Spatiotemporal Dynamics of Typical Watershed Lakes on the Northern Slope of the Kunlun Mountains from 1990 to 2024

Zhang Qifei, Yuan Zewu, Chen Yaning, Xiang Yanyi, Jia Rong, Liu Yuting

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Abstract

As sensitive indicators of climate change in arid regions, lakes exhibit spatiotemporal dynamics and driving factors whose accurate identification is of great significance for the scientific allocation and efficient utilization of regional water resources. Based on multi-source remote sensing data and meteorological records from 1990 to 2024, combined with the normalized difference water index (NDWI) and manual interpretation correction, lake information on the northern slope of the Kunlun Mountains was systematically extracted and cataloged, and its spatiotemporal dynamics and driving factors over 35 a were analyzed. The results show that: (1) From 1990 to 2024, both the number and area of lakes on the northern slope of the Kunlun Mountains increased significantly. The number of lakes rose from 125 to 396, an increase of 216.80%; the area increased from 1439.18 km2 to 2614.22 km2, an increase of 81.65%. (2) Spatially, the lake area in the Qarqan River Basin increased most significantly, expanding by approximately 3.6 times (a net increase of 138.86 km2); the lake area in the Hotan River Basin increased by approximately 1 time (a net increase of 46.98 km2); and the lake area in the Kumukuli Basin increased by 73.20% (a net increase of 989.20 km2). In terms of elevation, the net increase in lake area in mountainous areas was 1144.47 km2, significantly higher than the 30.57 km2 in plain areas. (3) In the time series, lake area changes exhibited distinct stages: from 1990 to 1995, the lake area showed a decreasing trend, with an average annual decrease of 23.26 km2 · a-1; after 1995, it continued to increase, with an increase as high as 52.56 km2 · a-1 from 1995 to 2000; the average annual increase from 2000 to 2005 was 39.90 km2 · a-1; after 2005, the rate of change fluctuated slightly across different stages, but the overall trend remained one of sustained growth. (4) The increase in lakes in the mountainous areas on the northern slope of the Kunlun Mountains was mainly attributed to the combined effects of ice and snow melting induced by rising temperatures and increased precipitation. Over the past 35 a, water storage in mountainous areas increased markedly; during the same period, temperature increased by 35.30% and precipitation increased by 13.18%, a pattern particularly evident in the Qarqan River and Kumukuli Basin. In contrast, fluctuations in lakes in plain areas were mainly caused by the combined effects of increased evaporation potential due to rising temperatures and fluctuations in precipitation. These findings provide an important scientific basis and policy reference for regional water resource management and climate response assessment on the northern slope of the Kunlun Mountains.

Full Text

Spatiotemporal Dynamics of Typical Watershed Lakes on the Northern Slope of the Kunlun Mountains from 1990 to 2024

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Abstract: Lakes, as sensitive indicators of climate change in arid regions, are of great significance for the scientific allocation and efficient utilization of regional water resources through accurate identification of their spatiotemporal dynamics and driving factors. Based on multi-source remote sensing data and meteorological data from 1990 to 2024, and by combining the normalized difference water index (NDWI) with manual interpretation and correction methods, lake information on the northern slope of the Kunlun Mountains was systematically extracted and compiled, and its spatiotemporal dynamic changes and driving factors over 35 a were analyzed. The results show that: (1) From 1990 to 2024, both the number and area of lakes on the northern slope of the Kunlun Mountains increased significantly. The number of lakes increased from 125 to 396, an increase of 216.80%; the area increased from 1439.18 km^2 to 2614.22 km^2, an increase of 81.65%. (2) Spatially, the increase in lake area was most significant in the Qarqan River Basin, expanding by approximately 3.6 times (a net increase of 138.86 km^2); the lake area in the Hotan River Basin increased by about 1 time (a net increase of 46.98 km^2); and the lake area in the Kumukuli Basin increased by 73.20% (a net increase of 989.20 km^2). In terms of elevation, the net increase in lake area in mountainous areas was 1144.47 km^2, significantly higher than the 30.57 km^2 increase in lakes in the plain area. (3) In the time series, lake-area change showed clear stage characteristics: from 1990 to 1995 it showed a declining trend, with an average annual decrease of 23.26 $km^{2 \cdot a}$-1; after 1995 it continued to increase, with the increase reaching 52.56 $km^{2 \cdot a}$-1 during 1995–2000 and averaging 39.90 $km^{2 \cdot a}$-1 during 2000–2005. After 2005, the rate of change fluctuated slightly in each stage, but overall maintained a continuous growth trend. (4) The increase in lakes in the mountainous area on the northern slope of the Kunlun Mountains was mainly attributable to the joint driving effect of snow and ice melt caused by rising temperatures and increased precipitation. Over the past 35 a, water storage in the mountainous area increased markedly; during the same period, temperature increased by 35.30% and precipitation increased by 13.18%, a feature especially prominent in the Qarqan River and Kumukuli basins. In comparison, the fluctuating changes of lakes in the plain area were mainly caused by the combined effects of increased evaporation potential resulting from rising temperature and fluctuations in precipitation. The research results provide an important scientific basis and policy reference for water-resource management and climate-response assessment in the northern-slope region of the Kunlun Mountains.

Key words: NDWI; lake dynamic change; climate change; northern slope of the Kunlun Mountains

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Mountain lakes in arid regions are among the geographical units most sensitive to global climate change, and their evolutionary characteristics reflect the integrated response of climate-system change and regional water cycling. In recent years, continued intensification of global warming, frequent extreme climate events, and the continuously rising intensity of human activities have led to significant changes in the spatiotemporal pattern of water resources in arid regions. As an important water-resource area in the arid region of Northwest China, the northern slope of the Kunlun Mountains shows an evident trend of rising temperature, which drives glacier melting and lake expansion, causing a decline in the timeliness of water resources and increasing uncertainty, thereby posing potential threats to the stability of downstream ecosystems and water-resource security[1].

Against the background of global climate change, since 1980 about 70% of inland perennial water bodies worldwide have shown a shrinking trend[2], but alpine lakes as a whole have exhibited significant expansion. This process helps alleviate local water-resource shortages and has become a key regulator of the mountain water cycle[3]. Global warming is reshaping the cryosphere; temperature increases are pronounced in high-altitude regions, and ···

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accelerated glacier and snowmelt, leading to a continuous increase in meltwater from alpine glaciers[4–5]; in arid regions, alpine lakes have therefore shown an expansion trend different from that of the past[6]. At the same time, the instability of glacial lakes has also increased the risk of disasters such as sudden outburst floods[7–9]. In the arid regions of northwestern China, the magnitude of warming in high-elevation areas is significantly greater than that in plateau areas[10–11], and the number and area of glacial lakes have continued to grow at an accelerating rate[12]. Existing studies on lakes on the northern slope of the Kunlun Mountains have mostly focused on individual typical lakes and their causes, such as the relationship between the expansion of the Aksayqin Lake area and increased recharge from glacier meltwater[13], and the relationship between the rise in the water level of Sayram Lake and increased runoff from precipitation[14], etc. Conclusions regarding driving mechanisms at the regional scale also differ: some studies emphasize the dominant role of climatic factors[15], whereas others point to the significant influence of human activities[16]. Overall, against the background of global warming, lakes on the northern slope of the Kunlun Mountains have already exhibited significant spatiotemporal dynamic changes, which have important implications for downstream ecological security and water-resource allocation. However, systematic monitoring and comprehensive analysis at the watershed scale based on long time series remain lacking. Therefore, further revealing their evolution patterns and multiple driving mechanisms is of important scientific value and practical significance for improving understanding of the water-cycle processes in arid regions of northwestern China, assessing alpine disaster risks, and supporting high-quality regional development.

Therefore, this paper takes typical basins on the northern slope of the Kunlun Mountains as the study area. Relying on multi-source remote-sensing image data such as Landsat series, Sentinel-2/MSI, ICESat-1, CryoSat-2, Envisat/RA-2, and ICESat-2 from 1990 to 2024, and combining automated extraction with manual interpretation and correction methods, it systematically analyzes the spatiotemporal dynamic evolution characteristics of lakes over the past 35 years. By introducing GRACE gravity-satellite data and ERA5-Land meteorological data, it explores the climatic and human-activity driving mechanisms of lake changes, and clarifies the response differences between lakes in mountainous areas and those in plateau areas. The research results help deepen understanding of water-cycle processes in arid regions under the background of climate change, and provide basic data support and policy references for scientific allocation of regional water resources, protection of alpine ecosystems, and early warning of sudden water-related disasters.

1 Data and Methods

1.1 Overview of the Study Area

The northern slope of the Kunlun Mountains is located along the southern margin of the Tarim Basin in Xinjiang; it borders the Taklimakan Desert to

Fig. 1 Location of the study area and typical river basins

Figure 1: Fig. 1 Location of the study area and typical river basins

the north and adjoins Tibet to the south. It covers four major hydrological units: the Hotan River Basin, the Keliyang River and other small-river basins, the Qarqan River Basin, and the Kumkol Basin (Fig. 1). This area lies in the hinterland of the Eurasian continent, is blocked by terrain, and is difficult for marine water vapor to reach; annual precipitation is extremely low, and it has a typical arid desert continental climate. The Qarqan River is the largest river on the northern slope of the Kunlun Mountains. It originates from Muztagh Peak, flows through Qiemo and Ruoqiang counties, and then enters Taitema Lake; it is the river with the most abundant water volume along the southeastern margin of the Tarim Basin.

(a) Overview of the study area

Legend: glacier; river; typical basin; basin boundary; lake. Scale: 0–350 km.

(b) Hotan River Basin

Legend: glacier; lake; basin boundary. Scale: 0–300 km.

(c) Qarqan River Basin

Legend: glacier; lake; basin boundary. Scale: 0–200 km.

(d) Kumkol Basin

Legend: glacier; lake; basin boundary. Scale: 0–200 km.

Fig. 1 Location of the study area and typical river basins

formed by the confluence of the Hotan River, the Karakash River, and the Yulongkash River; it flows from south to north across the Taklimakan Desert and ultimately empties into the Tarim River. Runoff in the two basins mainly depends on glacier and snowmelt recharge, with summer precipitation contributing secondarily. From 2010 to 2023, the average annual runoff of the Hotan River and the Qarqan River was 51.00×10^8 m^3 and 7.77×10^8 m^3, respectively[17]; among these, runoff from June to September accounted for more than 80% of the annual total, and the spatiotemporal distribution was extremely uneven. The mean annual precipitation in the two basins is only 18.6 mm and 39.6 mm, whereas annual evaporation reaches 2507 mm[18] and 2648.7 mm[19], with evaporation–precipitation ratios exceeding 70, further highlighting their extremely arid characteristics. The Kumkol Basin is located between the Kunlun Mountains and the Altun Mountains. It is an enclosed high-altitude fault basin surrounded by high mountains, with an overall terrain sloping from west to east and an east–west length of about 350 km. The central part of the basin is divided by the Langya Mountains into the two major basins of Aqqikkol Lake and Ayakkum Lake, and its topographic enclosure is pronounced. The region has a cold and dry climate, with a mean annual temperature of $0 \sim 1\,^{\circ}$C and annual precipitation of 100–200 mm; precipitation is mainly concentrated in summer, and the eastern part is slightly wetter than the western part.

1.2 Data Sources

1.2.1 Remote-Sensing Satellite Data

This study used Landsat TM/ETM+/OLI and Sentinel-2/MSI remote-sensing images, and systematically extracted lake information for eight periods from 1990 to 2024 on the northern slope of the Kunlun Mountains (1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2024). Among them, lake information from 1990 to 2020 was extracted mainly based on Landsat series data (TM/ETM+/OLI), at 5-year intervals for 7 periods, with a spatial resolution of 30 m, covering 15 orbit path/row strips (140-033, 141-033, 141-034, 142-033, 142-034, 142-035, 143-035, 146-032, 146-034, 146-035, 146-036, 147-034, 147-035, 147-036, 148-034), totaling 35 images. All images underwent preprocessing such as geometric correction, mosaicking, and clipping (Table 1), and images from August to October with cloud cover less than 5% were selected for lake extraction. The 2024 lake data were based on Sentinel-2 surface reflectance (SR) data from the Google Earth Engine (GEE) with 10 m resolution. Lake information from August 18 to October 31 was extracted using the normalized difference water index (NDWI), and cloud layers and cirrus interference in the data were removed using the QA60 band. The combination of Landsat long-term time-series data and Sentinel-2 high-resolution images accommodates both the needs of long-term time-series analysis and high-precision feature extraction.

Lake water-level data for the northern slope of the Kunlun Mountains during 2002–2022 were mainly based on multi-source altimetry satellite record data, including EnviSat/RA-2 satellite altimetry data for 2002–2012, ICESat-1/GLAS satellite altimetry data for 2003–2009, CryoSat-2/SIRAL satellite altimetry data for 2010–2022, and ICESat-2/ATLAS satellite altimetry data for 2018–2022. This paper used GRACE Level-2 RL06 Mascon gravity-field model data released by the Center for Space Research (CSR) at the University of Texas (https://www2.csr.utexa-s.edu/grace/RL06_mascons.html) to calculate changes in regional water storage from April 2002 to December 2023. This product is based on the point-mass block (Mascon) inversion method; by dividing the Earth' s surface into irregular cells and solving them independently, it effectively reduces signal leakage and striping noise that readily occur in mountainous valley regions when using the spherical-harmonic coefficient method. During data processing, regularized constrained optimization steps, including Gaussian filtering, are integrated. The spatial resolution of the product is $0.25^{\circ} \times 0.25^{\circ}$, and the maximum degree is 60. To address the problem that 33 months lacked valid data (e.g., June–July 2002, June 2003, etc.), missing values were filled using multi-year cumulative means and interpolation of adjacent months, ensuring the completeness of the time series and the reliability of the analysis.

1.2.2 Other Data

ERA5-Land monthly temperature and precipitation data from 1990 to 2024 were selected and processed on the GEE platform, with a spatial resolution of 9 km, for analysis of long-term climate change on the northern slope of the Kunlun Mountains. Elevation data used the Copernicus digital elevation model with a resolution of 30 m; these data were obtained from the Copernicus Open Data Platform (https://registry.opendata.aws/copernicus-dem/) and integrate multi-source data, accurately reflecting terrain relief.

1.3 Research Methods

1.3.1 Lake-Information Extraction Method

This study adopted a method combining automatic extraction of water-body information with manual correction. ENVI 5.3 and ArcGIS 10.8 software were used to conduct radiometric calibration and atmospheric correction processing on Landsat TM/ETM+/OLI remote-sensing images; Sentinel-2/MSI remote-sensing image data were preprocessed through the GEE platform. Water-body information was extracted using the NDWI proposed by McFeeters in 1996[20]. The calculation formula is as follows:

$$\text{NDWI} = (\text{Green} - \text{NIR})/(\text{Green} + \text{NIR}) \qquad (1)$$

In the formula: NDWI is the normalized difference water index; Green is the green-light band; NIR is the near-infrared band. These correspond respectively to band 2 and band 4 in Landsat TM/ETM+ images, band 3 and band 5 in Landsat OLI images, and band 3 and band 8 in Sentinel-2/MSI remote-sensing images.

First, NDWI was used to extract lake information. The NDWI value range is $-1 \sim 1$. Because water bodies have relatively high reflectance in the green band and strong absorption in the near-infrared band, their NDWI values are usually positive; whereas non-water objects such as vegetation, bare land, and buildings have relatively high reflectance in the near-infrared band, and their NDWI values are mostly negative. Because NDWI is affected by factors such as water-body type, terrain conditions, and remote-sensing image quality, its values have a certain degree of dynamism; therefore, a fixed threshold is not suitable for lake extraction.

Table 1 List of satellite images used in this study

Year	Sensor type	Resolution/m	Path-row	Cloud cover/%	Year	Sensor type	Resolution/m	Path-row	Cloud cover/%
1990	Landsat5 (TM)	30	140–033, 141–033, 141–034	1.03, 2.77, 2.99	2005	Landsat7 (ETM+)	30	146–035, 146–036, 147–034	0.27, 0.89, 1.67
1990	Landsat5 (TM)	30	142–033, 142–034, 142–035	0.01, 0.47, 0.26	2005	Landsat7 (ETM+)	30	147–035, 147–036, 148–034	0.09, 0.73, 4.11
1990	Landsat5 (TM)	30	143–035, 146–032, 146–034	2.16, 0.13, 0.28	2010	Landsat5 (TM)	30	140–033, 141–033, 141–034	0.03, 1.39, 4.81
1990	Landsat5 (TM)	30	146–035, 146–036, 147–034	0.03, 1.07, 3.97	2010	Landsat5 (TM)	30	142–033, 142–034, 142–035	3.36, 1.06, 0.76
1990	Landsat5 (TM)	30	147–035, 147–036, 148–034	2.74, 4.99, 0.26	2010	Landsat5 (TM)	30	143–035, 146–032, 146–034	0.15, 0.97, 0.88
1995	Landsat5 (TM)	30	140–033, 141–033, 141–034	3.40, 0.30, 0.69	2010	Landsat5 (TM)	30	146–035, 146–036, 147–034	0.34, 0.29, 0.46
1995	Landsat5 (TM)	30	142–033, 142–034, 142–035	1.05, 0.58, 4.23	2010	Landsat5 (TM)	30	147–035, 147–036, 148–034	4.88, 0.62, 0.49

Year	Sensor type	Resolution/m	Path-row	Cloud cover/%	Year	Sensor type	Resolution/m	Path-row	Cloud cover/%
1995	Landsat5 (TM)	30	143–035, 146–032, 146–034	2.16, 0.13, 0.28	2015	Landsat8 (OLI, TIRS)	30	140–033, 141–033, 141–034	0.32, 4.59, 3.43
1995	Landsat5 (TM)	30	146–035, 146–036, 147–034	2.19, 1.45, 3.35	2015	Landsat8 (OLI, TIRS)	30	142–033, 142–034, 142–035	0.95, 0.66, 3.12
1995	Landsat5 (TM)	30	147–035, 147–036, 148–034	0.86, 2.13, 0.06	2015	Landsat8 (OLI, TIRS)	30	143–035, 146–032, 146–034	2.73, 1.09, 1.40
2000	Landsat5 (TM)	30	140–033, 141–033, 141–034	0.58, 1.20, 0.58	2015	Landsat8 (OLI, TIRS)	30	146–035, 146–036, 147–034	1.64, 1.78, 3.32
2000	Landsat5 (TM)	30	142–033, 142–034, 142–035	1.27, 0.67, 0.06	2015	Landsat8 (OLI, TIRS)	30	147–035, 147–036, 148–034	1.61, 5.92, 0.11
2000	Landsat5 (TM)	30	143–035, 146–032, 146–034	3.96, 1.75, 0.44	2020	Landsat8 (OLI, TIRS)	30	140–033, 141–033, 141–034	0.55, 1.01, 3.97
2000	Landsat7 (ETM+)	30	146–035, 146–036, 147–034	0.03, 1.60, 0.77	2020	Landsat8 (OLI, TIRS)	30	142–033, 142–034, 142–035	0.79, 0.24, 1.26

Year	Sensor type	Resolution/m	Path-row	Cloud cover/%	Year	Sensor type	Resolution/m	Path-row	Cloud cover/%
2000	Landsat7 (ETM+)	30	147-035, 147-036, 148-034	0.02, 0.33, 2.37	2020	Landsat8 (OLI, TIRS)	30	143-035, 146-032, 146-034	3.93, 2.82, 1.07
2005	Landsat5 (TM)	30	140-033, 141-033, 141-034	2.16, 1.94, 1.83	2024	Sentinel-2 (MSI)	10		<5
2005	Landsat5 (TM)	30	142-033, 142-034, 142-035	0.38, 0.76, 0.25					
2005	Landsat5 (TM)	30	143-035, 146-032, 146-034	1.51, 0.40, 2.91					

In view of the natural geographical characteristics of the northern slope of the Kunlun Mountains, this study selected remote-sensing images from multiple years and different sensors to calculate NDWI, and determined the possible distribution range of lakes through histogram analysis of NDWI. In the specific application, to avoid the omission of water-body information caused by setting the threshold too high, the lower recognition limit of NDWI was set to 0.1. Pixels with NDWI values greater than 0.1 were identified as water bodies; otherwise, they were identified as non-water bodies. Subsequently, the automatically extracted lake boundaries were inspected and corrected in combination with false-color composite images interpreted visually. For the extraction of lake information in 2024, based on Sentinel-2 imagery, 30 validation points were selected to construct a confusion matrix. The results showed that the Kappa coefficient was greater than 0.9, and the overall classification accuracy reached 92%, verifying the reliability of the method. When analyzing lakes on the northern slope of the Kunlun Mountains in eight periods from 1990 to 2024, only lakes with an area greater than 0.05 km^2 were selected as the study objects, and they were divided by area into four classes: >1.00 km^2, 0.50-1.00

km^2, 0.10–0.50 km^2, and 0.05–0.10 km^2. In addition, according to elevation, the lakes were divided into two categories: mountain lakes (>1500 m), which are mainly driven by climate change; and plain lakes (( )1500 m), which are mostly located in arid areas and are more markedly affected by human activities.

1.3.2 Dynamic changes in lakes The lake change rate is used to reflect changes in lake area and number within a certain time range in a study area. This indicator can be used to quantitatively study changes in the area and number of a certain lake type.

the calculation formulas are:

$$L_1 = U_b - U_a \qquad (2)$$

$$L_2 = (U_b - U_a)/T \qquad (3)$$

where: L_1 is the total magnitude of lake change during the study period (km^2); L_2 is the annual magnitude of lake change during the study period (km$^2 \cdot$ a^{-1}); U_a and U_b are the lake areas at the beginning and end of the study period, respectively (km^2); and T is the number of years in the study interval (a).

To quantitatively reflect the relative strength of area change of each lake in different periods, this paper introduces a lake change intensity index for analysis. This index can be used to measure the relative degree of lake area change magnitude and change rate, and its calculation formula is as follows:

$$C = \frac{A_b - A_a}{\Delta A_{ba} \times \Delta t} \times 100\% \qquad (4)$$

where: C is the lake change intensity index (%); ΔA_{ba} is the lake area change between years a and b during the study period (km^2); A_a is the total area of the lake in year a (km^2); and Δt is the time interval between years a and b (a).

1.3.3 Error analysis

There are two typical types of misclassification in extracting water-body information using NDWI: first, water bodies are misclassified as non-water bodies; second, non-water objects (such as mixed pixels, mountain shadows, and ice-snow-covered areas) are misclassified as water bodies. This is mainly because water bodies and mountain shadows have similar spectral characteristics in NDWI images, causing shadows not only to reduce the accuracy of lake mapping but also to increase the difficulty of lake area identification. For cloud-covered areas (especially in high-altitude zones), when Landsat images are obscured by clouds, manual interpretation combined with multi-scene imagery is used to delineate glacier and lake extents, and high-resolution WorldView-2 imagery is used to verify the actual existence of lake basins. To reduce interference from ice and snow cover, remote-sensing images with good image quality during the high-temperature period from August to October were selected to ensure temporal consistency; however, interannual differences in ice–snow meltwater and precipitation may still lead to periodic changes in the water level of the same lake.

The uncertainty of lake area is mainly affected by spatial resolution and registration error. Compared with low-resolution images, high-resolution data can significantly reduce the uncertainty of lake identification. The Landsat TM/ETM+/OLI images used in this study were all subjected to standard terrain correction (Level 1T), and lake area was calculated based on whole entity units rather than single pixels; therefore, the influence of registration error on area measurement can be ignored. However, because of the lack of ground-measured data, accuracy validation still has certain limitations. This study uses the buffer-zone method to estimate the uncertainty of lake information extraction. This method assumes that the lake area error from manual interpretation follows a Gaussian distribution. Considering that pure lake-water pixels are often surrounded by mixed pixels, the boundary error caused by the spatial resolution of Landsat and Sentinel-2/MSI images is estimated using a buffer range of ± 0.5 pixels. Specifically, assuming the uncertainty of a single pixel is 0.5 pixels, multiplying this value by one-half of the single-pixel area, and combining registration accuracy and pixel resolution, the error estimation formula is constructed as follows:

$$\mathrm{ua} = \frac{\lambda p}{2\sqrt{\lambda^2 + \lambda^2}} = \frac{p}{2\sqrt{2}} \qquad (5)$$

where: ua is the lake area error (km^2); λ is the original pixel resolution (km); and p is the lake perimeter (km). According to the statistics in Table 2, from 1990 to 2024, the error ranges of lake area in eight periods in the Chagel Chaghan River basin, the Hotan River basin, and the Kumukuli Basin were 3.28%–24.17%, 9.30%–25.35%, and 0.70%–1.50%, respectively. Overall, the error ranges were within acceptable limits, and the measurement accuracy could meet the analytical requirements for the dynamic change process of lakes on the northern slope of the Kunlun Mountains.

Table 2 Error information of lake area on the northern slope of Kunlun Mountains from 1990 to 2024 /km^2

Year	Chagel Chaghan River	Hotan River	Kumukuli Basin
1990	2.84 (5.55%)	3.18 (9.30%)	12.08 (0.89%)
1995	1.68 (3.28%)	3.44 (10.06%)	8.69 (0.70%)
2000	10.56 (20.64%)	8.67 (25.35%)	12.53 (0.92%)
2005	8.28 (16.18%)	4.06 (11.87%)	16.45 (1.01%)

Year	Chagel Chaghan River	Hotan River	Kumukuli Basin
2010	9.06 (17.71%)	4.24 (12.40%)	16.56 (0.90%)
2015	6.38 (12.47%)	3.86 (11.29%)	16.10 (0.81%)
2020	12.37 (24.17%)	6.75 (19.74%)	32.76 (1.50%)
2024	16.38 (9.26%)	8.38 (8.67%)	24.56 (1.05%)

Note: Values in parentheses are the relative errors of lake area extraction.

1.3.4 Trend test and correlation analysis

To analyze the temporal evolution trends of lakes on the northern slope of the Kunlun Mountains and their coupling relationships with climatic factors, this paper adopts the Mann-Kendall (M-K) trend test, Pearson correlation analysis, and linear regression. As a non-parametric statistical method, the M-K test can effectively identify significant monotonic trends in time series, and determines trend significance using the Z value and P value. Pearson correlation analysis is used to quantify the strength and direction of the linear relationship between lake area, water depth, and meteorological factors; linear regression further establishes dependency models between variables, enabling quantitative description of their dynamic relationships.

2 Results and Analysis

2.1 Spatial distribution and spatiotemporal dynamic changes of lakes

Based on analysis of 2024 Sentinel-2/MSI remote-sensing imagery (Figure 2),

(a) 1990 (b) 1995

Legend: lakes; rivers; typical basins
0 500 km

(c) 2000 (d) 2005

Legend: lakes; rivers; typical basins
0 500 km

(e) 2010 (f) 2015

Legend: lakes; rivers; typical basins
0 500 km

(g) 2020 (h) 2024

Legend: lakes; rivers; typical basins
0 500 km

Note: Lake information for 1990–2020 was extracted based on Landsat remote-sensing images; lake information for 2024 was extracted based on Sentinel-2 images. The same below.

Figure 2. Spatiotemporal distribution and dynamic changes of lakes on the northern slope of the Kunlun Mountains

Fig. 2 Spatiotemporal distributions and dynamic changes of lakes on the northern slope of Kunlun Mountains

There are 396 lakes on the northern slope of the Kunlun Mountains, with a total area of 2614.22 km^2 and an average area of 6.60 km^2 per lake. In terms of spatial distribution, the lake area in the Kumukuli Basin in the southeast reaches 2340.65 km^2, accounting for 89.53% of the total lake area; in the west, the lake areas in the Qarqan River and Hotan River basins are 176.94 km^2 and 96.63 km^2, respectively, accounting for 6.77% and 3.70% of the total lake area. The lakes are mainly medium and small in scale; lakes with an area of $<$1 km^2 account for 82.07% of the total number of lakes, but their area accounts for only 2.50% of the total area.

From 1990 to 2024, the lake area on the northern slope of the Kunlun Mountains showed a significant increasing trend (Table 3), increasing from 1439.18 km^2 to 2614.22 km^2, an increase of 1175.04 km^2 over 35 a (an increase of 81.65%). In the time series,

Table 3 Changes in lake area on the northern slope of the Kunlun Mountains from 1990 to 2024 /km^2

Tab. 3 Changes in lake area on the northern slope of Kunlun Mountains from 1990 to 2024 /km^2

Year	Qarqan River Basin	Hotan River Basin	Kumukuli Basin	Total area
1990	38.08	49.65	1351.45	1439.18
1995	22.66	52.16	1248.08	1322.90
2000	141.44	78.80	1365.46	1585.70
2005	94.82	67.55	1622.82	1785.19
2010	125.29	58.93	1847.22	2031.44
2015	116.48	70.97	1995.40	2182.85
2020	158.79	74.18	2184.21	2417.18
2024	176.94	96.63	2340.65	2614.22

From 1990 to 2000, it increased by 146.52 km^2 (an increase of 10.18%); from 2000 to 2010, the increase was the largest, reaching 445.74 km^2 (an increase of 28.11%); in 2010-2020 and 2020-2024, it increased by 385.74 km^2 (an increase of 18.99%) and 197.04 km^2 (an increase of 8.15%), respectively.

From 1990 to 2024, the lake area on the northern slope of the Kunlun Mountains showed an increasing trend (Fig. 3). The lake area in the Qarqan River basin increased from 38.08 km^2 in 1990 to 176.94 km^2 in 2024, a net increase of 138.86 km^2, with an increase of 364.65%, showing obvious staged fluctuation

Fig. 3 Dynamic changes of lakes on the northern slope of Kunlun Mountains from 1990 to 2024

Figure 2: Fig. 3 Dynamic changes of lakes on the northern slope of Kunlun Mountains from 1990 to 2024

characteristics: in 1990-1995, the area decreased by 15.42 km^2 (a decrease of 40.49%); in 1995-2000, the lake area rebounded markedly, with an increase as high as

Fig. 3 Dynamic changes of lakes on the northern slope of Kunlun Mountains from 1990 to 2024

524.18% (an increase of 118.78 km^2); during 2000-2005 it decreased again by 46.62 km^2 (a decrease of 32.96%); after 2005 it entered a stage of sustained expansion, with an increase of 86.61% from 2005 to 2024. The lake area in the Hotan River Basin increased by nearly 35 a, rising by 94.62% (a net increase of 46.98 km^2) (Fig. 3c-d). Among these periods, it expanded rapidly by 58.71% from 1990 to 2000 (a net increase of 29.15 km^2); decreased by 12.76% (8.62 km^2) during 2005-2010; and grew steadily at a rate of 4.57% $\cdot$ a^{-1} from 2010 to 2024. In particular, the area increased by 22.45 km^2 during 2020-2024, at a rate of 7.57% $\cdot$ a^{-1}, reaching the peak growth rate in recent years. The Keriya Basin is the main distribution area of lakes, with area increasing from 1351.45 km^2 in 1990 to 2340.65 km^2 in 2024, a net increase of 989.20 km^2 (an increase of 73.20%) (Fig. 3e-f). The area decreased by 7.65% (103.37 km^2) during 1990-1995, and then continued to expand; during 2000-2005 the lake-area growth rate was 51.47 km^2 $\cdot$ a^{-1}, the largest increase over the entire period. During 2010-2024, lake area increased by 493.43 km^2, and its contribution to the growth of the total regional lake area reached 84.2%, indicating a significant dominant role.

2.2 Dynamic change characteristics of lakes of different sizes

From 1990 to 2024, both the number and area of lakes larger than 0.05 km^2 on the northern slope of the Kunlun Mountains showed increasing trends (Table 4). Among them, the number of lakes with areas of 0.05-0.10 km^2 increased by 88, and the area increased by 6.13 km^2 (an increase of 214.34%); the number of lakes with areas of 0.10-0.50 km^2 increased by 114, and the area increased by 23.84 km^2 (an increase of 214.97%); the number of lakes with areas of 0.50-1.00 km^2 increased by 27, and the area increased by 18.56 km^2 (635.62%). In comparison, the number of lakes with areas >1.00 km^2 increased by only 51, but the total area expanded continuously and steadily, by 81.71%. The results indicate that small lakes respond more sensitively to environmental change, with notable increases in number, whereas large lakes have only limited growth in number but maintain continuous and stable area expansion; the two differ significantly.

2.3 Dynamic change characteristics of lakes at different elevations

The lakes on the northern slope of the Kunlun Mountains are mainly mountain lakes, accounting for 83.33% (330 lakes) of the total number, and 97.97% (2561.27 km^2) of the total area. From 1990 to 2024, both the number and area of lakes in mountainous and plain areas showed increasing trends (Fig. 4). Among them, the number of mountain lakes increased by 236 (251.06%), and area increased by 1144.47 km^2 (80.78%); the number of plain lakes increased by 35 (112.90%), and area increased by 30.57 km^2 (136.57%). In terms of spatial distribution, in the Qarqan River Basin, mountain-lake area increased by 132.08 km^2 (357.59%), and plain-lake area increased by 6.78 km^2 (595.40%); in the Hotan River Basin, mountain-lake area increased by 23.19 km^2 (81.66%), and plain-lake area increased by 23.79 km^2 (111.98%); in the Keriya Basin, the number of mountain lakes increased by 10, and area increased by 989.20 km^2 (73.20%). Overall, lakes of different elevation types all showed increasing trends, among which mountain lakes remained dominant, and their significant expansion is of great importance for the evolution of the regional water-resource pattern.

From 1990 to 2024, the areas of lakes at different elevations on the northern slope of the Kunlun Mountains exhibited marked spatial heterogeneity (Fig. 5). Plain lakes at elevations of 500–1000 m increased substantially during 2005–2010 (10.02 km^2), followed by 1995–2000 (7.11 km^2). The area of plain lakes at elevations of 1000–1500 m increased by 22.08 km^2 (101.56%) during 1995–2000 and by 20.91 km^2 (65.89%) during 2020–2024. In contrast, the increase in mountain-lake area was more pronounced: except for a slight decrease during 1990–1995, it expanded continuously from 1995 onward, increasing from 1300.91 km^2 to 2561.27 km^2 in 2024, a growth of 96.88% over 30 a. Among these, 2010–2015 and 2020–2024 were peak expansion periods, increasing respectively

Table 4 Changes in lake number and area from 1990 to 2024

Tab. 4 Changes in lake number and area from 1990 to 2024

Year	0.05–0.10 km^2 Number/lake	0.05–0.10 km^2 Area/km^2	0.10–0.50 km^2 Number/lake	0.10–0.50 km^2 Area/km^2	0.50–1.00 km^2 Number/lake	0.50–1.00 km^2 Area/km^2	>1.00 km^2 Number/lake	>1.00 km^2 Area/km^2
1990	40	2.86	52	11.09	4	2.92	20	1402.65
1995	32	2.35	30	6.28	5	3.64	19	1310.63
2000	104	7.18	160	33.17	21	14.50	40	1520.79
2005	89	5.96	109	23.96	19	12.00	35	1743.27
2010	89	6.17	124	25.88	29	20.91	29	1978.48
2015	93	6.57	106	23.36	20	13.81	32	2139.11
2020	109	7.59	153	32.62	26	17.84	41	2359.13
2024	128	8.99	166	34.93	31	21.48	71	2548.81

Year	0.05–0.10 km^2 Number/lake	0.05–0.10 km^2 Area/km^2	0.10–0.50 km^2 Number/lake	0.10–0.50 km^2 Area/km^2	0.50–1.00 km^2 Number/lake	0.50–1.00 km^2 Area/km^2	>1.00 km^2 Number/lake	>1.00 km^2 Area/km^2
1990–2024	220.00%	214.34%	219.23%	214.97%	675.00%	635.62%	255.00%	81.71%

(a) Number of lakes
Legend: mountain-area lakes; plain-area lakes; linear trend line (mountain-area lakes); linear trend line (plain-area lakes).
Vertical axis: number of lakes / lakes. Horizontal axis: year.
Trend equations shown: $y = 27.464x + 70$; $y = 4.5833x + 34.25$.

(b) Lake area
Legend: mountain-area lakes; plain-area lakes; linear trend line (mountain-area lakes); linear trend line (plain-area lakes).
Left vertical axis: mountain-area lake area / km^2. Right vertical axis: plain-area lake area / km^2. Horizontal axis: year.
Trend equations shown: $y = 2.6669x + 23.589$; $y = 21.153x + 45.091$.

Fig. 4 Changes in the number and area of lakes in the mountainous and plain areas on the northern slope of the Kunlun Mountains from 1990 to 2024

(a) Plain-area lakes
Legend: 500–1000 m; 1000–1500 m.
Vertical axis: lake area / km^2. Horizontal axis: year.

(b) Mountain-area lakes
Legend: 1500–3000 m; 3000–4500 m; 4500–6000 m; >6000 m.
Vertical axis: lake area / km^2. Horizontal axis: year.

Fig. 5 Changes in lake areas in the plains and mountains at different altitudes on the northern slope of Kunlun Mountains from 1990 to 2024

145.16 km^2 (96.88%) and 176.29 km^2 (7.39%), indicating that lakes in high-altitude areas are more sensitive to climate change and that the expansion trend is especially significant.

2.4 Dynamic variation characteristics of water levels in typical lakes

Based on multi-source satellite altimetry data, analysis of the three large lakes with areas greater than 250 km^2 in the study area found (Fig. 6) that from 1990 to 2024 the total area of the three lakes increased from 1258.51 km^2 to 2228.26 km^2, an increase of 77.06% (969.75 km^2) over 35 a. Among them, the areas of Ayakkum Lake, Aqqikkol Lake, and Jingyu Lake increased by 273.84 km^2

(78.18%), 551.57 km^2 (85.56%), and 144.34 km^2 (54.77%), respectively. From 2003 to 2022, lake water levels showed a highly significant rising trend ($P < 0.01$); the rates of water-level rise in Ayakkum Lake, Aqqikkol Lake, and Jingyu Lake were 0.40 $m \cdot a^{-1}$, 0.46 $m \cdot a^{-1}$, and 0.48 $m \cdot a^{-1}$, respectively. Combined with multi-year mean lake-area calculations, since 2003 the water volumes of the three lakes have increased by 4.77 km^3, 6.38 km^3, and 2.92 km^3, respectively.

3 Discussion

Lakes on the northern slope of the Kunlun Mountains are dominated by high-altitude mountain lakes, and are mostly distributed in glacier-covered areas, where annual precipitation is significantly higher than in the plains. Changes in the water volume of mountain lakes are mainly governed by glacial and snow meltwater driven by rising temperatures; temperature affects the rate of glacier and snow melting and thus becomes the core driver of lake expansion[^21]. Over the past 35 a, air temperature on the northern slope of the Kunlun Mountains has risen significantly at a rate of 0.31 $°C \cdot (10a)^{-1}$ ($P < 0.01$, Fig. 7), an increase greater than the global average. Statistical results show that the area of mountain lakes is strongly correlated with air temperature ($R^2 = 0.83$), but only weakly correlated with precipitation ($R^2 = 0.40$). In comparison, the replenishment mechanisms of plain-area lakes are more complex: they are jointly affected by multiple factors such as precipitation, groundwater, and river diversion[^17,^22], while also being constrained by strong evaporation and human water withdrawals[^23]. The results of this study indicate that the area of plain-area lakes is negatively correlated with air temperature and positively correlated with precipitation.

(a) Aksai Chin Lake

Legend: water level; linear trend line

$y = 0.3953x + 3878.1$

Axes: water level/m; year

(b) Whale Lake

Legend: water level; linear trend line

$y = 0.4763x + 4713.6$

Axes: water level/m; year

(c) Aksai Chin Kule Lake

Legend: water level; linear trend line

$y = 0.462x + 4254.3$

Axes: water level/m; year

Map showing spatial changes in terrestrial water storage on the northern slope of Kunlun Mountains from 2002 to 2024. Legend: rivers, basin boundary, southern Xinjiang; terrestrial water storage change rate / mm · month^{-1}, ranging from $-3.0 \sim -2.5$ to $1.5 \sim 2.0$; dots indicate $P < 0.05$.

Figure 3: Map showing spatial changes in terrestrial water storage on the northern slope of Kunlun Mountains from 2002 to 2024. Legend: rivers, basin boundary, southern Xinjiang; terrestrial water storage change rate / mm · month^{-1}, ranging from $-3.0 \sim -2.5$ to $1.5 \sim 2.0$; dots indicate $P < 0.05$.

(d) Water-level change

Legend: Aksai Chin Lake; Whale Lake; Aksai Chin Kule Lake

Axes: water-level change amplitude/m; year

Fig. 6 Dynamic changes in lake water level on northern slope of Kunlun Mountains from 2003 to 2022

(a) Temperature

Legend: temperature; linear trend line

$y = 0.0311x - 6.4667$

Axes: temperature/℃; year

(b) Precipitation

Legend: precipitation; linear trend line

$y = 1.1614x + 370.64$

Axes: precipitation/mm; year

(c) Mountain-area lakes

Legend: lake area; precipitation; temperature

Axes: lake area/km^2, precipitation/mm; temperature/℃; year

(d) Plain-area lakes

Legend: lake area; precipitation; temperature

Axes: lake area/km^2, precipitation/mm; temperature/℃; year

Fig. 7 Changes in temperature and precipitation on the northern slope of Kunlun Mountains from 1990 to 2024

图 8 2002—2024 年昆仑山北坡陆地水储量空间变化

Fig. 8 Spatial changes in terrestrial water storage on the northern slope of Kunlun Mountains from 2002 to 2024

However, the degree of association is relatively low, suggesting that rising temperature may inhibit lake expansion by intensifying evaporation.

From 2002 to 2024, terrestrial water storage on the northern slope of the Kunlun Mountains showed a significant increasing trend, with the increase being especially pronounced in the mountainous areas (Fig. 8). Spatially, terrestrial water storage in the Hotan River basin fluctuated only slightly from year to year, but displayed a spatial differentiation pattern of "decrease in the west and increase in the east." During the same period, terrestrial water storage in the Qarqan River basin and the Keriya River basin increased significantly, with rates of increase of $0.23\ \mathrm{mm \cdot month^{-1}}$ and $0.91\ \mathrm{mm \cdot month^{-1}}$, respectively ($P < 0.01$); the increase was most significant in mountainous areas. Zhu Chenggang et al. [17] found that the glacier accumulation in the northern slope of the Kunlun Mountains was generally stable, and that glacier area and thickness had increased slightly in recent years; surface runoff in the Qarqan River basin increased by 54.67% during 1998–2019 compared with 1957–1997 [18]. Increased summer precipitation in mountainous areas is often accompanied by cooling, especially in high-altitude regions [24]; in recent years, glacier mass balance in the Karakoram–Kunlun region has been stable or in positive balance [25]. Changes in lake water depth on the northern slope of the Kunlun Mountains further verify the driving effect of temperature rise on lake-area expansion. Satellite altimetry data show that lake water depth is strongly positively correlated with air temperature ($R^2 = 0.78$, $P < 0.01$), but only weakly correlated with precipitation ($R^2 = 0.25$, $P < 0.05$), indicating that changes in lake water volume in mountainous areas are mainly driven by snow and ice meltwater rather than precipitation recharge. This result further supports the dominant role of rising temperature in lake expansion.

Against the background of global warming, accelerated melting of snow and ice in arid regions has increased ice-and-snow meltwater, promoting downstream lake expansion and increases in river runoff. Since 1990, the number, area, and volume of glacier-fed lakes in high mountains worldwide have increased by 53%, 51%, and 48%, respectively [26]. From 2000 to 2020, the annual expansion rate of lakes on the Qinghai–Tibet Plateau reached $3.7\% \cdot \mathrm{a}^{-1}$–$5.2\% \cdot \mathrm{a}^{-1}$, significantly higher than the global mean level for high-mountain lakes of $1.2\% \cdot \mathrm{a}^{-1}$–$2.5\% \cdot \mathrm{a}^{-1}$ [27]. In this study, the annual expansion rate of lakes on the northern slope of the Kunlun Mountains reached $2.41\% \cdot \mathrm{a}^{-1}$, also higher than the global average; this may be related to the significant "temperature–elevation dependence" in the region. Existing studies have shown that the magnitude of warming on the Qinghai–Tibet Plateau and in high-altitude regions such as the Tianshan Mountains is generally higher than that in low-altitude areas [11,28]. The northern slope of the Kunlun Mountains has high glacier coverage and complex terrain, making it more sensitive to climate warming and changes in snow and ice meltwater. Meanwhile, the continued trend toward "warming and wetting" in the arid areas of northwestern China, together with improvement of the green-oasis ecological environment in the Tarim River basin [29], has jointly intensified the regional hydrological cycle. As global warming continues, hydrological-cycle processes in arid regions will be further strengthened, and uncertainty in water-resource regulation will also increase. Rapid expansion of glacier lakes at high elevations may increase the risk of outburst floods and mountain torrents, whereas lakes on low-altitude plains are affected by both climate change and human activities, and their fluctuations may potentially affect agricultural irrigation, industrial water use, and domestic water supply. Therefore, enhanced quantitative assessment and risk early warning are urgently needed.

4 Conclusions

(1) The number, area, and terrestrial water storage of lakes on the northern slope of the Kunlun Mountains all showed sustained increasing trends. From 1990 to 2024, the number of lakes on the northern slope of the Kunlun Mountains increased from 125 to 396, and the area increased from 1439.18 km^2 to 2614.22 km^2, representing increases of 216.80% and 81.65%, respectively. Lake expansion exhibited stage-specific characteristics: 1995–2000 was the peak expansion period; after 2005, although fluctuations occurred, the overall trend remained increasing. Among them, large lakes with areas > 250 km^2 increased in area by as much as 77.06% during 1990–2024; the rate of water-level rise was $0.40 \sim 0.48$ m $\cdot$ a^{-1}; lake water volume increased significantly, and regional water-storage capacity was markedly enhanced.

(2) There were significant spatial differences in lake expansion on the northern slope of the Kunlun Mountains. Over the past 35 years, lake area in the Qarqan River basin increased by 138.86 km^2 (increase ···

an increase of 364.65%. Among them, the largest increase occurred in 1995-2000, reaching 118.78 km^2 (an increase of 524.18%); the lake area in the Hotan River Basin increased by 46.98 km^2 (an increase of 94.62%), expanding by 51.07% and 30.26% in 1995-2000 and 2020-2024, respectively; the lake area in the Keriya Basin expanded most significantly, increasing by 989.20 km^2 (an increase of 73.20%). Although a short-term decrease occurred in 1990-1995, it rebounded rapidly during 2000-2010, increasing by 18.85% and 13.83% in 2000-2005 and 2005-2010, respectively.

(3) In terms of driving mechanisms, lake expansion in the mountainous area on the northern slope of the Kunlun Mountains is mainly jointly driven by glacier and snow meltwater induced by rising air temperature and by increased precipitation; the responses of the Qarqan River and Keriya basins are the most significant. By comparison, changes in lakes on the plains fluctuate more strongly. In addition to the influence of interannual fluctuations in rising air temperature and precipitation, they are also disturbed by human activities such as irrigation water withdrawal and groundwater exploitation, and their driving mechanisms are more complex. Overall, temperature change is the core climatic factor driving lake expansion on the northern slope of the Kunlun Mountains; mountain lakes are more

sensitive in their response to climatic forcing, whereas plain lakes reflect the coupled effects of natural factors and human activities.

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Spatiotemporal dynamic changes of typical lakes on the northern slope of Kunlun Mountains from 1990 to 2024

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Abstract: As sensitive indicators of climate change in arid regions, lakes provide critical insights into regional water resource allocation and utilization. Thus, the accurate identification of their spatiotemporal dynamics and driving mechanisms is of great significance. Employing multisource remote sensing and meteorological records from 1990 to 2024 and integrating the normalized difference water index with manual interpretation and correction, this study systematically extracted and cataloged lake dynamics on the northern slope of Kunlun Mountains. The spatiotemporal evolution of lakes and their driving mechanisms over the past 35 years were subsequently analyzed. The results indicate the following: (1) From 1990 to 2024, the number and total area of lakes on the northern slope of Kunlun Mountains increased significantly. While the number of lakes increased from 125 to 396 (216.80% increase), the total lake-area expanded from 1439.18 km^2 to 2614.22 km^2 (81.65% increase). (2) Spatially, the most significant lake-area expansion occurred in the Cherchen River Basin, where the lake-area increased by ~3.6 times, corresponding to a net gain of 138.86 km^2. This was followed by the Hotan River Basin, where the lake-area approximately doubled, with a net gain of 46.98 km^2, and the Kumukuli Basin, where the lake-area increased by 73.20%, corresponding to a net gain of 989.20 km^2. Regarding elevation, mountain lakes exhibited a net area increase of 1144.47 km^2, which was substantially higher than the 30.57 km^2 increase observed for plain lakes. (3) Temporally, lake-area variations exhibited distinct stage-wise characteristics. Lake-area declined from 1990 to 1995, with an average annual loss of 23.26 km$^{2\cdot a}$-1, followed by continuous expansion after 1995. Notably, this period accounted for a rapid increase of 52.56 km$^{2\cdot a}$-1. Between 2000 and 2005, the mean annual growth rate of lake-area was 39.90 km$^{2\cdot a}$-1. After 2005, the rate of extreme changes fluctuated slightly but maintained an overall increasing trend. (4) Lake expansion on the northern slope of Kunlun Mountains was primarily driven by glacier and snowmelt resulting from the combined effects of soaring temperatures and increased precipitation. Over the past

35 years, mountain water storage has increased markedly and was accompanied by increases of 35.30% and 13.18% in temperature and precipitation, respectively. The Cherchen River and Kumukuli Basin exhibited particularly strong responses to these climatic changes. Conversely, fluctuations in plain lakes were mainly governed by the synergistic effects of enhanced evaporative demand associated with rising temperatures and variability in precipitation. These findings provide important scientific evidence and policy-relevant implications for water resource management and climate impact assessment in the northern Kunlun Mountains region.

Keywords: normalized difference water index(NDWI); lake dynamic change; climate change; the northern slope of Kunlun Mountains

Note: Figure translations are in progress. See original paper for figures.