



1 **Rapidly Changing Lake-Terminating Glaciers in High** 2 **Mountain Asia: A Dataset from 1990 to 2022**

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10 **Abstract.** Lake-terminating glaciers (LTGs) typically exhibit higher rates of retreat and thinning
11 compared to land-terminating glaciers. However, a comprehensive inventory for LTGs and their
12 associate proglacial lakes across High Mountain Asia (HMA) is currently lacking, limiting further
13 understanding of their spatial heterogeneity in glacier change. This study employs a semi-automated
14 identification method, coupled with rigorous visual inspection, to construct a comprehensive inventory
15 of LTGs and proglacial lakes in HMA for 1990 and 2022. Our data indicate that, by 2022, HMA hosted
16 1740 LTGs ($5082.08 \pm 13.15 \text{ km}^2$), among which 667 glaciers ($3454.59 \pm 12.43 \text{ km}^2$) remained in contact
17 with proglacial lakes since 1990, 1073 ($1627.49 \pm 4.30 \text{ km}^2$) are newly developed and 468 ($960.13 \pm$
18 3.18 km^2) had disconnected from proglacial lakes during the investigation period. Accordingly, 645
19 proglacial lakes ($207.18 \pm 0.82 \text{ km}^2$) remained in contact with ice, 1123 new lakes ($54.85 \pm 0.35 \text{ km}^2$)
20 formed, and 485 lakes ($45.31 \pm 0.34 \text{ km}^2$) detached from ice (including 25 disappeared). During the past
21 32 year, the total area of proglacial lakes increased by $138.19 \pm 1.18 \text{ km}^2$ (81.7%), alongside a glacier
22 area loss of $324.43 \pm 19.23 \text{ km}^2$ (5.1%). The southern regions of HMA, particularly the Hindu Kush,
23 Himalayas, Nyainqentanglha, and Gangdise Mountains, exhibiting the highest concentration and rapidest
24 changes of the glacier-lake system. We hope that this dataset will improve our understanding of mountain
25 glacier-lake interactions, water availability, as well as glacier-related hazards in HMA.
26 The dataset is available at <https://doi.org/10.5281/zenodo.17369580> (Luo and Liu, 2025).



27 **1 Introduction**

28 Proglacial lakes in direct contact with glacier termini play a critical role in glacier evolution (Liu et
 29 al., 2020; Truffer and Motyka, 2016; Chernos et al., 2016) and are a primary driver of spatial
 30 heterogeneity in glacier responses to climate change (Brun et al., 2019; Maurer et al., 2019). Proglacial
 31 lakes typically form behind end or lateral moraines, on debris-covered glaciers often developed through
 32 the coalescence of multiple supraglacial ponds near the glacier terminus (Carrivick and Tweed, 2013;
 33 Quincey et al., 2007; Mertes et al., 2017). The influence of lake water on glacier change operates
 34 primarily through two mechanisms: (1) thermal undercutting by lake water (Truffer and Motyka, 2016)
 35 and calving at the glacier front (Benn et al., 2007a), which together accelerate subaquatic and frontal
 36 ablation; and (2) when glacier termini come into contact with sufficiently deep water, the buoyancy of
 37 the lake reduces basal effective pressure, thereby enhancing glacier flow and dynamic thinning
 38 (Sugiyama et al., 2011; Sutherland et al., 2020; Benn et al., 2007b). (Sato et al., 2022; Tsutaki et al., 2019;
 39 Tsutaki et al., 2017). Observations indicate that LTGs in HMA have mass loss rates 18–97% higher than
 40 the regional average (Brun et al., 2019), and under comparable geographic conditions, their flow
 41 velocities are typically two- to threefold greater than those land-terminating counterparts. Furthermore,
 42 Zhang et al. (2023) reported that existing geodetic methods, by failing to account for the replacement of
 43 glacier ice by lake water, underestimate the mass loss of Himalayan LTGs by approximately 6.5%.

44 HMA encompassing the entire Tibetan Plateau and its surroundings contains the largest
 45 concentration of mid-latitude mountain glaciers on Earth. Driven by ongoing global warming, glaciers
 46 in HMA have undergone a persistent negative mass balance, with an average mass loss rate of -20.1 Gt
 47 a^{-1} during 2000–2019 (Hugonnet et al., 2021). Glacier meltwater has driven substantial runoff and
 48 facilitated the formation and expansion of glacial lakes. From 1990 to 2018, the number of glacial lakes
 49 in HMA increased by 11%, and their total area expanded by 15% (Wang et al., 2020). The ongoing
 50 increase in both the number and extent of proglacial lakes underscores the critical need for a
 51 comprehensive assessment of lake-terminating glacier-proglacial lake systems in HMA. Such an
 52 evaluation is essential for elucidating feedback between the lake and ice, forecasting their responses to
 53 future climate change, and informing evidence-based strategies for water resource management and
 54 disaster risk mitigation. Although several regional-scale glacial lake inventories have been published in



recent years (Wang et al., 2020; Chen et al., 2021; Zhang et al., 2015; Worni et al., 2013; Salerno et al., 2012; Shugar et al., 2020), most datasets do not distinguish the contact status and its change between glaciers and proglacial lakes. Moreover, there is currently no comprehensive inventory of lake-terminating glacier-proglacial lake systems covering the entire HMA, and their spatiotemporal evolution remains poorly understood. Therefore, this study aims to construct a dataset of LTGs and proglacial lakes for HMA based on multi-source remote sensing data, thereby filling this research gap and providing fundamental database to support studies on regional glacier change, water resource assessment, disaster management, and glacier hydrology.

2 Study area

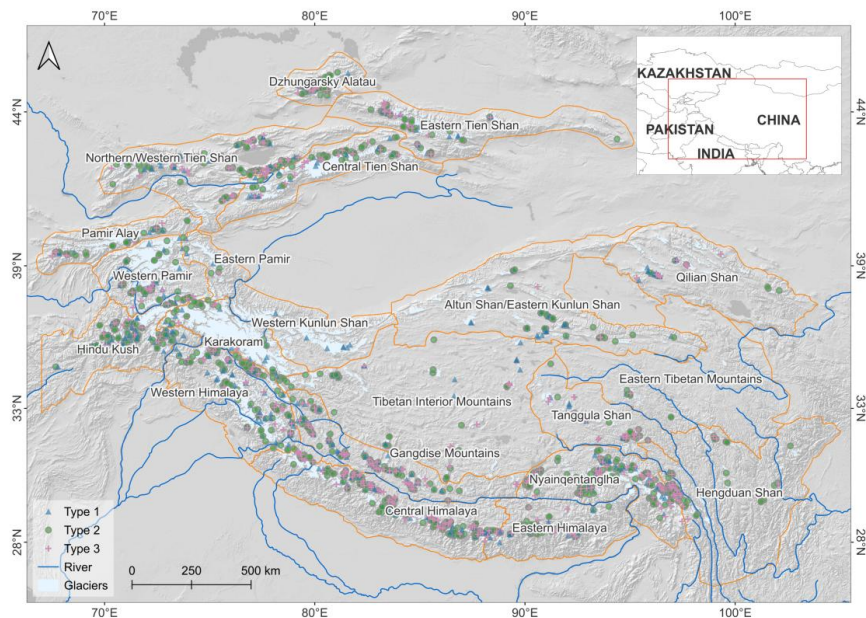


Figure 1: Location of HMA and distribution of LTGs. Glacier outlines from the Randolph Glacier Inventory (RGI v7.0). Types of LTGs are shown in Table 1.

High Mountain Asia (HMA), encompassing the Tibetan Plateau and its surrounding ranges—including the Himalayas, Karakoram, and Pamir Plateau, etc.—constitutes the most glacier-rich region in the mid-latitudes (Figure 1). HMA lies between 26°–45°N and 67°–105°E. It has an average elevation of approximately 4,500 m. The region features a complex topography. This topography is characterized by



71 higher elevations in the northwest and lower elevations in the southeast. It comprises a network of
 72 interwoven mountain ranges, valleys, and river systems. The dominant orographic orientation is east-
 73 west. The Tanggula Shan, located in the central part of the region, rise above 6,000 m, while the
 74 Himalayas contain 15 peaks exceeding 8000 m, and most peaks on the northern plateau surpass 6500 m.
 75 North-south trending ranges are mainly distributed in the southeastern Tibetan Plateau and the Hengduan
 76 Shan, forming the geomorphological framework of the region and controlling the overall topographic
 77 configuration of the plateau.

78 Climatically, the southern part of HMA is dominated by the South Asian and East Asian monsoons,
 79 bringing abundant precipitation, whereas the northern and western sectors are under the influence of the
 80 mid-latitude westerlies, characterized by arid conditions and scarce precipitation (Yao et al., 2012). This
 81 pronounced north-south climatic contrast results in a highly heterogeneous spatial pattern of glacier
 82 accumulation and ablation across the region. HMA serves as the source region for several major Asian
 83 rivers, including the Yellow River, Yangtze River, Yarlung Tsangpo, Indus, Ganges, Salween, Mekong,
 84 and Irrawaddy, which are vital for downstream hydrological processes and water resource availability.
 85 According to the Randolph Glacier Inventory (RGI 7.0), HMA hosts 94,058 modern glaciers, covering
 86 approximately 99,468.4km², making it the most extensively glacierized region outside polar areas. Most
 87 glaciers in HMA are undergoing retreat (Brun et al., 2017; Hugonnet et al., 2021). However, slight mass
 88 gains have been observed in parts of the Karakoram and western Kunlun ranges (Gardelle et al., 2012;
 89 Kääb et al., 2015), though recent studies suggest this trend may be diminishing (Hugonnet et al., 2021).

90 **3 Data and methodology**

91 **3.1 Extraction of proglacial lake outlines**

92 Before developing a comprehensive inventory of LTGs shown in Figure 1, we first generated a
 93 proglacial lake dataset using an automated delineation workflow within the Google Earth Engine (GEE)
 94 platform. We used Landsat imagery from the Thematic Mapper (TM) and Operational Land Imager (OLI)
 95 sensors, selected for their long-term record (since 1972), 30 m resolution, global coverage, and open
 96 access. All images were pre-processed in GEE, including radiometric, atmospheric, and geometric
 97 corrections. To minimize seasonal variability and the presence of snow and ice, we selected images



98 acquired from July to November. Two-time windows were defined: 1990 ± 2 years (historical) and
 99 2022 ± 1 year (recent). Due to limited image availability around 1990, imagery from 1993 to 1996 was
 100 used to supplement data gaps. A 2 km buffer around each glacier was applied to focus on potential ice-
 101 contact proglacial lakes. Cloud contamination was reduced using the CFMask algorithm (Foga et al.,
 102 2017) to detect and mask clouds and shadows, followed by compositing cloud-free mosaics (Figure 2ab).
 103 In total, 4570 Landsat TM scenes were used for the 1990 period and 5493 OLI scenes for the 2020 period
 104 (Figure 2cd).

105 Glacial lake extents were delineated using an automated mapping algorithm based on hierarchical
 106 image segmentation and terrain analysis (Li and Sheng, 2012; Zhang et al., 2017). To reduce the influence
 107 of mountain shadows, pixels with slopes $>20^\circ$ or shaded relief values <0.25 were excluded (Zheng et al.,
 108 2021). Previous studies applied varying minimum area thresholds for glacial lake identification: 0.0054
 109 km^2 (Wang et al., 2020), 0.0081 km^2 (Chen et al., 2021), 0.0036 km^2 (Luo et al., 2020), and 0.01 km^2 (Li
 110 et al., 2020). Smaller thresholds can lead to greater uncertainties due to the limitations of pixel resolution
 111 (Salerno et al., 2012). To improve the accuracy of lake-terminating glacier identification, we adopted a
 112 minimum lake area threshold of 0.0036 km^2 (equivalent to at least four pixels), following Luo et al.
 113 (2020).

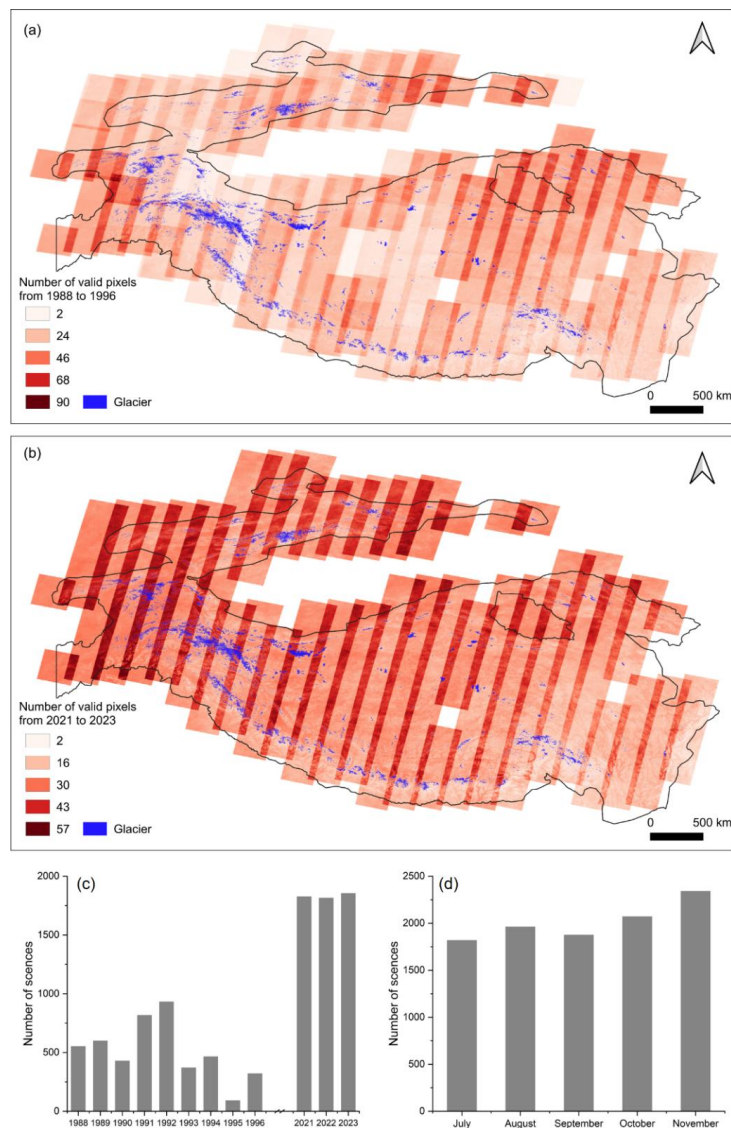


Figure 2: The number of usable pixels remaining in the study area after cloud removal during 1988–1996 (a) and 2021–2023 (b). Temporal distribution of the number of images used, by year (c) and by month (d).

3.2 Mapping of LTGs

In this study, LTGs are defined as glaciers that develop proglacial lakes along the direction of ice flow and are in direct contact with these lakes. The proglacial lake dataset was cross-referenced with the RGI 7.0 glacier inventory to identify LTGs. Results were refined through detailed visual inspection and manual correction using multi-source data, including Landsat and Planet Labs imagery, online maps (e.g.,



122 Google Earth, Esri basemap), and existing glacial lake datasets (Wang et al. 2020, Chen et al. 2021,
123 Zhang et al. 2023). The identification of glacier-lake contact followed a two-step procedure. (1)
124 Preliminary screening: A 500 m buffer was applied to assess spatial intersections between glacier
125 boundaries and proglacial lakes, identifying potentially connected glacier-lake pairs. (2) Manual
126 verification: Different criteria were applied for different periods. For the year 2020, multi-source
127 moderate-to-high resolution imagery (e.g., Planet Labs, Landsat, Google Earth, Esri basemaps) was used.
128 Glacier-lake contact was confirmed when proglacial lakes overlapped with glacier terminus and
129 exhibited diagnostic geomorphic features, such as terminal ice cliffs or transverse crevasses
130 perpendicular to the flow direction. Due to limited data availability and the relatively coarse spatial
131 resolution of Landsat imagery (30 m) in 1990, direct identification of LTGs for that year involved
132 considerable uncertainty, particularly for small glaciers, where boundary errors increase with decreasing
133 glacier area. To address this, a temporal cross-validation approach was employed. Glaciers with
134 ambiguous contact in 1990 were classified as interacting if satellite imagery from 1990 to 2022 showed
135 lake expansion toward the glacier terminus. Based on the temporal evolution of glacier-lake contact,
136 LTGs were categorized into three types (Table 1): (1) terminus persistent contacting with proglacial lake
137 (Type 1); (2) terminus experiencing transition from supraglacial lake to proglacial lake (Type 2); and (3)
138 terminus detaching from proglacial lake (Type 3).



139 **Table 1** The classification system of glaciers is based on the dynamic changes in glacier–lake contact. The
 140 **basemap is derived from Landsat imagery.**

Types	Characteristics			
Type 1	Persistent contact between glacier and lake from 1990 to 2022. Case location: 94.51053E, 30.63100N			
Type 2	Transition from supraglacial lake to proglacial lake from 1990 to 2022. Case location: 88.23816E, 27.81772N			
Type 3	Detachment of the proglacial lake from the parent glacier from 1990 to 2022. Case location: 85.84583E, 28.20793N			

142 3.3 Uncertainty estimates

143 When interpreting glacial lake and glacier boundaries using remote sensing data, errors are
 144 inevitable even when manual visual delineation is applied. These errors are typically associated with
 145 various factors related to image quality, such as spatial resolution, cloud cover, mountain shadows, and
 146 subjective interpretation biases. Previous studies have reported that the area error in delineating glacier
 147 or glacial lake boundaries from remote sensing imagery is approximately ± 0.5 pixels, depending on the
 148 quality of the imagery. The uncertainty (δ) and relative error (E_l) of glacial lake area was estimated using
 149 the equation (Hanshaw and Bookhagen, 2014):

$$150 \quad \delta = \frac{P}{G} \times \frac{G^2}{2} \times 0.6872 \quad (3)$$

$$151 \quad E_l = \frac{\delta}{A} \times 100\% \quad (4)$$

152 where P is the perimeter of the glacial lake, and A is the glacial lake area.

153 The uncertainty (λ) and relative error (E_g) in glacier area was estimated to using the equation
 154 (Bolch et al., 2010):

$$155 \quad \lambda = N \times \frac{G^2}{2} \quad (1)$$



$$E_g = \frac{\lambda}{S} \times 100\% \quad (2)$$

where N is the total count of pixels along the outline of ice coverage, G is the spatial resolution of the images used, and S is the glacier area.

3.4 Attributes of inventory data

In this inventory, 9 attribute fields (Table 2) were recorded for the LTG, including a unique identifier, type, associated mountain range, area, mapping uncertainty, location (longitude and latitude), RGI7 ID, and feature code. Similarly, the proglacial lake inventory contains 9 attribute fields (Table 3), including a unique identifier, associated mountain range, type, mapping uncertainty, location (longitude and latitude), feature code, and a flag indicating whether the lake has disappeared. Both LTG and proglacial lake datasets include data for two time periods: 1990 and 2022, with identical attributes for both periods. The unique identifier is an automatically generated sequential integer, while the feature code follows the formats GmmmmmmEnnnnnN (Feature_ID) for glaciers and GLmmmmmmEnnnnnN (Feature_ID) for lakes, where G denotes glacier, GL denotes glacier lake, m and n represent the longitude and latitude multiplied by 1000, respectively, and E and N indicate east longitude and north latitude. Identical LTGs and proglacial lakes share the same feature code (Feature_ID) to facilitate data linkage. Area and perimeter are calculated automatically from the feature geometry. The type of classification follows the criteria described in Section 3.2. Each feature's associated mountain range is determined by overlaying with mountain range boundaries, and mapping uncertainty is estimated according to Section 3.3.



184

185 **Table 2 Attributes of the glacier dataset**

Filed name	Type	Description
UID	Object ID	Unique code (Number)
Type	String	The classification of glaciers based on the relationship of interaction between glaciers and glacial lakes (Table 1)
Mountain	String	Mountain name where the glaciers is in
Area	Double	Area of glacier coverage(km ²)
Error	Double	Area uncertainty of glacier mapping(km ²)
Latitude	String	Latitude of the centroid of glacier
Longitude	String	Longitude of the centroid of glacier
rgi_id	String	RGI 7.0 id
Feature_ID	String	GmmmmmmEnnnnnN

186

187 **Table 3 Attributes of the proglacial lake dataset**

Filed name	Type	Description
UID	Object ID	Unique code (Number)
Type	String	The classification of glacial lakes based on the relationship of interaction between glaciers and glacial lakes (Table 1)
Mountain	String	Mountain name where the glacial lake is in
Area	Double	Area of glacial lake coverage (km ²)
Error	Double	Area uncertainty of glacial lake mapping (km ²)
Latitude	String	Latitude of the centroid of glacier
Longitude	String	Longitude of the centroid of glacier
Disappear	String	Whether the proglacial lake disappeared in 2022 (Y)
Feature_ID	String	GLmmmmmmEnnnnnN

188



4 Results

4.1 Spatial distribution of LTGs and proglacial lakes

Based on the changes in glacier-proglacial lake contact relationships from 1990 to 2022, glaciers were classified into three types (Table 1). Among them, Type 1 and Type 2 glaciers remained in contact with proglacial lakes from 1990 to 2022 and are therefore defined as LTGs. In contrast, Type 3 glaciers had become disconnected from proglacial lakes by 2022. Accordingly, only Type 1 and Type 2 glaciers were included when analyzing the distribution and extent of LTGs in 2022. In 2022, a total of 1740 LTGs were identified, with a combined area of $5082.08 \pm 13.15 \text{ km}^2$. Concurrently, 1768 proglacial lakes were detected, with a total area of $262.10 \pm 0.89 \text{ km}^2$. The discrepancy between glacier and lake counts stems from multi-lake associations per glacier and multi-glacier lakes were associated with two glaciers, and two lakes were in contact with three glaciers. The spatial distribution of LTGs in HMA shows marked heterogeneity (Figure 3). Predominantly concentrated along the southern margin, including the Himalayas, Nyainqentanglha, Gangdise Mountains, and Hindu Kush, these glaciers total 994, representing 57.13% of the study population (Figure 3b, Table A 1). The Central Himalaya hosts the highest number, with 232 glaciers (Table A 1), while the Nyainqentanglha accounts for the largest total glacier area ($1,001.05 \pm 3.32 \text{ km}^2$, Figure 3c). Glaciers were classified into nine size categories, ranging from $<0.05 \text{ km}^2$ to $>100 \text{ km}^2$ (Table A2). Among these, 1,095 glaciers (62.93%) are smaller than 1 km^2 , covering $399.05 \pm 1.07 \text{ km}^2$ (7.85% of the total area), while 93 glaciers (5.35%) exceed 10 km^2 , covering $2964.68 \pm 4.85 \text{ km}^2$ (58.34%). Only three glaciers exceed 100 km^2 , spanning $785.42 \pm 10.96 \text{ km}^2$. LTGs in HMA span elevations from 2,735 to 8,016 m, with a mean elevation of 5074 m (Figure 4). They are primarily concentrated between 5,000 and 6,000 m, where their combined area reaches $3030.2 \pm 5.72 \text{ km}^2$ (59.52% of the total glacier area). Regional variations in elevation distribution are evident (Figure 4). In the Central Himalaya, Eastern Himalaya, Gangdise Mountains, Tibetan Interior Mountains, and Western Kunlun Shan, glacier area peaks occur around 6000 meters.

Proglacial lakes in HMA are predominantly concentrated along the southern margin, with 1010 lakes (57.09%) in the Himalayas, Nyainqentanglha, Gangdise Mountains, and Hindu Kush (Table A 3). The Central Himalayas host the most lakes (240), with the largest total area ($86.91 \pm 0.54 \text{ km}^2$, Figure 3 e). Proglacial lakes were grouped into five size categories (<0.05 to $>1 \text{ km}^2$, Table A 4). Lakes smaller



217 than 0.1 km² are the most abundant, totaling 1384 (78.28%) and covering a combined area of 47.12 ±
 218 0.30 km². Proglacial lakes in HMA span elevations from 2684 to 6012 m, with most concentrated
 219 between 5000 and 5700 m, where 748 lakes (42.34%) cover 106.46 ± 0.59 km². Regional variations in
 220 elevation distribution are evident (Figure 5). Gangdise Mountains and Western Kunlun Shan, proglacial
 221 lake numbers and areas peak around 5700 m. Conversely, in the Hindu Kush, Nyainqentanglha, Tanggula
 222 Shan, and Western Kunlun Shan, peak lake areas occur at lower elevations than peak lake numbers
 223 (Figure 5).

224 Significant variations exist in the number and area distributions among glacier types in HMA. From
 225 1990 to 2022, Type 2 glaciers, those forming new proglacial lakes, were the most numerous (1073, Table
 226 A 1), dominating in all regions except Altun Shan/Eastern Kunlun Shan, Qilian Shan, and Tanggula Shan.
 227 Conversely, Type 1 glaciers have the largest total area (3454.59 ± 12.43 km²), concentrated primarily
 228 in the Himalayas, Nyainqentanglha, Central Tien Shan, Qilian Shan, Tanggula Shan, and Western Kunlun
 229 Shan (Table A 1). The Central Himalaya host the most glaciers across all types: 94 Type 1 (552.77 ± 2.71
 230 km²), 138 Type 2 (244.80 ± 1.56 km²), and 84 Type 3 (202.67 ± 1.11 km²). All glacier types show
 231 consistent area peaks between 5,000 and 6,000 m, with similar patterns across subregions (Figure 4). In
 232 2022, Type 2 proglacial lakes were the most numerous in HMA (1123, Table A3), dominating in number
 233 across all regions except Altun Shan/Eastern Kunlun Shan, Qilian Shan, Karakoram, and Western Kunlun
 234 Shan. Conversely, Type 1 lakes had the largest total area (207.18 ± 0.82 km²) and accounted for the
 235 largest share of total area in all regions except the Western Pamir, Hengduan Shan, Dzhungarsky Alatau,
 236 and Eastern Tibetan Mountains. The central Himalaya hosted the greatest abundance of all three lake
 237 types, with 91 Type 1 (76.89 ± 0.51 km²), 149 Type 2, and 80 Type 3 (15.70 ± 0.21 km²) lakes. The
 238 Eastern Himalaya had the largest Type 2 lake area (10.73 ± 0.03 km², Table A3). In HMA, the elevation
 239 distribution of proglacial lake types is generally consistent, with peak numbers between 5000 and 5700
 240 m and peak areas between 4700 and 5400 m (Figure 5). However, regional variations are observed in the
 241 elevation distribution of lake numbers for different lake types. Specifically, in the Nyainqentanglha
 242 region, Type 2 proglacial lakes exhibit a higher peak number range, between 5200 and 5400 m. Regarding
 243 area-elevation patterns, certain subregions display lower peak elevations, encompassing Type 2 lakes in



the Eastern Himalaya and Northern Tibetan Mountains, and Type 1 lakes in the Eastern Pamirs, Hindu Kush, Nyainqentanglha, and Tanggula Shan (Figure 4).

4.2 Temporal changes in LTGs and proglacial lakes

From 1990 to 2022, glacier size has been continuously shrinking (Figure 3d). The total area of all glacier types decreased by approximately $324.43 \pm 19.22 \text{ km}^2$, with Type 1 glaciers experiencing the largest absolute loss of $137.46 \pm 17.62 \text{ km}^2$, accounting for 42.37% of the total reduction (Table A 5). The Central Himalay showed the most pronounced absolute area loss, with a decrease of $74.46 \pm 3.46 \text{ km}^2$, while the Hengduan Shan exhibited the highest relative shrinkage at 16.42%. The Central Himalaya also recorded the largest absolute losses for all three glacier types, with reductions of $37.20 \pm 3.91 \text{ km}^2$ for Type 1, $20.13 \pm 2.26 \text{ km}^2$ for Type 2, and $17.13 \pm 1.62 \text{ km}^2$ for Type 3 glaciers. In contrast, the Hengduan Shan had the highest relative losses for all three types, at 25.34%, 13.95%, and 17.37%, respectively (Table A 5).

Small glaciers ($<0.5 \text{ km}^2$) exhibited a significant increase in number, particularly those smaller than 0.05 km^2 , which grew by 51 in count with a total area increase of $1.68 \pm 0.08 \text{ km}^2$ (Table A 6). In contrast, glaciers in the $0.5\text{--}50 \text{ km}^2$ range showed a declining trend in number. Among them, glaciers sized $0.5\text{--}1 \text{ km}^2$ experienced the largest numerical decrease (-57) and the greatest relative area loss (-13.56%), while those in the $1\text{--}5 \text{ km}^2$ range incurred the most substantial absolute area reduction, losing $97.17 \pm 3.5 \text{ km}^2$ (Table A 6).

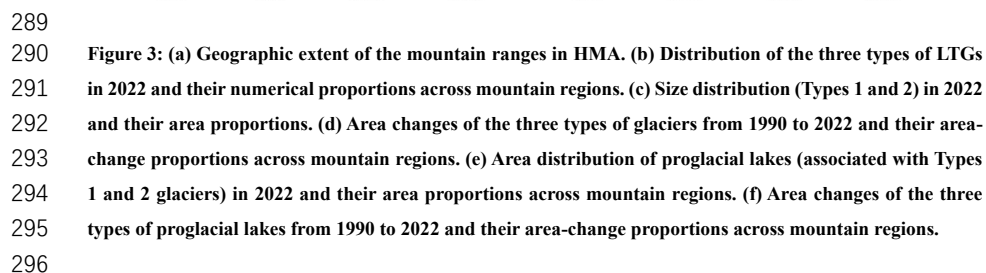
Among the different glacier types, Type 1 glaciers experienced the greatest absolute area loss, decreasing by $137.46 \pm 17.62 \text{ km}^2$ (Table A 5). However, their relative area reduction of 3.83% was the smallest among the three types. By size class (Table A 6), Type 1 glaciers showed the largest loss ($63.39 \pm 6.38 \text{ km}^2$) in the $10\text{--}50 \text{ km}^2$ range; Type 2 glaciers experienced the greatest reduction ($52.52 \pm 2.21 \text{ km}^2$) in the $1\text{--}5 \text{ km}^2$ range. Type 3 glaciers showed the most significant loss ($27.51 \pm 1.57 \text{ km}^2$) in the $5\text{--}10 \text{ km}^2$ range. For all three types, the $0.5\text{--}1 \text{ km}^2$ size class exhibited the highest relative area reduction, at 9.06%, 15.37%, and 15.15%, respectively.

Between 1990 and 2022, the total area of proglacial lakes increased by $138.19 \pm 1.18 \text{ km}^2$, representing a 62.09% expansion (Figure 3f and Table A2). The Central Himalaya experienced



272 the most significant absolute growth, with an increase of $42.32 \pm 0.72 \text{ km}^2$ (70.19%), while the
 273 Western Pamirs recorded the fastest relative growth, surging by 210.24%. The Central
 274 Himalaya also saw the largest area increases across all three glacier types, with growth of 30.42
 275 $\pm 0.64 \text{ km}^2$ for Type 1 lakes, $10.02 \pm 0.16 \text{ km}^2$ for Type 2, and $1.88 \pm 0.29 \text{ km}^2$ for Type 3.
 276 Regionally, the Dzhungarsky Alatau had the highest proportional increase in Type 1 lake area
 277 at 176.38%, whereas the Eastern Himalaya recorded the largest proportional growth for Type 3
 278 lakes at 29.48% (Table A7).

279 During the study period, 1123 new proglacial lakes formed, while 25 lakes disappeared.
 280 The number of small proglacial lakes ($<0.5 \text{ km}^2$) increased significantly, especially those
 281 smaller than 0.05 km^2 , which increased by 702 and accounted for 64.11% of the total increase
 282 in lake numbers (Table A 8). Lakes larger than 1 km^2 contributed the largest increase in area
 283 ($60.44 \pm 0.81 \text{ km}^2$), accounting for 43.74% of the total area growth. Moreover, lakes smaller
 284 than 0.05 km^2 had the highest proportional area growth at 114.49%. Type 1 proglacial lakes
 285 exhibited the most significant area growth, reaching $79.36 \pm 1.02 \text{ km}^2$, with a growth rate of
 286 62.09%. Among size categories, the number of Type 1 lakes increased most in the $0.05\text{--}0.1 \text{ km}$
 287 2 range, with 49 new lakes added, while lakes larger than 1 km^2 showed the greatest area
 288 increase at $52.07 \pm 0.79 \text{ km}^2$ and the highest proportional growth at 85.19%.



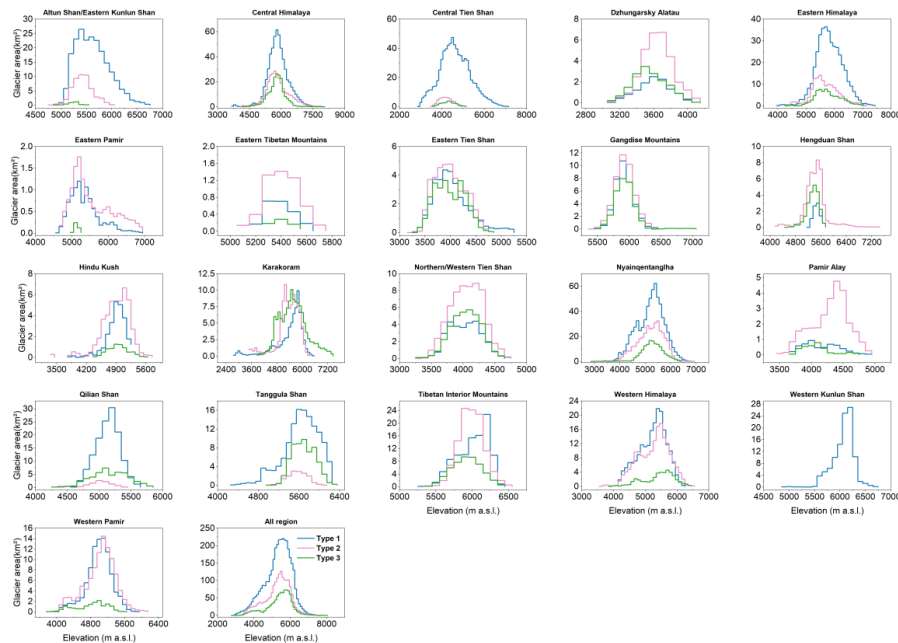


Figure 4: Area-Elevation distribution of LTGs across subregions, showing glacier area within 100 m elevation bins.

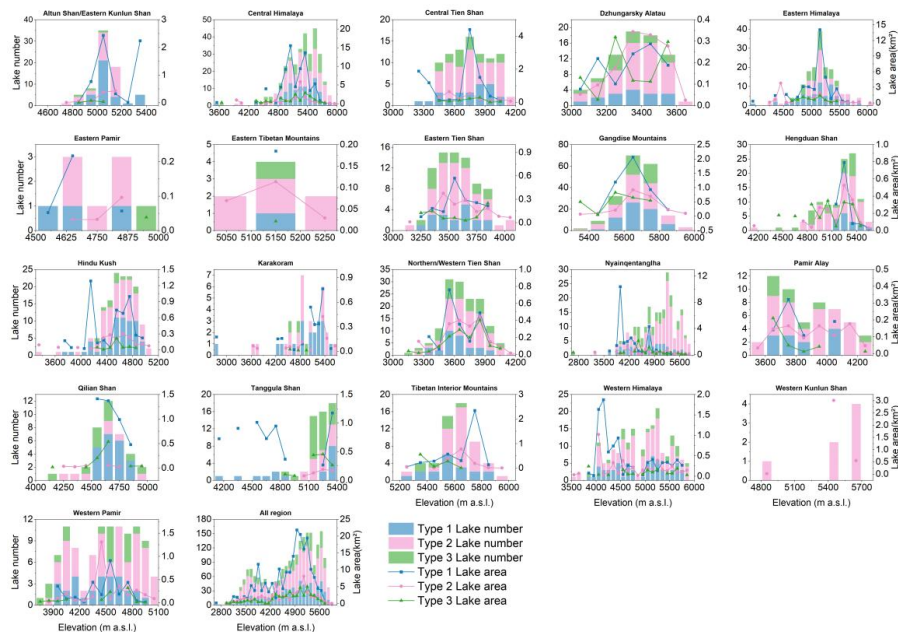


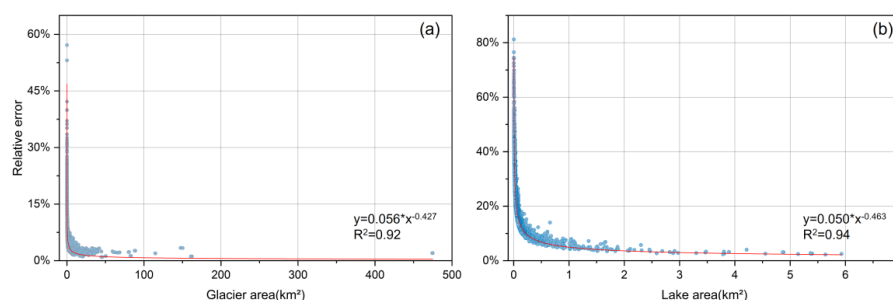
Figure 5 Distribution of proglacial lake numbers and areas across elevation ranges in each subregion. The number and area of proglacial lakes are presented within 100 m elevation bins for each subregion.



303 5 Discussion

304 5.1 Assessment of accuracy and errors

305 The uncertainty estimates indicate that as the glacier or lake area increases, the relative error of
 306 individual features decreases. In the study area, the total absolute area error for glaciers in 1990 and 2022
 307 were $\pm 13.65 \text{ km}^2$ and $\pm 13.53 \text{ km}^2$, respectively, with average relative errors of $\pm 7.24\%$ and $\pm 8.12\%$.
 308 The relative error of glacier area shows a significant power-law relationship with the glacier size ($y =$
 309 $0.056 \times x^{-0.427}$, $R^2 = 0.92$, Figure 6a). Additionally, the total absolute area error for proglacial lakes
 310 in 1990 and 2022 were $\pm 0.69 \text{ km}^2$ and $\pm 0.96 \text{ km}^2$, respectively, with average relative errors of $\pm 21.99\%$
 311 and $\pm 23.69\%$, following a similar significant power-law relationship ($y = 0.050 \times x^{-0.463}$, $R^2 = 0.94$,
 312 Figure 6b).



313
 314 **Figure 6: Estimation of relative errors for glaciers and proglacial lakes in the study area. (a) Glaciers (b)**
 315 **Proglacial lakes**

316 5.2 Comparison and limitations

317 Publicly available data on LTGs and their proglacial lakes in HMA remain scarce, with recent
 318 datasets primarily focusing on glacial lakes. Consequently, this study selected two glacial lake datasets
 319 that partially overlap in time with our research and include proglacial lakes for comparison (Table 4).
 320 The results indicate that, within the same study area, our data closely align with those of Zhang et al.
 321 (2023). In 1990, the overlap rate of proglacial lakes between the dataset of Zhang et al. (2023) and ours
 322 exceeded 90%, while in 2020/2022, the overlap rate was 79%. In contrast, significant discrepancies were
 323 observed with the dataset of Chen et al. (2021). For the period 2017/2022, the dataset of Chen et al. (2021)
 324 identified 7850 proglacial lakes, whereas our study identified only 1,768, with an overlap rate of 67.82%.
 325 Through examining these datasets, we attribute these differences to variations in the identification of
 326 glacier-proglacial lake contact. Our study employs strict classification criteria (see Section 3.2), which



327 are reflected in three key aspects: (1) the lake must be located at the forefront of the glacier's flow
328 direction; (2) a comprehensive evaluation of the glacier-lake contact surface based on the spatiotemporal
329 evolution of both lake and glacier surface morphology; and (3) exclusion of ambiguous cases to ensure
330 classification reliability. Additional factors, such as image quality, acquisition dates, and vectorization
331 workflows, may also contribute to the observed discrepancies.

332 A global inventory of LTGs was released in 2025 (Steiner et al., 2025). This dataset was derived
333 from the RGI7 glacier outlines, primarily using Landsat 5–7 TM/ETM+ imagery (ca. 1998–2002),
334 supplemented by ASTER data in some high-latitude regions. Existing regional proglacial lake inventories
335 (when close to 2000) were also incorporated, and the identification of LTGs was conducted through
336 manual interpretation and expert cross-validation. Based on the degree of glacier–lake contact, glaciers
337 were classified into four types. In HMA, a total of 1912 LTGs were identified. Although the glacier
338 termini in this dataset were delineated for 2000 ± 2 , the overlap with our 2022 dataset is 47.4%. Given
339 that our results indicate that glacier–lake contact is not always stable, differences in the timing of
340 terminus delineation are likely the primary source of the observed discrepancies.

341 Although this study employed standardized criteria for the qualitative identification of LTGs and
342 their proglacial lakes, subjective factors remain challenging to eliminate entirely during remote sensing
343 imagery analysis. Differences in how analysts interpret imagery, apply calibration standards, and process
344 data quality directly impact the results. While measures such as independent labeling and cross-validation
345 by multiple analysts can reduce subjective bias, uncertainties stemming from variations in individual
346 experience, judgment criteria, and image quality remain difficult to fully resolve. Consequently, further
347 quantification of identification criteria is of paramount importance. In the future, more refined technical
348 approaches can optimize the identification of glacier-lake contact lines, leveraging high-resolution
349 imagery and automated analysis tools to enhance accuracy. Additionally, quantifying the depth of glaciers
350 within lakes will provide more precise data support. These quantitative standards not only effectively
351 minimize human-induced variability but also significantly improve the precision of glacier-lake contact
352 relationship assessments, laying a more reliable data foundation for subsequent studies of glacier
353 dynamics.



Table 4: Comparisons of glacial lake mapping in this study with previous studies for the similar extended region.

Year (previous/this study)	Region	Area threshold (km ²)	Source	Count (Area/km ²) Previous studies	Count (Area/km ²) This study	Overlap count
1990/1990	Greater Himalaya	0.0036	(Zhang et al., 2023)	651(129.76±0.89)	645(122.08±0.59)	615(95.35%)
2020/2022				1115(192.42±1.23)	1029 (199.83±0.79)	841(79.11%)
2017/2022	HMA	0.0081	(Chen et al., 2021)	7850(684.62±10.06)	1768(262.03±0.89)	1199(67.82%)

6 Conclusions

Using Landsat imagery, we applied a semi-automated mapping approach in Google Earth Engine (GEE) to inventory proglacial lakes across High Mountain Asia (HMA) in the 1990s and 2020s, and compiled the first region-wide dataset of LTGs and their proglacial lakes. In 2022, HMA contained 1740 LTGs (5082.08 ± 13.15 km²), of which 667 glaciers (3454.59 ± 12.43 km²) maintained lake contact since 1990, and 1073 glaciers ($1,627.49 \pm 4.30$ km²) developed new proglacial lakes. These glaciers were mainly distributed between 2735 and 8016 m a.s.l. Additionally, 468 glaciers (960.13 ± 3.18 km²) lost lake contact during the period.

A total of 1768 proglacial lakes (262.10 ± 0.89 km²) were connected to glaciers in 2022, including 645 lakes (207.18 ± 0.82 km²) with continuous glacier contact and 1123 newly formed lakes (54.85 ± 0.35 km²). Lakes were mainly distributed between 2684 and 6012 m a.s.l. Meanwhile, 485 lakes (45.31 ± 0.34 km²) lost glacier contact, with 25 disappearing entirely. From 1990 to 2022, LTGs retreated by 324.43 ± 19.23 km² (−5.1%), while proglacial lake area increased by 138.19 ± 1.18 km² (+81.7%). The development and evolution of lake-terminating glacier–proglacial lake systems are predominantly concentrated along the southern margin of HMA, including the Hindu Kush, Himalayas, Nyainqentanglha, and Gangdise Mountains.

This dataset offers a robust basis for examining spatially heterogeneous glacier responses to climate change, coupled glacier–lake evolution, glacier hydrological modeling, glacial lake outburst flood (GLOF) assessment, and water resource management. Nevertheless, further improvements in data quality



376 remain necessary, particularly in quantifying glacier–lake contact line length, the degree of glacier–lake
377 contact (e.g., lake depth and subaqueous glacier front depth), and water temperature measurements.

378

379 **Financial support.** This work was funded by the National Key R&D Program of China (Grant No.
380 2024YFC3013400) and National Science Foundation of China (Grant No. 42361144874).

381

382 **Author contributions.** YL designed the study, developed the methodology, performed analysis, and
383 wrote the manuscript. QL provided funding, support and supervision. XL, YY and JY produced data and
384 performed analysis. All other authors discussed and drafted the formulation of the specifications of the
385 glacial lake inventory in this study. All authors contributed to the final form of the paper.

386 **Competing interests.** The authors declare that they have no conflict of interest.

387

388 **Code and data availability.** Data described in this manuscript can be accessed at Zenodo under
389 <https://doi.org/10.5281/zenodo.17369580> (Luo and Liu, 2025). The code for proglacial lake ident
390 -ification can be accessed via [https://code.earthengine.google.com/00573a1f3c8684d6f3e0722677f5](https://code.earthengine.google.com/00573a1f3c8684d6f3e0722677f54b64)
391 4b64.

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Appendix A



Table A 1 Glacier type statistics (number and area) across subregions

Region	Glacier number				Glacier area (km ²)			
					2020s			
	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total
Central Himalaya	94	138	84	316	589.97±2.81	264.93±1.64	219.8±1.17	1074.7±3.46
Western Himalaya	66	106	28	200	198.31±2.11	176.41±1.67	42.54±0.47	417.26±2.74
Eastern Himalaya	64	68	48	180	419.67±2.06	155.37±1.07	87.2±0.68	662.24±2.42
Gangdise Mountains	64	77	50	191	35.19±0.32	45.65±0.37	33.34±0.33	114.17±0.59
Hindu Kush	61	75	12	148	26.49±0.31	45.82±0.41	8.71±0.17	81.02±0.54
Nyainqentanghla	55	126	48	229	677.08±3.76	368.21±2.96	164.46±1.28	1209.75±4.95
Altun Shan/Eastern Kunlun Shan	32	30	3	65	197.95±0.85	62.54±0.42	4.09±0.09	264.59±0.95
Northern Western Tien Shan	32	73	40	145	31.78±0.37	63.81±0.53	37.44±0.35	133.03±0.74
Western Pamir	30	59	17	106	93.74±0.95	99.99±0.84	16.58±0.29	210.3±1.09
Central Tien Shan	25	49	17	91	733.67±10.9	53.48±0.64	29.86±0.6	817.01±10.94
Qilian Shan	21	7	10	38	119.22±0.92	11.38±0.19	59.35±0.54	189.95±1.08
Eastern Tien Shan	18	46	18	82	33.23±0.54	39.06±0.38	29.91±0.54	102.2±0.85
Karakoram	18	18	6	42	66.51±0.78	102.94±0.99	128.82±2.25	298.24±2.58
Tanggula Shan	17	17	27	61	130.26±0.94	14.97±0.24	62.7±0.54	207.93±1.11
Tibetan Interior Mountains	17	34	9	60	96.32±0.72	112.16±0.74	53.53±0.49	262.02±1.14
Dzhungarsky Alatau	16	45	14	75	12.85±0.2	32.15±0.31	17.71±0.26	62.71±0.45
Hengduan Shan	16	65	27	108	10.75±0.18	49.63±0.5	27.82±0.31	88.2±0.61
Pamir Alay	11	29	8	48	5.79±0.12	27.8±0.38	3.42±0.11	37±0.42
Western Kunlun Shan	7	0	0	7	104.03±1.08	0	0	104.03±1.08
Eastern Pamir	2	5	1	8	6.89±0.22	14.14±0.28	0.39±0.03	21.43±0.35
Eastern Tibetan Mountains	1	6	1	8	2.35±0.08	5.75±0.14	0.76±0.05	8.86±0.16
Total	667	1073	468	2208	3592.05±12.49	1746.17±4.43	1028.43±3.28	6366.64±13.65



Table A 2 Area and number distribution of three glacier types across different size classes

Glacier size (km ²)	Glacier number (1990s)						Glacier number (2022s)						Glacier area (km ²) (1990s)						Glacier area (km ²) (2022s)					
	Type 1		Type 2		Type 3		Type 1		Type 2		Type 3		Type 1		Type 2		Type 3		Type 1		Type 2		Type 3	
	Total		Total		Total		Total		Total		Total		Total		Total		Total		Total		Total		Total	
<0.05	8	9	21	20	33	19	72	0.31±0.03	0.33±0.03	0.15±0.02	0.78±0.04	0.72±0.04	1.05±0.05	0.69±0.04	2.46±0.07				0.72±0.04	1.05±0.05	0.69±0.04			
0.05-0.1	28	43	97	37	72	28	137	2.22±0.07	3.24±0.08	1.86±0.06	7.32±0.12	2.72±0.08	5.36±0.11	2.07±0.06	10.15±0.15				2.72±0.08	5.36±0.11	2.07±0.06			
0.1-0.5	166	437	739	168	442	151	761	44.18±0.34	118.86±0.54	39.44±0.31	202.48±0.71	45.06±0.34	118.54±0.54	43.13±0.33	206.73±0.72				45.06±0.34	118.54±0.54	43.13±0.33			
0.5-1	126	239	466	118	205	86	409	92.8±0.53	166.86±0.72	71.75±0.47	331.41±1.01	84.4±0.52	141.21±0.66	60.88±0.44	286.49±0.94				84.4±0.52	141.21±0.66	60.88±0.44			
1-5	197	277	628	188	256	141	585	478.95±1.49	563.75±1.61	343.68±1.24	1386.38±2.52	459.59±1.47	515.28±1.55	318.5±1.18	1289.21±2.44				459.59±1.47	515.28±1.55	318.5±1.18			
5-10	71	43	144	67	41	26	134	498.24±1.92	303.8±1.57	207.84±1.19	1009.87±2.75	455.09±1.82	287.6±1.51	180.33±1.09	927.97±2.56				455.09±1.82	287.6±1.51	180.33±1.09			
10-50	63	23	16	102	61	22	99	1347.15±4.57	432.18±2.45	248.78±1.6	2028.11±5.43	1268.56±4.37	432.17±2.49	240.09±1.54	1931.43±5.26				1268.56±4.37	432.17±2.49	240.09±1.54			
50-100	5	2	7	5	2	0	7	343.42±2.96	157.16±2.78	0	500.58±4.06	332.14±2.97	155.79±2.76	0	487.93±4.05				332.14±2.97	155.79±2.76	0			
>100	3	0	1	4	3	0	4	784.78±10.96	0	114.93±2.23	899.7±11.18	785.42±10.96	0	114.44±2.22	899.86±11.18				785.42±10.96	0	114.44±2.22			
Total	667	1073	2208	667	1073	468	2208	3592.05±12.49	1746.17±4.43	1028.43±3.28	6366.64±13.65	3454.59±12.43	1627.49±4.3	960.13±3.18	6042.24±13.53				3454.59±12.43	1627.49±4.3	960.13±3.18			



Table A.3 Glacial lake type statistics (number and area) across subregions

Region	Lake number (1990s)						Lake number (2022s)						Lake area (km ²) (1990s)						Lake area (km ²) (2022s)					
	Type 1			Type 2			Type 3			Total			Type 1			Type 2			Type 3			Total		
	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total
Central Himalaya	91	0	86	177	91	149	80	320	46.7±0.38	0	13.8±0.2	60	29±0.43	76.89±0.51	10.02±0.16	15.7±0.21								102.62±0.58
Western Himalaya	65	0	28	93	65	107	27	199	4.17±0.11	0	1.2±0.05	5.38±0.12	9.02±0.15	4.13±0.09	1.51±0.06									14.66±0.19
Eastern Himalaya	57	0	50	107	56	75	49	180	23.92±0.26	0	5.05±0.11	28.98±0.29	36.75±0.36	10.89±0.18	6.55±0.13									54.19±0.42
Gangdise Mountains	65	0	51	116	65	79	51	195	3.72±0.1	0	3.19±0.08	6.91±0.13	4.49±0.1	2.32±0.07	2.67±0.07									9.48±0.14
Hindu Kush	60	0	12	72	61	75	12	148	2.97±0.08	0	0.61±0.04	3.58±0.09	4.83±0.11	1.81±0.06	0.49±0.04									7.13±0.12
Nyainqentanglha	52	0	51	103	52	135	49	236	12.53±0.18	0	5.78±0.13	18.31±0.22	28.57±0.3	8.16±0.14	7.52±0.14									44.25±0.36
Altun Shan/Eastern Kunlun Shan	33	0	3	36	32	38	3	73	4.83±0.14	0	0.17±0.02	5±0.14	5.68±0.14	1.06±0.05	0.11±0.02									6.85±0.15
Northern/Western Tien Shan	32	0	41	73	31	75	39	145	1.15±0.05	0	1.44±0.05	2.6±0.07	2.3±0.07	1.97±0.06	1.51±0.06									5.77±0.11
Western Pamir	28	0	19	47	28	60	19	107	1.27±0.05	0	0.91±0.04	2.17±0.07	2.81±0.08	3.04±0.08	0.89±0.04									6.74±0.12
Central Tien Shan	26	0	17	43	25	49	16	90	10.78±0.17	0	0.71±0.04	11.49±0.18	10.37±0.21	1.81±0.06	0.81±0.04									13±0.22
Qilian Shan	20	0	11	31	20	8	11	39	2.81±0.07	0	0.95±0.04	3.76±0.09	4.24±0.1	0.26±0.02	0.88±0.04									5.37±0.11
Eastern Tien Shan	17	0	20	37	17	47	16	80	0.76±0.04	0	0.73±0.04	1.49±0.05	1.72±0.06	1.56±0.05	0.8±0.04									4.08±0.09
Kankoran	19	0	5	24	19	17	3	39	1.69±0.07	0	0.32±0.03	2.02±0.07	2.64±0.08	0.98±0.04	0.05±0.01									3.66±0.09
Tanggula Shan	17	0	28	45	17	17	26	60	3.1±0.08	0	2.28±0.09	5.38±0.12	6.15±0.12	0.57±0.03	1.35±0.05									8.07±0.14
Tibetan Interior Mountains	14	0	9	23	14	35	7	56	2.56±0.11	0	0.94±0.05	3.5±0.12	3.58±0.14	1.75±0.06	0.91±0.04									6.23±0.16
Dzhungarsky Alatau	14	0	16	30	14	48	15	77	0.37±0.03	0	1.17±0.05	1.54±0.06	1.03±0.05	1.38±0.05	1.25±0.05									3.66±0.09
Hengduan Shan	15	0	28	43	15	66	27	108	0.71±0.04	0	1.63±0.06	2.35±0.07	1.26±0.06	1.84±0.06	1.91±0.07									5.01±0.11
Pamir Alay	12	0	8	20	12	32	8	52	0.5±0.03	0	0.34±0.02	0.84±0.02	0.77±0.04	0.94±0.04	0.33±0.02									2.03±0.05
Western Kunlun Shan	7	0	0	7	7	0	0	7	3.17±0.08	0	0	3.17±0.08	3.59±0.09	0	0									3.59±0.09
Eastern Pamir	3	0	1	4	3	5	1	9	0.22±0.03	0	0.05±0.01	0.26±0.03	0.33±0.02	0.16±0.02	0.04±0.01									0.53±0.03
Eastern Tibetan Mountains	1	0	1	2	1	6	1	8	0.1±0.01	0	0.04±0.01	0.14±0.02	0.19±0.02	0.21±0.02	0.02±0.01									0.42±0.03
Total	648	0	485	1133	645	1123	460	2228	127.82±0.61	0	41.33±0.32	169.15±0.69	207.18±0.82	54.85±0.35	45.31±0.34									307.34±0.96



Table A 4 Area and number distribution of three lake types across different size classes

Glacier size (km ²)	Lake number						Lake area (km ²)									
	1990s			2022s			1990s			2022s						
	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total				
<0.05	338	0	289	627	197	887	245	1329	7.62±0.12	0	7.5±0.12	15.12±0.16	5.71±0.11	20.58±0.19	6.13±0.11	32.42±0.25
0.05-0.1	96	0	93	189	145	155	92	392	6.58±0.12	0	6.45±0.12	13.03±0.17	10.02±0.15	10.81±0.15	6.56±0.12	27.39±0.24
0.1-0.5	157	0	90	247	204	72	111	387	32.46±0.28	0	17.77±0.21	50.24±0.34	47.07±0.35	13.19±0.17	23.25±0.24	83.51±0.46
0.5-1	30	0	12	42	47	6	9	62	20.03±0.25	0	8.44±0.17	28.47±0.3	31.18±0.32	4.43±0.14	5.67±0.13	41.28±0.37
>1	27	0	1	28	52	3	3	58	61.12±0.45	0	1.17±0.06	62.29±0.45	113.19±0.65	5.84±0.12	3.7±0.12	122.73±0.67
Total	648	0	485	1133	645	1123	460	2228	127.82±0.61	0	41.33±0.32	169.15±0.69	207.18±0.82	54.85±0.35	45.31±0.34	307.34±0.96



Table A 5 Area changes of different glacier types in each subregion (1990–2022)

Region	Area loss(km²)			Area loss(%)				
	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total
Central Himalaya	37.2±3.91	20.13±2.26	17.13±1.62	74.46±4.8	6.31	7.6	7.79	6.93
Western Himalaya	5.81±2.97	9.17±2.34	2.26±0.65	17.24±3.84	2.93	5.2	5.31	4.13
Eastern Himalaya	26.74±2.85	18.41±1.45	8.55±0.93	53.7±3.33	6.37	11.85	9.8	8.11
Gangdise Mountains	3.39±0.44	5.54±0.5	3.8±0.46	12.73±0.81	9.65	12.14	11.41	11.16
Hindu Kush	2.91±0.43	4.48±0.56	0.88±0.23	8.27±0.74	10.98	9.78	10.13	10.21
Nyainqentanglha	26.54±5.29	17.7±4.15	9.72±1.77	53.96±6.95	3.92	4.81	5.91	4.46
Altun Shan/Eastern Kunlun Shan	3.87±1.19	2.57±0.59	0.14±0.13	6.58±1.33	1.95	4.1	3.38	2.48
Northern/Western Tien Shan	2.99±0.51	5.42±0.74	3.99±0.49	12.4±1.02	9.42	8.49	10.66	9.32
Western Pamir	3.79±1.33	5.95±1.16	1.24±0.4	10.98±1.81	4.04	5.95	7.51	5.22
Central Tien Shan	3.84±15.42	4.38±0.88	2.08±0.83	10.3±15.47	0.52	8.19	6.97	1.26
Qilian Shan	2.62±1.28	1.07±0.27	1.7±0.75	5.39±1.51	2.2	9.4	2.86	2.84
Eastern Tien Shan	2.74±0.75	3.74±0.52	2.45±0.75	8.93±1.18	8.25	9.58	8.18	8.74
Karakoram	1.41±1.09	2.29±1.39	0.72±3.18	4.42±3.64	2.12	2.22	0.56	1.48
Tanggula Shan	5.94±1.31	1.22±0.33	4.07±0.75	11.23±1.55	4.56	8.18	6.49	5.4
Tibetan Interior Mountains	1.01±1.02	2.69±1.04	1.92±0.68	5.62±1.61	1.04	2.4	3.58	2.14
Dzhungarsky Alatau	2.07±0.26	3.66±0.43	2.3±0.36	8.03±0.62	16.1	11.38	12.99	12.8
Hengduan Shan	2.73±0.24	6.92±0.69	4.83±0.41	14.48±0.84	25.34	13.95	17.37	16.42
Pamir Alay	0.67±0.17	2.06±0.53	0.37±0.15	3.1±0.58	11.55	7.4	10.75	8.36
Western Kunlun Shan	0.89±1.53	0	0	0.89±1.53	0.86	0	0	0.86
Eastern Pamir	0.08±0.3	0.36±0.39	0.02±0.04	0.46±0.49	1.1	2.57	5.37	2.15
Eastern Tibetan Mountains	0.23±0.11	0.92±0.19	0.12±0.06	1.27±0.23	9.81	15.94	16.33	14.35
Total	137.46±17.62	118.68±6.18	68.29±4.58	324.43±19.23	3.83	6.8	6.64	5.1

Table A 6 Area and number changes of three glacier types across different size classes

Glacier size	Number change(count)				Area change(km²)				Area change(%)			
	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total
<0.05	12	24	15	51	0.41±0.05	0.73±0.05	0.54±0.04	1.68±0.08	133.95	224.58	367.1	215.87
0.05-0.1	9	29	2	40	0.58±0.1	2.04±0.13	0.21±0.09	2.83±0.19	26.17	62.92	11.3	38.68
0.1-0.5	2	5	15	22	1.67±0.48	-1.11±0.77	3.68±0.46	4.25±1.02	3.78	-0.93	9.33	2.1
0.5-1	-8	-34	-15	-57	-8.41±0.74	-25.65±0.97	-10.87±0.64	-44.93±1.38	-9.06	-15.37	-15.15	-13.56
1-5	-9	-21	-13	-43	-19.48±2.11	-52.52±2.21	-25.17±1.71	-97.17±3.5	-4.07	-9.32	-7.32	-7.01
5-10	-4	-2	-4	-10	-38.2±2.62	-16.19±2.18	-27.51±1.57	-81.9±3.75	-7.67	-5.33	-13.24	-8.11
10-50	-2	-1	0	-3	-63.39±6.38	-24.61±3.4	-8.69±2.22	-96.69±7.56	-4.71	-5.69	-3.49	-4.77
50-100	0	0	0	0	-11.28±4.19	-1.37±3.92	0	-12.65±5.74	-3.28	-0.87		-2.53
>100	0	0	0	0	0.64±15.5	0	-0.48±3.15	0.16±15.82	0.08		-0.42	0.02
Total	0	0	0	0	-137.46±17.62	-118.67±6.17	-68.29±4.57	-324.42±27.18	-3.83	-6.8	-6.64	-5.1



Table A 7 Area changes of different glacial lake types in each subregion (1990–2022)

Region	Area change (km ²)				Area change (%)		
	Type 1	Type 2	Type 3	Total	Type 1	Type 3	Total
Central Himalaya	30.42±0.64	10.02±0.16	1.88±0.29	42.32±0.72	65.46	13.6	70.19
Western Himalaya	4.84±0.19	4.13±0.09	0.31±0.07	9.28±0.22	115.95	25.8	172.62
Eastern Himalaya	12.83±0.45	10.89±0.18	1.49±0.17	25.22±0.51	53.63	29.49	87.04
Gangdise Mountains	0.77±0.14	2.32±0.07	-0.52±0.11	2.57±0.19	20.7	-16.32	37.21
Hindu Kush	1.86±0.13	1.81±0.06	-0.11±0.05	3.55±0.15	62.57	-18.1	99.15
Nyainqentanglha	16.04±0.35	8.16±0.14	1.74±0.19	25.95±0.42	128.03	30.11	141.75
Altun Shan/Eastern Kunlun Shan	0.85±0.2	1.06±0.05	-0.05±0.02	1.86±0.21	17.59	-30.3	37.21
Northern/Western Tien Shan	1.14±0.09	1.97±0.06	0.07±0.08	3.17±0.13	98.76	4.86	122.14
Western Pamir	1.54±0.09	3.04±0.08	-0.02±0.06	4.57±0.14	121.66	-2.2	210.24
Central Tien Shan	-0.41±0.27	1.81±0.06	0.11±0.06	1.51±0.28	-3.8	15.59	13.14
Qilian Shan	1.43±0.12	0.26±0.02	-0.07±0.06	1.61±0.14	50.93	-7.34	42.8
Eastern Tien Shan	0.96±0.08	1.56±0.05	0.07±0.06	2.59±0.11	126.23	9.62	174
Karakoram	0.94±0.11	0.98±0.04	-0.28±0.03	1.64±0.12	55.52	-86.41	81.3
Tanggula Shan	3.04±0.14	0.57±0.03	-0.93±0.1	2.69±0.18	98.01	-40.83	50
Tibetan Interior Mountains	1.02±0.18	1.75±0.06	-0.03±0.07	2.73±0.2	39.92	-3.18	78.03
Dzhungarsky Alatau	0.66±0.06	1.38±0.05	0.08±0.07	2.12±0.1	176.38	6.85	137.53
Hengduan Shan	0.55±0.07	1.84±0.06	0.28±0.09	2.66±0.13	76.97	17.13	113.23
Pamir Alay	0.27±0.05	0.94±0.04	-0.02±0.03	1.19±0.07	54.26	-5.82	141.49
Western Kunlun Shan	0.42±0.12	0	0	0.42±0.12	13.26		13.26
Eastern Pamir	0.11±0.04	0.16±0.02	-0.01±0.01	0.26±0.04	50.87	-20.66	98.25
Eastern Tibetan Mountains	0.08±0.02	0.21±0.02	-0.01±0.01	0.28±0.04	77.14	-27.51	199.92
Total	79.36±1.02	54.85±0.35	3.98±0.47	138.19±1.18	62.09	9.63	81.7

Table A 8 Area and number changes of proglacial lakes of three glacier types across different size classes

Glacier size (km ²)	Number change				Area change(km ²)				Area change(%)		
	Type 1	Type 2	Type 3	Total	Type 1	Type 2	Type 3	Total	Type 1	Type 3	Total
<0.05	-141	887	-44	702	-1.91±0.16	20.58±0.19	-1.36±0.16	17.31±0.3	-25.07	-18.14	114.49
0.05-0.1	49	155	-1	203	3.44±0.19	10.81±0.15	0.11±0.17	14.36±0.29	52.27	1.71	110.23
0.1-0.5	47	72	21	140	14.61±0.44	13.19±0.17	5.47±0.32	33.27±0.57	45	30.77	66.22
0.5-1	17	6	-3	20	11.15±0.4	4.43±0.14	-2.76±0.21	12.82±0.48	55.66	-32.72	45.04
>1	25	3	2	30	52.07±0.79	5.84±0.12	2.53±0.13	60.44±0.81	85.19	215.49	97.02
Total	-3	1123	-25	1095	79.36±1.02	54.85±0.35	3.98±0.46	138.19±1.18	62.09	9.63	81.7



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