Lake Changes and Their Driving Factors on the Mongolian Plateau, 2000-2020: A Postprint

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Abstract

Based on Landsat remote sensing imagery, lake area information for water bodies exceeding 1 km^2 in the Mongolian Plateau was extracted annually from 2000 to 2020 to analyze their spatiotemporal variation characteristics. The results indicate that: (1) Prior to 2009, both lake area and quantity exhibited a decreasing trend, whereas after 2009 they displayed an increasing trend; overall, during 2000–2020, lake area and quantity showed a decreasing trend. (2) Variations differed significantly among lake size classes, with super-large and medium-sized lakes remaining relatively stable, while large lakes experienced the most substantial reduction. (3) Lake changes also varied regionally, with lakes in the northwestern region remaining relatively stable and those in the central-eastern region undergoing more drastic changes. (4) The spatial clustering of lakes in the study area demonstrated a weakening trend with heterogeneous causes but consistent direction. (5) Lake area showed significant correlations with mean annual temperature, annual precipitation, annual evaporation, vegetation index, and four-layer soil moisture, with pronounced differences in the degree of influence between the two time periods. Understanding the spatiotemporal dynamics of lakes on the Mongolian Plateau and their underlying causes provides a valuable reference for research on climate regulation and biodiversity conservation in the Mongolian Plateau and globally.

Full Text

Lake Changes and Their Influence Factors in the Mongolian Plateau from 2000 to 2020

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Abstract

Based on Landsat remote sensing imagery, this study extracted lake area information for water bodies exceeding 1 km^2 across the Mongolian Plateau and analyzed their spatiotemporal variation characteristics from 2000 to 2020. The results demonstrate: (1) Both lake area and quantity exhibited decreasing trends before 2009 and increasing trends thereafter, though the overall study period showed a net decline. (2) Lakes of different size classes displayed markedly different patterns of change, with super-large and medium-sized lakes remaining relatively stable while large lakes experienced the most significant reduction. (3) Regional variations were also evident, with relatively stable conditions in the northwest but more dramatic changes in the central and eastern regions. (4) The spatial distribution agglomeration of lakes showed a weakening trend with heterogeneous causes but consistent directionality. (5) Lake area correlated significantly with annual mean temperature, precipitation, evaporation, vegetation index, and four-layer soil moisture, though the degree of influence varied distinctly between the two sub-periods. Understanding the spatiotemporal dynamics of lakes in the Mongolian Plateau and their driving mechanisms provides a valuable reference for climate regulation and biodiversity conservation research in the region and globally.

Keywords: lakes; temporal and spatial changes; influencing factors; Mongolian Plateau

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Lakes serve as crucial water resources with multiple functions, including climate regulation, flood control and irrigation, industrial and domestic water supply, and supporting aquatic ecosystems. They foster the development of fisheries, improve regional ecological environments, enhance environmental quality, and provide recreational spaces, playing vital roles in both ecological and economic development [1]. The Mongolian Plateau, with its vast territory, complex topography, diverse vegetation types, and harsh natural conditions, represents a sensitive zone responding to global change [2]. Among the nine known global migratory bird routes, three pass through the Mongolian Plateau. The plateau hosts numerous lakes, mostly small and shallow with pronounced seasonal fluctuations. Under the influence of climate change and human activities, plateau lakes have experienced substantial reductions in both area and number over recent decades [3-5]. Lake area contraction and water level decline have increased dust storm frequency, deteriorated the ecological environment of lake regions, and impacted bird breeding habitats, leading to decreased reproductive populations [6-8]. Research on lake changes in the Mongolian Plateau remains limited, with most studies concentrating on typical large lakes [9-10] and focusing primarily on meteorological and anthropogenic factors [11-12]. Investigations of small lakes and the relationship between lake area and soil environmental factors are relatively scarce. Therefore, monitoring the spatiotemporal distribution characteristics of lakes in the Mongolian Plateau and revealing their influencing factors using multi-angle natural element data holds significant practical importance for climate change research, protection of migratory bird habitats, and water environment and fauna-flora studies in the region and beyond.

1 Study Area Overview

The Mongolian Plateau is located in northeastern Asia, extending from the Greater Khingan Mountains in the east to the Altai Mountains in the west, bounded by the Sayan, Khentei, and Yablonovy ranges in the north. In the narrow sense, its southern limit reaches the Yinshan Mountains [13], while in the broad sense it extends southward along the Great Wall [14], encompassing the entirety of Mongolia, southern Russia, and northern China. This study selected the main body of the Mongolian Plateau within Mongolia and China' s Inner Mongolia region (Fig. [Figure 1: see original paper]), with geographic coordinates between 87.50°–126.07°E and 37.25°–53.10°N. The terrain shows considerable relief, gradually decreasing from west to east. The topography is complex and diverse, featuring high mountains, medium mountains, low mountains, hills, plateaus, and plains. The northwestern part belongs to humid and semi-humid zones with predominantly high and medium mountain terrain and vegetation types including montane coniferous forests, typical steppe, and meadow steppe. The southwestern part is arid, characterized mainly by hills and plains with vegetation of Gobi desert and desert steppe. The central-eastern region is primarily semi-arid, with numerous plains, hills, and platforms, and typical steppe vegetation. The eastern area is climatically humid and semi-humid, with medium mountains and hills supporting diverse vegetation including broadleaf forests, coniferous forests, meadow steppe, shrubland, and farmland. The southern region is semi-arid, dominated by hills, plains, and sandy land with sandy vegetation, shrubland, and farmland.

2 Data and Methods

2.1 Data Sources

This study utilized Landsat TM/ETM+/OLI series satellite imagery from the United States Geological Survey (USGS) as the primary data source, selecting cloud-free images from the flood season (July–August) for each year from 2000 to 2020, with occasional substitutions from June or September when necessary. Digital elevation data (DEM) were derived from SRTM data jointly measured by NASA and the Department of Defense National Geospatial-Intelligence Agency. Vegetation index and daytime land surface temperature data were obtained from MOD13A2 and MOD11A2 MODIS products, respectively. Meteorological components including temperature, precipitation, and evaporation were sourced from the ERA5-Land reanalysis dataset [15] from the Copernicus Climate Data Store, with a spatial resolution of 0.1° × 0.1°. Four-layer soil moisture data at different depths were also used: the first layer (0–7 cm), second layer (7-28 cm), third layer (28-100 cm), and fourth layer (100–289 cm).

2.2 Research Methods

The Modified Normalized Difference Water Index (MNDWI) was employed to extract water body information from Landsat imagery [16]. This method effectively distinguishes shadows from water bodies and differentiates saline-alkali land from water [17], calculated as:

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

where Green represents the green band (0.52–0.60 m) and MIR represents the middle infrared band (1.55–1.75 m) in Landsat TM/ETM+/OLI imagery. Combined with manual visual interpretation, lake area information for water bodies exceeding 1 km^2 across the Mongolian Plateau was obtained. Accuracy was assessed by extracting 200 samples and comparing them with high-resolution Google Earth data, achieving accuracies of 98.20% for lakes >1 km^2 and 84.03% for lakes >0.1 km^2. Treating lakes as point features, the nearest neighbor index method was applied to reveal the degree of spatial proximity among lakes and its changes. When the nearest neighbor index is less than 1, lake distribution is clustered; when greater than 1, it is discrete; and when equal to 1, it is random. A Z-score was used to test significance, with $Z > 2.58$ indicating significant clustering at the 99% confidence level.

3 Results

3.1 Temporal Variation of Lakes

Analysis of annual lake area and quantity changes revealed considerable interannual variability across the Mongolian Plateau from 2000 to 2020, with decreasing trends before 2009 and recovery thereafter (Fig. [Figure 2: see original paper]). Lake surface area reached its maximum of 19,345.19 km^2 in 2002 and its minimum of 17,176.82 km^2 in 2009, representing a change rate of -11.17% and an overall reduction of 2,168.37 km^2 during the study period. Lake numbers decreased from a maximum of 365 in 2000 to a minimum of 324 in 2009, totaling a reduction of 41 lakes (11.17% change rate).

To determine change trends for different lake sizes, lakes were classified into five categories: small (1-10 km^2), medium (10-100 km^2), large (100-1,000 km^2), and super-large (>1,000 km^2). Analysis showed that total area ranking followed size ranking (super-large > large > medium > small), while total quantity ranking showed the inverse pattern (Table). Super-large lakes remained stable in number but decreased in area by 378.28 km^2 (-2.20% change rate), contributing 18.93% to the total lake area reduction. Large lakes exhibited the greatest reduction amplitude, decreasing by 745.65 km^2 (-51.64% change rate) and contributing 46.22% to total area reduction. Medium lakes decreased by 273.76 km^2 (-18.96% change rate), contributing 13.80% to total reduction, while their numbers decreased by 26 (23.08% change rate). Small lakes decreased by

770.68 km^2 (-25.31% change rate), contributing 21.05% to total area reduction, but showed the greatest numerical decrease with 150 fewer lakes (41.47% change rate).

3.2 Spatial Variation of Lakes

To analyze spatial differentiation characteristics, lake area changes were categorized into five types: disappeared (present at study start but dry at end), shrunk (area change rate $<$ -2%), stable (between -2% and 2%), expanded ($>$2%), and newly formed (absent at start but present at end). The results (Fig. [Figure 3: see original paper]) show that lakes were densely distributed in the central-eastern, northwestern, and southern regions of the Mongolian Plateau. Overall, 273 lakes (31.22%) experienced shrinkage, primarily in the central-eastern, northwestern, and southern concentrated distribution zones. Disappeared lakes numbered 68 (7.50%), mainly in the central-eastern region. Expanded lakes totaled 99 (11.28%), scattered across various regions but more concentrated in the southern area. Stable lakes numbered 69 (7.50%), predominantly in the northwestern region. Newly formed lakes comprised 77 (8.79%), primarily in the central-eastern region.

The spatial distribution pattern showed that most lakes shrank during the entire study period, with more disappeared lakes in the early stage and more newly formed and expanded lakes in the later stage. Shrunken lakes were relatively dispersed, while disappeared lakes from the early period and newly formed lakes from the later period showed consistent distribution patterns, concentrated mainly in the central-eastern region. Stable lakes were concentrated in the northwestern region.

Changes in lake numbers alter spatial distribution patterns, thereby affecting water resource allocation and migratory bird routes. The nearest neighbor index analysis (Table) revealed that all indices across the study period were less than 1, indicating clustered distributions that were statistically significant ($Z > 2.58$). The index increased continuously from 0.61 in 2000 to 0.71 in 2020, while the expected mean distance first increased then decreased. This indicates that before 2009, decreasing lake numbers in the dense central-eastern region combined with new lakes in the sparse southwestern region weakened spatial agglomeration. After 2009, increasing lake numbers in the central-eastern region combined with new lakes in the sparse central region further dispersed the overall distribution, continuing the weakening trend despite different underlying causes.

3.3 Influencing Factors of Lake Changes

3.3.1 Changes in Environmental Factors Lake area changes are influenced by various environmental elements. From atmospheric, surface, and soil environmental perspectives, this study analyzed annual mean temperature, precipitation, evaporation, vegetation index (NDVI), land surface temperature, and four-layer soil moisture. Annual mean temperature fluctuated considerably, showing an overall increasing trend with a maximum of 3.02°C in 2013 and minimum in 2000 (Fig. [Figure 4: see original paper]). Annual precipitation showed slight fluctuating increases, peaking in 2003 and reaching its minimum in 2009, with higher levels in 2002–2003 coinciding with lake area peaks. Annual evaporation showed slight fluctuating decreases, with maximum in 2002 and minimum in 2010; higher evaporation in 2002–2003 corresponded to larger lake areas, while lower evaporation in 2009–2010 corresponded to smaller lake areas. NDVI showed a significant increasing trend overall, with smaller fluctuations before 2009 and larger interannual variations thereafter. Land surface temperature showed slight fluctuating decreases, peaking in 2003 and reaching its minimum in 2018, with 2009 as a trough year corresponding to a lake area peak. Soil moisture trends varied by depth: the first three layers showed decreasing trends with slight increases only in 2009, while the fourth layer showed a significant decreasing trend throughout the study period (Fig. [Figure 4: see original paper]).

3.3.2 Factors Influencing Lake Area Changes Correlation analysis between lake area and environmental factors for two periods (2000–2009 and 2009–2020) revealed distinct relationships. During 2000–2009, lake area reduction correlated significantly with increasing temperature, decreasing evaporation, and decreasing soil moisture in the first three layers, with correlation coefficients of -0.67, 0.71, and 0.57–0.73, respectively (Fig. [Figure 5: see original paper]). Correlations with precipitation, NDVI, and land surface temperature were weaker. During 2009–2020, lake area showed significant positive correlations with precipitation, evaporation, NDVI, and soil moisture in the first three layers ($r = 0.53$–0.82), but weak correlations with temperature, land surface temperature, and fourth-layer soil moisture (Fig. [Figure 6: see original paper]).

Comparative analysis showed that evaporation and soil moisture in the first three layers maintained consistently significant positive correlations with lake area changes across both periods, with stronger correlations during the expansion phase after 2009. Overall, increasing temperature and decreasing fourth-layer soil moisture had greater impacts on lake area shrinkage, while increasing NDVI and precipitation were more significantly related to lake area expansion.

4 Discussion

Numerous scholars have investigated lake area changes in typical lakes or small regions [18-21]. While some studies have examined large regions like Central Asia and the Tibetan Plateau [22-24], analyzing numerous lakes, most have not integrated large spatial scales, small lakes, and temporal continuity, particularly in the Mongolian Plateau. Monitoring lake area and quantity changes across the Mongolian Plateau and revealing their spatial distribution patterns are crucial for understanding water source transitions, biodiversity conservation for migratory birds, and warnings for global warming and drying.

Previous research on lake area influencing factors has focused primarily on natural elements such as temperature, precipitation, evaporation, and vegetation [25-27], with few studies incorporating other natural elements. Lake water balance is affected not only by atmospheric and surface environments but also by groundwater hydrology, with small shallow lakes being particularly sensitive to environmental changes. Therefore, analyzing numerous accurately monitored lakes as extensive samples to reveal relationships between lake area and temperature, precipitation, evaporation, NDVI, land surface temperature, and soil moisture provides deeper understanding of water balance mechanisms. This approach helps identify primary influencing factors across different periods, offering theoretical guidance for lake water source protection.

Regional-scale lake studies are essential for understanding different regional responses to climate change [28]. The Mongolian Plateau and Tibetan Plateau are both sensitive to climate change, yet their lake area trends differ markedly. While Tibetan Plateau lakes have generally increased in recent decades [29-31], Mongolian Plateau lakes showed an overall decreasing trend despite slight recovery after 2009. The fundamental factors—precipitation and temperature—are the same, but their mechanisms and outcomes differ. This highlights the necessity of seeking explanations from the geographic environmental characteristics of study areas to enhance understanding of lake change processes and mechanisms, which has theoretical and practical significance for regional environmental change and watershed management.

This study analyzed correlations between atmospheric, surface, and soil environmental elements and lake area across the entire Mongolian Plateau, identifying primary influencing factors in different periods. However, mechanistic analysis remains insufficient. Theoretically, increased vegetation cover should enhance rainfall infiltration, recharge groundwater, and subsequently supply lakes through subsurface flow. However, results showed lake area shrinkage despite increasing NDVI after 2009, suggesting that vegetation' s water conservation function may not be effectively realized. The strong correlation between soil moisture and lake area indicates that besides direct precipitation recharge, groundwater contributes significantly to lake water in the Mongolian Plateau. These findings suggest that further research is needed on the interaction mechanisms among specific factors.

5 Conclusions

(1) Lake area and quantity in the Mongolian Plateau fluctuated considerably from 2000 to 2020, showing an overall decreasing trend with distinct 阶段性变化. The period 2000-2009 showed decreasing trends, while 2009-2020 exhibited increasing trends. Small lakes were most numerous, while super-large lakes had the greatest area. Except for unchanged super-large lake numbers, all other lake size classes experienced reductions in both area and number, with large lakes showing the greatest change rate.

(2) Lakes were densely distributed in the central-eastern, northwestern, and

southern regions of the Mongolian Plateau, with significant differences in lake numbers and distribution patterns across change types and periods. Shrunken lakes were most numerous in both periods, concentrated in dense lake regions. Stable lakes were predominantly distributed in the northwestern region. More lakes disappeared before 2009, concentrated in the central-eastern region, while more new and expanded lakes appeared after 2009, also mainly in the central-eastern region.

(3) The spatial distribution of lakes showed significant clustering throughout the study period. However, the nearest neighbor index increased continuously, indicating weakening spatial agglomeration. Before 2009, decreasing lake numbers in the dense central-eastern region combined with new lakes in the sparse southwestern region weakened clustering. After 2009, increasing lake numbers in the central-eastern region combined with new lakes in the sparse central region further dispersed distribution, continuing the weakening trend.

(4) Environmental factors showed varying trends: annual mean temperature and NDVI increased significantly, fourth-layer soil moisture decreased significantly, and other factors fluctuated without consistent direction. Among these factors, increasing temperature and decreasing fourth-layer soil moisture significantly impacted lake area shrinkage before 2009, while increasing NDVI, precipitation, and soil moisture in the first three layers were significantly related to slight lake area recovery after 2009.

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