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Response of Lake Dynamics to Climate Change in the Qilian Mountains from 1990 to 2020

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Abstract: Lakes are sensitive indicators of climate change. Based on the lake dataset and Landsat remote sensing data, we analyzed the changes in area and number of lakes (>1km^2) in the Qilian Mountains from 1990 to 2020, as well as the boundary changes of lakes(>100km^2). In addition, we discussed the impact of climate change on lake area. The results showed that: (1) From 1990 to 2020, the total area and total number of lakes in the Qilian Mountains showed an overall increasing trend, with a total area increase of 492.47km^2 and a total number increase of 10. Among them, Qinghai Lake, Hala Lake, Xiao Qaidam Lake, and Nauru Nor Lake showed an overall expansion trend, while Caka Salt Lake and Da Caidam Lake showed an overall shrinking trend. (2)The main reasons for the expansion of Qinghai Lake and Hala Lake was the increase in precipitation, while the main reason for the expansion of Xiao Qaidam Lake and Nauru Nor Lake was the increase in temperature and precipitation. The main reason for the shrinkage of Caka Salt Lake was the enhancement of evapotranspiration. (3) Lakes in the Qilian Mountains were mainly expanding, which has a good promoting effect on improving the ecological environment of this region and even larger area. However, we should also pay attention to problems such as floods and salt-alkali land caused by lake expansion in a timely manner. In addition, governments and all sectors of society should take corresponding measures to alleviate further shrinkage of Caka Salt Lake.

1. Introduction

Lakes are vital water resources that play a crucial role in the water cycle, serving functions like flood control, climate regulation, and water purification. As integral components of the natural environment, lakes are essential contributors to ecosystem services within the broader "mountains, waters, forests, farmlands, lakes, grasses, sands" community [1]. Notably, lakes are considered sensitive indicators of climate change due to their responsiveness to environmental shifts. With global warming, lakes worldwide are undergoing changes in number, size, and distribution. This scientific importance has led to the inclusion of lake research in international climate initiatives such as the United Nations Framework Convention on Climate Change and the IPCC.

The Qilian Mountains region holds immense ecological significance in China, serving as a critical source of freshwater resources and ecological protection. It plays a vital role in supporting neighboring areas such as the Hexi Corridor, Tsaidam Basin, Qinghai Lake Basin, and Hehuang Valley, with far-reaching ecosystem service benefits [2]. Recognizing its ecological importance, the Chinese government established the Qilian Mountains National Park in September 2017, designating it as one of the country's first national parks. This high-altitude, ecologically fragile area faces challenges linked to rising temperatures, including glacier melting, reduced snowfall, and permafrost degradation [3]. Given its harsh environment and low population density, the region's lake expansion or shrinkage is primarily driven by climate change. While past research has focused on specific lakes like Qinghai Lake and Hala Lake, there is a significant lack of studies covering the entire Qilian Mountains range. Therefore, studying Qilian Mountain lakes and their dynamic changes within the context of climate change is crucial for advancing ecological protection, restoration efforts, and sustainable water resource management in the area.

Early lake water information was collected manually or from hydrological monitoring stations. In the 1950s, China initiated its first national lake resource data collection, leading to the establishment of a fundamental lake hydrological database and publications that filled gaps in Chinese lake science [4]. However, this traditional approach was time-consuming and labor-intensive despite its accuracy. Subsequently, advancements in remote sensing technology allowed for the extraction of surface water information from satellite images, progressing from manual methods to semi-automated spectral and spatial techniques. Today, deep learning-based fully automated water body extraction methods offer high precision. These advancements have enabled rapid, accurate, and large-scale extraction of water body information, driving significant research progress in the field of lake studies.

2. Overview of the study area

The Qilian Mountains(35.8 °~40.0 °N; 93.4 °~103.4 °E), spanning northeastern Qinghai and western Gansu, border the Hexi Corridor to the north, the Altai Mountains to the west, and the Qaidam and Caka Basins to the south. In the southeast, they connect with the Yellow River Valley, Qinling, and Liupan Mountains. This region covers approximately 18.17×104km^2 and features high terrain in the west, sloping eastward. It hosts diverse ecological resources like grasslands, forests, lakes, rivers, snow, glaciers, and permafrost, supporting major rivers: Shiyang, Heihe, and Shule. Influenced by the Siberian High Pressure, East Asian monsoon, and westerly jet stream, it experiences long, cold, dry winters and short, cool, humid summers [5-6]. The climate is continental, with precipitation mainly from May to September [7].

Due to the scarcity of lakes larger than 1 km^2 in the Qilian Mountains and the challenges in accurately delineating lakes smaller than 100 km^2, our primary focus was on analyzing changes in lake area and the boundaries of Qinghai Lake, Hala Lake, and Caka Salt Lake. Among these, Qinghai Lake stands as the largest in the Qilian Mountains, situated in the southeast, boasting the title of China's largest saltwater lake, with an average elevation of 3.20×10^{3}m and an area around 4.29×10^3 km^2. The second largest is Hala Lake, found in the southern part of Shule South Mountain in the western Qilian Mountains, a saltwater lake with an average elevation of 4.78×10^{3}m and covering about 602 km^2 (Figure 1). As for Caka Salt Lake, located in the southern Qilian Mountains, it is a landlocked lake with an average elevation of 3.06×10^{3}m, expanding to approximately 116.1 km^2 during the flood season. Notably, only the northern portion of Caka Salt Lake falls within the Qilian Mountains region.

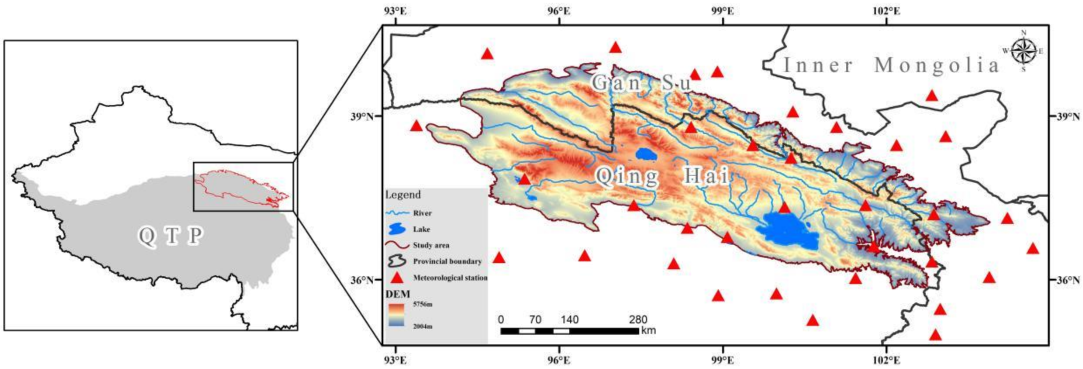


Figure 1: Study area.

3. Data and Methods

3.1. Data

3.1.1. Lake data

The analysis of the characteristics of changes in the number and area of lakes in the Qilian Mountains was based on the Chinese Lake Dataset released by the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn). This dataset contained observation data of lakes with an area greater than 1 km^2 in the past 60 years (1960s, 1970s, 1990, 1995, 2000, 2005, 2010, 2015, 2020). The data format was vector data. The number and area data of lakes in the Qilian Mountains from 1990 to 2020 were obtained through clipping and geometric calculation tools on the ArcGIS software platform.

3.1.2. Meteorological data

To explore meteorological factors influencing lake changes, we selected five factors: temperature, precipitation, evapotranspiration, wind speed, and sunshine hours. Temperature, precipitation, and wind speed data were sourced from the National Oceanic and Atmospheric Administration (https://www.psl.noaa.gov) for 35 meteorological stations in the Qilian Mountains and surroundings, provided in csv format. Raster data for spatial distribution were created using inverse distance weighting interpolation in ArcGIS. Actual evapotranspiration data were derived from the GLEAM model (https://www.gleam.eu) with a spatial resolution of 0.25 °×0.25 °and a time resolution of 1 day. Sunshine hours data were obtained from the National Meteorological Science Data Sharing Service Platform-China Ground Climate Data Daily Value Dataset. This dataset provides daily data for each observation station. We used the Barnes method to interpolate into grid data with a 0.1 °×0.1 ° resolution and then averaged the data regionally to calculate annual sunshine hours.

3.1.3. Glacier and permafrost data

Glacier data were obtained from the Chinese Second Glacier Catalogue Dataset (V1.0) (2006-2011) from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn). This dataset includes vector and attribute data for glaciers in western China. Permafrost data came from the China Permafrost Distribution Map (2000) available on the Space-Time Three-Level Environment Big Data Platform (http://poles.tpdc.ac.cn/zh-hans/), reflecting permafrost distribution around 2000 in China. We used ArcGIS software to extract glacier and permafrost information in the Qilian Mountains through clipping.

3.2. Method

3.2.1. Normalized Water Index

We used Normalized Difference Water Index (NDWI) to extract lake information. The method selects specific bands by analyzing the spectral characteristics of water to construct different index models and give corresponding thresholds to extract water. Mcfeeters created the Normalized Difference Water Index (NDWI), which can greatly reduce vegetation information and highlight water information by taking the ratio of the difference between the green band and the near-infrared band and the sum of the two bands [8].

Its expression is:

$$NDWI = \frac{(G - NIR)}{(G + NIR)} \tag{1}$$

In formula (1), *G* represents the green band and *NIR* represents the near-infrared band.

3.2.2. Pearson Correlation Analysis

Pearson correlation analysis is the most commonly used statistical value to measure the correlation between two variables [9]. The correlation coefficient between lake area and various meteorological elements was calculated to determine the influence of different meteorological elements on lake area changes.

The calculation formula is:

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - \bar{X}}{\delta_X}\right)\left(\frac{Y_i - \bar{Y}}{\delta_Y}\right) \tag{2}$$

In formula (2), *r* is the Pearson correlation coefficient, n is the number of samples, *X* is the area of the lake, and *Y* is the value of the meteorological element.

4. Results and Analysis

4.1. Lake Change Characteristics

4.1.1. Lake Time Change

Overall (Figure 2), the total area and number of lakes larger than 1 km^2 showed an increasing trend from 1990 to 2020, with a total area increase of 492.47 km^2 and a total number increase of 10. In terms of stage changes, the total area slowly fluctuated and increased from 1990 to 2015, and rapidly and continuously increased from 2015 to 2020, with an increase rate of about 9.09 km^2/a and 53.02 km^2/a, respectively. The area decreased in 1995-2000 and 2010-2014, with a decrease of 159.31 km^2 and 123.85 km^2, respectively; the total number slowly fluctuated and increased from 1990 to 2015, and rapidly fluctuated and increased from 2015 to 2020, with an increase of three in the first twenty-five years and seven in the last five years. The number increased more in 2015-2016, increasing by five in one year. In terms of individual lakes larger than 5 km^2, Qinghai Lake, Hala Lake, Xiao Qaidam Lake, and Nagonor showed an overall expansion trend from 1990 to 2020, with an area increase of about 222.31 km^2, 48.58 km^2, 66.98 km^2, and 3.69 km^2, respectively; while Caka Salt

Lake and Da Qaidam Lake showed an overall shrinking trend, with an area decrease of 6.44 km^2 and 13.89 km^2, respectively. Among them, Qinghai Lake area continued to decrease from 1990 to 2005 and continued to increase from 2005 to 2020; Hala Lake area continued to decrease from 1990 to 2000 and fluctuated and increased from 2000 to 2020, with a faster increase rate from 2017 to 2020 at about 8.57 km^2/a; Caka Salt Lake area continued to increase from 1990 to 2010 and reached its maximum point (137.55 km^2) in 2010; Da Qaidam Lake area continued to decrease rapidly from 1990 to 2000 and reached its minimum point (16.16 km^2) in 2000; it fluctuated greatly and frequently from 2000 to 2020; Xiao Qaidam Lake area slowly fluctuated and increased from 1990 to 2015 and rapidly fluctuated and increased from 2015 to 2020 with a high linear fitting degree; Nagonor Lake area slowly fluctuated and increased from1990 to 2010 and rapidly decreased continuously from 2010 to 2014 and rapidly fluctuated upward from 2014 to 2020.

(c) Caka Salt Lake; (d) Da Qaidam Lake; (e)Xiao Qaidam Lake; (f) Nauru Nor Lake.

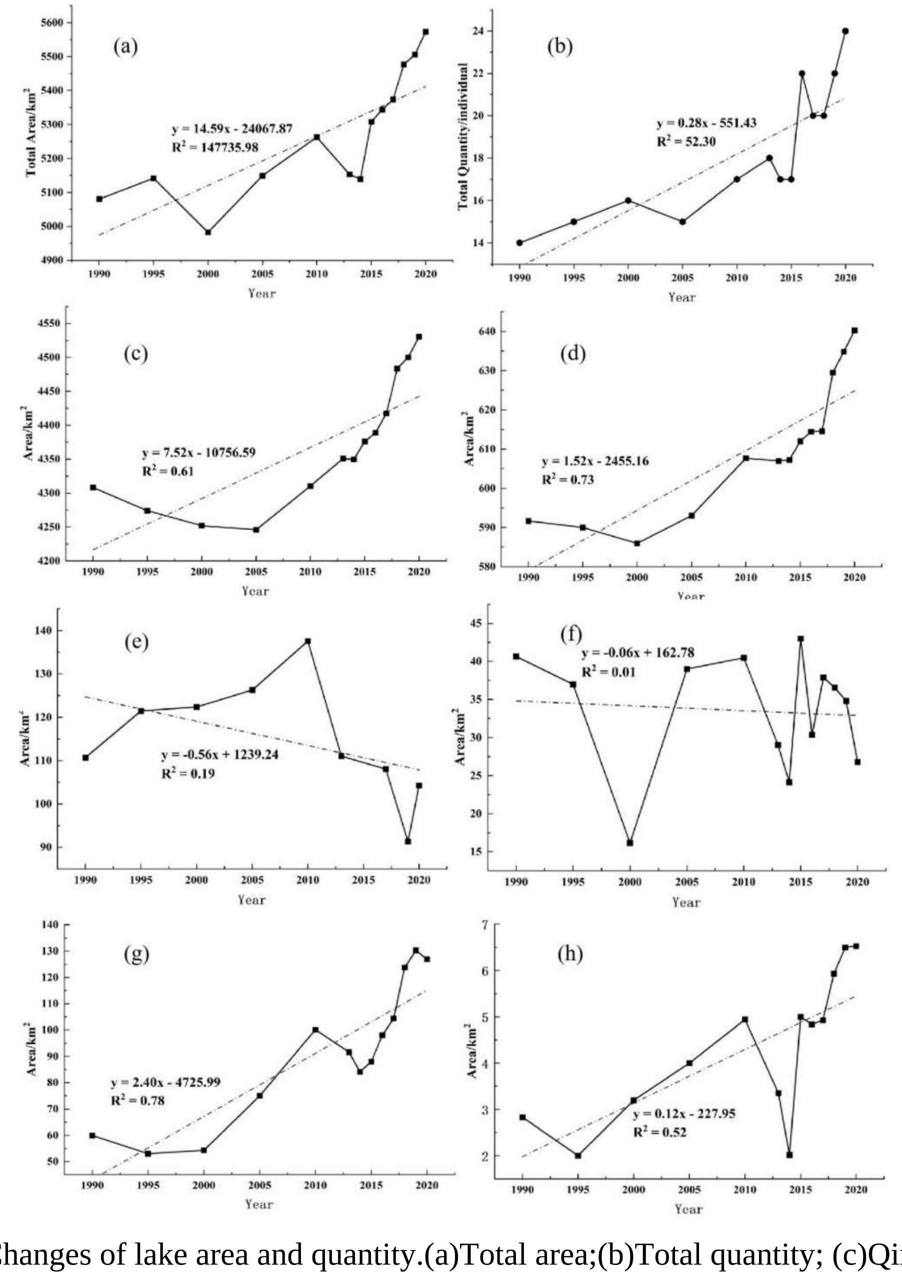


Figure 2: Changes of lake area and quantity.(a)Total area;(b)Total quantity; (c)Qinghai Lake; (d)Hala Lake; (e)Caka Salt Lake;(f)Da Qaidam Lake;(g)Xiao Qaidam Lake;(h)Nauru Nor Lake.

4.1.2. Spatial changes in lakes

Lakes larger than 1 km^2 in the Qilian Mountains are almost all distributed in the middle and eastern parts of Qinghai Province (Figure 3). As of 2020, there were 25 lakes in Qinghai Province and only one lake in Gansu Province, located in the northwest of Gansu Province. From 1990 to 2020, about 79% of the lake area increased, mainly including Qinghai Lake in the southeast of Qilian Mountains, small lakes in the east, and Hala Lake and small lakes nearby; about 21% of the lake area decreased, which was relatively scattered and located in the southwest (one), middle (two), and east (two) of the Qilian Mountains.

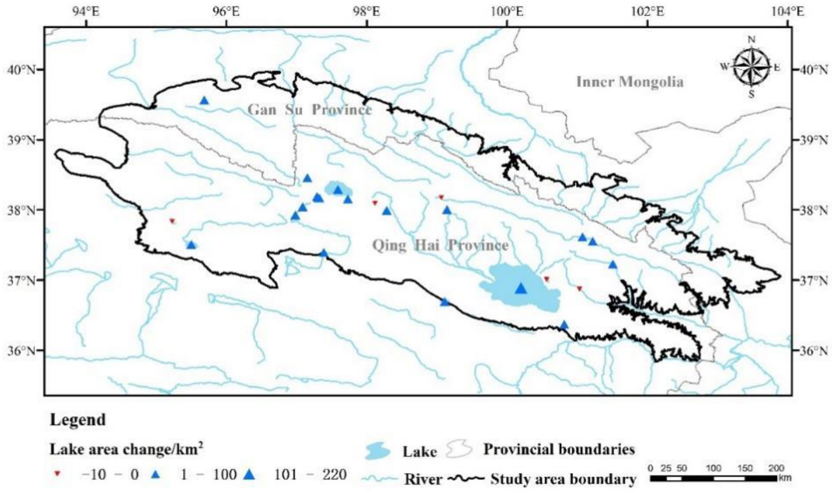


Figure 3: Spatial distribution of lake area change

4.2. Climate Change Characteristics

From 1990 to 2020, the overall trend of temperature, precipitation, evapotranspiration and wind speed showed an increasing trend, with linear regression slopes of about 0.14, 10.17, 0.21 and 0.02 respectively(Figure 4). Only sunshine hours showed a decreasing trend, with a linear regression slope of about −4.52. In terms of stage changes, the temperature showed a large fluctuation and increasing trend from 1990 to 2005, with an increase of about 3.87 ℃. From 2005 to 2020, it showed a small fluctuation and decreasing trend, with a decrease of about 0.03 ℃; precipitation showed a slow fluctuation and increasing trend from 1990 to 2015, with an increase of about 168.23 mm. From 2015 to 2020, it showed a rapid fluctuation and increasing trend, with an increase of about 301.98 mm; actual evapotranspiration was relatively stable from 1990 to 2009 (except for 2003), fluctuating around 230 mm. Evapotranspiration was low in 2003, at about 201.03 mm. From 2010 to 2020, the fluctuation range was relatively large; wind speed showed a fluctuating downward trend from 1990 to 2000, decreasing by about 0.56 knots. From 2000 to 2020, it showed a fluctuating upward trend, increasing by about 0.46 knots; sunshine hours showed a slow fluctuating downward trend from 1990 to 2015, decreasing by about 115.73 h. From 2015 to 2020, it showed a rapid fluctuating downward trend, decreasing by about 189.38 h.

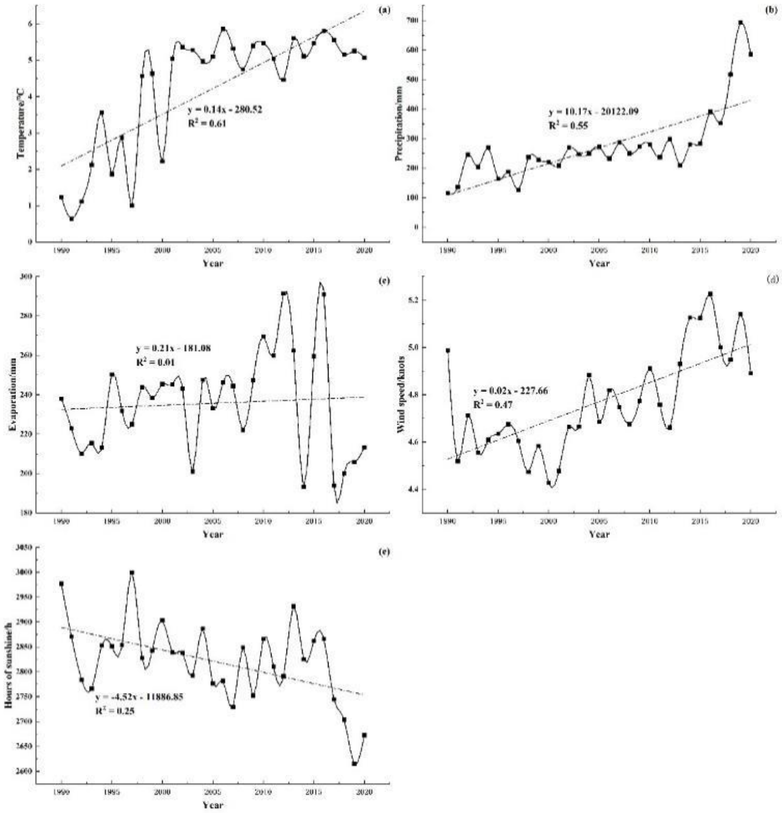
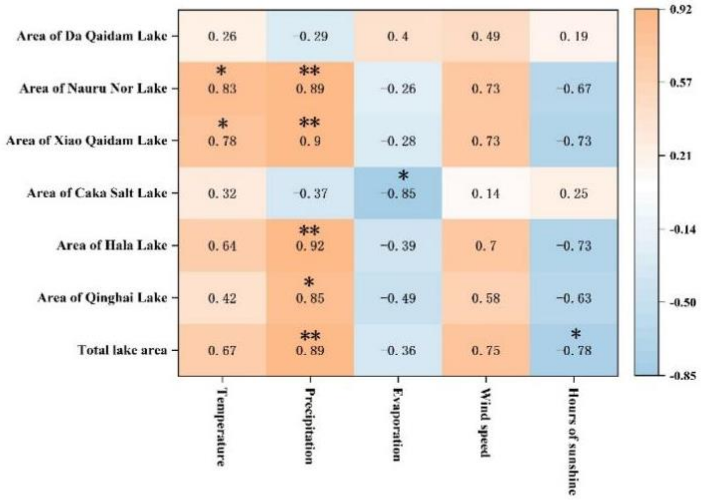


Figure 4: Folding line graph of meteorological elements trend in Qilian Mountains from 1990 to 2020

5. Correlation between Lake Area and Meteorological Factors

We used correlation analysis to study the relationship between the total area of lakes and specific lakes such as Qinghai Lake, Hala Lake, Caka Salt Lake, Xiao Qaidam Lake, Nauru Nor Lake, and Da Qaidam Lake, and various factors including temperature, precipitation, actual evapotranspiration, wind speed, and sunshine hours. The Pearson correlation coefficient was used to indicate the strength of the correlation. The total area of lakes was significantly positively correlated with precipitation, with a correlation coefficient of 0.89 and a significance level of 0.01; Qinghai Lake area was significantly positively correlated with precipitation, with a correlation coefficient of 0.85 and a significance level of 0.05; Hala Lake area was significantly positively correlated with precipitation, with a correlation coefficient of 0.92 and a significance level of 0.01; Caka Salt Lake area was significantly negatively correlated with evapotranspiration, with a correlation coefficient of −0.85 and a significance level of 0.05; Xiao Qaidam Lake area was significantly positively correlated with temperature and precipitation, with correlation coefficients of 0.78 and 0.90 respectively, and precipitation had a greater significance; Nauru Nor Lake area was significantly positively correlated with temperature and precipitation, with correlation coefficients of 0.83 and 0.89 respectively, and precipitation had a greater significance; Da Qaidam Lake area was not highly correlated with meteorological factors and does not show significance(Figure 5).

It can be seen that the expansion of Qinghai Lake and Hala Lake was mainly related to the increase in precipitation. The increase in precipitation lead to an increase in surface runoff and groundwater recharge, as well as an increase in lake water volume and area. For Xiao Qaidam Lake and Nauru Nor Lake, the expansion of lake area was mainly due to the increase in temperature in addition to the increase in precipitation. There were permafrost mountains in the northeast of Xiao Qaidam Lake, while Nauru Nor Lake was surrounded by permafrost mountains and there were glaciers in the northeast. The rise in temperature may cause permafrost glaciers near these two lakes to melt, resulting in increased water volume and expansion of lake area due to runoff into the lakes. Caka Salt Lake is an inland closed lake without outlets. It can only reduce its water volume through evaporation. On the other hand, it is a brine lake with solid-liquid coexistence. There are salt layers as thick as several meters under brine. High-concentration brine is easily evaporated, so the enhancement of evapotranspiration was the main reason for the shrinkage of Caka Salt Lake.



(*P<0.05, **P<0.01)

Figure 5: Correlation coefficient between lake area and each meteorological factor

6. Conclusion and Discussion

6.1. Conclusion

1) From 1990 to 2020, the total area and number of lakes larger than 1 km^2 showed an overall increasing trend, with a total area increase of 492.47 km^2 and a total number increase of 10. Among them, Qinghai Lake, Hala Lake, Xiao Qaidam Lake, and Nauru Nor Lake showed an overall expansion trend, with an area increase of about 222.31 km^2, 48.58 km^2, 66.98 km^2, and 3.69 km^2 respectively. However, Cha Ka Salt Lake and Da Qaidam Lake showed an overall shrinking trend, with an area decrease of 6.44 km^2 and 13.89 km^2 respectively.

2) From 1990 to 2020, about 79% of the lake area in Qilian Mountain area increased, mainly including Qinghai Lake in the southeast of Qilian Mountain, small lakes in the east, Hala Lake and small lakes nearby; about 21% of the lake area decreased, which were distributed relatively scatteredly in the southwest (one), central (two), and east (two) parts of Qilian Mountain area.

3) From 1990 to 2020, Qilian Mountain area developed towards warm-humidification as a whole. The evapotranspiration and wind speed also increased, while sunshine hours showed a decreasing trend. The increase in precipitation led to the expansion of Qinghai Lake and Hala Lake areas; the increase in temperature and precipitation led to the expansion of Xiao Qaidam Lake and Nauru Nor Lake areas; the enhancement of evapotranspiration led to the shrinkage of Cha Ka Salt Lake area.

6.2. Discussion

In fact, there is a time lag and spatial difference in the response of lake area to meteorological factors, which is determined by the dynamic balance process of lake water and the complexity of lake hydrological characteristics. The time lag is manifested as a certain delay in the response of lake area to meteorological factor changes, which is related to the input and output process of lake water. The spatial difference is manifested as different sensitivities and intensities of different regions, types and scales of lakes to meteorological factor changes, which is related to the climate region, topographic conditions, water supply mode and other factors where the lakes are located. We analyzed the changes of lake area and meteorological factors on an annual scale. The impact of climate change in the previous year or years on lake area was not significant, and the time lag may not be obvious. If it is on a seasonal or monthly scale, the time lag cannot be ignored. In addition, there were spatial differences in climate in Qilian Mountain area, so the impact of climate on lake area in different regions was different. We only studied the climate of the entire Qilian Mountain area, lacking research on the impact of climate change in different regions on different lakes.

In addition to climate change affecting lake area, human activities also play a certain role. For example, in 2008, Qinghai Province launched a 10-year “Qinghai Lake Basin Ecological Environment Protection and Comprehensive Management Plan”, which implemented artificial rainfall enhancement, wetland protection, Qinghai Lake National Nature Reserve capacity building and other projects. The expansion of Qinghai Lake area was an important manifestation of these ecological governance achievements. In addition, as China’s “Sky Mirror”, Cha Ka Salt Lake had problems such as overloaded tourist attractions and serious pollution [10]. Therefore, human activities were also a key factor affecting the expansion and shrinkage of lakes in Qilian Mountain area, especially Qinghai Lake and Hala Lake.

In recent years, the expansion of lake area had been dominant in Qilian Mountains area. However, the expansion of lake area has two sides. On the one hand, it is conducive to increasing water resources storage in Qilian Mountain area, improving hydrological conditions in arid and semi-arid areas, maintaining wetland ecosystem functions, and promoting vegetation recovery and species diversity increase locally. Moreover, under the trend of global warming, Qilian Mountain area will experience a long period of warm-humidification, and lake area may continue to expand, which has a good promoting effect on improving local ecological environment and even larger areas. On the other hand, continuous expansion of lake area will also bring risks such as flood disasters and salinization.

Acknowledgement

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