

Spatiotemporal Characteristics and Trend Analysis of Area Changes in Small and Medium-sized Lakes in Xinjiang, 1991–2020: Postprint

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Abstract

Lakes, as critical components of terrestrial ecosystems, serve as vital safeguards for regional economic development and ecological security. This study analyzed the area dynamics of 74 small and medium-sized lakes in Xinjiang from 1991 to 2020, conducting a comprehensive analysis of lakes across different altitudes and geographical characteristics. The findings reveal that between 1991 and 2020, the total lake area in Xinjiang increased from 167.98 km² to 400.51 km², with the most pronounced expansion occurring in mountain lakes. Monthly-scale analysis indicates that mountain lake area variations exhibit distinct seasonal patterns. Statistical analysis demonstrates that lakes at different altitudes in Xinjiang display varied responses to climate change. The significant expansion of mountain lake areas in Xinjiang is primarily driven by climate change, particularly the increase in annual mean temperature. In plain lake regions, human activities (especially irrigation) constitute the main drivers of lake area changes, while climatic factors exert relatively minor influence.

Full Text

Preamble

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Spatio-temporal Characteristics and Trends of Area Changes in Small and Medium-sized Lakes in Xinjiang from 1991 to 2020

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Abstract

Lakes, as key components of terrestrial ecosystems, serve as critical safeguards for regional economic development and ecological security. This study analyzed the area dynamics of 74 small and medium-sized lakes in Xinjiang during 1991–2020, conducting a comprehensive analysis of lakes across different altitudes and geographical characteristics. The findings revealed that from 1991 to 2020, the total lake area in Xinjiang expanded from 167.98 km² to 400.51 km², with the most significant growth occurring in mountainous lakes. Monthly-scale analysis demonstrated pronounced seasonal characteristics in the area changes of mountainous lakes. Statistical analysis indicated that lakes at different altitudes in Xinjiang exhibited varied responses to climate change. The substantial expansion of mountainous lakes in Xinjiang was primarily driven by climate change, particularly the rise in average annual temperature. In plain lake regions, human activities (especially irrigation) emerged as the main driving factor for lake area changes, while the influence of climatic factors was relatively minor.

Keywords: small to medium-sized lakes; area change; remote sensing monitoring; Xinjiang

Lakes play a vital role in terrestrial ecosystems, providing critical habitats for flora and fauna while regulating climate and ecosystem services. Additionally, as essential water resources, lakes support human livelihoods and economic activities. Lakes are particularly sensitive to climatic and environmental changes, capable of recording the impacts of climate change and human activities on regional hydrological processes across different temporal scales. Over recent decades, inland lakes have undergone dramatic transformations due to the combined pressures of natural environmental changes and human activities, making lake area change a focal point in limnological research. Studies have demonstrated that changes in lake surface area exhibit spatial heterogeneity across different geographical regions, altitude zones, and landscape types.

Xinjiang, located in an arid to semi-arid climate zone, has long faced water resource constraints. The region hosts numerous lakes that play crucial ecological and economic roles both locally and within broader watershed ecosystems, influencing ecological balance and sustainable development. Under the multiple pressures of climate change, human activities, and water resource management—exacerbated by overgrazing, irrigation, and sand mining—most lakes in Xinjiang

currently exhibit unstable conditions. While previous research has predominantly focused on large or typical lakes such as Bosten Lake and Taitema Lake, small and medium-sized lakes have received comparatively less attention. These smaller lakes are nonetheless indispensable components of ecosystems, and due to their limited surface area, they demonstrate more pronounced fluctuations in response to climate change and human activities than larger lakes. This is particularly true for small and medium-sized mountain lakes, whose ecological environments are more sensitive and responsive to change. Consequently, these lakes provide unique and important insights for understanding regional hydrological and ecological transformations. Furthermore, the responses of Xinjiang's small and medium-sized lakes to different altitude gradients and regional climate factors remain unclear.

Since 2018, Xinjiang has incorporated numerous lakes into its lake inventory system. These lakes, due to their geographical locations, scales, and varying degrees of impact, are representative for studying the responses of Xinjiang's lake systems. This study selected 74 small and medium-sized lakes from Xinjiang's lake inventory to analyze their area change trends across different spatial scales and altitude gradients. Considering Xinjiang's unique arid environment, this research employs the Google Earth Engine platform and structural equation models to analyze lake area changes in Xinjiang since the 1990s. The objectives include: (1) analyzing interannual variation trends in Xinjiang lake areas based on remote sensing imagery; (2) investigating spatio-temporal variation trends of lake areas across different altitude gradients; and (3) comprehensively evaluating the response mechanisms of lake area changes to climate change and human activities.

1.1 Study Area Overview

Xinjiang is situated in the northwestern border region of China, geographically positioned between $34^{\circ}25' - 49^{\circ}10' \text{ N}$ and $73^{\circ}40' - 96^{\circ}23' \text{ E}$, covering a land area of $1.66 \times 10^6 \text{ km}^2$, approximately one-sixth of China's total land area (Fig. 1). The terrain comprises the Altai, Tianshan, and Kunlun Mountains, along with the Junggar and Tarim Basins, forming a unique "three mountains sandwiching two basins" pattern. The region is characterized by deserts and high mountains, with important oases formed along riverbanks. Xinjiang's climate is dry with scarce precipitation and strong evaporation, representing a typical inland arid zone. Located deep within the mid-latitude Eurasian continent, far from oceans, moist oceanic air masses rarely reach the region, resulting in an average annual precipitation of less than 200 mm. The average annual temperature ranges from $4 - 8^{\circ}\text{C}$ in northern Xinjiang to $9 - 12^{\circ}\text{C}$ in southern Xinjiang.

1.2 Data Sources

The Global Surface Water dataset was used to extract monthly-scale surface area data for different lakes during 1991–2020. This product, developed by the Euro-

pean Commission's Joint Research Centre (JRC, <https://centre.ec.europa.eu/>), is an outcome of the Copernicus Programme JRC Monthly Water History. The dataset preserves historical information on water body area at a monthly scale, derived from analysis of high-resolution images from Landsat 5 satellites. Each pixel is individually classified as water (pixel value 1), non-water (pixel value 0), or no observation (pixel value 2). This study calculated monthly surface area data for the lakes based on the Google Earth Engine (GEE) remote sensing big data computing platform.

The meteorological data selected for this study were sourced from the TerraClimate dataset, which features high spatial resolution ($1/24^\circ$). Monthly meteorological data include precipitation, maximum and minimum temperatures, wind speed, water vapor pressure, and solar radiation. Compared with low-resolution grid data, the TerraClimate dataset demonstrates significantly improved absolute error overall, providing important input data for ecological and hydrological research worldwide. Based on this, our study selected historical climate change characteristic variables from 1991–2020 provided by this dataset, including precipitation, temperature, evaporation, and snow water equivalent, to analyze the variability of meteorological variables in different study regions.

NASA SRTM DEM data were used for lake elevation calculations. This product, provided by NASA JPL, has a resolution of 30 meters. For further processing of the data, European NASA DEM data were integrated. Note: The base map was produced using the standard map from the Ministry of Natural Resources, with review number GS(2023)2767, and no modifications were made to the map boundaries. The same applies below.

Fig. 1 [Figure 1: see original paper] Overview map of the study area

1.3 Data Analysis

To ensure accuracy, rigorous quality control was applied to each lake's area time series. This included removing outliers where area values were below 10 km^2 to guarantee the reliability of results. Meteorological data and Global Surface Water data were both obtained through the GEE platform. To comprehensively analyze spatio-temporal dynamics of lake areas across different regions and gradients, this study categorized the 74 lakes into three major geographical regions: Altai region, Tianshan region, and Kunlun region. Based on altitude data, lakes were further divided into two categories: plain lakes (altitude $<1500 \text{ m}$) and mountain lakes (altitude $\geq 1500 \text{ m}$). This study selected 1500 m as the boundary based on several scientific considerations: First, historical temperature data show a clear temperature demarcation at 1500 m in the Tianshan Mountains, which may represent a critical threshold for temperature response. Second, precipitation analysis indicates that areas above 1500 m experience significantly increased precipitation, suggesting this altitude serves as an important precipitation change boundary. Additionally, biotic community research, particularly on animal species such as antelope and golden monkeys, shows they are mainly

concentrated in areas above 1500 m, reflecting differentiated responses of biological communities to climate change across altitudes. Therefore, using 1500 m as the boundary between mountain and plain lakes is based on both climate change data for temperature and precipitation, and considerations of ecosystem responses to environmental variable changes. This classification method facilitates more accurate assessment and understanding of climate change impacts on lake ecosystems at different altitudes.

The long-term trend of time series was analyzed using linear trend estimation, establishing a simple linear regression equation between the area variable (y) and corresponding time (x):

$$y = ax + b$$

where a is the linear regression coefficient, representing the rate of lake water area change. A positive a value indicates an increasing surface area trend, while a negative value indicates a decreasing trend.

This study employs Structural Equation Modeling (SEM) as the primary analytical method. SEM is a comprehensive statistical data analysis approach that integrates variance analysis, regression analysis, path analysis, and factor analysis, effectively handling multiple cause-multiple effect relationships and latent variables. This model analyzes complex relationships among multivariate data based on variable covariance matrices, and according to researchers' prior knowledge, establishes dependency relationships among factors within the system to determine the strength of relationships between various factors. In SEM, dependency relationships are typically represented by arrows: in graphical frameworks, unidirectional arrows represent relationships from predictor variables to response variables, while bidirectional arrows indicate bidirectional or uncertain causal relationships between variables. In this study, no latent variables were involved; the focus was on path relationships between exogenous and endogenous variables. The structural equation model is expressed as:

$$\mathbf{y} = \mathbf{B}\mathbf{y} + \mathbf{x} +$$

where \mathbf{y} is the column vector of endogenous variables; \mathbf{x} is the column vector of exogenous variables; \mathbf{B} represents the matrix of random relationships among endogenous variables; $\mathbf{\Gamma}$ represents the direct random effects of exogenous variables on endogenous variables; and ϵ is the residual term of the structural equation, reflecting the unexplained portion of \mathbf{y} in the equation. Through path analysis, combined with path diagrams and effect values, the influence of various factors on regional lake area changes was analyzed.

Previous studies have shown that mountain lakes are primarily affected by climate change, while plain lakes are influenced by both climate change and human

activities, with climate change widely recognized as the main driver of historical lake changes in China. For mountain lakes, this paper uses average annual temperature, annual precipitation, and potential evapotranspiration (PET) as regional climate indicators to quantify the contribution of climate variables to lake changes. Climate values for each lake were derived from TerraClimate data. For plain lakes, this study uses five explanatory variables—annual average temperature, annual precipitation, potential evapotranspiration, irrigation, and grazing intensity—to analyze the impacts of climate and human activities on regional lake changes. Xinjiang’s grazing data (annual sheep and goat numbers) and agricultural data (irrigated farmland area) were obtained from the *Xinjiang Statistical Yearbook*. All data analyses were implemented using the R language.

Given Xinjiang’s high latitude, lakes frequently experience ice formation during winter. This study defines lakes as ice-covered when the monthly average temperature is below 0°C. Although the Global Surface Water dataset is reliable, data during ice cover periods may be incomplete.

Fig. 2 [Figure 2: see original paper] Spatial distribution of small and medium-sized lakes in Xinjiang across different regions and altitudes

2.1 Spatial Distribution of Small and Medium-sized Lakes in Xinjiang

From 1991 to 2020, the average total area of small and medium-sized lakes in Xinjiang was $274.3 \pm 86.6 \text{ km}^2$ (mean \pm standard deviation). Specifically, the average area of mountain lakes was $209.6 \pm 76.6 \text{ km}^2$, while that of plain lakes was $64.8 \pm 15.1 \text{ km}^2$, accounting for 7

Furthermore, from an altitude perspective, the vast majority of lakes in the Kunlun region are distributed in mountainous areas, with mountain lakes accounting for 99.3% of the region’s total lake area. In contrast, lakes in the Tianshan region are mainly distributed in plains, with plain lakes comprising 81.2% of the region’s total lake area. Lakes in the Altai region are evenly distributed between mountains and plains, with mountain and plain lake area ratios of 58.7% and 41.3%, respectively.

According to the distribution of lake average areas (Fig. 4), most lakes (65 lakes) fall within the 1–5 km² range, with a combined area of 102.3 km², accounting for 37.3% of Xinjiang’s small and medium-sized lake average total area. However, there are only 9 lakes with average areas exceeding 10 km², yet their total area reaches 128.9 km², occupying 46.5% of Xinjiang’s small and medium-sized lake average total area. Additionally, 12 lakes have average areas smaller than 1 km², with their total area comprising only 2.2% of Xinjiang’s small and medium-sized lake average total area.

Regarding individual lakes, the largest average area belongs to Jutou Lake,

located in the mountainous area of the Kunlun region, with an average annual area of 40.5 km². The smallest average area belongs to Yuleken Qiao Shi Ha Le Lake, located in the plains of the Altai region, with an average annual area of only 0.01 km².

Fig. 3 [Figure 3: see original paper] Annual average area proportion of 74 small and medium-sized lakes in Xinjiang from 1991 to 2020 across different regions and altitudes

2.2 Interannual Variation of Small and Medium-sized Lakes in Xinjiang

From 1991 to 2020, the total area of small and medium-sized lakes in Xinjiang experienced significant growth, increasing from 167.98 km² to 400.51 km² at a rate of 9.52 km² yr⁻¹ ($P < 0.001$) (Fig. 5). This growth was dominated by mountain lakes, which increased at a rate of 8.41 km² yr⁻¹ ($P < 0.001$), while plain lakes also expanded significantly at a rate of 1.11 km² yr⁻¹ ($P < 0.001$). Geographically, the total lake area in all regions showed increasing trends. The Kunlun region dominated the increase in Xinjiang's total small and medium-sized lake area, with its total lake area increasing at a rate of 8.22 km² yr⁻¹ ($P < 0.001$). Within this region, mountain lakes increased significantly at 8.22 km² yr⁻¹ ($P < 0.001$), while plain lakes showed no significant growth or decline ($P = 0.55$). Similarly, the Tianshan region's lakes expanded significantly at 0.94 km² yr⁻¹ ($P < 0.001$), with plain lakes in the Tianshan region (0.84 km² yr⁻¹, $P < 0.01$) playing a dominant role in the region's total lake area growth. As for the Altai region, the total lake area increased at a rate of 0.09 km² yr⁻¹ ($P < 0.05$), with both mountain and plain lakes showing significant growth.

Regarding individual lakes, compared to their average area during 1991–2000, most lakes showed an expanding trend during 2001–2020, though 13 lakes experienced area reduction during this period (Fig. 6). Among these lakes, 11 showed area change magnitudes exceeding 10 km². Specifically, Jutou Lake's average area increased by 25.17 km², representing the largest increase, while Mugai Kule Lake's average area decreased by 27.19 km², representing the largest decrease. Compared to their average area during 1991–2010, most lakes showed increasing trends during 2011–2020, while only 7 lakes experienced average area reduction. Among these, only 2 lakes showed area change magnitudes exceeding 10 km². Again, Jutou Lake showed the largest average area increase of 40.5 km², while Yuleken Qiao Shi Ha Le Lake showed the smallest average area of only 0.01 km².

Fig. 4 [Figure 4: see original paper] Average area distribution of 74 small and medium-sized lakes in Xinjiang from 1991 to 2020 (categorized by lake size)

Fig. 5 [Figure 5: see original paper] Area change of 74 small and medium-sized lakes in Xinjiang from 1991 to 2020 across different altitudes

2.3 Intra-annual Variation of Small and Medium-sized Lakes in Xinjiang

At the monthly scale, the area of small and medium-sized lakes in Xinjiang exhibited clear seasonal variations (Fig. 8). Notably, the intra-annual fluctuation magnitude of mountain lakes was significantly higher than that of plain lakes, with intra-annual coefficients of variation of 0.36 and 0.27, respectively. Specifically, the total area of mountain lakes was smaller during January–March, ranging between 192.61–227.79 km², and larger during July–September, reaching a maximum of 274.53 km² in August. Plain lakes reached their minimum total area of 60.29 km² in June and their maximum of 77.04 km² in October.

Regionally, plain lakes in the Altai, Kunlun, and Tianshan regions showed different seasonal patterns (Fig. 9). The monthly average total areas for the Altai, Kunlun, and Tianshan regions were 13.12 km², 55.44 km², and 1.33 km², respectively. Among these regions, plain lakes in the Tianshan region showed the smallest intra-annual fluctuation magnitude, with a coefficient of variation of 0.27, reaching their maximum total area of 16.57 km² in October. The Altai region ranked second with a coefficient of variation of 0.36, reaching its maximum total area of 16.25 km² in May. Among these regions, mountain lakes in the Kunlun region exhibited the smallest intra-annual fluctuation magnitude, with a coefficient of variation of 0.27, reaching their maximum total area of 241.49 km² in September. In contrast, plain lakes in the Kunlun region showed the largest intra-annual fluctuation magnitude, with a coefficient of variation of 0.36. For mountain lakes, the Altai region, Kunlun region, and Tianshan region had monthly average total areas of 10.64 km², 204.21 km², and 63.31 km², respectively. Among these, mountain lakes in the Tianshan region showed the largest intra-annual fluctuation magnitude, with a coefficient of variation of 0.36, reaching their maximum total area of 13.49 km² in August.

Fig. 6 [Figure 6: see original paper] Area change of small and medium-sized lakes in Xinjiang from 1991 to 2020 across different regions and altitudes

Fig. 7 [Figure 7: see original paper] Area change of small and medium-sized lakes in Xinjiang between 1991–2000 and 2001–2010, and between 2001–2010 and 2011–2020

Fig. 8 [Figure 8: see original paper] Monthly scale area change of small and medium-sized lakes in Xinjiang (categorized by lake size) (km²)

Fig. 9 [Figure 9: see original paper] Monthly scale area change of small and medium-sized lakes in Xinjiang across different regions and altitudes (km²)

3.1 Factors Influencing Mountain Lake Area Changes

Influenced by geographical location and other factors, mountain lake area changes are less disturbed by human activities. Therefore, this study focused on examining climate change as the primary driving factor for mountain lake area changes. During 1991–2020, the potential evapotranspiration of mountain lakes increased significantly ($P < 0.01$), typically indicating higher

water evaporation. However, this trend did not lead to reduced lake water volume, likely due to increased compensatory water sources. Simultaneously, the average annual temperature rose significantly ($P < 0.01$), directly affecting mountain snow and glaciers. Temperature increases accelerated glacier and snowmelt, providing additional water sources for lakes. This finding is crucial for understanding lake area changes, demonstrating that despite increased evaporation, the added meltwater can compensate for these losses and even cause lake expansion. Although annual precipitation showed no significant trend ($P > 0.05$), studies indicate that the frequency of extreme rainfall events in mountainous areas has increased in recent years. These extreme rainfall events provide additional water to lakes, significantly positively influencing lake area increases.

Through comparative analysis across the three regions, the complex influence of climate factors on lake area changes becomes evident: In the Kunlun and Tianshan regions, temperature rise is the primary driving factor, while in the Altai region, extreme precipitation events play a more important role.

Fig. 10 [Figure 10: see original paper] Results of the structural equation model analysis on the influencing factors of area change in small and medium-sized mountain lakes in Xinjiang

3.2 Factors Influencing Plain Lake Area Changes

In plain lake basins, human activities are frequent, including agricultural irrigation, reservoir construction, and grazing, which significantly impact lake water volume and area changes. This study applied structural equation modeling (SEM), incorporating five explanatory variables—annual average temperature, annual precipitation, potential evapotranspiration, irrigation, and grazing intensity—to explore the relationship between plain lake area and human activities as well as climate factors. The study collected grazing data (sheep and goat numbers) and agricultural data (irrigated farmland area) from the prefecture-level cities where lakes are located to reflect human activity intensity. Considering that the total area change of plain lakes in the Kunlun region remained relatively stable and that the plain area of the Kunlun region only includes two lakes, this research focused on plain lakes in the Altai and Tianshan regions to analyze their area change trends and driving factors. The results showed that irrigation is the primary anthropogenic driving factor for lake area changes (Fig. 11).

Both the Altai and Tianshan regions' plain lakes exhibited significant expansion trends. Over the past decades, cultivated land area in Xinjiang's plains has expanded, with large tracts of wasteland converted to farmland. Farmland requires irrigation, but plain rainfall is limited, so upstream rivers are dammed or diverted to provide irrigation water, indirectly causing downstream plain lake expansion. For example, effective management and regulation of the Irtys River significantly influence plain lake surface area. Increased grazing intensity

implies increased water consumption by livestock, but human water diversion activities offset the water loss caused by grazing, thereby increasing lake area. Meanwhile, typical Xinjiang lakes such as Bosten Lake and Jili Lake demonstrate the important influence of human activities on plain lake area changes. Bosten Lake's area changes are closely related to Kaidu River flow. During 1991–2020, Bosten Lake experienced a process of first expanding, then contracting, then expanding again, a process closely related to Kaidu River flow changes and their influences from climate change and human activities. Jili Lake further confirms this impact. Over the past 30 years, Jili Lake area has shown a significant expansion trend. A dam built on the Kuyiga River between Ulungur Lake and Jili Lake at the end of the 20th century clearly demonstrates the role of human activities in controlling Jili Lake area. In contrast, plain lakes in the Kunlun region, including Beilek Kule Lake and Tamulik Lake, show different conditions. Beilek Kule Lake showed no significant area change during the study period, while Tamulik Lake decreased slightly. A multiple linear model established specifically for Tamulik Lake indicated that anthropogenic and climatic factors jointly explained 65.8% of lake area variation.

Fig. 11 [Figure 11: see original paper] Results of the structural equation model analysis on the influencing factors of area change in small and medium-sized lakes in the Xinjiang plains

4 Conclusion

This study examined 74 small and medium-sized lakes included in Xinjiang's lake chief system, analyzing the dynamic changes in lake area across different regions and altitude zones in Xinjiang from 1991 to 2020, and discussed the influencing factors of lake area changes, leading to the following conclusions:

- (1) From 1991 to 2020, the average total area of small and medium-sized lakes in Xinjiang was $274.3 \pm 86.6 \text{ km}^2$. The average annual area of mountain lakes and plain lakes accounted for 76.4% and 23.6% of the total area, respectively, while only 9 lakes had average areas exceeding 10 km^2 , yet their total area accounted for 46.5% of Xinjiang's small and medium-sized lake average total area.
- (2) From 1991 to 2020, the total area of small and medium-sized lakes in Xinjiang expanded significantly at a rate of $9.52 \text{ km}^2 \text{ yr}^{-1}$. Both mountain and plain lake total areas showed significant increasing trends at rates of $8.41 \text{ km}^2 \text{ yr}^{-1}$ and $1.11 \text{ km}^2 \text{ yr}^{-1}$, respectively. Mountain lakes dominated the growth of Xinjiang's total small and medium-sized lake area. The total lake areas in the Kunlun, Altai, and Tianshan regions increased significantly at rates of $8.22 \text{ km}^2 \text{ yr}^{-1}$, $0.36 \text{ km}^2 \text{ yr}^{-1}$, and $0.94 \text{ km}^2 \text{ yr}^{-1}$, respectively, with the Kunlun region dominating the increase in Xinjiang's total small and medium-sized lake area.
- (3) The area of small and medium-sized lakes in Xinjiang showed obvious seasonal variations. The intra-annual coefficients of variation for mountain and plain lakes were 0.36 and 0.27, respectively, indicating that mountain

lake area fluctuation was higher than that of plain lakes. The total area of mountain lakes was smaller during January–March, reached its minimum in March, and was larger during July–September, while the total area of plain lakes reached its maximum in October.

- (4) The significant expansion of mountain lakes in Xinjiang was primarily driven by climate change. The increase in average annual temperature promoted glacier and snowmelt, providing additional water sources for lakes despite increased potential evapotranspiration. In contrast, in plain lake regions, human activities, particularly irrigation and grazing, became the main driving factors for lake area changes. Irrigation activities especially caused significant water area expansion in plain lakes of the Altai and Tianshan regions, demonstrating the important influence of human activities on lake area changes in areas with intensive human intervention.

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

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