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Dataset of Maximum Extent and Type of Glacial Lake in the Asia (1980s–2019)

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Abstract: Based on the JRC Global Surface Water (GSW) dataset, combined with visual interpretation and quality control, the authors carried out a spatial cataloging of the Asian glacial lakes (≥ 0.01 km^2) formed and developed during the period 1980s–2019, with a total absolute area error of 98.91 km^2, with the mean relative error is 19.1%. According to the relationship between glacial lakes and glaciers, glacial lakes can be divided into glacier-fed lakes (including Supraglacial Lake, Ice-contacted Lake and Ice-uncontacted Lake) and non-glacier-fed lakes, 2 types. Meanwhile, the spatial distribution characteristics of different types of glacial lakes were analyzed, and finally the Dataset of maximum extent and type of glacial lake in Asia (1980s–2019) was developed. The dataset includes: (1) spatial data, the maximum extent and types of glacial lakes in Asia during1980s–2019; (2) table data, including the statistics of the number and area of glacial lakes at different size, type and elevation scales in the Asia during 1980s–2019. The dataset is archived in .shp and .kmz data formats, and consists of 9 data files with data size of 21.8 MB (Compressed to one single file with 4.92 MB).

Keywords: GSW; Asia; Glacial Lake; type; remote sensing

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Dataset Availability Statement:

The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at: https://doi.org/10.3974/geodb. 2021.11.02.V1 or https://cstr.escience.org.cn/CSTR:20146.11.2021.11.02.V1.

1 Introduction

Global warming is especially evident in high elevation areas, where glaciers are shrinking or thinning rapidly[1–3]. Continuous glacial ablation and meltwater replenishment promote the circulation of surface water and increase the abundance of glacial lakes[4]. Glacial lakes

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[2] Ma, J. S., Song, C. Q., Wang, Y. J., *et al*. Classification dataset of Asia glacial lakes and their maximum areas (1980s–2019) [J/DB/OL]. *Digital Journal of Global Change Data Repository*, 2021. https://doi.org/10.3974/geodb.2021.11.02.V1. https://cstr.escience.org.cn/CSTR:20146.11.2021.11.02.V1.

retain huge amounts of glacial melt water and play an important role in maintaining freshwater resources in high mountain regions[5]. Second, in view of the expansion and instability of glacial lakes around the world, their accidental outbreak will cause catastrophic floods, which will seriously threaten the safety of downstream residents, infrastructure, and regional ecological environment[6]. Therefore, real-time and all-round survey of glacial lakes must be conducted.

In view of the rapid development of remote sensing technology, various high-resolution satellites and sensors have shown excellent potential in the identification, extraction, and monitoring of glacial lakes[7]. The optical image sequences for nearly 50 years provided by the US Landsat Program have become the main data source for monitoring the dynamics of glacial lakes. Based on remote sensing data, several studies have conducted remote sensing surveys on the spatial distribution characteristics of glacial lakes in high mountain regions in Asia, such as TianShan[8], Himalayas[9], TanggulaShan[10], etc. Such studies provided an effective way to reveal the temporal and spatial change characteristics of glacial lakes, understand the response of glacial lakes to climate change, and obtain the data source for subsequent glacial lake water volume estimation and flash flood research.

At present, the studies on Asian glacial lakes indicate that given local or regional characteristics, different glacial lake inventories have different prior knowledge (definition, identification criteria, and classification of glacial lakes), and a limited number of research have been performed to carry out the spatial cataloging of glacial lakes on a large regional scale in accordance with consistent temporal and spatial reference standards. New and detailed spatial data of glacial lakes are needed to deepen the understanding of the impact of Asian glacial lakes on the mountain environment and their response to climate changes. To this end, this paper used remote sensing products to catalog the maximum flooded extent layer (max_extent) glacial lakes in the entire Asia in accordance with the same standard and further analyzed the spatial heterogeneity of glacial lakes to compensate for the deficiency of existing glacial lake data.

2 Metadata of the Dataset

Table 1 provides the name, author, geographical region, data year, temporal resolution, spatial resolution, data format, data size, data publishing and sharing service platform, data sharing policy, and other relevant information of the Dataset of maximum extent and type of glacial lake in the Asia (1980s–2019)[11].

3 Data Research and Development Methods

3.1 Data Source

Based on the JRC Global Surface Water (GSW) dataset[13], this paper completed the spatial cataloging of the Asian max_extent glacial lakes. As a sub-product of Landsat data, GSW has been widely used in various water change studies. Based on nearly 4 million Landsat images from 1984 to 2019, Pekel's team adopted the expert system classification method to separately classify each pixel in the image into water and non-water bodies, sorted the results into data for the entire period and monthly and annual data, and synthesized them into GSW data. The dataset had a spatial resolution of 30 m, contained seven wavebands (see Table 2 for details of each waveband), and was stored on the GEE (Google Earth Engine)[1] cloud platform for open use by users worldwide. This paper used the max_extent in the dataset to obtain the boundary of glacial lakes.

[1] https://code.earthengine.google.com/.

Table 1 Metadata summary of the Classification dataset of Asia glacial lakes and their maximum areas (1980s–2019)

Items	Description
Dataset full name	Classification dataset of Asia glacial lakes and their maximum areas (1980s–2019)
Dataset short name	GlacialLakeAsia_1980s-2019
Authors	Ma, J. S., Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences; School of Geographical Sciences, Nanjing University of Information Science and Technology, 20191210011@nuist.edu.cn Song, C. Q., Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, cqsong@niglas.ac.cn Wang, Y. J., School of Geographical Sciences, Nanjing University of Information Science and Technology, yjwang78@163.com Zhang, D. P., Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences; School of Surveying and Land Information Engineering, Henan Polytechnic University, zdp_1994@163.com
Geographical region	Asia
Year	1980s–2019
Temporal resolution	Decade
Spatial resolution	30 m
Data format	.shp, .xlsx
Data size	4.92 MB (After compression)
Data files	Spatial data: spatial distribution of maximum area of glacial lakes in Asia during 1980s–2019 Table data: Statistics of the number and area of glacial lakes at different size, type and elevation scales in the Asia during 1980s–2019
Foundations	Chinese Academy of Sciences (XDA23100102); Ministry of Science and Technology of P. R. China (2019YFA0607101)
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	***Data*** from the Global Change Research Data Publishing & Repository includes metadata, datasets (in the *Digital Journal of Global Change Data Repository*), and publications (in the *Journal of Global Change Data & Discovery*). ***Data*** sharing policy includes: (1) ***Data*** are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new datasets, the 'ten per cent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[12]
Communication and searchable system	DOI, CSTR, Crossref, DCI, CSCD, CNKI, SciEngine, WDS/ISC, GEOSS

Table 2 GSW data waveband

Waveband	Introduction
occurrence	The frequency with which water was present
change_abs	Absolute change in occurrence between two epochs: 1984–1999 vs. 2000–2019
change_norm	Normalized change in occurrence: (epoch1–epoch2)/(epoch1+epoch2)×100
seasonality	Number of months water is present
recurrence	The frequency with which water returns from year to year
transition	Categorical classification of change between first and last year
max_extent	Binary image containing 1 anywhere water has ever been detected

In addition, the Shuttle Radar Topography Mission (SRTM v3) digital elevation data jointly provided by the National Aeronautics and Space Administration and the National Imagery and Mapping Agency has a spatial resolution of up to 1 arc-second[2] and can accurately extract the elevation of a glacial lake (the elevation of the centroid point of a

[2] http://gdex.cr.usgs.gov/gdex/.

glacial lake); RGI 6.0 global glacier contour data[3] covers all modern glaciers and provides detailed glacier attributes to determine the buffer range of the glacial lake data distribution.

3.2 Research Method

3.2.1 Cataloging Method of the Max_extent Glacial Lake

At present, the extraction methods of the glacial lake boundary mainly include computer automatic extraction and manual visual interpretation. The computer automatic extraction method has the advantages of fast interpretation speed and independence of subjective factors; the visual interpretation method has high precision, is easy to implement, and is widely used in the glacial lake cataloging studies in various regions[14,15]. The public release of GSW data facilitates the extraction of glacial lake water range, but the dataset depicts all different types of surface water bodies, such as rivers, tidal flats, lakes, and reservoirs. Manual inspection can effectively eliminate the noise of non-glacial lakes and improve the accuracy of the glacial lake inventory.

Vast numbers of studies have been conducted on glacial lakes, but no consensus has been reached on the definition or specific identification rules of glacial lakes. The multiple definitions of glacial lakes are based on different viewpoints. Yao *et al*.[16] defined glacial lakes as natural water bodies with modern glacier melt water as the main source of replenishment or formed by the accumulation of water in glacial drift depressions. Although this concept has been recognized by numerous researchers, it still unable cannot accurately identify glacial lakes in the glacial lake cataloging process when combined with the characteristics of the GSW dataset. The studies of predecessors on glacial lakes often combined the research purpose and geographical conditions of the research region and established several thresholds to distinguish glacial lakes from other natural or artificial lakes. Other research emphasized the relationship between glacial lakes and glaciers and assumed that glacial lakes were natural water bodies produced by glacier movement since the last glacial maxima period; they set buffer zones (3, 5, or 10 km) from the terminus of modern glaciers as the glacial recession distance since the glacial maxima period and regarded the lakes within this range as glacial lakes[17–19]. In addition, several studies set elevation thresholds and other parameters to define glacial lakes[20]. The extraction method of glacial lakes by elevation thresholds is not universal (the elevations of different glacier regions vary significantly), and the method of establishing buffer zones is still the current mainstream method of extracting or assisting in identifying glacial lakes.

Based on the visual experience of Asian glaciers and surrounding lakes, screening waters in the buffer zone 3 km from the terminus of the glacier is relatively reasonable. In addition, we carried out further manual quality control of the lakes around the buffer zone: deleting the misidentified glacial lakes (mainly certain tectonic lakes) and supplementing the omitted glacial lakes. In addition, the glacial lake inventory in the research aims to provide basic data for climate-glacier-glacial lake interaction, freshwater resource management, and glacial lake burst disaster studies (when a glacial lake bursts, the glacial lake with an area of more than 0.01 km^2 will pose a serious threat to the downstream basin[6]); thus, glacial lakes are defined as a natural lake formed by glacier action within 3 km from the terminus of modern glaciers and with an area $\geq$ 0.01 km^2. To ensure the accuracy of glacial lake cataloging data, we superimposed high-resolution Google image-aided manual identification, and all glacial lakes in the area were carefully identified by professionals. This process is extremely time-consuming, but it realizes consistency check and high-quality control of glacial lakes. Figure 1 shows the detailed cataloging process of glacial lakes.

[3] https://www.glims.org/RGI/.

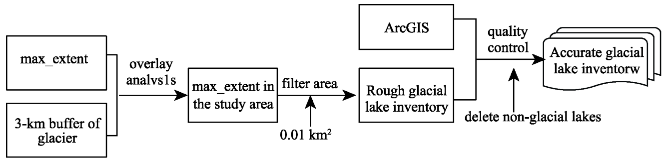

Figure 1 Flow chart of glacial lake cataloging

3.2.2 Classification System of Glacial Lakes

The classification of glacial lakes is essential to understand the formation mechanism and evolution process of glacial lakes. The characteristics of glacial lakes, including the lake formation process, shape of the lake basin, type of lake dams or material composition, and replenishment water source, are the bases of the classification system of glacial lakes. Combined with existing studies, the classification system can be summarized into two types. The first type is based on the relationship between glacial lakes and glaciers. When Chen *et al*.[17] researched the inter-annual variations of high mountain Asian glacial lakes, the lakes were divided into four types: ice-marginal, proglacial, supraglacial, and unconnected glacial lakes. The other type is based on the formation mechanism of glacial lakes; Wu *et al*.[21] divided glacial lakes in the Hindu Kush-Himalayan region into three categories (ice-eroded, moraine-dammed, and ice-dammed lakes) and 10 subcategories. In general, accurate determination of the formation mechanism of glacial lakes based on remote sensing images only is difficult. The glacial lake classification system used in this research is based on the relationship between glacial lakes and glaciers (Table 3). This classification system can reflect the important role that glaciers play in the formation of glacial lakes. To obtain reliable classification results, we superimposed high-resolution remote sensing images and RGI 6.0 glacier contours to distinguish glacial lakes.

Table 3 Classification system of glacial lakes

Types of glacial lake		Introduction
Non-glacier-fed lake (NGFL)		Lakes without modern glacial meltwater supply
Glacier-fed lake (GFL)	Supraglacial (SGL)	Lakes developed on glacier surface
	Ice-uncontacted lake (IUL)	Lakes not contacting the glacier but fed directly by glacial meltwater
	Ice-contacted lake (ICL)	Lakes contacting the glacier terminal or margin

3.2.3 Uncertainty Assessment of Glacial Lake Area

Affected by the attributes of remote sensing products (such as spatial resolution, cloud-covered, water extraction algorithm, etc.), prior knowledge of visual interpretation personnel, subjectivity of operation, identification criteria for glacial lakes, and minimum area thresholds of glacial lake inventories, inevitable errors will occur in the cataloguing of glacial lakes. This research adopted a semi-automatic method to map the inventory of glacial lakes and verified or edited each lake. However, no reasonable and quantifiable indicator is available for the manual correction process. Therefore, this article assumed that the area error of the glacial lake caused by manual correction followed a Gaussian distribution, and only the extraction error of the glacial lake area caused by the spatial resolution of the remote sensing product was considered. The research showed that the mixed pixels caused by spatial resolution are the key factor of the error source, and the error of one pixel on both sides of the delineated lake boundary was used[22]. Therefore, the uncertainty of the area of a single lake is follows:

$$\mathrm{e} = n^{1/2} \times m \quad (1)$$

$$r = \frac{e}{A} \times 100\% \tag{2}$$

where e is the absolute area error of each glacial lake (m^2), n is the number of pixels on the glacial lake boundary (approximately the ratio of the lake perimeter to the spatial resolution), and m is the area of each pixel of the remote sensing product (the spatial resolution of the GSW dataset is 30 m; thus, m = 900 m^2); r is the relative error of a single lake, and A is the area of the lake. The area error obtained from the above equation shows that the total absolute area error of Asian glacial lakes is 98.91 km^2, the average relative error is 19.1%, and the relative area error of each lake is between 0.2% and 47.7%. Figure 2 shows the relationship between the relative area error of each glacial lake and the size of glacial lake. The change trend revealed that the relative area error of the glacial lake has a significant power function relationship with the size of glacial lake, that is, with the increase in the area of a glacial lake, the relative area error presents a decreasing trend. The analysis showed that when the areas of glacial lakes are 0.02, 0.06, and 0.15 km^2, the relative area errors are 20%, 10%, and 5%, respectively.

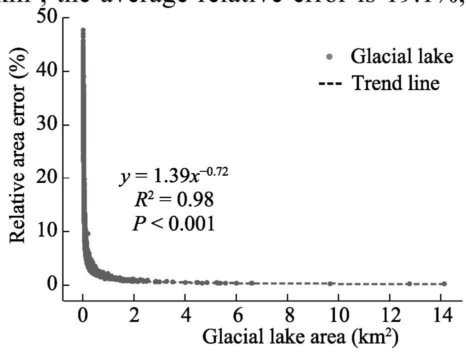

Figure 2 Relative area error of glacial lake

4 Data Results

4.1 Dataset Composition

The dataset is the spatial distribution data and statistical table data of the max_extent of Asian glacial lakes. The spatial data included the max_extent data (.shp) of different types of glacial lakes in Asia from 1980s to 2019. The table data included the statistics of the number and area of glacial lakes of different sizes, types, and elevation scales in Asia from 1980s to 2019.

4.2 Data Results

4.2.1 Regional Distribution Characteristics of Glacial Lakes in the Asia

Based on the GSW dataset, 17,213 glacial lakes (≥ 0.01 km^2) were identified in Asia, with a total area of about 1,299.06 ± 98.91 km^2. The glacial lakes are widely distributed and clustered and are mainly distributed in the Tibet Plateau and adjacent mountains, such as the Himalayas, Tianshan, and Kunlunshan (Figure 3). Glacial lakes are also distributed in low-elevation areas, such as the Kamchatka Peninsula. In general, the glacial lakes in Asia are mainly small lakes with an area between 0.01–14.27 km^2; several larger glacial lakes are all located in the Himalayas. The glacial lakes with an area of less than 0.1 km^2 accounted for about 85.3% of the total number, but their areas accounted for 35.7% of the total area. The glacial lakes with an area of more than 0.1 km^2 accounted for 14.7% of the total number, but their areas accounted for 64.3%. Therefore, although Asia has numerous small glacial lakes, the total area of glacial lakes in this region is still dominated by larger lakes (Figures 4a, 4b).

Figures 3, 4c, and 4d show the spatial distribution, the number, and area of different types of glacial lakes, respectively. Different types of glacial lakes varied significantly, of which the GFLs far exceeded non-glacier-feeding lakes (NGFLs), accounting for 82.2% of the number and 87.5% of the area. Specifically, among the four types of glacial lakes, the number of non-contacting lakes (IULs) was the largest, accounting for about 53.6%,

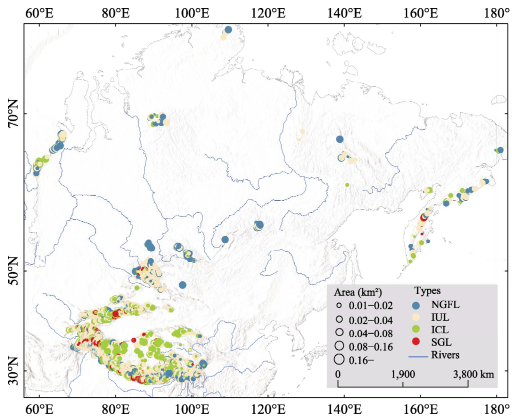

Figure 3 Spatial distribution characteristics of glacial lakes of different sizes and types in Asia from 1980s to 2019

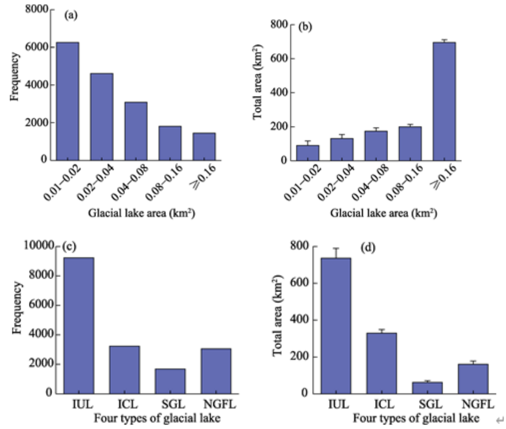

Figure 4 Number and area of glacial lakes of different sizes (a–b) and types (c–d) in Asia from 1980s to 2019

(Note: IUL, ICL, SGL, and NGFL indicate glacier non-contacting lakes, glacier contacting lakes, super-glacier lakes, and non-glacier-feeding lakes, respectively)

whereas the proportions of glacier contacting lakes (ICLs), super-glacier lakes (SGLs), and NGFLs were relatively small, accounting for 18.8%, 9.8%, and 17.8%, respectively. In terms of glacial lake area, the four types of glacial lakes (IULs, ICLs, SGLs, and NGFLs) accounted for 57.0%, 25.5%, 5.0%, and 12.5%, respectively. Compared with other glacial lakes, the average area of ICLs is larger mainly because such lakes are connected to the terminus of glaciers and can evolve with glacial ablation.

4.2.2 Elevation Distribution Characteristics of Glacial Lakes

Elevation zones with an interval of 1,000 m were defined to analyze the dependence of the distribution of Asian glacial lakes based on elevation. Figure 5 shows the distribution of the number and area of Asian glacial lakes at different elevations. As the elevation increased, the number and area of glacial lakes were approximately normally distributed.

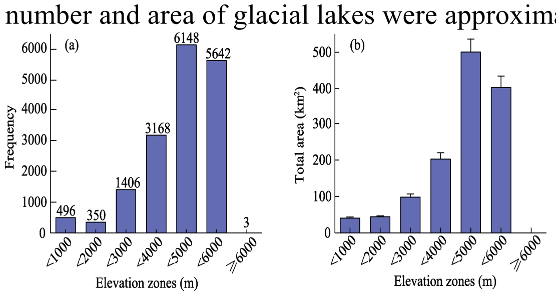

Figure 5 Number (a) and area (b) of glacial lakes in different elevation zones in Asia from 1980s to 2019

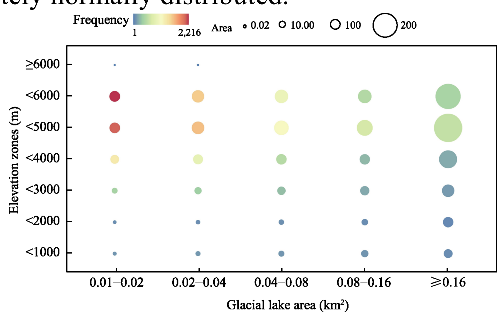

Figure 6 Distribution of glacial lakes of different sizes in elevation zones with an interval of 1,000 m in Asia

Further analysis showed that in different elevation zones, the distribution of glacial lakes of different sizes was uneven with significant difference (Figure 6). Glacial lakes were mainly distributed between 4,000–6,000 m. Most of them were small lakes (≤0.04 km^2), whereas larger lakes were distributed in relatively low-elevation areas mainly because the low-elevation areas are flat and provide a good water storage environment for certain larger

NGFLs and several IULs[10].

All glacial lakes mapped were distributed in the elevation range of 69–6,044 m, with an average elevation of 4,301 m. Affected by glacial action, nearly 68.5% of glacial lakes were distributed between 4,000–6,000 m; the total area of glacial lakes reached the peak value, which is 503.62 ± 35.40 km^2 (accounting for 38.8% of the total area), between 4,000–5,000 m (mainly in the Himalayas).

5 Summary

Through a semi-automatic method, we used the open-source remote sensing product (GSW) to carry out the spatial cataloging of Asian glacial lakes and compiled an inventory of different types of glacial lakes. The result analysis showed the following:

Asia has a wide area, where a total of 17,213 glacial lakes (≥0.01 km^2) were identified with a total coverage area of about 1,299.06 ± 98.91 km^2. These lakes are mainly distributed in the Tibet Plateau and adjacent mountains, such as the Himalayas, TianShan, KunlunShan, etc. Asia is dominated by small glacial lakes; the glacial lakes with an area of less than 0.1 km^2 account for about 85.3% of the total number, and the area of a single glacial lake is between 0.01–14.27 km^2. In addition, the number and area of GFLs far exceed those of NGFLs, accounting for 82.2% and 87.5%, respectively. The number (53.6%) and area (57.0%) of the IULs are the largest, and the number (9.8%) and area (5.0%) of the SGLs in this region are the least. Comparatively speaking, the average area of the ICL is the largest (0.1 km^2).

In the vertical direction, all glacial lakes are distributed in the elevation range of 69–6,044 m, with an average elevation of 4,301 m. Glacial lakes are centrally distributed at an elevation of 4,000–6,000 m. Within 4,000–5,000 m, the total area of the glacial lake reached the peak value of 503.62 ± 35.40 km^2. In addition, in different elevation zones, glacial lakes of various sizes are unevenly distributed, presenting the characteristics of small glacial lakes at high average elevation and large glacial lakes at low average elevation.

This research provides a complete set of max_extent and type spatial distribution data of glacial lakes in Asia, an effective way to reveal the temporal and spatial change characteristics of glacial lakes, understand the response of glacial lakes to climate change, and obtain the data source for subsequent glacial lake water volume estimation and flash flood research.

Author Contributions

Song, C. Q. made the overall design for the dataset development; Ma, J. S. collected and processed data on the max_extent and types of Asian glacial lakes; Wang, Y. J. and Zhang, D. P. verified the data and directed the paper writing; Ma, J.S. wrote the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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