Lake Changes and Their Causes in the Kumu Kuli Basin, East Kunlun, 1986–2023: A Postprint

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Abstract

Systematic investigation of lake area variations and their causative mechanisms in the East Kunlun–Kumkuli Basin holds significant practical implications for understanding climate change and hydrological cycle characteristics in the East Kunlun mountainous region, as well as for addressing water resource scarcity issues in southern Xinjiang. Utilizing the Google Earth Engine (GEE) remote sensing cloud computing platform, water body extraction was conducted on remote sensing imagery of the East Kunlun–Kumkuli Basin spanning 1986–2023, and lake area changes along with their influencing factors were analyzed by integrating meteorological, glacial, land use, and other relevant datasets. The results indicate: (1) During the period 1986–2023, both the number and area of lakes in the East Kunlun–Kumkuli Basin exhibited increasing trends. The total lake area in the basin expanded from 1196.47 km2 in 1986 to 2190.43 km2 in 2023, representing an increase rate of 26.16 km2 · a-1. (2) From 1986 to 2023, Ayakekum Lake—the largest lake in the Kumkuli Basin—demonstrated the most pronounced area expansion, with its surface area increasing by 50.17%; the number of lakes exceeding 1 km2 in area rose from 6 in 1986 to 9 in 2023. (3) The lake area expansion in the East Kunlun–Kumkuli Basin is predominantly driven by temperature and precipitation, with precipitation serving as the primary factor, contributing 63.80% to the observed changes; temperature contributes through accelerated glacial meltwater supply to lakes, though its contribution rate is lower than that of precipitation.

Full Text

Preamble

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Lake Change and Genetic Analysis in East Kunlun Kumukuli Basin from 1986 to 2023

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Abstract: Conducting a systematic study on lake area changes and their underlying causes in the east Kunlun Kumukuli Basin holds significant practical importance for understanding climate change patterns and water cycle characteristics in the east Kunlun Mountains, and for addressing critical water shortage issues in southern Xinjiang. Utilizing the Google Earth Engine (GEE) remote sensing cloud computing platform, this study extracted water bodies from Landsat remote sensing images of the Kumukuli Basin spanning 1986–2023, and analyzed lake area changes and their influencing factors in combination with meteorological, glacier, and land use data. The results reveal several key trends: (1) Both the number and total area of lakes increased significantly, with basin-wide lake area expanding from 1196.47 km^2 in 1986 to 2190.43 km^2 in 2023, representing an average annual increase of 26.16 km^2. (2) Ayakumu Lake, the largest lake in the basin, exhibited the most pronounced expansion with a 50.17% increase in area, while the number of lakes larger than 1 km^2 grew from six in 1986 to nine in 2023. (3) The primary driver behind this lake expansion is precipitation, which contributes 63.80% of the increase. Although rising temperatures accelerate glacier melt that supplements lake water, temperature's contribution rate remains lower than that of direct precipitation input.

Keywords: lake area; temperature; precipitation; Kumukuli Basin

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Inland lakes exist within relatively independent interior water circulation systems, where variations in lake surface area represent the integrated outcome of water balance within their catchments. This balance is primarily constrained by the accumulation and evaporation of solid water resources such as glaciers and permafrost, along with surface water and groundwater inflow. Consequently, changes in lake size and quantity can reflect regional climate variations to some degree. As integral components of water bodies, lake area directly determines water storage capacity, which in turn influences basin water resources and affects water distribution, river discharge, and flood season dynamics. Plateau inland lakes, in particular, have significant impacts on basin water balance. These lakes are typically closed systems without outflow outlets, characterized by large surface areas and depths that provide strong water regulation capacity and enable better balancing of water variations between wet and dry seasons. Combined with the unique climatic conditions of the plateau, these lakes serve as ideal sites for investigating climate change impacts, feedback mechanisms, water balance, and climate interactions. Most lakes on the Tibetan Plateau are inland lakes minimally affected by human activities, responding primarily to natural environmental changes and thus serving as indicators of regional climate conditions. Numerous studies have demonstrated lake sensitivity to climate change, showing that physical, chemical, and biological lake characteristics respond rapidly to climatic fluctuations.

Systematic monitoring and analysis of lakes in the Kumukuli Basin using remote sensing imagery have been conducted by various researchers. Zhou et al. analyzed salt lake area changes in the Kumukuli Basin using Landsat imagery from multiple periods combined with meteorological data, finding that average temperature, precipitation, and relative humidity all promoted lake expansion, with temperature playing a dominant role. Li et al. examined the temporal variation of Ayakumu Lake area and its climate response, revealing that after 2000, lake area exhibited staged expansion well-correlated with winter temperature surges. Zhang et al. studied Ayakumu Lake's changes from 1973–2018, noting slight fluctuations before 2000 followed by accelerated expansion afterward, with positive correlations to annual precipitation and temperature. Chen et al. identified regional climate warming and wetting as the primary background for Ayakumu Lake's water volume increase, with increased precipitation directly driving water level rises and sustained temperature increases promoting glacier melt that significantly contributed to lake expansion. While these studies examined changes in major lakes such as Ayakumu, Aqikekule, and Whale Lake during different periods, they were limited by short remote sensing time spans and large intervals, making it difficult to capture recent basin-wide changes and detailed interannual trends over extended periods. This study utilizes long time-series Landsat imagery to extract lake water body information from 1986–2023, systematically investigating spatiotemporal variation characteristics of lakes larger than 1 km^2 while integrating meteorological, hydrological, and glacier data to analyze driving mechanisms.

1 Study Area Overview

The Kumukuli Basin is located between the Altun Mountains and Kunlun Mountains (35°30 –37°30 N, 87°30 –92°00 E), representing a typical tectonic basin and a closed, high-altitude intermontane basin. The basin 主体 lies between the Kunlun Mountains and Qimantag Mountain, with China's highest desert (Kumukuli Desert) in the east, Qimantag Mountain to the north, Kumubuyan Mountain to the west, and extension to the Arkar Mountains in the south. Situated on the northern margin of the Tibetan Plateau, the basin has long been influenced by plateau tectonic movements, undergoing prolonged, multi-dimensional uplift events that ultimately formed its characteristics as a closed, high-altitude fault basin. The basin extends approximately 550 km east-west, with a maximum width of 350 km in the central region, exhibiting a topography that is lower in the east and higher in the west. The central Langya Mountain divides the water system into the Aqikekule Lake watershed and Ayakumu Lake watershed. The highest point is Muztag Peak in the southwest corner, while the lowest is Ayakumu Lake.

The basin climate is dry and cold, without summer seasons, with an average annual temperature of -4.6°C and July as the warmest month (average 6–8°C). Annual precipitation ranges 100–200 mm, concentrated in summer, increasing from west to east spatially. Higher elevations around the basin receive more precipitation, with mountain valleys being relatively humid. Rivers including the Pitilek, Seskeya, and Aqikekule flow through the basin, collecting precipitation from surrounding high mountains and creating numerous plateau lakes. The basin contains Xinjiang's largest lake (Ayakumu Lake) in the north, its second-largest lake (Aqikekule Lake) in the west, and its highest-altitude lake (Whale Lake) in the south. The basin's lakes are rich in brine with surface brine covering entire lake surfaces. Prevailing westerly and northwesterly winds with speeds of 10–15 $m \cdot s^{-1}$ create significant sandstorms. Sparse vegetation and exposed rocks and soils characterize this high-cold desert vegetation zone.

[Figure 1: see original paper]

2 Data and Methods

2.1 Data Sources and Preprocessing

To achieve long-term dynamic monitoring of lake areas in the Kumukuli Basin, this study selected the Landsat Global Surface Water dataset from the GEE database as the primary data source. High-quality remote sensing image datasets covering the study area from 1986–2023 were selected, with images from July–September (when lakes are ice-free) and cloud cover less than 10%. Downloaded remote sensing images underwent correction, cloud removal, and shadow removal processing. Appropriate band combinations were selected based on Landsat imagery characteristics. Using the GEE platform, cloud mask extraction algorithms removed invalid images and masked areas affected by mountain shadows, clouds, and glacier snow.

To investigate lake change causes, this study employed third-pole region long-term high-resolution (1/30°) temperature and precipitation datasets from 1986–2020 to analyze relationships between lake area changes and climatic variations. Meteorological data were obtained from the National Tibetan Plateau Science Data Center (http://data.tpdc.ac.cn/zh-hans/), while glacier data derived from two glacier inventories and project interpretations.

2.2 Methods

2.2.1 Calculation of Modified Normalized Difference Water Index Water index methods utilize spectral characteristics by selecting spectral bands related to water information, constructing appropriate models to calculate water index values, and selecting optimal thresholds for water body extraction. The Modified Normalized Difference Water Index (MNDWI) offers high computational efficiency and strong water identification capability, particularly for turbid water, high vegetation cover areas, and distinguishing snow/ice from water. The formula is:

$$\text{MNDWI} = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}}$$

where Green is the green band and SWIR is the short-wave infrared band.

2.2.2 GEE-Based Water Area Extraction Algorithm Using the GEE platform, annual lake areas in the Kumukuli Basin were extracted through the following steps: (1) Import the study area vector file and set the extraction period to 1986–2023. (2) Image clipping and compositing: Filter Landsat series data to obtain original imagery for the Kumukuli Basin, applying masks for mountain shadows, clouds, and glacier snow. (3) Generate annual MNDWI: Select appropriate bands for pixel-by-pixel MNDWI calculation. Values closer to 1 indicate higher likelihood of water. (4) Calculate water frequency and extract water bodies: The Otsu algorithm, a threshold segmentation method based on maximum inter-class variance, automatically calculates optimal thresholds for water/non-water separation. Pixels with MNDWI values exceeding the threshold are classified as water. (5) Extract individual lake boundaries and calculate water area: Lake area equals the sum of all valid water pixel areas multiplied by water frequency. (6) Export results, water images, and original images to extract lake areas from 1986–2023.

Through GEE platform extraction and calculation of lake water bodies from 1986–2023, this study identified 9 lakes larger than 1 km^2 in the Kumukuli Basin: Ayakumu Lake, Aqikekule Lake, Whale Lake, Yixiekepati Lake, Kumukule Lake, Keqikekumukule Lake, Xiaoku Lake, Beilike Lake, and Beilekeleke Lake. After MNDWI calculation combined with visual interpretation of multi-temporal lake images (Fig. 2), the algorithm demonstrated reliable extraction results.

[Figure 2: see original paper]

2.2.3 Pearson Correlation Analysis Pearson correlation analysis is a widely used statistical method for measuring linear relationships between two variables. The Pearson correlation coefficient remains relatively stable and is less affected by extreme values. This study employed Pearson correlation for long-term trend detection and correlation analysis between lakes and meteorological factors:

$$R = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where R is the Pearson correlation coefficient, X_i is the lake area data for month i, $\bar{X}$ is the mean lake area, Y_i is the climate factor (temperature or precipitation) for month i, and $\bar{Y}$ is the mean climate factor value.

3 Results

3.1 Lake Area Changes

From 1986–2023, the number of lakes in the Kumukuli Basin showed an increasing trend, growing from 6 lakes in 1986 to 9 lakes after 2000. While new lakes have formed, the primary area increase resulted from expansion of existing tectonic lakes formed by intense basin uplift, north-south compression, east-west extension, and fault block subsidence. The largest tectonic lake is Ayakumu Lake, followed by Aqikekule Lake, with Whale Lake being the highest-altitude tectonic lake. Under neotectonic and climatic influences, these lakes exhibit distinct north-south zonation and east-west partitioning.

Overall, Kumukuli Basin lake area displayed a "shrinkage-expansion" trend from 1986–2023. Lake area decreased from 1196.47 km^2 in 1986 to 1081.86 km^2 in 1990, expanded to 1298.86 km^2 by 2000, shrank again to 1195.30 km^2 in 2005, then entered a fluctuating expansion phase after 2010, reaching 2180.34 km^2 by 2023. The total area increased by 993.96 km^2 at an average rate of 26.16 $km^2 \cdot yr^{-1}$. Ayakumu Lake contributed most significantly to this expansion, increasing by 556.93 km^2 (growth rate 48.60 $km^2 \cdot yr^{-1}$), followed by Aqikekule Lake (+243.02 km^2) and Whale Lake (+14.66 km^2).

3.2 Characteristics of Typical Lake Area Changes

Ayakumu Lake, Aqikekule Lake, and Whale Lake all showed significant expansion trends throughout the study period ($P < 0.05$). Ayakumu Lake expanded most dramatically, primarily extending toward the Yixiekepati River, constrained by terrain to form a wide-middle, narrow-ends shape. Aqikekule Lake grew from 332.15 km^2 to 595.80 km^2 (growth rate 6.94 $km^2 \cdot yr^{-1}$), expanding mainly southwestward. Whale Lake, the highest-altitude lake in the basin, showed minimal change, increasing from 386.75 km^2 to 400.41 km^2 (growth rate 3.44 $km^2 \cdot yr^{-1}$), expanding primarily southeastward.

[Figure 3: see original paper] [Figure 4: see original paper]

3.3 Influencing Factors of Lake Evolution

3.3.1 Climate Change Impacts Climate change significantly affects inland lake formation and evolution by altering precipitation, evaporation, and ice/snow storage. From 1986–2020, the Kumukuli Basin's average annual temperature showed an increasing trend at $0.26°C \cdot (10a)^{-1}$, exceeding the national average of $0.22°C \cdot (10a)^{-1}$. After 2000, temperatures remained in a high oscillation phase, averaging -3.0°C compared to -4.6°C before 2000. Annual precipitation also showed fluctuating increases.

Correlation analysis revealed significant positive correlations between both temperature and precipitation with lake area ($P < 0.05$). Temperature-lake area correlation was $R^2 = 0.478$ ($P < 0.05$) for 1986–2020, while precipitation-lake area correlation was $R^2 = 0.677$ ($P < 0.01$). Using geographical detector models, precipitation contributed 63.80% to lake area expansion, while temperature contributed 41.22%, primarily through accelerating glacier melt.

[Figure 5: see original paper]

3.3.2 Glacier Change Impacts As crucial cryosphere components, glaciers respond sensitively to climate change. Under warming conditions, glaciers have retreated continuously, with studies indicating Tibetan Plateau ice storage decreased to current levels by the end of the 20th century. In endorheic regions, glacier melt is a major lake water source. The Kumukuli Basin's high altitude makes its glaciers exceptionally sensitive to climate change, with substantial glacier distribution across the Kunlun, Arkar, Qimantag, and Kumubuyan mountains (Fig. 6).

From 1990–2020, total glacier area in the basin decreased from 654.86 km^2 to 629.92 km^2 (retreat rate 0.83 $km^2 \cdot yr^{-1}$). Ayakumu Lake watershed retreated 5.27 km^2 (0.18 $km^2 \cdot yr^{-1}$), Aqikekule Lake watershed 3.28 km^2 (0.11 $km^2 \cdot yr^{-1}$), and Whale Lake watershed 16.39 km^2 (0.55 $km^2 \cdot yr^{-1}$). Glacier storage decreased by 65.78 km^3 (retreat rate 2.34 $km^3 \cdot yr^{-1}$), with Ayakumu Lake watershed showing the highest retreat rate. Glacier area and lake area showed significant negative correlation ($R^2 = 0.83$, $P < 0.01$), indicating glacier retreat contributed to lake expansion.

[Figure 6: see original paper] [Figure 7: see original paper]

3.3.3 Land Use Impacts Kumukuli Basin lakes are located in uninhabited areas with minimal human impact. Different land use types affect watershed-scale infiltration, runoff generation, evapotranspiration, and water supply-demand relationships, thereby influencing lake area. Analysis of Landsat imagery from 1990, 2000, 2010, and 2020 revealed four primary land use types: bare land (64.44–73.62%), grassland (22.71–31.33%), water bodies (1.31–2.31%), and ice/snow (2.02–3.74%).

From 1990–2020, water body area increased from 1.31% to 2.32% of the study area, while grassland decreased from 28.01% to 26.44% and bare land expanded. Grassland degradation resulted from intensified drought conditions on the Tibetan Plateau, reducing vegetation cover, expanding bare land, decreasing water conservation capacity, and allowing more water to flow into lakes, thereby expanding lake area.

[Figure 8: see original paper] [Figure 9: see original paper]

4 Discussion

Located on the northern margin of the Tibetan Plateau, the Kumukuli Basin is an intermontane fault basin formed during plateau uplift, with climate strongly influenced by the Tibetan Plateau. Under global warming, this region exhibits particularly significant temperature increases, with warming rates exceeding global averages and precipitation showing multi-scale variation trends primarily characterized by increases. This study's finding of significant lake area expansion positively correlated with temperature aligns with previous research.

While rising temperatures should theoretically increase evaporation and reduce lake area, the observed lake expansion in Kumukuli Basin is primarily attributed to increased glacier melt and permafrost thaw supplementation. Sustained temperature increases have caused rapid water level rises in high-altitude, glacier-fed lakes, particularly in northern Tibet where lake expansion is dominated by increased glacier melt. However, if glacier retreat continues under global warming, Kumukuli Basin lakes may eventually shrink. Future research should continue monitoring climate, glacier, river, and lake changes to predict future water resource conditions. Under the premise of maintaining ecosystem stability, exploring possibilities for utilizing excess water resources through diversion could help alleviate water shortages in Xinjiang or the Qaidam Basin.

5 Conclusions

Based on 1986–2023 Landsat imagery and GEE platform analysis of Kumukuli Basin lake areas, this study reveals spatiotemporal variation characteristics and investigates causes using temperature and precipitation raster data. Major conclusions are:

1) Kumukuli Basin lake area showed significant overall growth, experiencing a "shrinkage-expansion" transformation. Total lake area increased by 993.96 km^2 from 1196.47 km^2 in 1986 to 2190.43 km^2 in 2023, with an average annual increase of 26.16 km^2. Ayakumu Lake contributed most to this expansion, increasing by 556.93 km^2 (growth rate 48.60 $km^2 \cdot yr^{-1}$).

2) Ayakumu Lake, Aqikekule Lake, and Whale Lake contributed most to basin-wide lake expansion, all showing significant growth trends ($P < 0.05$). Ayakumu Lake showed the most significant increase, expanding by 243.02 km^2 (growth rate 14.66 $km^2 \cdot yr^{-1}$).

3) Kumukuli Basin lake area changes showed significant positive correlation with temperature and precipitation ($P < 0.01$). Precipitation is the primary factor driving lake expansion, while temperature is an important factor. Glacier changes showed negative correlation with lake area, serving as an indirect influencing factor.

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