Temporal Variation and Attribution of Lake Barkol Area in Xinjiang, 1995-2020: Postprint

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Abstract

Barkol Lake is an inland closed lake situated in the eastern Tianshan Mountains. Understanding its evolution characteristics holds great significance for lake conservation and ecological environment management. This study extracted the time series of lake surface area from 1995 to 2020 using 308 scenes of Landsat and Sentinel-2 remote sensing imagery, and analyzed the lake' s changing trends under the influences of climate change and human activities by incorporating meteorological data from the Barkol weather station and cultivated land area data extracted from remote sensing imagery. The results indicate that the lake experienced two distinct phases: a shrinkage phase from 1995 to 2006, during which the annual mean area decreased from 57.33 km^2 to 35.53 km^2 at a rate of 1.98 km$^2 \cdot$ a^{-1}, representing a 35.79% reduction; and an expansion phase from 2006 to 2020, during which the annual mean area increased from 35.53 km^2 to 46.59 km^2 at a rate of 0.79 km$^2 \cdot$ a^{-1}, representing a 31.12% increase. Multi-year statistical analysis of monthly lake area variations reveals that the lake attains its maximum area in May (73.09$\pm 21.01km^{\{2\})anditsminimumareainNovember(43.90\pm 16.97km}\{2\}$). Regarding influencing factors: from 1995 to 2006, precipitation exhibited minor variations, while increased agricultural water consumption and evaporation were the primary causes of Barkol Lake' s shrinkage; after 2006, Barkol County implemented various wetland protection measures that controlled the expansion trend of cultivated land, and significantly increased precipitation coupled with decreased evaporation became the main drivers of lake area expansion.

Full Text

Temporal Variation in the Barkol Lake Area and Its Driving Factors in 1995-2020

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Abstract

Barkol Lake is a closed inland lake located in the eastern Tianshan Mountains. Understanding its evolutionary characteristics is crucial for lake protection and ecological environment management. This study extracted time series of lake water surface from 1995 to 2020 using 308 Landsat series and Sentinel-2 remote sensing images. Combined with meteorological data from Barkol Station and cultivated land area data extracted from remote sensing imagery, we analyzed lake change trends under climate change and human activity influences through time series analysis, correlation analysis, Mann-Kendall trend analysis, and abrupt change testing. Results show that Barkol Lake experienced two distinct stages: from 1995 to 2006, the lake area shrank significantly from an annual mean of 57.33 km^2 to 35.53 km^2 at a rate of -1.98 $km^2 \cdot a^{-1}$, representing a 35.79% reduction; from 2006 to 2020, the area expanded from 35.53 km^2 to 46.59 km^2 at a rate of 0.79 $km^2 \cdot a^{-1}$, achieving a 31.12% increase. Monthly statistics reveal that the lake reached its maximum area of $(73.09\pm21.01) km^{2}$ in May and minimum of $(43.90\pm16.97) km^{2}$ in November. Regarding driving factors, during 1995–2006, precipitation showed minimal variation while increased agricultural water consumption and evaporation were the primary causes of lake shrinkage. After 2006, Barkol County implemented various wetland protection measures that controlled cultivated land expansion, and the lake area increase was mainly driven by significantly higher precipitation and reduced evaporation.

Keywords: Barkol Lake; lake area change; remote sensing; influencing factors; Xinjiang

1. Introduction

Inland lakes in arid regions represent critical water resources that are highly sensitive to climate change and human activities, playing vital roles in maintaining regional socioeconomic development and ecological balance. In recent decades, intensified water resource exploitation has caused severe lake shrinkage and even disappearance, seriously damaging inland lake ecosystems. Consequently, studying the spatiotemporal dynamics of arid region lakes and investigating impacts of natural and anthropogenic factors are essential for lake resource development and ecological protection. However, many lakes in arid regions lack hydrological observation data, making remote sensing technology the primary approach for information reconstruction in data-scarce areas.

The volume of remote sensing data required for lake information reconstruction varies depending on geographic location and basin characteristics. For large alpine lakes with regular changes, interannual area variations can reflect water volume changes. However, lakes with substantial seasonal fluctuations require monthly area change data, particularly for shallow lakes with gentle basins where water level changes frequently. Sparse imagery cannot fully characterize the temporal variation process. Dense time-series satellite remote sensing data can accurately describe seasonal water surface fluctuations. Therefore, for unstable lakes, dense long-term remote sensing imagery is more effective for exploring change mechanisms and responses to climate and human activities.

Barkol Lake is a typical alpine inland lake with a gentle basin, large seasonal water surface differences, and high sensitivity to climate change and human activities. The Barkol inland basin has undergone large-scale agricultural development for decades, with extensive cultivated land severely reducing inflow water and causing lake shrinkage and surrounding wetland degradation. Since 1995, the lake has been divided into two parts, and western exploitation of mirabilite resources has further damaged the ecological environment. Against the background of national "mountain-river-forest-farmland-lake-grassland" ecosystem restoration, investigating Barkol Lake' s changes and driving factors over recent decades is significant for lake ecosystem management and rational water resource development.

Current research on Barkol Lake primarily focuses on paleoclimate and environmental change reconstruction from lake sediments, with limited modern area change studies using only a few remote sensing images or short study periods. These approaches cannot clearly describe the temporal change process or systematically investigate key influencing factors. For such dramatically changing lakes with gentle basins and frequent water level fluctuations, dense time-series remote sensing imagery is needed to monitor seasonal changes and analyze key driving factors of water volume changes. This study uses long-term Landsat imagery supplemented by Sentinel-2A/2B data to extract dense time-series lake area information from 1995 to 2020, reconstruct monthly-scale lake changes, analyze water regime changes after dam construction from annual, monthly, and spatial perspectives, and identify key driving factors combined with climate elements and agricultural development, thereby providing references for lake ecosystem restoration and protection.

1.1 Study Area Overview Barkol Lake (43°36 -43°43 N, 92°43 -92°51 E) is located approximately 18 km northwest of Barkol Kazakh Autonomous County in Hami Prefecture, Xinjiang. As the terminal lake for numerous rivers on the northern slope of the Tianshan Mountains, its largest tributary is the Liutiao River, originating from the southern slope of the Moqinwula Mountains in the eastern Tianshan range with a catchment area of 4500 km^2. The lake sits at an elevation of about 1575 m, with maximum depth of 1.1 m and average depth of 0.5 m. Annual precipitation is 210 mm and annual evaporation reaches 1620 mm. The lake contains abundant Artemia and mirabilite resources, with mirabilite distribution covering approximately 60 km^2, representing a characteristic resource of Barkol County. In 1995, large-scale mirabilite dehydration engineering divided the lake with a dam, separating it into an eastern brine area and western anhydrous mirabilite mining area.

1.2 Data Sources and Processing **Remote Sensing Data:** Landsat series satellite imagery (Landsat-5 TM, Landsat-7 ETM+, Landsat-8 OLI) were obtained from the United States Geological Survey (USGS) at Level-1 processing. These data underwent geometric and terrain correction with errors within half a pixel, maintaining consistent radiometric and geometric quality across sensors and time periods. Landsat' s long-term repetitive coverage capability includes orbit P139R030, which completely covers Barkol Lake. Additionally, 55 Sentinel-2 images were used to supplement incomplete monthly data. For Landsat-7 data after the Scan Line Corrector failure, gap-filling was performed using adjacent temporal images with minimal lake boundary changes [Figure 2: see original paper].

Meteorological Data: Daily climate data from Barkol Meteorological Station were selected for three key factors: precipitation, temperature, and evaporation. Annual evaporation data were only available until 2018.

Cultivated Land Data: Based on Hami Statistical Yearbook, Barkol County' s crops are primarily spring wheat, supplemented by cotton, potatoes, Hami melons, and vegetables. Combining crop phenology and remote sensing observations, cultivated land area was extracted through visual interpretation of Landsat imagery in ArcMap during July-August, with multi-month results synthesized into annual cultivated land area.

1.3 Research Methods A semi-automated approach extracted lake area ranges using the Normalized Difference Water Index (NDWI). ENVI+IDL software determined segmentation thresholds from histograms, converted raster files to vector format, and batch-processed the data. Manual editing in ArcMAP ensured correct lake boundary delineation for each image. Temporal variation analysis employed line charts to observe trends, using annual maximum, minimum, and mean values to analyze change rates and significance through Mann-Kendall trend testing. Monthly data from multiple years characterized seasonal patterns, while multi-temporal vector boundaries analyzed spatial changes after dam construction. Driving factors were examined through change tendency rates, Mann-Kendall abrupt change tests, and Pearson correlation analysis between water surface area and various factors.

2. Results

2.1 Temporal Variation of Water Surface Barkol Lake area showed dramatic interannual variation with distinct fluctuation amplitudes and means across periods, displaying an overall trend of initial decline followed by increase. The lake experienced two stages from 1995-2020: significant shrinkage from 1995-2006 (annual mean decreasing from 57.33 km^2 to 35.53 km^2 at -1.98 $km^2 \cdot a^{-1}$) and significant expansion from 2006-2020 (annual mean increasing from 35.53 km^2 to 46.59 km^2 at 0.79 $km^2 \cdot a^{-1}$). The minimum area (13.10 km^2) occurred in 2002, while the maximum (105.44 km^2) occurred in 2019. Due to dam construction, when inflow was insufficient, water could not flow westward; during high water periods, overflow caused sudden area increases, making annual maximum values highly variable. The critical area for water crossing the dam was 62.55 km^2; exceeding this threshold allowed water to spill into the western section [Figure 3: see original paper].

2.2 Seasonal Variation of Water Surface Barkol Lake exhibited substantial intra-annual fluctuations. Monthly multi-year means and standard deviations revealed that lake area generally increased from January to May, reaching maximum values, then continuously shrank from June to November to minimum values. The overall multi-year mean was 57.16 km^2, with standard deviation of 17.16 km^2. Standard deviation was largest in May (21.01 km^2) and smallest in November (16.97 km^2), indicating more stable lake surfaces in winter.

Because a dam divides the lake into east and west sections, different seasonal patterns emerged. When eastern water levels remained below the dam crest, water was confined to the eastern side, creating a crescent shape with smooth seasonal variation and small multi-year mean standard deviation of 8.84 km^2. When water overtopped the dam, sudden area increases occurred in the west. However, without sustained inflow, the shallow western water body quickly evaporated, creating larger seasonal differences and more dramatic fluctuations [Figure 4: see original paper].

2.3 Spatial Variation Characteristics To describe spatial change patterns, six typical lake boundaries were selected—three without dam overflow and three with overflow—and overlaid on Landsat imagery. When eastern water remained below the dam' s minimum elevation, the lake presented as a crescent shape. The southern and southeastern boundaries near the Tianshan Mountains showed only minor changes due to steep slopes, while the northern and northeastern shorelines changed significantly, representing the main spatial change direction. When water exceeded the dam' s southern end (the lowest point), it rapidly expanded northward across the flat western basin, causing sudden area increases. With sufficient overflow, the lake shape approximated its original elliptical form before dam construction. As a seasonal lake in an area with strong evaporation, when eastern inflow ceased, water levels dropped, overflow stopped, and the shallow western area quickly dried, returning the lake to its crescent shape. Thus, post-dam spatial changes became more dramatic and periodic [Figure 5: see original paper].

3. Analysis of Area Change Causes

3.1 Climate Characteristics of the Barkol Lake Region Precipitation data from 1990–2020 showed an overall increasing trend with a change tendency rate of 22.05 mm $\cdot$ $(10a)^{-1}$. Mann-Kendall testing identified an abrupt change point in 2006, with precipitation mostly below the mean before 2006 and above after. Temperature showed an overall upward trend (0.456°C $\cdot$ $(10a)^{-1}$) with a significant increasing trend after 1997 ($P<0.05$). Evaporation displayed a decreasing trend (-91.69 mm $\cdot$ $(10a)^{-1}$), with an increasing trend before 2002 and decreasing trend after, reaching significant levels after 2006 ($P<0.05$) [FIGURE:6-8].

3.2 Cultivated Land Changes in the Barkol Lake Region Cultivated land in the basin distributes linearly along the Liutiao River and Barkol wetlands. Visual interpretation of Landsat imagery revealed that total cultivated land area increased from 309.9 km^2 in 1995 to 368.8 km^2 in 2006, with rapid expansion before 2006 and minimal change after 2006. Spatial distribution frequency analysis showed early cultivation concentrated near both sides of Barkol wetlands, gradually expanding outward [Figure 9: see original paper].

3.3 Correlation Between Barkol Lake Area and Influencing Factors Pearson correlation analysis between lake water surface area and influencing factors across three periods (1995–2006 decline, 2006–2011 fluctuation, 2011–2020 rise) revealed that temperature showed weak negative correlation with lake area across all periods, indicating limited direct impact. Precipitation correlated positively with lake area only during 2011–2020 ($P<0.05$), suggesting increased precipitation was an important factor for lake expansion. Evaporation showed extremely significant negative correlation with lake area across all periods ($P<0.01$), indicating its crucial influence. Cultivated land area showed extremely significant negative correlation during 1995–2006 ($P<0.01$), the period of highest correlation and primary factor for lake shrinkage, but weaker correlation in other periods .

4. Discussion

For inland lakes with minimal human disturbance, closed basins and weak anthropogenic activity make lake area extremely sensitive to climate change, allowing dominant factors to be identified through climate analysis alone. However, Barkol Lake experiences strong human intervention, requiring combined analysis of climate and human activity factors. Atmospheric precipitation and seasonal snowmelt runoff constitute the main water sources, making upstream irrigation interception a critical factor affecting inflow. During periods with small precipitation changes (1995–2006), lake area trends were determined by increased agricultural water use and evaporation. During periods with significant precipitation trends (2006–2020), precipitation became an important factor for lake area changes.

Agricultural water use in Barkol County accounts for 79.59% of total water resource utilization. To meet water demands from expanding cultivated land, severe groundwater over-exploitation caused water table declines of 2.9 m in the county seat, 1.27 m in Kuisu Town, and 1.25 m in Dahe Town from 2006–2013, reducing subsurface water supply to the lake. Additionally, numerous small reservoirs built in downstream gullies created multiple layers of flow interception, further decreasing inflow. Therefore, increased agricultural water consumption reduced lake water supply from both surface and groundwater sources.

In 2006, Barkol County government issued the "Interim Measures for Ecological Function Protection and Management of Barkol Lake," controlling cultivated land expansion and increasing water-saving irrigation area annually. Under the "land quota, household total" water management model, agricultural water use was controlled. By 2019, the region' s water-saving irrigation area reached 1.92$\times10^{4}$ hm^2, accounting for 82.7% of irrigated area, reducing agricultural water consumption and increasing inflow. This policy marked the turning point from lake shrinkage to expansion. However, evaporation remained the primary water consumption pathway as an endorheic lake without outflow, significantly affecting lake area throughout the study period.

5. Conclusions

1) **Interannual variation characteristics**: Barkol Lake shrank from 1995–2006 (annual mean decreasing from 57.33 km^2 to 35.53 km^2 at -1.98 $km^2 \cdot a^{-1}$, 35.79% reduction) then expanded from 2006–2020 (annual mean increasing from 35.53 km^2 to 46.59 km^2 at 0.79 $km^2 \cdot a^{-1}$, 31.12% increase).

2) **Seasonal variation characteristics**: Lake area increased from January to May, reaching maximum values, then shrank from June to November to minimum values. Years without dam overflow showed smooth seasonal variation, while overflow years exhibited sudden area increases and greater seasonal differences.

3) **Spatial variation characteristics**: When eastern water remained below the dam crest, the lake presented as a crescent shape with major shoreline changes in the north and northeast. When water overtopped the dam' s southern end, rapid northward expansion occurred in the western basin, potentially restoring the pre-dam elliptical shape. Post-dam spatial changes became more dramatic and periodic.

4) **Driving factors**: From 1995–2006, increased agricultural water use and evaporation were the main causes of lake shrinkage. After 2006, wetland protection measures controlled cultivated land development, and the lake area increase was primarily driven by significantly increased precipitation and decreased evaporation.

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