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Research article

Analysis of lake changes and their influence factors in the three river regions from 2000 to 2020 in the Sanjiangyuan Region, China

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ABSTRACT

An important factor for investigating climate change in the Sanjiangyuan is the evolution of the spatio-temporal pattern of lakes in this region. The present study used the Google Earth Engine (GEE) platform to extract lakes from 2000 to 2020. The present approach created a lake distribution dataset yearly and analyzed spatial and temporal patterns over 20 years. The analysis of lakes focused on the reaction of the Sanjiangyuan Lakes area to changes in climate, glaciers, and permafrost. The findings indicated that the Sanjiangyuan region contains 143 lakes, the majority of which are predominantly small, measuring 1–10 km^2. The small lakes account for 60.14 % of the total and are primarily located in the source regions of the Yangtze River and Yellow River. The findings demonstrated that the Sanjiangyuan lakes experienced a significant expansion over the past two decades, particularly from 2011 to 2020. These lakes are divided into expanded, atrophic, and stable categories. Expanded lakes showed significant inter-annual trends in expansion, while atrophic lakes showed smaller fluctuations. The area of stable lakes experienced a consistent decline after 2010, despite a consistent expansion tendency from 2001 to 2010. Moreover, the results indicated that alterations in the size of glaciers and ice reserves in the Sanjiangyuan region have had the greatest influence on the fluctuation in lake area. Among the factors that affect the climate, temperature had the most significant effect on the change in lake area, followed by precipitation.

1. Introduction

Sanjiangyuan is located in southwest Qinghai Province and includes highly riverine and lake-filled territory in the hinterland of the Qinghai-Tibet Plateau. "Chinese Water Tower" is the name given to it. The Sanjiangyuan region's climatic shift is a typical reaction to global climate change. Previous studies reported that climate change is the main factor responsible for hydrological and ecosystem

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changes due to the sparse population and low anthropological impact in the Sanjiangyuan region [1,2]. Hence, temperature and precipitation variations in the Sanjiangyuan region have dominated the spatiotemporal pattern of the lakes' history. As a result, this pattern serves as a useful indicator for researching climate change in the area.

Researchers are consistently investigating the wide-ranging effects and hazards of natural phenomena in order to gain a deeper understanding of their impacts and assist decision-makers in mitigating the consequences of these events [3–6]. The outcome of studying these natural occurrences is the ability for researchers to assess the influence of such events on sustainable development. Sustainable development seeks to fulfill present demands while preserving the capacity of subsequent generations to satisfy their individual requirements. It encompasses economic expansion, social integration, and environmental preservation. Human activities contribute to sustainable development through primarily carbon emissions, which influence global warming and climate change [7–11].

Climate change affects the achievement of sustainable development in various aspects, such as impacts on groundwater and surface water resources. The impacts of climate variations influence temperature and precipitation, leading to modified discharge and changes in water quality [12–15]. The climate system is inherently uncertain due to complex interactions [16–18]. Hence, making it challenging to address water-related issues under different climate change scenarios [19–22]. Climate change can significantly impact the global water cycle, increasing floods and droughts [23–26]. It is essential to consider these impacts when designing hydraulic structures for potential flooding [27]. Climate change can also affect ecological health by modifying aquatic environments, agricultural production, and food security [28–31]. Therefore, studying climate change in key geographical areas is crucial for decision-makers to address challenges in water resource management [32,33].

The process of glacial melting, the retreat of the snowline, and the subsequent increase in runoff in the Sanjiangyuan headwaters are having a direct impact on the availability of water resources in the Yangtze and Yellow Rivers [34,35]. This poses a substantial risk to the long-term viability of sustainable development in the region [36–38]. Hence, it is essential to precisely evaluate the impacts of climate change on lakes and perform quantitative analysis on the distribution, volume, and spatial-temporal pattern evolution of lakes in the Sanjiangyuan region. This is necessary for protecting and restoring lake ecosystems in alignment with local circumstances and promoting the advancement of ecological civilization.

For the importance of the Sanjiangyuan region, it has always been interesting for researchers to investigate this area from different research aspects, especially the hydrological and ecosystem changes of the region and climate changes. For example, some studies focused on carbon emissions and regional carbon storage in the Sanjiangyuan region that are influenced by climate change [39–42]. Wang et al. [43] found that glaciers in Sanjiangyuan National Park are a sensitive indicator of climate change. Zhai et al. [44] conducted a study on alpine grassland degradation in the Sanjiangyuan region and found climate change, precipitation, wind speed, and human activities intensified the degradation. Wang et al. [45] indicated that the glacier area will decrease by the end of the 21st century due to climate warming in the Sanjiangyuan region. Zhang and Zhou [46], investigated precipitation trends and land cover changes on the Qinghai-Tibet Plateau. The evidence indicated that there had been a variable increase in annual precipitation in this area from 1967 to 2016. Qu et al. [47] analyzed water consumption in the Sanjiangyuan Region from November 2019 to October 2020, finding that it is higher in the south than in the north. These mentioned research efforts conducted in the Sanjiangyuan Region reflect the direct or indirect effects of climate change in the area.

Research on surface water changes is essential for assessing water availability, quality, and environmental impacts, establishing effective water management strategies, and preserving environmental and human health [48,49]. In recent years, remote sensing technologies and Google Earth Engine (GEE) have been effectively used to monitor earth surface changes, analyze water bodies, and detect lake changes in various areas [50–54]. The following studies used the GEE platform for monitoring lakes. For instance, Gong et al. [55] studied the lake area in Wuhan city from 1987 to 2019 and found a significant correlation between precipitation, temperature, and lake size. Zhao et al. [56] analyzed wetland data from 1988 to 2020 in the Dianchi Basin, revealing an increasing trend in the wetland area. Zhao et al. [57] estimated the average chlorophyll-a (Chl-a) concentration for the largest global lakes from 2019 to 2021 using remote estimation. Nguyen et al. [58] investigated lake changes in New Zealand and revealed that most lakes' spatial areas remained consistent despite climate variability from 2014 to 2018. Chen et al. [59] assessed water quality in China during 2015, finding yellow and green as the most prevalent lake colors. Albarqouni et al. [60] analyzed the water surface area of three lakes in Turkey's Lakes Region from 2000 to 2021. They concluded that there has been a decrease or no change in the lake area. Jiang et al. [61] used the GEE platform to evaluate surface water changes in Baiyangdian Lake, located in the north of China, from 2014 to 2020. They observed a gradual increase in the surface water area of Baiyangdian Lake. Hence, the above investigations demonstrated that remote sensing image data is a reliable scientific technique for monitoring lake surfaces and water bodies. In addition, remote sensing technologies have been applied to study various parameters of the Sanjiangyuan region. For example, Lu et al. [62] conducted a study on nitrogen and phosphorus nutrients over the period of 2012–2015. They realized the mean nutrient concentrations exceeded the water quality criteria in this area. Cao et al. [63] analyzed ecosystem variations from 2000 to 2015, revealing increasing climate warming and humidification. Zhu et al. [64] presented a suitable model for net primary productivity (NPP) estimation from 2001 to 2020.

The Sanjiangyuan region plays a crucial role in the preservation of water resources and the maintenance of ecological equilibrium in China. As far as the knowledge of the authors shows, a comprehensive study on the analysis of lake changes in the Sanjiangyuan region has not been done using historical data. Therefore, this study emphasizes the analysis of lake change in this region. Analysis of lake changes is crucial for understanding climate change's impact on water resources, aquatic ecosystems, temperature, precipitation patterns, and glacial melt in the Sanjiangyuan region. Monitoring and analyzing lake changes is crucial for better resource utilization and management, as well as promoting sustainable use of water resources and maintaining ecological balance. Furthermore, the changes in lakes are very responsive to variations in climate and environmental conditions. The present study utilized the Google Earth

Engine (GEE) platform to collect data on lakes in the Sanjiangyuan region from 2000 to 2020. The analysis of changes in lake areas provides valuable information for decision-makers in this area.

2. Overview of the study area

Sanjiangyuan Region of Qinghai Province is situated between 31°39′N-37°10′N and 89°24′E−102°27′E, with a total area of approximately 30.25×10^4 km^2. The typical climate characteristics of the region are as follows: The daily temperature variation is significant, whereas the annual temperature discrepancy is negligible. Furthermore, the region has abundant sunlight and high levels of radiation. There are several lakes and extensive glaciers in the area. For rivers in China and even East Asia, this is a crucial region for water conservation. Fig. 1 depicts its location geographically.

3. Data sources and methodology

3.1. Data source

The geographic data and remote sensing satellite images from several sources were available on the Google Earth Engine (GEE) platform. The GEE platform's Landsat5 TM, Landsat8 OLI, and Landsat 7 ETM + series of satellite image data were used in this article as data sources. Additional data was provided by Landsat7 ETM + images. The quality, quantity, and continuity of remote sensing photos were taken into consideration while utilizing the top of the atmosphere reflectance data (TOA) following geometric correction and radiometric calibration of Landsat images taken between 2000 and 2020. Additionally, since most lakes in the Sanjiangyuan area were susceptible to freezing in November and had a steady period from September to November, August through October was the primary month chosen for image acquisition. Lastly, remote sensing photos with less than 20 % cloud cover were filtered out for mosaic stitching using the GEE platform. The National Aeronautics and Space Administration (NASA) provided the SRTM digital elevation product, which has a resolution of 30 m and is the source of the geographic elevation data used in this present study [65].

The elevation map of the Sanjiangyuan region was created in accordance with the research area's vector border. After that, Geographic Information System (GIS) software was utilized for data extraction, processing, and handling to create the Sanjiangyuan elevation data. The China Meteorological Science Data Sharing Service Network provided the meteorological data used in this article [66], and the Food and Agriculture Organization of the United Nations' updated Penman method was used to calculate evaporation. The Sanjiangyuan Region's 23 meteorological observation stations provided yearly value data on temperature, precipitation, evaporation, sunlight hours, and maximum frozen soil active layer thickness from 2000 to 2020. These data were used to study changes in the region's climate and frozen soil. The glacier data in this article was extracted using the band ratio approach from Landsat remote sensing images. More details are provided in the following section.

3.2. Research methodology

3.2.1. Calculation of normalized difference water index

The best way to retrieve water body information from inland lakes on the Tibetan Plateau is to use the automated categorization technique in conjunction with the computation of the water body index. McFeeters [67] presented the normalized water index

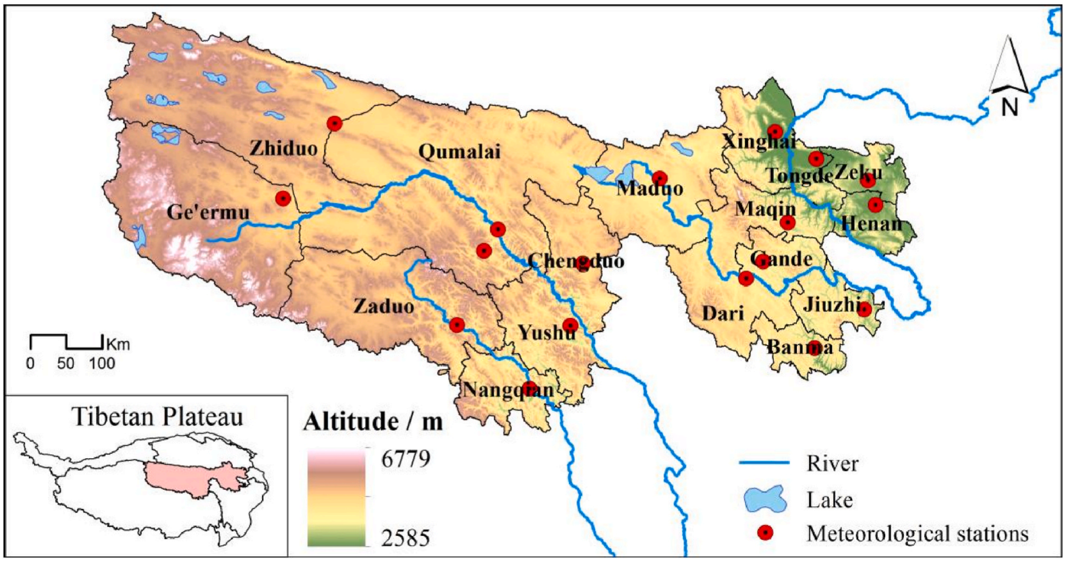

Fig. 1. Map of the study region.

algorithm, a method for calculating the water index that minimizes interference from plants and soil and adds water information. The formula is as follows:

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

In Equation (1), "Green" represents the reflectivity of the second band in Landsat 5 TM and the third band in Landsat 8 OLI, while "NIR" represents the reflectivity of the fourth band in Landsat 5 TM and the fifth band in Landsat 8 OLI. This distinction is crucial for accurately interpreting and comparing NDWI values derived from different Landsat datasets, as it ensures consistency in the spectral bands used for vegetation and water body analysis across various satellite missions.

3.2.2. GEE-based lake extraction

Lake water in the research region was extracted using the random forest approach implemented in JavaScript using the GEE platform. Breiman created the random forest technique, a classification algorithm made up of many decision trees. It is a multi-dimensional, concurrently operating, high-accuracy machine learning algorithm. Its benefits include high model stability, quick processing speed, few parameters, and more accurate classification results when handling high-dimensional data. Wetland classification research has made extensive use of the random forest method in recent years, with encouraging classification outcomes [68]. The GEE platform is configured to use the random forest algorithm by using ee.Classifier "ee.Classifier.smile Random Forest ()."Adjust the code for implementation.

3.2.3. Analysis of the trend of lake area change

A one-way linear regression model of lake area and year was constructed using the least squares approach in order to statistically assess the changing trend of various lakes in the research region with an area larger than 1 km^2. The formula is as follows:

$$y = \mathrm{a}\cdot x + \mathrm{b} \tag{2}$$

where y is the annual lake area, x is the corresponding year, a is the trend of lake area, b is a constant, and a and b are identified by least squares. When a is 0.02, the linear inclination angle of the regression model is about 10°, which means that the lake area in the study area changes gently during the study period, and the evolution trend of the lake area is divided into three categories: shrinking, stable, and expanding according to $\mathrm{a}<-0.02$, $|a| \leq 0.02$ and $\mathrm{a}>0.02$.

3.2.4. Correlation analysis

The understand the response connection of lake dynamics to climate, glacier, and permafrost changes correlation analysis was conducted. Correlation analysis was utilized to investigate the link between lake area and climatic driving variables, maximum permafrost active layer thickness, glacier area, and ice storage.

4. Analysis of results

4.1. The distribution of lakes

According to the results of the lake image interpretation, there were 143 lakes with an area larger than 1 km^2 in the Sanjiangyuan region, with a total area of 6997.56 km^2.The majority of the lakes are found in the Yangtze River source area, which makes up 5091.29 km^2 and accounts for approximately 72.75 % of all the lakes. The lakes in the Yellow River source region make up just 27.24 % of all lakes, with an area of 1906.27 km^2. The lakes in the Lancang River are extremely little and essentially insignificant. The lake data for 2020 was separated into four categories: small, medium, big, and super-large, with cut-off points of 10 km^2, 100 km^2, and 500 km^2. With 4000 m, 4500 m, and 5000 m serving as the demarcation marks, the height gradient was split into four categories: low altitude, medium altitude, medium high altitude, and high altitude. The statistical findings are displayed in Table 1. Only 4 large lakes with an area of more than 500 km^2 exist in the Sanjiangyuan region, the largest of which is Ngoring Lake. The majority of the lakes in the source of the Sanjiangyuan region are tiny lakes, ranging in size from 1 to 10 km^2, making up 60.14 % of all the lakes in this region. The lakes in the Sanjiangyuan region are all located in the region above 4000 m above sea level, with 62.94 % of the lakes concentrated in

Table 1
The numbers, areas and elevations of different groups of lakes in the Three-River Regions.

Source area	Numbers	Areas (km^2)	Area Segmentation S/km^2	Numbers	Areas (km^2)	Altitude Segmentation h/m	Numbers	Areas (km^2)
The Three-River Regions	143	6997.56	$1<S \leq 10$	86	278.11	$h \leq 4000$	–	–
The Yangtze River Region	108	5091.29	$10<S \leq 100$	41	1387.32	$4000<h \leq 4500$	43	2432.56
The Yellow River Region	35	1906.27	$100<S \leq 500$	12	2780.62	$4500<h \leq 5000$	90	4404.45
The Lancang River Region	–	–	$S > 500$	4	2551.51	$h > 5000$	10	160.55

the 4500–5000 m range. Only 10 lakes are located above 5000 m above sea level.

4.2. *Characteristics of lake variation*

The study categorized the Sanjiangyuan region's lakes into expended, atrophic, and stable types to better understand the variability in area changes. The trend of lakes larger than 1 km^2 at the three rivers' sources is depicted in Fig. 2. It is evident that the three rivers' sources contain 82 expended lakes, 15 atrophic lakes, and 46 stable lakes. From the standpoint of various source areas, the Yangtze River source area has a distribution of the three types of lakes, with expanded lakes making up the majority (59.29 %). The Yellow River source area has lakes that are both expansive and stable, with 56.67 % of the lakes being expansive. The Sanjiangyuan lakes' area expansion declined as their size increased, whereas the tiny lakes' area expansion was the greatest. This pattern of area change was comparable with small lakes' features on the Tibetan Plateau [69]. From an altitude viewpoint, lakes that are shrinking are often found in high-altitude regions, whereas lakes that are expanding are found at all altitudes. The intensity of the expansion range of lakes in middle- and high-altitude regions is greater than that of lakes at higher altitudes (Fig. 2).

It is worth mentioning that the expansion of lake area in the Sanjiangyuan region decreases with the increase in area size due to several interconnected factors. Larger lakes face more significant constraints compared to smaller lakes, such as geographical, hydrological, climatic, ecological, and anthropogenic constraints. These constraints interact to slow down the rate of expansion as the lake grows, resulting in a diminishing return on area increase as size increases. The expansion of larger lakes is often constrained by natural barriers, while smaller lakes typically have more space to grow in their surroundings before encountering such limitations. Larger lakes have larger catchment areas, which are the regions that drain into them. During heavy rains or snowmelt, these areas can fill up with water and stop draining into the lake as quickly. This can reduce the impact of additional inflow on the lake's level. In addition, larger lakes have a greater surface area exposed to the air. This leads to a higher rate of evaporation, which removes water from the lake and counteracts the incoming flow of water. This can slow down the lake's expansion. On the other hand, larger lakes have a larger volume of water, making their levels more resilient to short-term changes in precipitation. In contrast, smaller lakes can fluctuate more rapidly in response to such changes, allowing for quicker, albeit smaller, expansions. It should also be noted that in the Sanjiangyuan area, larger lakes are more likely to be affected by human activities such as agriculture and water extraction for human consumption. This anthropogenic impact can restrict the natural expansion of larger lakes more than smaller lakes.

The lakes in the Sanjiangyuan region showed an overall expansion trend over the past 20 years (Slope $= 76.12$ km^2/a, $R^2 = 0.92$), particularly from 2011 to 2020 (Slope $= 75.20$ km^2/a, $R^2 = 0.65$), according to Fig. 3a, which analyzes the area of the lakes in the Sanjiangyuan region from 2000 to 2020. After analyzing the specific trends of the three types of lakes, Fig. 3b–d shows that the expanded lake area's interannual variation trend is significant (Slope $= 85.33$ km^2/a, $R^2 = 0.95$) (Fig. 3b). The lake area peaked in 2000 at 5068.20 km^2, and from 2011 to 2020, the area growth trend became more evident (Slope $= 92.73$ km^2/a, $R^2 = 0.88$). Because expansive lakes predominate in the Sanjiangyuan lakes, the overall trend of expansive lakes is similar to that of the Sanjiangyuan lakes. It is worth mentioning that such factors as increased temperatures due to climate change have led to more glacial melt and increased water input into the lakes, contributing to lake expansion.

The atrophic lake area decreased with little interannual variation (Slope $= -9.03$ km^2/a, $R^2 = 0.19$), but after 2010, the atrophic lake area fluctuated and declined more (Slope $= -15.82$ km^2/a, $R^2 = 0.11$) (Fig. 3c). While the area of stable lakes showed no obvious trend (Slope $= -0.06$ km^2/a, $R^2 = 0.01$), with larger interannual fluctuations, showing a steady expansion trend from 2001 to 2010

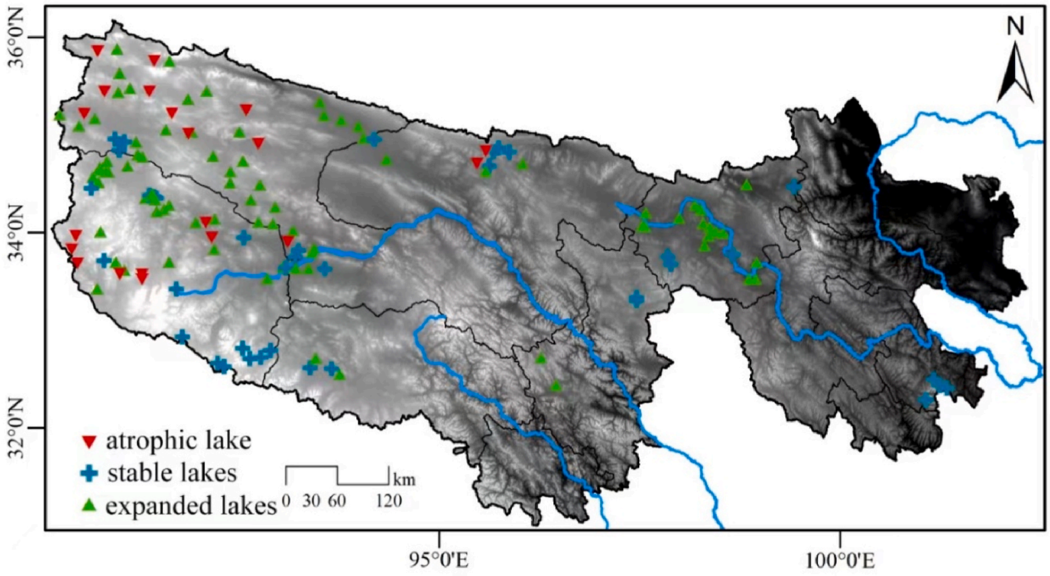

Fig. 2. Classifications of lake area changes in the Three-River Regions with an area of more than 1 km^2.

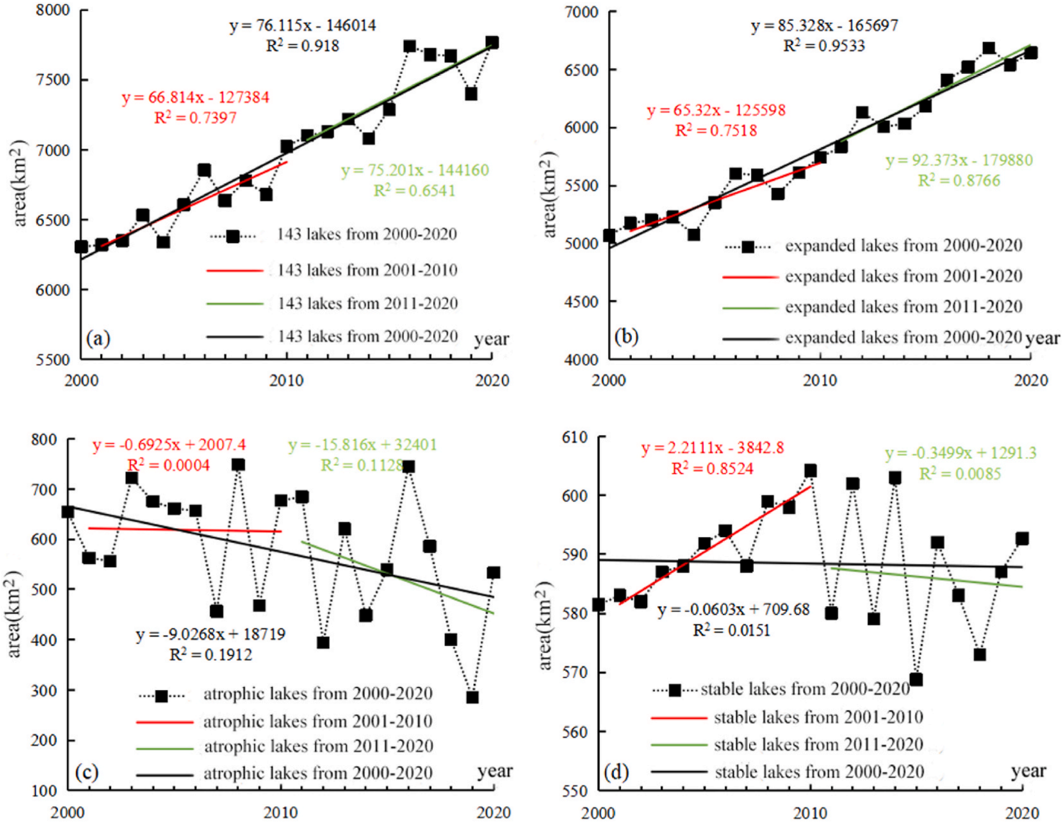

Fig. 3. Trends of lake area changes in the Three-River Regions since 2000 (a. 143 lakes; b. expanded lakes; c. atrophic lakes; d. stable lakes).

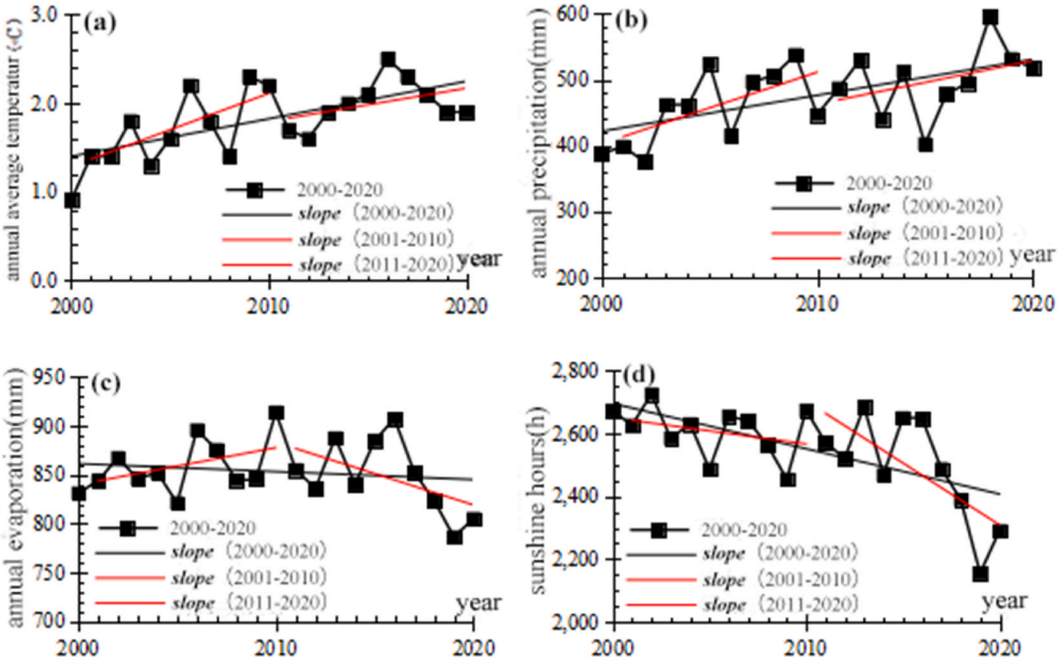

Fig. 4. Climate change characteristics in the Three-River Regions between 2000 and 2020.

(Slope = 2.21 km^2/a, R^2 = 0.85), while the lake area declined yearly after 2010 Slope = −0.35 km^2/a, R^2 = 0.01) (Fig. 3d).

4.3. *Climate change characteristics*

The trends of the Sanjiangyuan region's meteorological stations' yearly average temperature, annual precipitation, annual evaporation, and annual sunlight hours are displayed in Fig. 4 from 2000 to 2020. The figure illustrates how the Sanjiangyuan region's temperature has fluctuated more over the last 20 years, with a rising rate of 0.42 °C•10 a^{-1}, greater than the Tibetan Plateau's multi-year average warming rate of 0.19 °C•10a^{-1} [70]. With an increasing rate of 54.68 mm•10a-1, the precipitation increased dramatically over the Tibetan Plateau, surpassing the multi-year average growth rate of 48.43 mm•10 a^{-1} [71]. In line with the Tibetan Plateau's tendency to change, the yearly evaporation exhibited a declining trend, and the number of sunlight hours dramatically fell [72,73]. It is worth mentioning that the result is consistent with the previous studies [74,75].

(a. annual average temperature; b. annual precipitation; c. annual evaporation in the headwaters; d. sunshine hours).

4.4. *Characteristics of glacial and permafrost changes*

The results of calculating ice reserves using Grinsted's algorithm [76] are displayed in Table 2. With an average variability of −5.75 km^2•a^{-1} and -0.39 km^3•a^{-1}, the glacier area and ice storage in the Sanjiangyuan region declined steadily and at an increased pace of retreat between 2000 and 2020, by 114.96 km^2 and 7.86 km^3, respectively. The glacier retreat rate in the Sanjiangyuan region reached its greatest values (−11.30 km^2•a^{-1} and -0.77 km^3•a^{-1}) between 2015 and 2020, suggesting that the glaciers have been melting more quickly since 2015. The Sanjiangyuan region's permafrost evolution trend is depicted in Fig. 5 for 2000–2020.

The chart shows that during the last two decades, the average yearly maximum permafrost depth of the three rivers' sources is 126.2 cm, with an overall trend of 1.08 cm•(10a)$^{-1}$. The average yearly maximum permafrost depth has decreased since 2010 (Fig. 5a), going from 140.5 cm in 2000 to 114.5 cm in 2020. The seasonal permafrost in the Sanjiangyuan region started to freeze in October, achieved its maximum value in January and February, and entered the thaw stage in March, as can be seen from the daily maximum permafrost depth curve (Fig. 5b). The maximum permafrost depth from 2011 to 2020 has a greater daily reduction than that from 2001 to 2010, according to a comparison of the daily variation characteristics of the two interdecadal average maximum permafrost depths from 2000 to 2010 and 2011 to 2020. The interdecadal variation characteristics are particularly noticeable from February to March. The period from February to March is critical due to the combined effects of seasonal temperature changes, increased solar radiation, and snowmelt.

4.5. *The response of lake area to changes in climate, glaciers, and permafrost*

This subsection examined the correlation between annual temperature, precipitation, evaporation, sunshine hours, permafrost depth, glacier area, and ice storage data and the total lake area in the Sanjiangyuan region. Table 3 shows that there is a substantial association between the remaining parameters and lake extent, with the exception of yearly evaporation. With a significance level of greater than 0.01 and a positive correlation between the annual average temperature and the lake area, the annual average temperature showed the strongest relationship with the lake area of Sanjiangyuan Lake. This suggests that increasing temperature and precipitation will result in an increase in the lake area, with temperature having a greater influence on the lake area. The correlation between the lake area and the annual maximum permafrost depth, glacier area, ice storage, and sunshine hours was negative. The correlation between the lake area and the glacier area, ice storage, and sunshine hours was higher than that of the other influencing factors, and the significance level was above 0.01; this suggests that the decrease in sunshine hours, maximum permafrost depth, glacier area, and ice storage was the primary cause of the increase in Sanjiangyuan's lake area, with glacier ablation playing the largest role.

The lakes in the Sanjiangyuan region showed an annual increase tendency between 2000 and 2020. Between 2000 and 2010, Sanjiangyuan area temperatures rose, causing permafrost to melt, glacier area and ice storage to decrease, and precipitation to increase. This resulted in an increase in precipitation and meltwater entering the lake, with the lake area exhibiting an increasing trend due to the combined recharge of precipitation and glacial meltwater. The Sanjiangyuan region's annual maximum permafrost depth decreased after 2010, the glacier melt intensified, sunshine hours and evaporation both showed a declining trend, and as a result, the

Table 2
Change of glacier area and ice storage in the Three-River Regions from 2000 to 2020.

Years	Glacier Area (km^2)	Ice Storage (km^3)	Steps	Glacier Area		Ice Storage	
				Changes (km^2)	Rate (km^2•a^{-1})	Changes (km^3)	Rate (km^3•a^{-1})
2000	1812.4	93.18					
2005	1787.22	91.44	2000–2005	−25.18	−5.04	−1.74	−0.35
2010	1778.86	90.86	2005–2010	−8.36	−1.67	−0.58	−0.12
2015	1753.94	89.16	2010–2015	−24.92	−4.98	−1.71	−0.34
2020	1697.44	85.32	2015–2020	−56.5	−11.30	−3.84	−0.77
			2000–2020	−114.96	−5.75	−7.86	−0.39

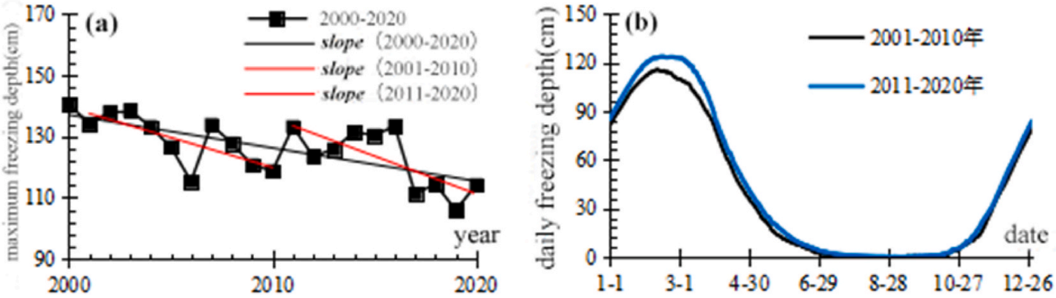

Fig. 5. Change of freezing in the Three-River Regions from 1981 to 2020(a: annual maximum freezing depth; b:daily freezing depth).

Table 3
Correlation between the effective factors and the lake areas.

	Temperature	Precipitation	Evapotran Spiration	Daylight Hours	Maximum Permafrost Depth	Glacier Area	Ice Storage
Spearman	0.582[b]	0.538[b]	−0.199	−0.521[a]	−0.722[b]	−0.859[b]	−0.860[b]

[a] is significant at the 0.05 level and.
[b] is significant at the 0.01 level.

lake area expanded continuously and at a faster rate from 2011 to 2020.

5. Discussion

Some studies were conducted recently on the variables that influence the change in lake area on the Tibetan Plateau [77–80]. Nonetheless, the majority of research concentrates on the influence of climate drivers such as temperature, precipitation, and evaporation. Although some studies have analyzed the impact of glacier changes on lake area, most of them focus on the dynamic response of glacier-recharged lakes to glacier changes [81,82]. Particularly, there are even fewer studies related to the driving factors of lake area changes in the Sanjiangyuan region. But permafrost meltwater also has an impact on lake area variations, in addition to temperature and glacier fluctuations; tiny lakes are particularly vulnerable to these influences [83,84]. Therefore, it is helpful to investigate the primary influencing factors and differences in the dynamic changes of the lakes in the Sanjiangyuan region. Additionally, monitoring the area changes of numerous lakes in the Sanjiangyuan and revealing the relationship between the changes in lake area and temperature, precipitation, evaporation, sunshine hours, glaciers, and permafrost has theoretical guidance significance for the protection of water sources in the Sanjiangyuan region.

Studies of lakes at the regional scale are crucial to comprehending how various regions are responding to climate change [85]. The three rivers' headwaters are vulnerable to climate change, and the region's lake area changes are trending upward, which is mostly in line with the features of the western Tibetan Plateau's lake area changes [86]. On the influencing factors of the area change of the lakes in the source of the three rivers, the contribution rate of evaporation is low among the driving factors affecting the area change of the lakes in the source of the three rivers in this paper, which is consistent with the results of Hao 's [87] study on the factors affecting the lake area change of Sanjiangyuan. Nonetheless, some research indicates that the primary cause of lake deterioration in the source area is higher evaporation [88]. The primary cause of this discrepancy could be because the variation in lake area reflects changes in the water balance of the inflow and outflow from the lake, which are mostly influenced by the disparity in precipitation and evaporation [89]. The influence of evaporation on lake water balance was lessened between 2000 and 2020 when precipitation increased significantly at the sources of the three rivers. The increase in precipitation in the Sanjiangyuan region from 2000 to 2020 was much larger than the change in evaporation, which weakened the effect of evaporation on the water balance of the lake.

6. Conclusion

In this work, the GEE platform was utilized to gather area data from Landsat remote sensing photos of lakes larger than 1 km^2 in the Sanjiangyuan region, and the lakes' spatiotemporal evolution patterns were examined from 2000 to 2020. Concurrently, the primary driving forces influencing the change in lake area in the Sanjiangyuan area during the last 20 years were briefly examined, along with the changes in climate, glaciers, and permafrost in the Sanjiangyuan region. The main findings of the present study are summarized as follows: (1) From the point of view of area size, the expansion of the area of lakes in the Sanjiangyuan region decreases with the increase in area size, and the expansion of small lakes is the largest due to various factors, including geographical, hydrological, climatic, ecological, and anthropogenic constraints. In addition, from the point of view of elevation, atrophic lakes are distributed at high elevations, and expanded lakes are distributed at all elevations. (2) Over the last two decades, there has been a general trend of lake extension in the Sanjiangyuan region, particularly between 2011 and 2020. Among them, expanded lakes have significant inter-annual trends in area, atrophic lakes have smaller inter-annual trends in area, and stable lakes have insignificant trends in area and large inter-annual fluctuations. (3) Over the last two decades, the Sanjiangyuan region has seen a rise in temperature and humidity, an ongoing rapid retreat of its glacier area and ice store, and a continual declining trend in the annual maximum permafrost depth. (4) Apart from the annual evaporation, there was a noteworthy association found between the variations in the Sanjiangyuan lakes' area and the annual mean temperature, annual precipitation, annual sunshine hours, annual maximum permafrost depth, glacier area, and ice storage, with the greatest contribution coming from glacier ablation.

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Data availability

All data generated or analyzed during this study are included in this published article.

CRediT authorship contribution statement

Ya'nan Hu: Investigation. **Hongmei Li:** Investigation. **Di Yu:** Investigation. **Xiaoli Feng:** Investigation. **Wenxue Ba:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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