-volume change of recently glacier-detached lakes was obtained by summing ΔV across all identified recently detached lakes.

2.7. Glacier runoff volume estimation

To estimate glacier runoff volume for 808 glaciers that feed 882 recently detached lakes, we used dynamic simulations from GloGEM (Global Glacier Evolution Model; Huss and Hock (2015)) updated to the most recent input data (Zekollari et al., 2024). The model accounts for snow accumulation, snow and ice melt, and glacier-geometry change for individual glaciers throughout the TPR. Results are calibrated to observed ice-volume change (Hugonnet et al., 2021), and future simulations are driven by a range of global circulation models and emission scenarios based on CMIP6. The model outputs monthly glacier runoff (m w.e.) for each glacier (identified by its RGIv6.0 ID) from 1990 to 2100. Due to randomly generated sub-monthly temperature variability (Huss and Hock, 2015), glacier runoff values for 1990-2020 may differ slightly among scenarios even though consistent monthly reanalysis forcing is used. Runoff values are referenced to the initial glacier surface area at the inventory date, with the contributing catchment assumed to be fully glacierized. Subsequent runoff originates from both the retreating glacier surface and the emerging

proglacial area.

To convert the runoff values into volumetric units (km³), we multiplied the monthly runoff (m w.e.) by the corresponding initial glacier area (km²) for each glacier:

$$GRV_{i,t} = GR_{i,t} * A_i \quad (11)$$

where $GRV_{i,t}$ is the glacier runoff volume (km³) for glacier i at time t , $GR_{i,t}$ is the glacier runoff (m w.e.), and A_i is the initial glacier area (km²). i is the RGI glacier ID and t is the time step (month).

Modeled glacier runoff is treated as a proxy for potential meltwater supply from the upstream glacier rather than as a direct measure of lake inflow. The fraction of runoff that ultimately contributes to lake storage may be modified by hydrological routing changes following detachment, infiltration through moraines or proglacial sediments, evaporation, temporary storage, and diversion of flow away from the lake. Therefore, runoff trends are used to provide hydrological context for lake evolution rather than to infer direct lake inflow or lake water balance.

2.8. Uncertainties

The uncertainty of the area of a single detached glacial lake was estimated based on the potential boundary offset of ± 0.5 pixels during manual delineation. Following previous studies, the absolute area uncertainty was calculated using the lake perimeter and image resolution as (Zhang et al., 2023a):

$$\partial A_i = P_i * \frac{G}{2} \quad (12)$$

where ∂A_i is the area uncertainty of lake i , P_i is its perimeter, and G is the spatial resolution of the Landsat image (30 m). This approach assumes that boundary uncertainty is concentrated within half a pixel width along the entire lake perimeter.

To estimate the cumulative uncertainty for all recently detached lakes, error propagation was applied following Wang et al. (2020):

$$E_T = \sqrt{\sum_{i=1}^n \partial A_i^2} \quad (13)$$

where E_T is the total area uncertainty across n recently detached lakes.

Uncertainty in lake-volume estimates was further quantified by propagating the uncertainty of the empirical

area–volume relationship. Because the relationship $V = cA^b$ was calibrated from a finite bathymetric dataset, both the coefficient c and exponent b are uncertain. We used 5000 paired bootstrap resamples of the 140 bathymetric measurements to quantify this uncertainty. For each bootstrap realization c , the bathymetric dataset was resampled with replacement, the power-law relationship was refitted, and a new pair of parameters (c^k, b^k) was obtained. Lake volumes before and after detachment were then recalculated as:

$$V_{1,i}^k = c^k A_{1,i}^{b^k}$$

$$V_{2,i}^k = c^k A_{2,i}^{b^k}$$

where $A_{1,i}$ and $A_{2,i}$ are the pre- and post-detachment areas of lake i , respectively. The bootstrap-based volume change of each lake was calculated as:

$$\Delta V_i^k = V_{1,i}^k - V_{2,i}^k$$

and the total net water-volume change across all recently detached lakes was calculated for each bootstrap realization as:

$$\Delta V_T^k = \sum_{i=1}^n \Delta V_i^k$$

where n is the number of recently glacier-detached lakes included in the volume-change calculation. The 2.5th and 97.5th percentiles of the 5000 bootstrap-derived ΔV_T^k values were used as the 95% confidence interval of the total net water-volume change. Predicted volumes and uncertainty ranges for the bathymetric calibration lakes are reported in Table S3.

Beyond boundary delineation errors, uncertainty may also arise from the construction of the recently detached lake inventory. In this study, manual correction was mainly used as a quality-control step after automatic extraction, including the removal of false positives such as misclassified glaciers, rivers, shadows, and bare land, as well as the correction of lake boundaries in complex areas such as glacier margins, shadowed regions, or poorly delineated shorelines. High-resolution Google Earth imagery was used as supplementary reference where coverage was available, but lake-boundary delineation and lake–glacier connectivity classification were primarily based on the Landsat inventories to maintain consistency across the TPR. Manual correction and connectivity classification were completed by one experienced operator and independently checked by another. Multi-temporal imagery, seasonal water-level fluctuations, and mixed pixels near shorelines may also affect lake-area measurements, although these effects were partly mitigated by applying an area-change threshold. The decadal to multi-decadal temporal resolution of the lake inventories introduces

uncertainty in the identification and timing of lake detachment. Our approach is designed to capture persistent changes in lake–glacier connectivity between inventory periods, but short-lived detachment events, temporary reconnections, rapid connectivity changes, and changes related to seasonal water-level fluctuations, snow/ice cover, or transient drainage may not be fully resolved. The reported detachment timing should therefore be interpreted at the scale of inventory intervals rather than as an exact year of detachment. Although this limitation may lead to an underestimation of short-lived detachment events, it is unlikely to alter the main regional patterns of persistent glacier–lake decoupling identified across the TPR.

This study integrates datasets with different spatial and temporal resolutions, including 30 m Landsat imagery, the ~90 m MERIT DEM, gridded climate products, geodetic glacier mass-balance estimates, and GloGEM runoff simulations. These scale mismatches may introduce uncertainty when linking lake-area change to climatic, glaciological, hydrological, and geomorphic drivers, particularly for individual lakes. Because our analyses focus on regional-scale contrasts between shrinking and non-shrinking recently detached lakes, the results should be interpreted as group-level statistical associations rather than site-specific process estimates. Driver variables also carry uncertainties: glacier thickness and elevation-change products affect estimates of subglacial abrasion and proglacial radius. DEM errors influence slope and headwall indices, and regional climate and glacier mass-balance datasets may not fully capture basin-scale variability. Volume estimates derived from empirical area–volume scaling should be regarded as first-order approximations, since sedimentation may decouple area and volume changes, and moraine-dammed versus bedrock-dammed lakes may differ systematically in depth. Overall, these uncertainties do not alter the regional-scale patterns revealed in this study but warrant caution when interpreting estimates for individual lakes.

3. Results

3.1. Widespread distribution and regional heterogeneity of recently glacier-detached lakes

A comprehensive inventory of glacial lakes across the TPR was compiled based on multi-temporal Landsat imagery (1990–2023), integrating automated extraction using a deep learning framework with manual refinement (Tang et al., 2024). Dam types were classified using high-resolution Google Earth imagery and digital elevation models (DEMs), and detachment status was determined based on temporal changes in glacier-lake connectivity. The TPR contained 3,024 glacier-contact lakes with a total area of ~281.0 km² in 2023. The majority (75.9%) were moraine-dammed lakes (2,295 lakes, ~257.4 km²), while the remaining (24.1%) were bedrock-dammed lakes (729 lakes, ~23.6 km²) (Figure S4a). Detachment is a prominent glacial lake type

transformation, alongside transitions from supraglacial to glacier-contact lakes and from detached to non-glacier-fed lakes (Figure S4b).

In total, 882 recently detached lakes were identified across the TPR between 1990 and 2023, with their spatial distribution and dam type of recently detached lakes exhibit significant regional heterogeneity (Figure 2). From 1990 to 2023, 882 recently detached lakes developed primarily in Central Tibet (163 lakes), Western Tianshan (156 lakes) and Eastern Tianshan (155 lakes). Moraine-dammed detached lakes (675 lakes) significantly outnumbered bedrock-dammed detached lakes (207 lakes). Western Tianshan showed the highest number of moraine-dammed detached lakes (121 lakes), as glaciers in this region are predominantly valley glaciers with abundant unconsolidated moraine deposits at their termini. Following glacier retreat, these deposits readily formed moraine-dammed lakes; while Central Tibet displayed the highest number of bedrock-dammed detached lakes (44 lakes), as the region is characterized by extensive plateau topography and relatively limited moraine deposition at glacier termini. Recently detached lakes develop from glacier-contact lakes detaching from the parent glacier (Figure 1a), and three distinct area change patterns following detachment were identified (Figure 1b–d): shrinkage, stability, and expansion.

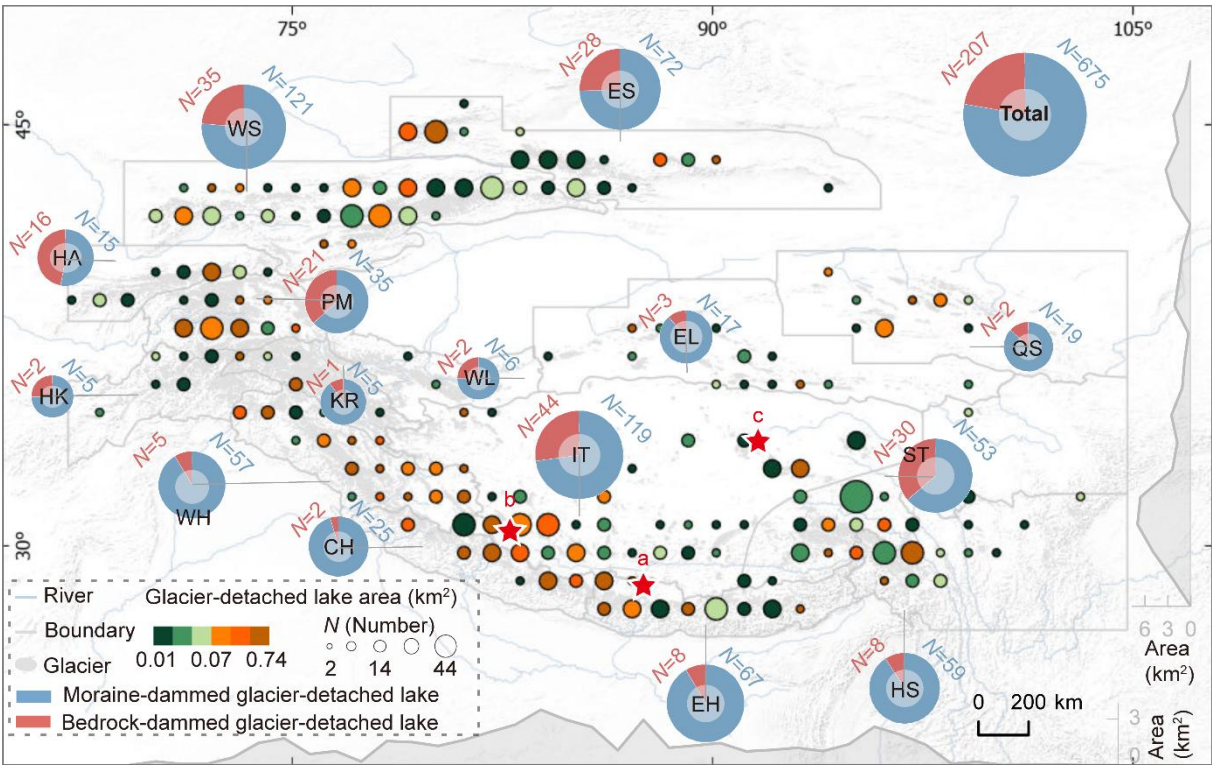


Figure 2. Spatial distribution and dam type of all recently glacier-detached lakes. The shade of the circle (from red to blue) represents the area of the lakes; the size of the blue circle represents the number of the lakes. Pie charts show the proportion of moraine-dammed (blue) and bedrock-dammed (red) lakes; *N* represents the number of the lakes. Red stars represent the locations of the lakes shown in Figure 1a, 1b and

1c. ES: Eastern Tien Shan, WS: Western Tien Shan, PM: Pamir, HA: Hissar Alay, HK: Hindu Kush, WL: Western Kun Lun, EL: Eastern Kun Lun, QS: Qilian Shan, ST: Southern and Eastern Tibet, HS: Hengduan Shan, EH: Eastern Himalaya, CH: Central Himalaya, WH: Western Himalaya.

3.2. The detachment rate of glacier-contact lakes has accelerated significantly since 1990

Detachment dynamics were assessed by tracking changes in glacier-lake connectivity using a multi-temporal inventory of glacier-contact lakes derived from Landsat imagery (1990–2023). Detachment was defined as the loss of direct contact between a glacier-contact lake and its parent glacier. From 1990 to 2023, the number of glacial lakes detached from their parent glaciers showed an accelerated growth, increasing from 121 in 1990–2000 (accounting for 7.2% of glacier-contact lakes in 1990, departure at a rate of +12.1 lakes/yr) to 587 in 2010–2023 (accounting for 25.6% of glacier-contact lakes in 2010, +45.2 lakes/yr) (Figure 3a).

There are differences in the spatial distribution of this increase. The Western Tianshan, Eastern Tianshan, Inner Tibet and Eastern Himalaya regions show the largest net increases between the two periods, with increases of 110, 68, 65 and 40 additional recently detached lakes respectively. The total area of recently detached lakes also exhibited a similar trend (Figure 3b), increasing from ~8.2 km² in 1990–2000 to ~24.7 km² in 2010–2023, indicating that the cumulative area of newly detached glacial lakes has doubled. Moraine-dammed lakes dominate the recently detached lake population, while the number of bedrock-dammed lakes has also increased over time (Figure 3). As glaciers further retreat up-valley, detached glacier-contact lakes may further develop to become devoid of any glacier influence if they are located in marginal basins that become disconnected from the main valley and thus the glacial stream. From 1990 to 2023, a total of 513 (~21.8 km², 3% of all detached glacier lakes) recently detached lakes transformed into non-glacier fed lakes, and this transformation is also accelerating from ~5/yr (0.2 km²/yr) in 1990–2000 to ~19/yr (0.7 km²/yr) in 2010–2023 (Figure S5).

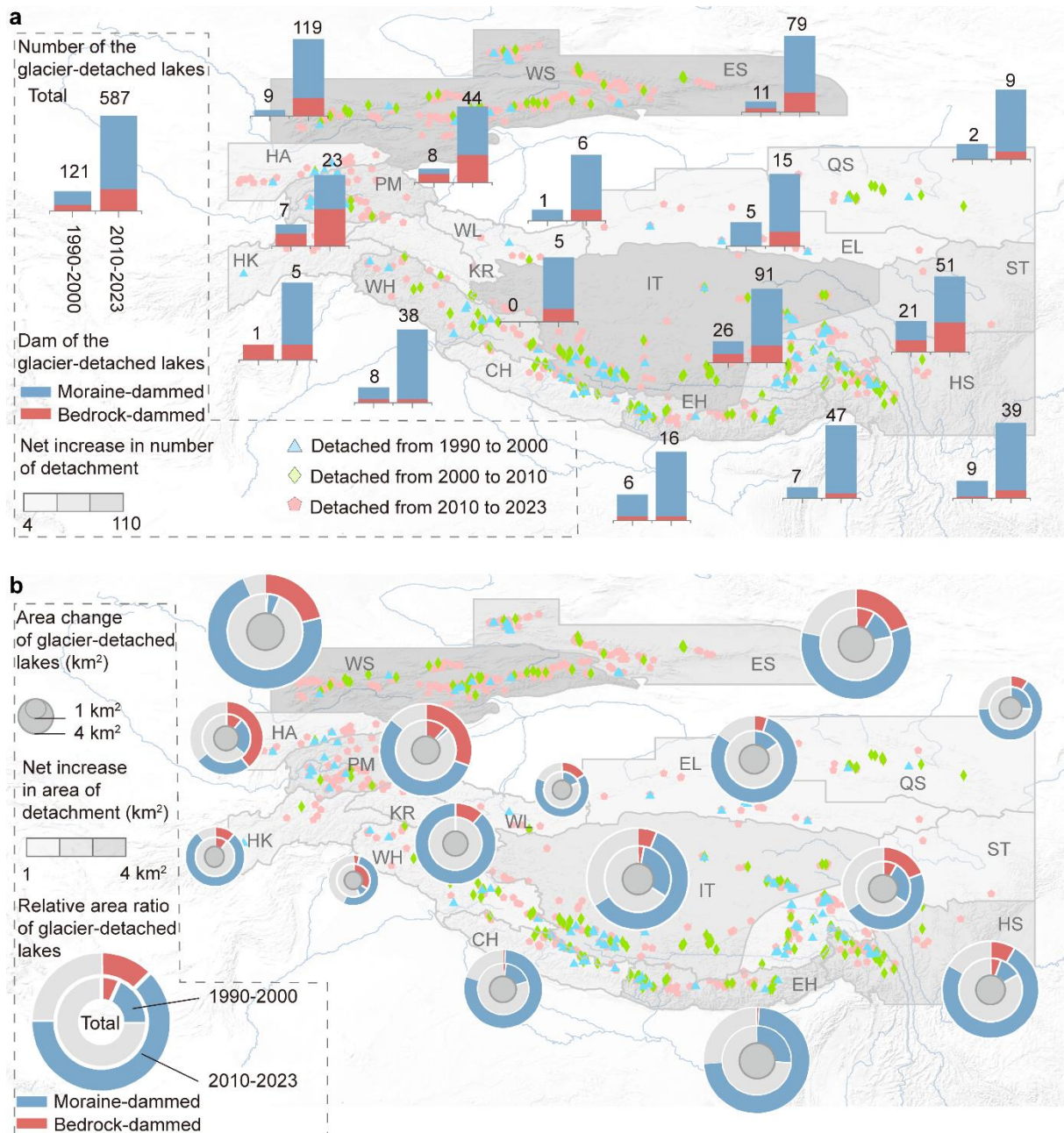


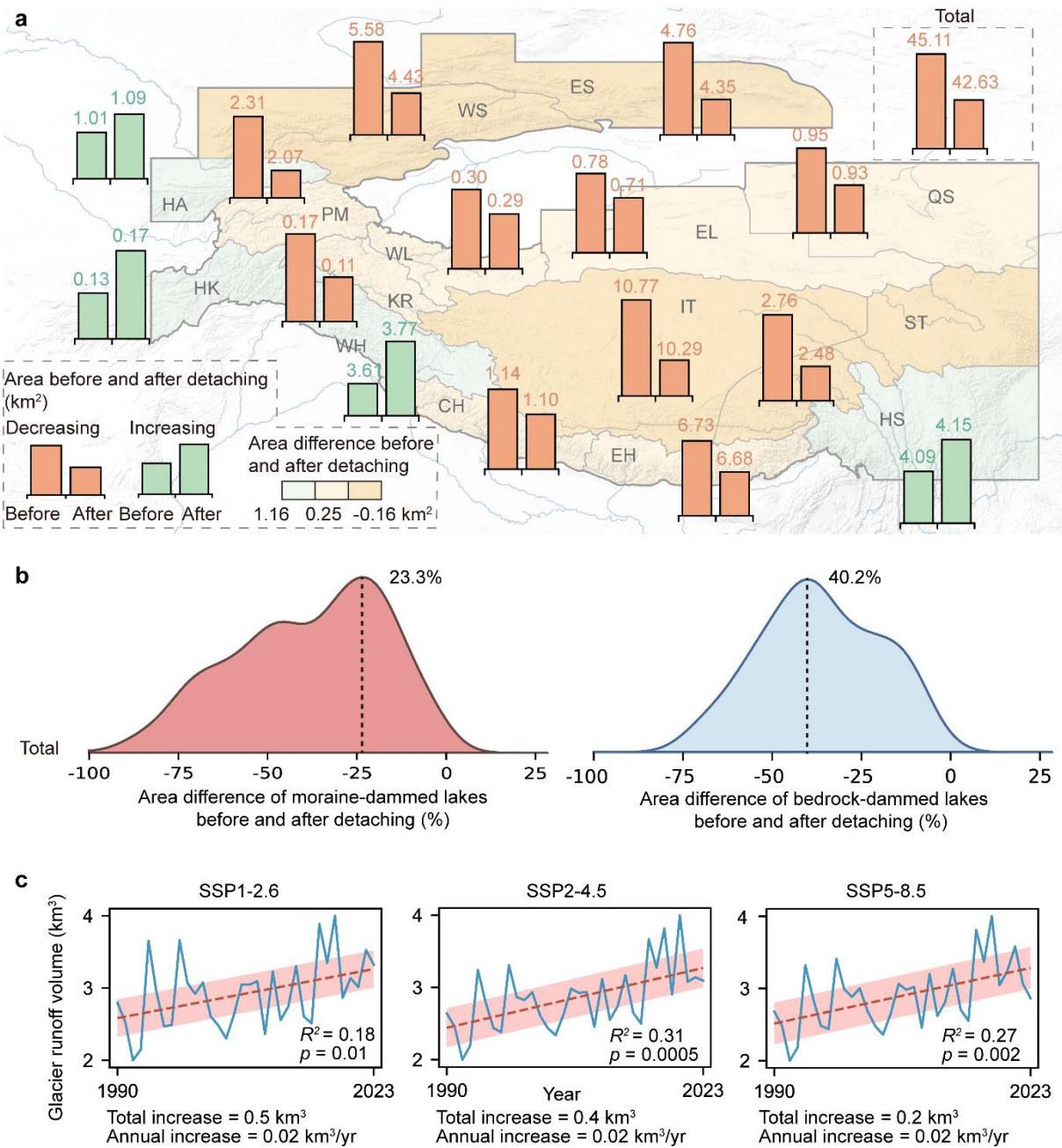
Figure 3. Number and area of glacier-contact lakes experiencing detachment from their parent glaciers in different periods. a) The number of the lakes experiencing detachment across different periods. The x-axis represents time (year), and the y-axis represents the number of the lakes. Blue bars indicate moraine-dammed lakes, while red bars indicate bedrock-dammed lakes. Points of different colors represent the spatial distribution of the lakes across different periods: blue points correspond to lakes detached during 1990–2000, green points to 2000–2010, and red points to 2010–2023. The number change ($N_{2023}-N_{1990}$) is illustrated by bars of varying lengths. The number change acceleration ($(N_{2023}-N_{2010})-(N_{2000}-N_{1990})$) is represented by varying shades of the gray background. **b)** The area of the lakes during different periods. Each ring represents a time period, with colored segments showing the proportion of the lake area (km²) contributed by each dam type. Segment lengths reflect the ratio to the total area across all periods. The area change ($A_{2023}-A_{1990}$) is represented by varying shades of the gray background, while the area change acceleration ($(A_{2023}-A_{2010})-$

($A_{2000}-A_{1990}$) is depicted by gray circles of different sizes.

3.3. Recently detached lakes shrink despite concurrent increases in glacier runoff

To evaluate post-detachment lake dynamics, we quantified area and estimated volume changes for 882 recently detached lakes before and after detachment. Lake extents were extracted from multi-temporal Landsat imagery, and volume changes were derived using an empirical volume–area scaling relationship. Lakes were further categorized by dam type (moraine or bedrock) to assess differences in shrinkage behavior. Glacier runoff volume were analyzed based on simulations from the Global glacier evolution model (Huss and Hock, 2015; Zekollari et al., 2024).

Overall, the total area of the 882 recently detached lakes decreased from 45.1 ± 0.02 to 42.6 ± 0.02 km², resulting in a volume loss of ~0.04 gigatonnes (Gt). The most significant shrinkage occurred in the regions of W Tien Shan (about 1.2 km², 20.6%), E Tien Shan (0.4 km², 8.6%), and S and E Tibet (0.3 km², 10.1%) (Figure 4a and Figure S6). However, four sub-regions showed further expansion after detachment, including W Himalaya (about 0.2 km²), Hissar Alay (0.1 km²), Hengduan Shan (0.1 km²), and Hindu Kush (0.1 km²). Moraine-dammed lakes (~3.9 km²) experienced greater absolute area loss than bedrock-dammed lakes (~0.9 km²) following detachment, whereas bedrock-dammed lakes (-40.2%) exhibited greater relative shrinkage than moraine-dammed lakes (-23.3%) (Figure 4b). Area shrinkage was observed in 156 detached glacial lakes, with shrinkage rates ranging from 2.1% to 100% (complete disappearance). 41 recently detached lakes exhibited shrinkage exceeding 50%; of these, 34 were dammed by moraines, with the largest shrinking moraine-dammed lake located in the eastern Tien Shan (0.1 km², 62%). Complete disappearance was documented in eight lakes, 63% of which were moraine-dammed, and 50% of which were in the Tien Shan region (Table S4 and Figure S7). From 1990 to 2023, annual glacier runoff volume increased significantly under all three scenarios, with an average annual increase of ~0.02 Gt/yr (SSP1-2.6, $R^2 = 0.18$, $p < 0.05$; SSP2-4.5, $R^2 = 0.31$, $p < 0.001$; SSP5-8.5, $R^2 = 0.27$, $p < 0.01$). The corresponding total increases over the same period were approximately 0.5, 0.4, and 0.2 Gt, respectively (Figure 4c). These runoff simulations indicate an increase in potential glacier-derived meltwater supply during these periods (Huss and Hock, 2018; Rounce et al., 2023). However, modeled runoff should not be interpreted as a direct measure of lake inflow or lake water balance, because the fraction of runoff reaching detached lakes may be modified by hydrological routing changes following detachment, infiltration through moraines or proglacial sediments, evaporation, temporary storage, and diversion of flow away from the lake.



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Figure 4. Area changes of recently glacier-detached lakes following detachment and trends in modelled annual glacier runoff volume from 1990 to 2023. a) Bar charts illustrate the area changes of recently glacier-detached lakes after detachment. Orange indicates shrinkage in area, while green represents expanding. **b)** Regional area change ratios of recently glacier-detached lakes by dam type. The horizontal axis shows the relative area change, and the vertical axis represents the kernel density. The left panel shows moraine lakes, while the right panel shows bedrock lakes. The kernel density curve illustrates the probability of distribution of lake area changes ratios before and after detachment, with the curve height reflecting the relative frequency of lakes falling within a given range of shrinkage. **c)** Modelled annual glacier runoff volume Trends from 1990 to 2023, the red curve is the fitting, and the shadow is the 95% confidence interval.

3.4. Higher proglacial erosion potential is associated with lake shrinkage despite increasing modeled runoff

Statistical comparisons were conducted between shrinking and non-shrinking recently detached lakes based on six glaciological and environmental variables, using the Mann–Whitney *U* test. Variables included temperature and precipitation change, glacier mass balance, proglacial erosion, headwall erosion, and glacier abrasion, with glacier abrasion here used only as a rough proxy for the potential production of subglacial sediments. Erosion indices were estimated from glacier slope, ice thickness, and local topographic conditions, while climate and glacier mass balance variables were extracted from regional datasets (see Methods).

The results revealed a significant difference in proglacial erosion potential between shrinking and non-shrinking lakes ($p < 0.05$; Figure 5a-b). The distributions of proglacial erosion potential and proglacial area were generally larger for shrinking lakes. The median proglacial erosion potential for shrinking lakes was 1.7 times greater, and the median proglacial area was 1.5 times greater than for non-shrinking lakes. Visual analysis of Cawuquden Co and Poiqu No. 2 shows expansion of exposed proglacial areas and sediment deposits along the lake margins, consistent with sediment delivery into the lakes and lake-area reduction (Figure 5c-f). Although the mean difference in the subglacial abrasion index was not significant, shrinking lakes tended to occur in areas with higher abrasion potential (Figure S8a). In contrast, temperature change ($p = 0.90$), precipitation change ($p = 0.87$), glacier mass balance ($p = 0.23$), and headwall erosion ($p = 0.078$) did not differ significantly between shrinking and non-shrinking lakes in the single-factor Mann–Whitney *U* tests (Figures S8–S10). However, this lack of statistical significance should not be interpreted as evidence that these factors have no influence on lake shrinkage. It only indicates that direct distributional differences in these factors between the two lake groups could not be detected in our current regional-scale, single-factor analysis.

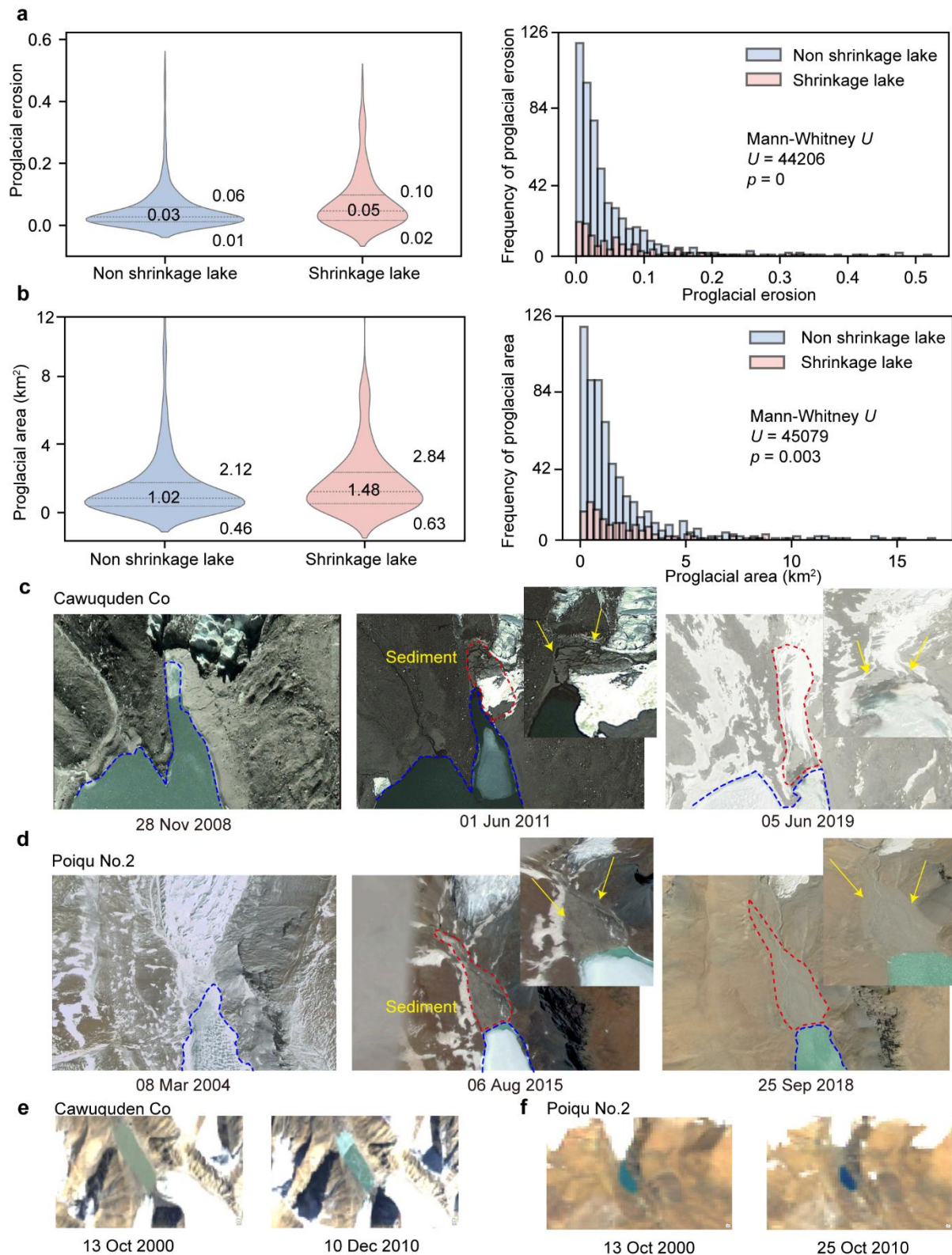


Figure 5. Comparison of shrinking and non-shrinking recently glacier-detached lakes based on proglacial erosion proxies and representative lake examples. a) Dimensionless normalized proglacial erosion index for shrinking and non-shrinking lakes. b) Proglacial area for shrinking and non-shrinking lakes. c) Typical recently glacier-detached lake shrinkage at Cawuquden Co; dashed lines indicate lake and sediment boundaries interpreted from imagery. d) Poiqu No. 2 recently glacier-detached lake; yellow arrow indicates

visible sediment/depositional area. e–f) Original Landsat scenes used in the analysis for Cawuquden Co and Poiqu No. 2, respectively.

3.5. Future expansion of proglacial zones signals a regime shift in lake evolution

Glacier runoff volume and proglacial area were analyzed based on simulations from the Global glacier evolution model (Huss and Hock, 2015; Zekollari et al., 2024). The model dynamically simulates glacier mass balance, retreat, and associated runoff for individual glaciers under CMIP6-based climate scenarios. It was calibrated using observed glacier volume changes (Hugonnet et al., 2021), and applied to 808 glaciers supplying 882 recently detached lakes. Proglacial areas were derived from the simulated retreat of glacier extents over time. Further methodological details are provided in the Methods section. As the glaciers continue to retreat, modelled annual glacier runoff volume generally shows a shift from increase to decrease in 1990–2100 (Figure 6a).

In the future, glacier runoff volume is projected to peak in 2035 (SSP1-2.6), 2057 (SSP2-4.5), and 2060 (SSP5-8.5), followed by a decline. The average annual decrease after the peak is approximately -0.01 Gt, with R^2 values of 0.53, 0.29, and 0.32 respectively (all $p < 0.001$; Figure 6a), indicating a gradual weakening in the ability of glaciers to replenish lakes. Thus, while reductions in glacial water supply are not the primary explanation for observed lake shrinkage, changes in glacier runoff remain an important background factor that interacts with geomorphic processes such as proglacial erosion and sedimentation.

At the same time, the proglacial area exposed by retreating glaciers continues to expand, which may play an increasingly important role in shaping future changes in glacial lake area (Bosson et al., 2023). The proglacial area generally shows a trend of continuous expansion and gradual acceleration (Figure 6b). During 1990–2023, the average annual increase of exposed proglacial area under the three scenarios was about 3.4 km²/yr (SSP1-2.6, $R^2 = 0.8$, $p < 0.001$), 3.1 km²/yr (SSP2-4.5, $R^2 = 0.7$, $p < 0.001$) and 3.0 km²/yr (SSP5-8.5, $R^2 = 0.8$, $p < 0.001$), respectively (Figure 6b). In the future (2024–2100), proglacial area expansion intensifies further, with average annual increases of 10.8, 14.5 and 19.2 km²/yr, respectively ($R^2 > 0.98$, $p < 0.001$) (Figure 6b). The rate of proglacial area expansion increases significantly under the SSP 5-8.5 scenario, implying that the much-intensified drastic glacier retreat under the high emissions pathway will expose more proglacial area. While glacier runoff will continue to provide an important water supply for glacial lakes, the continuous and accelerating expansion of proglacial areas suggests that geomorphic processes such as erosion and sedimentation will play an increasingly important role in shaping lake evolution in the future.

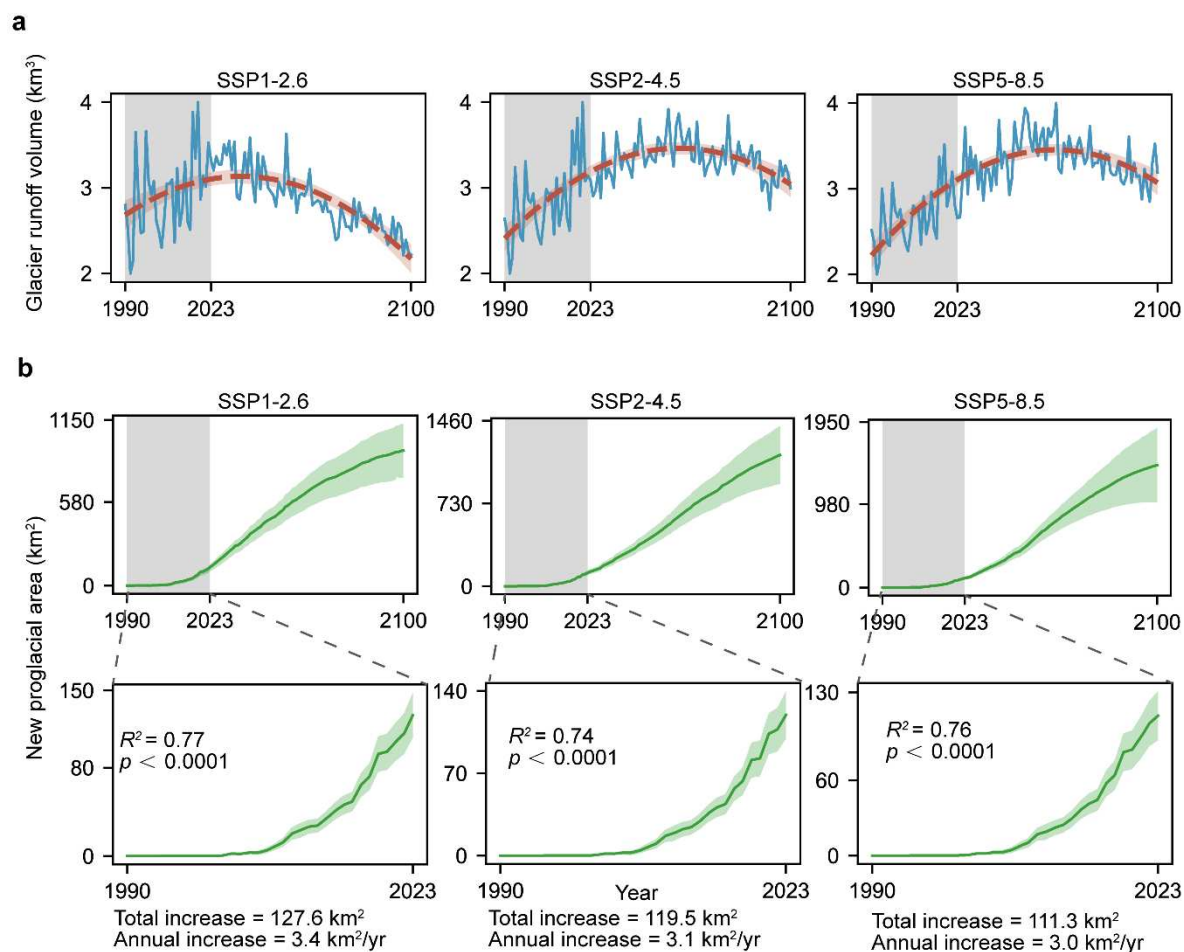


Figure 6. Trends in modelled annual glacier runoff volume and new proglacial area under different emission scenarios from 1990 to 2100. All time series refer to results inferred with GloGEM (Huss and Hock, 2018) for 808 glaciers that feed 882 recently glacier-detached lakes (see Methods for details). a) Interannual trend of annual glacier runoff volume under three emission scenarios. SSP1-2.6, SSP2-4.5, SSP5-8.5; the red curve is the fit, and the shadow is the 95% confidence interval. b) Interannual trend of annual new proglacial area under different emission scenarios from 1990 to 2100. The light orange band is the estimated uncertainty interval. The grey background is the historical modelled period (1990-2023). Lower panels show enlargements of the historical period, including the linear regression trend and corresponding statistics.

4. Discussion

4.1. Primary and supplementary mechanisms controlling the shrinkage of recently glacier-detached lakes

As glaciers retreat, proglacial zones emerge and expand (Bosson et al., 2023). These newly exposed areas are typically composed of unconsolidated glacial sediments, making them highly dynamic environments prone to intense erosion and deposition (Delaney et al., 2018). Proglacial erosion is primarily driven by meltwater flow and the mechanical transport of sediments (Boulton and Hindmarsh, 1987; Savi et al., 2023;

Zhang et al., 2022), and can influence recently detached lake evolution through multiple mechanisms. Erosion accelerates the delivery of sediment into lakes, leading to infilling that gradually reduces in lake area and volume (Carrivick and Heckmann, 2017; Emmer, 2024a; Hardmeier et al., 2024). As glaciers continue to retreat, fine- and coarse-grained sediments become increasingly exposed, making them highly susceptible to riverine erosion. During periods of high meltwater discharge, glacier-contact lakes receive high-energy inflows that are typically sediment-laden and highly turbid. Coarse bedload materials predominantly settle near the inflow, building deltas, while finer suspended sediments may deposit more diffusely across the lake floor in thin, stratified layers. These sediments can further interact with thermal and chemical processes, potentially disrupting lake stratification (Carrivick and Tweed, 2013) and compromising the stability of glacier-contact lake margins. Recently detached lakes also experience suspension settling, which gently drapes the lake bathymetry. These sedimentations have important implications for changes in lake volume, the long-term storage capacity of lakes, like hydropower potential and the accumulation of glacier-derived minerals, nutrients, and pollutants. Consequently, a self-reinforcing mechanism emerges between proglacial erosion and sedimentation within a lake basin. Increased sediment input reduces the lake volume, with coarse material accumulating faster in smaller basins, though fine sediments may be more easily flushed out due to shorter residence times.

This study focuses on the shrinkage of detached glacial lakes driven by erosion in proglacial areas and subsequent sedimentation within lake basins. This process is pronounced in proglacial areas exposed after glacier retreat, where continuous sediment accumulation gradually reduces lake basin capacity and ultimately leads to a decrease in lake area. However, this interpretation does not imply that climatic and glaciological factors are unimportant. Rather, our results indicate that sediment-related geomorphic processes show the clearest direct contrast between shrinking and non-shrinking lakes at the regional scale. Beyond these dominant factors, there are additional mechanisms that may operate under specific circumstances. In moraine-dammed lakes, a gradual decline in lake water level may also be a potential mechanism contributing to area shrinkage. Although the overall supply of glacial meltwater has increased due to accelerated glacier mass loss (Huss and Hock, 2018), natural outflow channels in moraine dams, such as shallow subsurface pathways within the moraine, may evolve over time (Müller et al., 2022; Müller et al., 2024). These channels can become progressively incised or open new drainage routes (Clague and Evans, 2000; Emmer and Cochachin, 2013), which can cause a sustained lowering of lake levels. This may lead to lake area shrinkage even in the absence of significant sediment infill. This process may explain why moraine-dammed lakes

exhibited greater absolute area loss ($\sim 3.9 \text{ km}^2$) following detachment, compared to bedrock-dammed lakes ($\sim 0.9 \text{ km}^2$). Subglacial processes may also exert some influence on lake shrinkage. Although the mean difference in the subglacial abrasion index between shrinking and non-shrinking lakes is not significant, the distributional characteristics indicate that shrinking lakes tend to occur in areas with higher abrasion potential (Figure S8a). This suggests that spatial variations in subglacial sediment production may, to some extent, contribute to the sedimentation processes affecting lake evolution.

Climate effects may still influence post-detachment lake evolution through indirect, lagged, nonlinear, or interacting pathways. Rising temperature can accelerate glacier retreat and enlarge newly exposed proglacial areas, thereby increasing the availability of unconsolidated sediment and the potential for erosion. Changes in precipitation may alter runoff generation, sediment transport capacity, and the frequency of high-flow events that deliver sediment into lake basins. Similarly, glacier mass balance influences both meltwater supply and the timing of proglacial terrain exposure. Therefore, the non-significant differences in temperature change, precipitation change, and glacier mass balance between shrinking and non-shrinking lakes should not be interpreted as evidence of no climatic influence. Instead, they suggest that these variables do not show detectable direct group-wise differences in our current regional-scale single-factor analysis.

In the TPR region, there is currently a lack of sufficient long-term and spatially extensive data to systematically quantify the effects of lake-level decline, subsurface drainage, seepage, and changes in inflow routing. Although short-term remote sensing studies have reported persistent lake level lowering for some lakes based on ICESat-2 data from 2019 to 2023 (Wang et al., 2025), the limited temporal coverage and lack of statistical significance make it difficult to assess the long-term impact of this process. Based on longer-term observations, most lakes exhibit relatively stable levels from 2000 to 2021 (Zhang et al., 2023a). We therefore interpret the observed statistical pattern as most consistent with an important role for proglacial erosion and sediment deposition within lake basins, while recognizing that lake-level decline, subsurface drainage, seepage, and routing changes may contribute locally. Future research should incorporate longer time series data, such as combining ICESat and ICESat-2 observations or including CryoSat-2, and should be complemented by in-situ lake-level monitoring, structural assessments of moraine dams, and more detailed observations of subglacial sedimentary processes.

4.2. Drivers of regional differences

Recently detached lakes exhibit distinct patterns of post-detachment area change across different regions.

The most significant shrinkage occurred in the Western Tien Shan (about 1.2 km², 20.6%), Eastern Tien Shan (0.4 km², 8.6%), and South and East Tibet (0.3 km², 10.1%) (Figure 4a, Figure S6). In contrast, several regions—including the Western Himalaya (about 0.2 km²), Hissar Alay (0.1 km²), Hengduan Shan (0.1 km²), and Hindu Kush (0.1 km²) showed further expansion after detachment. These regional contrasts should be interpreted as net regional area changes, rather than as evidence that all recently detached lakes within a given region followed the same trajectory. In regions with fewer recently detached lakes or smaller total lake area, the net regional signal may be influenced by a limited number of lakes with relatively large area changes. These differences may be explained by the combined effects of lake size and dam type. The proportion of small recently detached lakes is higher in the Western Tien Shan, Eastern Tien Shan, and South and East Tibet (Figure 2). Such small lakes are more susceptible to rapid area reduction under continuous sediment input. And these regions also have a relatively high proportion of bedrock-dammed lakes. Although sediment supply to bedrock-dammed lakes is generally limited, their smaller storage capacity makes them more likely to experience higher relative shrinkage (Figure 4). The combined effect of these two factors contributes to the pronounced shrinkage observed in these regions. By contrast, regions such as the Western Himalaya, Hissar Alay, Hengduan Shan, and Hindu Kush contain a larger proportion of large lakes. Their greater storage capacity makes them less vulnerable to rapid infilling and area loss in the short term. Some lakes in these regions may continue to expand after detachment because they still receive substantial glacier meltwater input, have available topographic accommodation space, or experience limited sediment infilling and efficient sediment export. In summary, the regional differences not only reflect the geographic and environmental settings of the lakes but also highlight the critical role of lake size and dam type in shaping post-detachment evolutionary trajectories.

4.3. Shrinkage of recently glacier-detached lakes as key evidence for paraglacial adjustment

This study demonstrates that glacier-contact lakes across the TPR have experienced areal shrinkage after detaching from their parent glaciers. This shrinkage is statistically linked to intense proglacial erosion. Shrinking lakes are associated with higher proglacial erosion indices and larger proglacial areas than non-shrinking ones, suggesting that as glacier retreat exposes more unstable land surfaces, lake evolution may gradually shift from being dominated by hydrological recharge to being governed by sediment infilling. These findings are consistent with the concept of the proglacial-to-paraglacial transition, whereby following glacier retreat, landscapes enter a transitional phase characterized by sediment redistribution, with sustained and

intense sedimentation and morphological adjustments (Church and Ryder, 1972; Ryder, 1971a; Ryder, 1971b). Paraglacial landscapes are essentially governed by a disturbance–recovery regime (Slaymaker, 2009; Slaymaker, 2011). The rapid shrinkage and infilling of recently detached lakes observed here can therefore be viewed as a specific manifestation of this disturbance–recovery regime in alpine lacustrine systems. Once detached, lakes enter a phase of enhanced sediment input and accelerated basin filling until they stabilize or eventually disappear.

It should be noted that the methodology applied in this study is simplified. We characterized the erosional potential of proglacial zones using slope and deglaciated area but did not directly quantify the amount of sediment storage. Previous studies have demonstrated that the presence, thickness, and distribution of glacial sediment stores exert a crucial influence on sedimentation rates and lake evolution (Otto, 2018; Piret and Bertrand, 2022). Our results thus provide a regional-scale context to supplement these insights, suggesting that glacial lake shrinkage should be understood within the broader framework of paraglacial responses. Because these indices are normalized across the study population, their physical meaning is relative. They should not be used to estimate absolute sediment yield, and sensitivity to buffer geometry, DEM resolution, and normalization choices remains a limitation.

This study enriches current knowledge on alpine lake systems, extending discussions that have traditionally focused on alluvial fans, slopes, and valleys to include alpine lake systems. Existing Quaternary studies of lake sedimentation rates and sediment budgets offer valuable references for explaining inter-lake differences and anticipating future evolutionary trajectories (Schiefer, 2006; Slaymaker et al., 2016). Future research that integrates field data on sediment thickness, sediment cores, and high-resolution process-based modeling will be essential for developing a more comprehensive understanding of glacial lake evolution during the paraglacial phase.

4.4. Future trends in glacial lake Evolution and implications for GLOF hazard/risk assessment and water resources

Although the trends in glacial lake areas have garnered significant attention, there remains a lack of systematic assessment about impacts of erosion and sedimentation processes on future glacial lake changes following glacier retreat. While some studies have begun to consider the influence of erosion and sedimentation on future glacial lake evolution (Steffen et al., 2022), most studies have traditionally focused on the direct impacts of climate change on glacier melt rates, often neglecting the highly dynamic erosional

processes within the proglacial environment and their crucial role in regulating sediment flux into glacial lakes. Proglacial erosion accelerates the transport of sediments by meltwater flow, thereby increasing sedimentation rates and reducing the area and volume of glacial lakes (Engel et al., 2024). Furthermore, proglacial erosion can undermine the stability of terminal moraine dams or other geomorphological barriers, potentially triggering lake drainage (Zheng et al., 2021). This erosion-sedimentation interplay is particularly significant, where rapid glacier retreat and permafrost degradation amplifies the influence of erosion and deposition processes on the morphology and stability of glacial lakes.

The response of glacial lakes to erosion and sedimentation exhibits considerable spatial and temporal heterogeneity. For instance, glacial lakes situated beneath steep terrains often experience rapid area shrinkage due to intensified hillslope and proglacial erosion, whereas delta formation and lacustrine deposition processes may play a dominant role in shaping long-term lake area changes in relatively flat deglaciation zones (Corte et al., 2024). At the same time, there is likely to be competition between sediment influx from glacier-fed runoffs (which may decline as runoff decreases after the mid-21st century) and sediment reworking from increasingly exposed proglacial areas. How this balance will play out in the future remains uncertain. These variations underscore the importance of capturing the dynamics of proglacial erosion rates and sediment transport when predicting future changes in glacial lake areas, particularly in the context of atmospheric warming. Higher-resolution investigations targeting pilot catchments will be required to clarify these competing influences.

While our large-scale approach highlights the importance of erosion and sedimentation as potential drivers of lake shrinkage, it provides only first-order insights into individual future trajectories. Incorporating erosion and sedimentation processes into frameworks for predicting glacial lake area changes is essential for a comprehensive understanding of the evolution pathways of glacial lake systems. Future studies should combine regional-scale assessments with high-resolution remote sensing (e.g., ICESat-2, UAV surveys, InSAR), advanced erosion-sedimentation models, and long-term field monitoring in representative catchments to better quantify the sustained impacts of these processes on glacial lake dynamics (Hardmeier et al., 2024). Such efforts will significantly enhance the accuracy and applicability of predictive models and help improve risk assessment and environmental management.

As detached glacial lakes shrink, their reduced volume may lessen the potential magnitude of GLOFs (Emmer et al., 2015). With less water in the lake, even if a GLOF occurs, the size and energy of the resulting flood is expected to be smaller, thereby potentially reducing the impact on downstream areas. However, it is

important to note that outbursts from even small lakes can still evolve into devastating cascading flood events (Sattar et al., 2022). As glaciers continue to retreat, the decoupling of glacial lakes from glacier dynamics may diminish the significance of the primary GLOF-triggering mechanisms, such as ice avalanches and calving (Veh et al., 2025). This does not imply that the hazard/risk of GLOFs has completely disappeared. While the direct threat of ice avalanches will diminish over time, glacial debuitressing and permafrost degradation will in many cases likely lead to an increase in rock fall or avalanches (Shugar et al., 2021); hence change in GLOF probability will typically depend on local geomorphic catchment dynamics (Carrivick et al., 2018a; Carrivick et al., 2018b; Carrivick and Rushmer, 2018; Mancini et al., 2025) . Therefore, future disaster and risk assessments should not only focus on glacier retreat, but also comprehensively incorporate the impact of geomorphic processes such as erosion and sedimentation. This needs to be combined with high-resolution DEM data and numerical modeling to dynamically simulate the interaction between potential GLOFs and landforms. Recently detached lakes should not be assumed to continue expanding with glacier retreat in the same way as glacier-contact lakes, and shrinking detached lakes should not automatically be regarded as low-risk. For lakes that have already detached and exhibit shrinking trends, hazard assessments based solely on lake area or volume may be insufficient. Practical assessments should also consider residual water storage, the evolution of proglacial erosion and sedimentation processes, and changes in exposure to potential rock- or ice-avalanche impacts. These factors can provide valuable supplementary information for regional-scale GLOF hazard and risk assessment.

Hydropower infrastructure in alpine regions often relies on the storage capacity of glacial lakes to provide a stable water supply (Farinotti et al., 2019; Schaefli et al., 2019; Yang et al., 2025). However, recently detached lakes tend to experience sedimentation infilling due to the loss of direct glacial recharge and the expansion of exposed proglacial terrain, resulting in a progressive decline in water volume that may substantially compromise their reservoir function and regulation capacity, particularly in larger glacial lakes (Farinotti et al., 2016; Farinotti et al., 2019). Moreover, sedimentation processes themselves carry important geochemical and environmental consequences. Glacier retreat releases minerals, organic carbon, and pollutants, which are transported into distal or recently detached lakes and ultimately settle in low-energy lakebed environments (Zhu et al., 2024). These sediments may serve as significant repositories of minerals and carbon, while also potentially accumulating environmental contaminants that may affect water quality further downstream (Zhu et al., 2020). Future research should therefore focus on monitoring and modeling sediment composition, accumulation rates, and impacts on lake water quality, to clarify the multifaceted role of glacial lakes in alpine

ecosystems and resource management. Assessments of future water availability in high mountain regions should account for the progressive loss of lake storage caused by sediment infilling in recently detached lakes. As sediment progressively fills lake basins, lake volume and water-storage capacity decline, potentially reducing the role of detached lakes as natural water reservoirs. Therefore, water-resource assessments, hydropower planning, and projections of lake regulation capacity should consider sediment infilling and the associated loss of storage volume to avoid overestimating future water storage and natural regulation capacity.

4.5. Uncertainties in volume estimation and complexity of multi-factor coupling

The lake volumes presented in this study should be regarded as first-order approximations. They are based on a TPR-wide empirical area–volume scaling relationship fitted from 140 published bathymetric measurements of glacial lakes across TPR. The relationship is $V = 42.57A^{1.414}$, with bootstrap-derived 95% confidence intervals of 39.31–45.51 for the coefficient and 1.273–1.517 for the exponent. While such scaling provides reasonable estimates of lake volume at a given point in time, its application to infer volume change from mapped area change carries greater uncertainty. By propagating the uncertainty of the area–volume relationship through 5000 bootstrap realizations, we estimated a net water-volume loss of 0.042 Gt for recently glacier-detached lakes, with a 95% confidence interval of 0.034–0.059 Gt. In particular, lake volume may decrease through the settlement of fine-grained sediments on the lake floor without producing appreciable changes in surface area, while delta progradation may substantially alter lake area but only modestly affect volume. This means that the area–volume relationship of a given lake may evolve as infilling progresses, and scaling-based estimates may not fully capture these dynamics. In addition, although the calibration dataset was expanded the TPR dataset, it remains strongly dominated by moraine-dammed lakes, with only one bedrock-dammed lake. We therefore pooled all available bathymetric measurements to fit a TPR-wide relationship rather than fitting dam-type-specific relationships. This may introduce systematic uncertainty if moraine-dammed and bedrock-dammed lakes differ in their depth structure and scaling behavior (Muñoz et al., 2020). The volume change estimates reported here therefore indicate overall trends rather than precise values. The reported confidence interval reflects uncertainty in the empirical area–volume relationship, but does not fully account for potential lake-specific effects of sediment infilling, lake-bottom morphology, dam type, or unobserved bathymetric change. Future work combining bathymetric surveys, in situ monitoring, and process-based modeling will be essential to refine estimates of volume dynamics and

sedimentation in detached glacial lakes.

This study employed the nonparametric Mann–Whitney U test to analyze potential driving factors. While this approach is well suited for comparing distributions across large and heterogeneous samples, it is inherently univariate and can only evaluate the distributional differences of individual factors between shrinking and non-shrinking lakes. It cannot capture potential interactions among multiple predictors. In reality, complex couplings often exist between climate variables (temperature, precipitation), glacial changes (mass balance), and geomorphic processes (erosion, sedimentation). For example, rising temperatures may indirectly enhance erosion by altering glacier mass balance, while changes in precipitation may interact with proglacial sediment availability to influence lake infilling. Thus, the conclusion that other factors were not significant only reflects the results of single-factor tests and does not preclude their influence within more complex interaction chains. Future research that integrates multivariate statistical approaches (e.g., multiple regression, generalized linear models, machine learning) and higher-resolution climate and glacial datasets will be essential to systematically assess the relative contributions of different drivers and their interactions, thereby providing a more comprehensive understanding of post-detachment lake evolution.

5. Conclusion

This study systematically investigates the transition of glacier-contact lakes to detached lakes across the TPR from 1990 to 2023, leveraging remote sensing imagery and deep learning techniques to analyze detachment dynamics and the drivers of subsequent lake shrinkage. The results reveal an accelerating trend in glacier-contact lake detachment, with the detachment rate increasing from about 12.1 lakes/yr in 1990–2000 to 45.2 lakes/yr in 2010–2023. Following detachment, although most lakes remained relatively stable, the total area decreased from 45.1 to 42.6 km², primarily driven by 156 lakes that experienced substantial shrinkage. Among these, shrinkage rates ranged from 2.1% to complete disappearance (100%), with 41 lakes shrinking by more than 50%. Dam type influenced sensitivity, with moraine-dammed lakes showing greater absolute loss (~3.9 km²), whereas bedrock-dammed lakes exhibited larger relative shrinkage (40.2%), reflecting divergent post-detachment trajectories. The spatial distribution of these changes also exhibited regional variability, with the most substantial shrinkage observed in Western Tianshan, Inner Tibet, and Eastern Tianshan. The analysis suggests that intensified proglacial erosion shows a statistically significant relationship with lake shrinkage, while subglacial abrasion is reflected in distributional patterns, with shrinking lakes preferentially occurring in areas of higher abrasion potential. Temperature change, precipitation change, glacier mass balance, and

headwall erosion did not show statistically significant differences between shrinking and non-shrinking lakes in the single-factor regional-scale tests. However, this does not exclude their indirect, lagged, nonlinear, or interacting influences on lake evolution. These factors may still affect detached lakes by regulating glacier retreat, meltwater supply, sediment availability, sediment transport capacity, and the timing of proglacial terrain exposure.

These findings suggest that proglacial erosion potential and associated sediment dynamics are important factors associated with the shrinkage of recently detached lakes across the TPR. The observed patterns are consistent with an ongoing shift from glacier-contact lake expansion toward post-detachment geomorphic adjustment, supporting the concept of a proglacial-to-paraglacial transition. However, the observed shrinkage is likely influenced by multiple interacting processes, including sediment infilling, changes in hydrological connectivity after detachment, seepage and subsurface drainage, and inflow-routing adjustments. Our results should therefore be interpreted as evidence of regional-scale associations, while the underlying mechanisms require further investigation. This study provides a first regional assessment of recently detached lake evolution across the TPR and offers new insights for future glacial-lake evolution studies, GLOF hazard assessments, and water-resource evaluations. Future work should combine long-term field observations, bathymetric surveys, hydrological measurements, and high-resolution topographic data to better constrain the mechanisms controlling post-detachment lake evolution.

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Temperature data used in this study is obtained from <https://www.tpdc.ac.cn/zh-hans/data/44a449ce-e660-44c3-bbf2-31ef7d716ec7>. Precipitation data is from <https://data.tpdc.ac.cn/zh-hans/data/e45be858-bcb2-4fea-bd10-5c2662cb34a5>. Glacier mass balance data is delineated from <https://doi.org/10.6096/13>. Landsat datasets are from the USGS data portal (<https://glovis.usgs.gov>). The Multi-Error-Removed Improved-Terrain (MERIT) DEM is from http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM. Randolph Glacier Inventory 6.0 and 7.0 data is from <http://www.glims.org/RGI>. Glacier thickness data is from <https://doi.org/10.6096/1007>. The inventory of glacial lakes generated in this study is publicly available via Zenodo ([doi:10.5281/zenodo.18268639](https://doi.org/10.5281/zenodo.18268639)). Code or new software was not developed for this study. Mathematical calculations were undertaken by using the open-source programming Python.

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Author contributions:

Q.T. and G.Z. designed the study. Q.T. wrote the draft of the manuscript. T. Y., M. H., J. C., A. E., C. H., S. A., D. L. edited the manuscript. All authors contributed to the final form of the study.

Supporting Information:

Supporting Information may be found in the online version of this article. <https://doi.org/XX/XX>.

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