ORIGINAL ARTICLE

Changes in and driving factors of the lake area of Huri Chagannao'er Lake in Inner Mongolia

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ABSTRACT

Inland lakes are an important component of the terrestrial water cycle in Inner Mongolia's typical steppe region, and their variations have far-reaching implications for the sustainable development of water resources in this region. Huri Chagannao'er Lake, one of Inner Mongolia's four major freshwater lakes and the second largest inland lake in the typical steppe region, was chosen as the research object. In this study, the spatiotemporal changes in the area of Huri Chagannao'er Lake over the last 30 years were analyzed using the modified normalized difference water index method and Landsat data. Then, we used regression analysis, correlation analysis, gray relational analysis, and Geodetector to investigate the potential causes of lake area changes. Changes in the lake's water balance, meteorological and climatic changes near the lake, and changes in land use and land cover in the drainage basin are all possible driving factors. Finally, the main driving factors of the lake area change are discussed in conjunction with the literature and field investigation, and measures and suggestions for the lake's sustainable utilization and protection are proposed. The findings revealed that i) from 1988 to 2017, the lake shrank from 98.99 km^2 to 29.81 km^2, with year 2000 marking the start of the dramatic changes in lake areas; ii) the lake shrinkage was primarily concentrated in the western part of the lake, while the eastern part of the lake remained stable; iii) human activities, such as water interception and storage, as well as excessive exploitation of water resources, were the most significant causes of the dramatic fluctuation in the area of the lake's western part; iv) climate change also had some influence on the lake area changes. The regional climate became warmer and drier, reducing the amount of water entering the drainage basin. The findings of this study highlight the dominant role of human activity intensity in lake area changes and provide a theoretical foundation and technical support for the study of inland lakes in Inner Mongolia's typical steppe region.

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Key words: Lake area changes; inland lakes; Inner Mongolia; typical steppe region; human activities; climate change.

All the authors made a substantive intellectual contribution, have read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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INTRODUCTION

Inner Mongolia's typical steppe region is one of China's regions with severe water shortages, and water resources are a key factor influencing the region's ecological, economic, and social development (Qin *et al.*, 2002; Piao *et al.*, 2010; Wang and Wang, 2012; Chen *et al.*, 2012). The local water resource system is fragile and sensitive, relying on rainfall, snowmelt, and ice melt (Qin *et al.*, 2002; Chen *et al.*, 2012). Inland lakes are an important part of the water resources in the typical steppe region in Inner Mongolia and they are extremely vulnerable to climate change and human activity (Yang *et al.*, 2010; Wang *et al.*, 2015).

There is an obvious conflict between economic development and ecological protection in the development and exploitation of lakes, and excessive water extraction and disorderly exploitation directly cause varying degrees of ecological problems in these lakes, which hinders the sustainable development of the local water resources (Yang *et al.*, 2010; Chen *et al.*, 2012; Wang *et al.*, 2015). Therefore, the close observation of the lake dynamics in this region and accurate identification of the response mechanism of lakes to various driving factors are of great significance for protecting these lakes, the local water resources, and the regional ecological environment.

Recently, studies conducted on lake area changes have been gradually providing deeper insights through extensive application of geographic information systems to lake area change analysis. Researchers have found that many lakes have exhibited varying degrees of lake area shrinkage in recent years, for example, the lakes in northern Poland (Skowron and Jaworski, 2017); the Alaska region (Roach *et al.*, 2011); the Yukon region (Chen *et al.*, 2014); Xinjiang, China (Yang *et al.*, 2010; Wang *et al.*, 2013); Inner Mongolia, China (Yang *et al.*, 2010; Zhu *et al.*, 2011; Wang *et al.*, 2013; Wang *et al.*, 2015); and the Northeast China Plain, the North China Plain, and the East China Plain (Yang *et al.*, 2010; Wang *et al.*, 2013). The shrinkage of the lake area in these regions is related to climate change and human activities, with increased climate warming, decreased precipitation, and intense human activities all playing important roles. It is worth noting that the Aral Sea in Central Asia has shrunk severely under the influence of human activities. At present, the South Aral Sea has almost dried up, leaving only the North Aral Sea (Williams and Aladin, 2010; Cretaux *et al.*, 2013; Micklin, 2016). However, the lakes in the Uganda region (Nsubuga *et al.*, 2015) have expanded in recent years, and this increase in lake area is related to changes in precipitation caused by climate change. In addition, the lakes on the Tibetan Plateau (Yan *et al.*, 2016) and in the high mountain regions of Xinjiang (Wang *et al.*, 2016b) have also been expanding in recent years, and the main reason for the increase in lake area is the melting of snow and ice caused by climate warming. These studies included extremely detailed investigations of the variations in the lakes, as well as the use of various remote sensing water indexes to analyze the reasons for the changes in the lake area from various perspectives. Currently, few studies on inland lakes in the typical steppe region in Inner Mongolia have been conducted (Liu *et al.*, 2015; Zhen *et al.*, 2021), so there is insufficient theoretical basis for protecting inland lakes in this region, as well as developing and using regional water resources in a reasonable and orderly manner. Understanding the variations in these lakes and accurately recognizing the impacts of natural and human factors on these lakes has thus become a hot topic in this region.

To solve the above problems, we selected Huri Chagannao'er (HC) Lake, one of the four major freshwater lakes in Inner Mongolia and the second largest inland lake in the typical steppe region in Inner Mongolia (People's Government of Abaga, 2020), as the research object. Based on related research, in this study, we analyzed the spatiotemporal changes in the lake area over the past 30 years using the modified normalized difference water index (MNDWI) method (Xu, 2005) and Landsat data. We then analyzed the water balance of the lake. Furthermore, we used regression analysis, correlation analysis, gray relational analysis, and Geodetector to analyze the driving factors that may affect lake area changes. More information on the methods is provided in the Methodology section. Finally, we also proposed suggestions and measures for lake protection and the sustainable development of the water resources in this region. The results of this study provide a theoretical basis and technical support for the study of inland lakes in the typical steppe region in Inner Mongolia.

METHODS

Overview of the study area

HC Lake (114°45′–115°04′ E, 43°22′–43°29′ N) is located in the southwestern part of the Abaga Banner of Xilin Gol League, Inner Mongolia (Fig. 1). The region of HC Lake is characterized by high terrain in its east and low terrain in the west, and the geological structure is stable, with a lake-bottom elevation of approximately 1,010 m (People's Government of Abaga, 2020; Liu *et al.*, 2015). The entire lake consists of two connected lake areas: a freshwater area of approximately 30 km^2 in the east and a saline area of approximately 80 km^2 in the west. In the past 30 years (1988-2017), the saline lake area in the west has fluctuated dramatically, especially after 2000, and lake drying has occurred repeatedly. The saline lake in the west has now completely dried up, and the lake

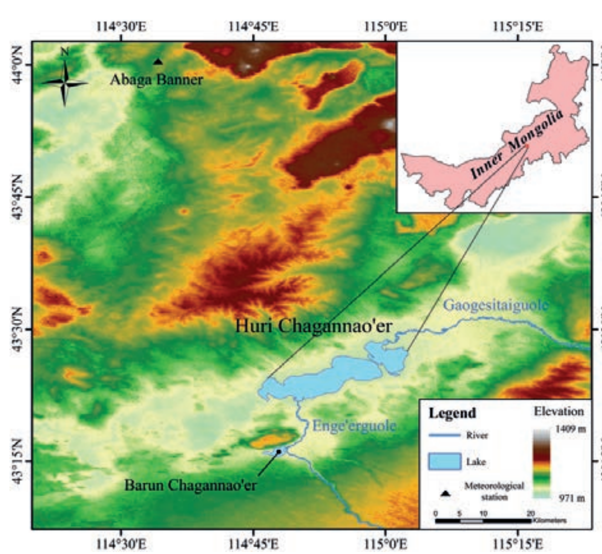

Fig. 1. Location of Huri Chagannao'er Lake and Abaga Banner meteorological station in Inner Mongolia, northern China.

basin has been exposed. Before the saline lake dried up, the entire lake had a mean water depth of 4.5 m and a water storage capacity of 4.4×10^8 m^3 (People's Government of Abaga, 2020). The two water areas were originally separated by a natural embankment, and an artificial embankment was built in 2000 with a sluice to control water flow from the eastern area to the western area (Liu *et al.*, 2015). HC Lake is a closed inland lake in the typical steppe region in Inner Mongolia, and its water is mainly derived from the Gaogesitaiguole River, the Enge'erguole River, and atmospheric precipitation. The lake is in the mid-temperate semiarid continental monsoon climate zone. According to the observation data of the Abaga Banner meteorological station from 1988 to 2017, the multi-year mean temperature is approximately 2.4°C, the multi-year mean precipitation is approximately 240 mm, and the multi-year mean evaporation is approximately 2,100 mm (small evaporator measurement data). Affected by the monsoon, the precipitation exhibits an uneven temporal distribution during a given year and is concentrated from June to August, accounting for approximately 70% of the annual precipitation.

Data and preprocessing

Landsat remote sensing data from the United States Geological Survey were used to calculate the lake area between 1988 and 2017. The spatial resolution of the data is 30 m. Landsat remote sensing data have a large temporal resolution and are prone to cloud interference. Therefore, the lake's Landsat remote sensing data that were measured under low cloud cover conditions during the normal-flow period of August to October each year were chosen. One image per year was selected, and a total of 30 images were used. Tab. S1 provides the information about the data used in this study. The above data have been preprocessed by radiometric calibration and atmospheric correction, and the obtained results are used as the MNDWI input data to extract the water body range.

The meteorological data were retrieved from the datasets of the daily values of the Chinese ground climate data released by the China Meteorological Data Service Center (http://data.cma.cn), which were measured at the Abaga Banner meteorological station from January 1, 1988, to December 31, 2017. This station was chosen because the climatic conditions in Abaga Banner are similar to those of the surrounding banners/counties, and the Abaga Banner meteorological station is the closest meteorological station to HC Lake, while the other meteorological stations are farther away. The arithmetic average method and the accumulation method were used to calculate and obtain the average annual temperature, average annual relative humidity, average annual wind speed, annual precipitation, annual evaporation, and annual sunshine duration in the study area.

The data for the water consumption by human activities were obtained from the Water Resources Bureau of Abaga Banner, Inner Mongolia. The data for the recharge from surface runoff were obtained from the Water Resources Bureau of Xilin Gol League, Inner Mongolia. The time range of these two sets of data is 2008–2017. Due to missing or incomplete data, earlier data could not be obtained in this study. Considering that the lake basin structure of HC Lake is stable, there is a stable correspondence between the lake water volume and lake area of this endorheic lake (Wang and Lv, 2007; Guan, 2015). Therefore, the absence of earlier data will not affect the conclusions of this study.

The land use data used in this study were obtained from the Resources and Environment Science and Data Center (https://www.resdc.cn/). The dataset had a total of 10 periods of data, and we selected six periods of data that were consistent with the study time period. The data years were 1990, 2000, 2005, 2010, 2015, and 2018.

The HC watershed is a closed inland lake drainage basin, and there is no outlet point, so the drainage basin cannot be generated using conventional hydrological analysis methods. Therefore, in this study, the lowest elevation point selected within the lake was artificially set as the outlet point, the value of the digital elevation model (DEM) corresponding to this point was set to no data, the modified DEM data were filled to generate the flow direction data, and finally, the drainage basin tool was used to generate the HC watershed. All of these operations were conducted in ArcGIS 10.2.

Lake area calculation

The water area was extracted using the MNDWI method developed by Xu, (2005). Compared with other methods, the MNDWI method has a particularly strong contrast between water and land, leading to a higher extraction accuracy and better results (Xu, 2005; Wang *et al.*, 2019). Studies have shown that the threshold stability of the MNDWI is extremely strong, the span from the 0 threshold to the optimal threshold is the smallest, and the accuracy is almost unchanged within the variation ranges of the different thresholds (Guo *et al.*, 2017; Xu, 2021). Therefore, the threshold value chosen in this study was 0. The MNDWI was calculated as follows:

$$MNDWI = \frac{(Green - MIR)}{(Green + MIR)}, \quad \text{(eq. 1)}$$

where *Green* is the spectral reflectance of the Landsat remote sensing images in the green band (band 2 for Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+); band 3 for Operational Land Imager (OLI)), and *MIR* is the spectral reflectance in the mid-infrared band (band 5 for TM and ETM+; band 6 for OLI). The area of the water bodies in the study region was calculated using ArcGIS as follows:

$$Area_{water} = n \times Area_0 , \qquad \text{(eq. 2)}$$

where n is the number of pixels for the water bodies, and $Area_0$ is the area that a single pixel represents, namely, 0.0009 km^2.

Water balance calculation

The variation in the lake water during a given period was calculated using the endorheic lake water balance equation (Wang and Lv, 2007; Guan, 2015):

$$P_L + R_{LsI} + R_{LgI} - E_L - R_{LgO} - Q_L = \pm \Delta S_L , \qquad \text{(eq. 3)}$$

where ΔS_L is the variation in the lake water in a certain period, P_L is the recharge from precipitation (RP), R_{LsI} is the recharge from surface runoff (RSR), R_{LgI} is the recharge from groundwater (RG), E_L is the loss of lake water through evaporation (LLWE), R_{LgO} is the loss of lake water through infiltration (LLWI), and Q_L is the water consumption by human activities (WCHA). P_L and E_L can be calculated as follows:

$$E_L = E_w S_{wi} , \qquad \text{(eq. 4)}$$

$$P_L = P S_{wi} , \qquad \text{(eq. 5)}$$

where S_{wi} is the lake area in year i, E_w is the annual evaporation per unit area of the lake, and P is the annual precipitation per unit area of the lake.

According to previous studies (Ren *et al.*, 2002; Wang and Lv, 2007; Cui *et al.*, 2012; Guan, 2015), the measured evaporation must be converted to the natural evaporation from the water surface using conversion factors. E_w can be calculated as follows:

$$E_w = K_1 E_{601} , \qquad \text{(eq. 6)}$$

$$E_{601} = K_2 E_s , \qquad \text{(eq. 7)}$$

where E_{601} is the data measured using an E-601 large evaporator, E_s is the data measured using a small evaporator, K_1 is the conversion factor between the data measured using the large E-601 evaporators and the evaporation data for large natural water bodies (usually 0.6), and K_2 is the conversion factor between the data measured using small evaporators and the data measured using large E-601 evaporators (usually 0.55).

Regression analysis

Data trend analysis is generally performed using regression analysis (Sheng *et al.*, 2008). In this study, the regressed lake area and meteorological indicators were set as the dependent variable Y and the time series was set as the independent variable x to obtain the trends of the lake area and the meteorological indicators over time. The parameters were determined using the least-squares method, and the coefficient of determination (R^2) and the significance test were used as metrics to measure the goodness-of-fit and the accuracy of the regression (Sheng *et al.*, 2008).

Correlation analysis

The Pearson correlation coefficient (Sheng *et al.*, 2008) was used to measure the degrees of correlation between the lake area changes (Y) and the various driving factors (X). The correlation coefficient (r) ranges from −1 to 1, with positive values indicating a positive correlation between X and Y, negative values indicating a negative correlation, and zero indicating no correlation. The higher the absolute value of r is, the stronger the correlation between X and Y is. A significance test was performed at two confidence levels: $\alpha = 0.01$ and $\alpha = 0.05$.

Gray relational analysis

Gray relational analysis (Liu, 2010) was used to judge whether two factors had a close interrelationship. The basic idea is to measure the degree of shape similarity between the trend curves of the factors. In this study, the lake area was used as the reference sequence $Y = \{y(k), k = 1, 2, 3..., n\}$, and the driving factors were used as the comparison sequences $X_i = \{x_i(k), k = 1, 2, 3..., n; i = 1, 2, 3..., m\}$, where i represents the number of driving factors, k represents the number of samples, and $x_i(k)$ represents the kth data point for the ith driving factor. To eliminate the influence of the data dimensions on the curve shape comparison, z-score standardization was applied to the original numbers, denoted as Y' and X_i'.

The gray relational coefficient can be calculated as follows:

$$\xi_i(k) = \frac{Min + \alpha Max}{\Delta_i(k) + \alpha Max}, \quad 0 < \alpha < 1 , \qquad \text{(eq. 8)}$$

where $\Delta_i(k)$ is the absolute difference, Max is the maximum absolute difference, Min is the minimum absolute difference, and α is the resolution coefficient. Given that extensive studies have shown that the best resolution is achieved when $\alpha \leq 0.5436$ (Liu, 2010), α was set to 0.5 in this study. $\Delta_i(k)$ can be calculated as follows:

$$\Delta_i(k) = \left| Y'(k) - X_i'(k) \right|, \quad k = 1, 2, 3, \ldots, n. \qquad \text{(eq. 9)}$$

The gray relational coefficient only measures the degree of relation between the comparison and reference sequences at a given time, and it cannot be directly used to compare and rank the overall gray relational degree (GRD). Therefore, it is necessary to calculate the mean GRD as follows:

$$r_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k). \qquad \text{(eq. 10)}$$

Geodetector

Geodetector is a new statistical software developed by the State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (http://www.geodetector.cn). The current version of the software is 1.0. In this study, Geodetector (Wang *et al.*, 2016a; Wang and Xu, 2017) was used to investigate the interactions between the explanatory variables X and the response variable Y. This was accomplished using the Geodetector q-statistic, where X explains 100q% of Y. A Geodetector, i.e., the Geographical Detector, is a statistical tool used to measure spatial stratified heterogeneity (SSH) and to make attributions for/by the SSH. The q-statistic can be calculated as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2}, \qquad \text{(eq. 11)}$$

where h $(h = 1, 2, 3\ldots, L)$ is the stratification of variable Y or factor X, which is classification or partitioned; N_h and N are the numbers of units in layer h and the entire area, respectively; and σ2 h and σ^2 are the variances of the result variable in layer h and the entire area, respectively. The value range of q is [0, 1]. The larger the q value is, the stronger the explanatory strength of the factor X to the variable Y is, and vice versa.

To identify the main driving factors of the lake area changes, correlation analysis and gray relational analysis were performed between several potential driving factors and the lake area to eliminate the driving factors with low correlations or strong autocorrelations. According to the calculation results, several driving factors were selected. The K-means discretization classification was performed on the values of the selected indicators, and then, they were analyzed using the Geodetector to identify the driving factors that had the greatest impact on the lake area changes.

RESULTS

Spatiotemporal characteristics of lake area

As is shown in Fig. 2, HC Lake exhibited a dramatic decreasing trend in lake area from 1988 to 2017. The lake shrank from 98.99 km^2 to 29.81 km^2, with a mean annual decrease of 2.31 km^2. The mean value of the lake area over the past 30 years was 67.66 km^2, with a standard deviation of 27.02. From 1988 to 1999, the lake area fluctuated smoothly within the range of 85 to 100 km^2, with a mean of 93.73 km^2, a maximum of 98.99 km^2, a minimum of 86.19 km^2, and a standard deviation of 3.70. From 2000 to 2017, the lake area exhibited strong inter-annual fluctuations, including four periods of shrinkage and three periods of expansion, with a mean lake area of 50.28 km^2, a maximum of 85.83 km^2, a minimum of 26.28 km^2, and a standard deviation of 21.28. During this period, there were 13 years (2001–2003, 2006–2011, and 2014–2017) in which the annual lake area was less than 67.66 km^2 (the mean value over the past 30 years), and five years (2000, 2004, 2005, 2012, and 2013) during which the annual lake area was far less than the average level before 2000. Tab. S2 provides the lake area information.

As shown in Fig. 3, the lake did not undergo apparent morphological changes from 1988 to 1999, exhibiting a winding shoreline and an intact lake morphology. From 2000 to 2017, the lake experienced four periods of shrinkage and three periods of expansion. Specifically, the first period of shrinkage occurred between 2000 and 2002, with the lake area rapidly decreasing from 86.19 km^2 to 27.69 km^2 in just two years. The western lake waters disappeared completely for the first time in 2002. The first

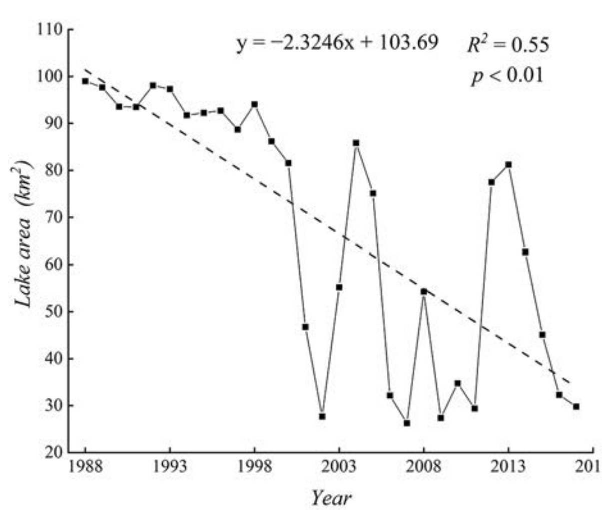

Fig. 2. Annual time series of the lake area between 1988 and 2017 showing the clear overall decreasing trend with time and major fluctuations occurring after 2000.

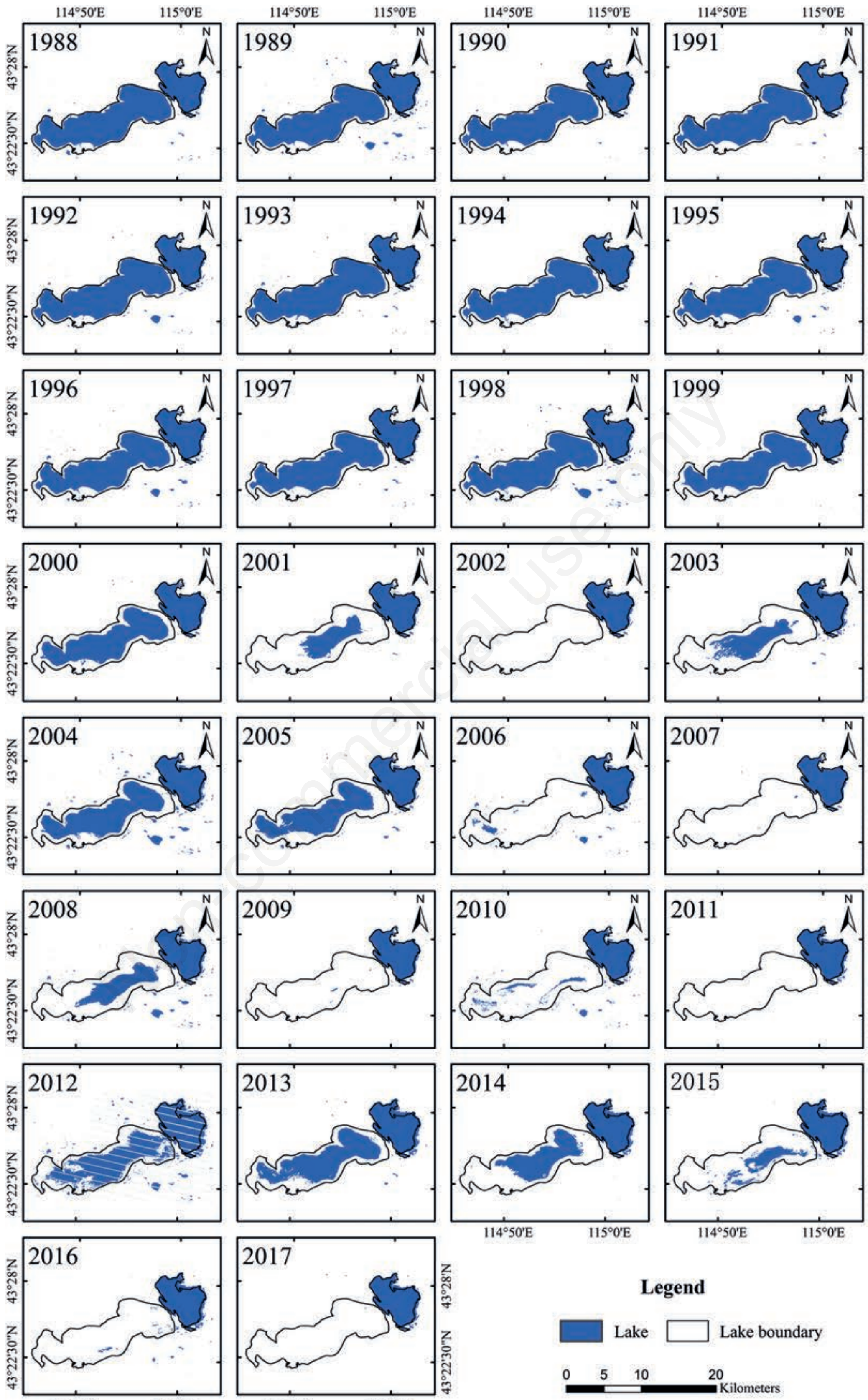

Fig. 3. Spatial distribution of the waters of Huri Chagannao'er Lake between 1988 and 2017 from Landsat data.

expansion period occurred from 2003 to 2004, with the area increasing to 85.83 km^2, i.e., the same level as in 1999. The second shrinkage period occurred between 2005 and 2007, with the lake area decreased to the same level as in 2002, accompanied by the second complete disappearance of the western lake waters. In 2008, the lake underwent the second expansion period, and the lake area increased to 54.27 km^2, with the western lake waters reappearing only in a small area in the central part of the western basin. From 2009 to 2011, the lake underwent the third shrinkage period, and the western lake waters almost dried up for three consecutive years, i.e., the third complete disappearance of the western lake waters. The third expansion period occurred from 2012 to 2013, during which the lake area increased to 81.23 km^2. The fourth shrinkage period occurred between 2014 and 2017, the lake area decreased to 29.81 km^2, accompanied by the fourth complete disappearance of the western lake waters.

Two field surveys conducted in the summers of 2017 and 2018 revealed that the western lake area had become an exposed saline lake basin, while the area and water volume of the eastern freshwater lake remained stable. As is shown by the above spatiotemporal characteristics, 2000 was an important time point when the area of HC Lake began to undergo significant changes, with the lake area reduction mainly concentrated in the western part of the lake.

Analysis of driving factors of lake area changes

The lake area change is only the appearance, and the water balance change is the fundamental decision of the lake area change. The water balance change is the result of the combined effects of natural and human factors. Therefore, to explore the main reasons for the lake area changes, we should first analyze the changes in the water balance of the lake and then analyze the natural factors (e.g., meteorological and climatic changes) and human factors (e.g., WCHA, land use in the drainage basin) that caused the changes in the water balance. Finally, we can analyze the degrees of influence of the main driving factors on the lake area changes.

Water balance change

The Gaogesitaiguole River is the most important river providing inflow to HC Lake and is the largest river in the Hunshandake Sandland. It flows westward into the eastern part of the lake. The multi-year mean flow of the Gaogesitaiguole River from the 1960s to the 1970s was 4.2677×10^7 m^3, and the flow has decreased to some extent in recent years (Liu *et al.*, 2015). Between 2008 and 2017 (Fig. 4a), the multi-year mean flow was 3.1374×10^7 m^3, with a maximum annual flow of 4.518×10^7 m^3 (2012) and a minimum of 2.021×10^7 m^3 (2017).

The Enge'erguole River is the second most important river providing inflow to HC Lake. It flows northward into the western part of the lake. Currently, the upstream section of the Enge'erguole River (Nugesitaiguole River section) is still flowing, but the downstream section (section from Barun Chagannao'er Lake to HC Lake) has been dry for many years (Liu *et al.*, 2015). Between 2008 and 2017 (Fig. 4a), the multi-year mean flow was 1.0176×10^7 m^3, with a maximum annual flow of 1.673×10^7 m^3 (2013) and a minimum of 7.04×10^6 m^3 (2017).

The water supply in Abaga Banner mainly comes from the surface water and groundwater in the HC watershed. The geological structure of the HC watershed is stable, the total groundwater storage is approximately 3.95×10^8 m^3, which has remained stable for many years, and RG and LLWI have not undergone significant changes for many years (People's Government of Abaga, 2020; Liu *et al.*, 2015). It is clear that the factors affecting the water balance of the lake are mainly the natural variation in the lake water (NVLW) and WCHA in the drainage basin (Fig. 4d). NVLW is represented by ΔS_{Ln}, and $\Delta S_{Ln} = P_L + R_{LsI} + R_{LgI} - E_L - R_{LgO}$. Using the controlled variable method, the fixed values (R_{LgI} and R_{LgO}) in the equation can be removed; and then, $\Delta S_{Ln} = P_L + R_{LsI} - E_L$ (Fig. 4b).

As is shown in Fig. 4c, although RSR has recently decreased to some extent, NVLWs have been greater than zero for a number of consecutive years, which indicates that the natural water in the drainage basin is still abundant. According to incomplete statistics from the Abaga Banner Water Resources Bureau, the average WCHA in Abaga Banner from 2008 to 2017 was approximately 4.5936×10^7 m^3. WCHA was much greater than NVLW (Fig. 4c). This is strongly indicative of excessive WCHA in this region.

Meteorological and climatic changes

The meteorological and climatic changes in the study area from 1988 to 2017 are shown in Tab. 1 and Fig. 5. The annual precipitation (Fig. 5a) exhibited a very insignificant decreasing trend, but it was generally low from 1999 to 2011, and the inter-annual fluctuations were large. The annual evaporation (Fig. 5b) tended to increase, with a rate of increase of 68.76 mm per decade, and it was generally high from 1999 to 2011. The average annual temperature (Fig. 5c) exhibited an increasing trend, with a rate of increase of 0.47°C per decade, which was higher than the global rate of increase of 0.20°C per decade, and it was generally high from 1999 to 2011. In addition, the average annual temperature increased or decreased sharply within a few years, which led to large inter-annual fluctuations. The average annual relative humidity (Fig. 5d) exhibited a slow decreasing trend, with a rate of decrease of 1.79% per decade and a small inter-annual variability, and it was generally low from 1999 to 2011. The annual sunshine duration (Fig. 5e) exhibited an extremely insignificant decreasing trend, and it increased or decreased sharply within a few years. The average annual wind speed (Fig. 5f) tended to increase while exhibiting a relatively small inter-annual variability, but the average annual wind speed sharply increased in 2016 and was far greater than the multi-year mean of 3.11 m/s.

Tab. 1. Maximum, minimum, and multi-year average values of the meteorological indicators in the Huri Chagannao'er watershed between 1988 and 2017.

Meteorological indicator	Maximum	Minimum	Multi-year average
Annual precipitation	433.70 mm (1998)	130.20 mm (1997)	238.92 mm
Annual evaporation	1416.40 mm (2017)	913.28 mm (1992)	1153.36 mm
Average annual temperature	4.10°C (2014)	0.50°C (2012)	2.41°C
Average annual relative humidity	63.00% (1992)	49.00% (2017)	54.87%
Annual sunshine duration	3104.20 h (2013)	2718.20 h (2002)	2971.81 h
Average annual wind speed	4.50 m/s (2016)	2.60 m/s (2014)	3.11 m/s

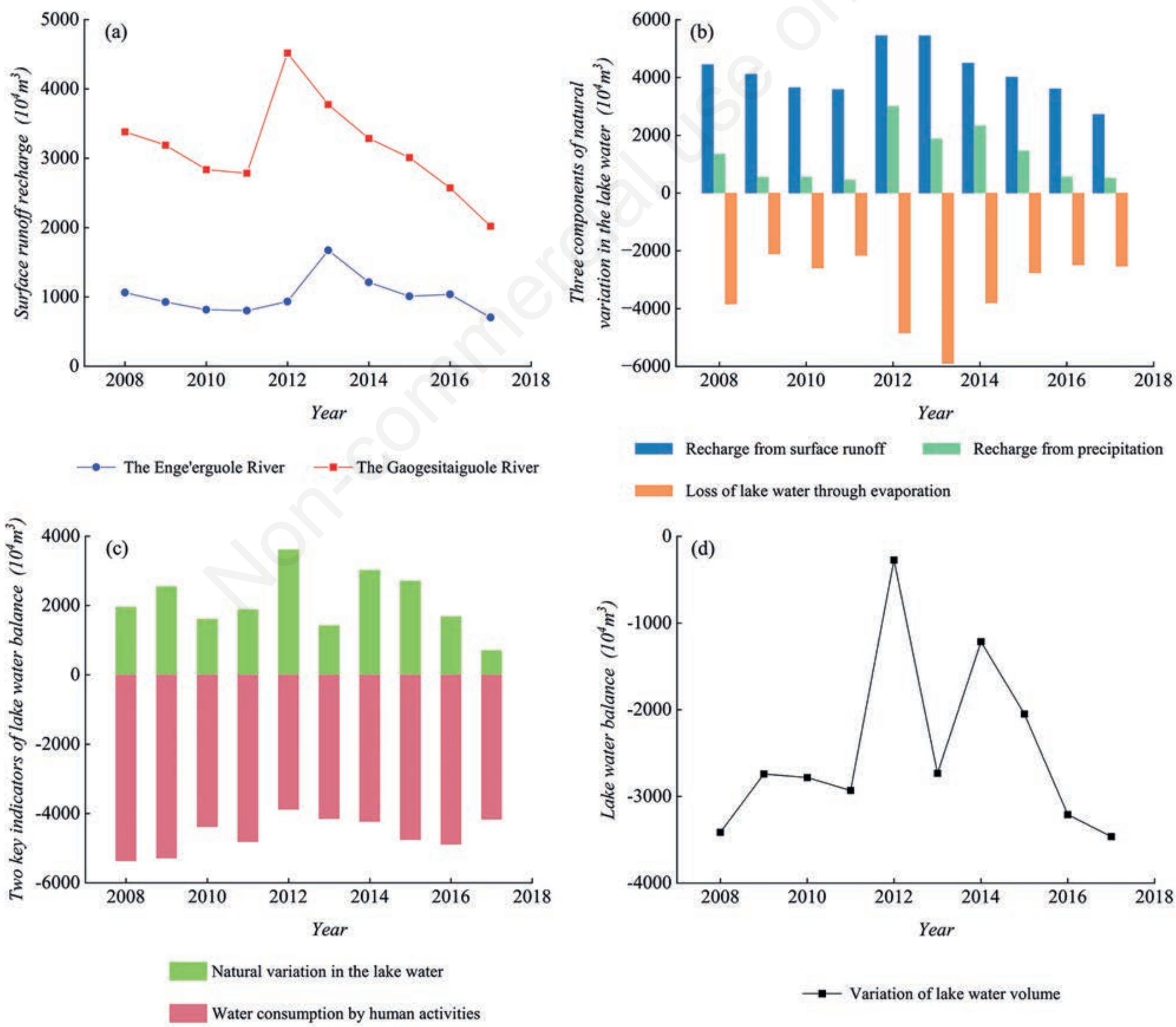

Fig. 4. The water balance changes in Huri Chagannao'er Lake between 2008 and 2017. a) Surface runoff recharge. b) Three components of natural variation in the lake water. c) Two key indicators of lake water balance. d) Lake water balance.

In summary, the study area generally experienced stable meteorological conditions during the 30-year study period and was characterized by a mid-temperate, semi-arid, continental monsoon climate. However, the region experienced drought and low rainfall, increased temperature, enhanced evaporation, and decreased relative humid-

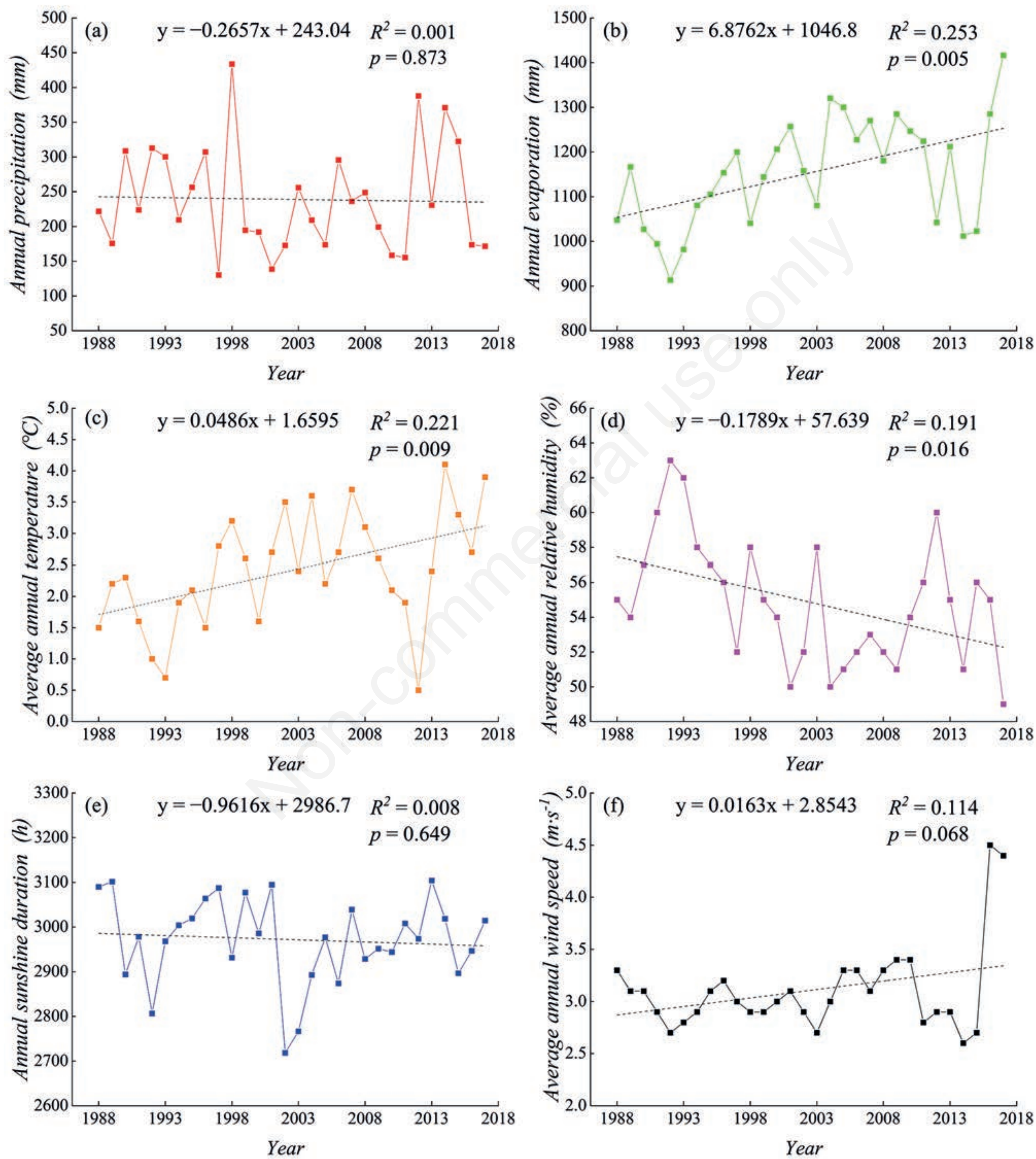

Fig. 5. Meteorological and climatic indicators in the Huri Chagannao'er watershed between 1988 and 2017 and their relationships. a) Annual precipitation. b) Annual evaporation. c) Average annual temperature. d) Average annual relative humidity. e) Annual sunshine duration. f) Average annual wind speed.

ity between 1999 and 2011, indicating gradual warming and drying of the regional climate occurred during this period. This is consistent with the conclusions of other studies (Liu *et al.*, 2015).

Land use and land cover changes

Fig. 6 and Tab. 2 show the land use and land cover changes in the HC watershed from 1990 to 2018. Among them, the period from 1990 to 2000 was mainly characterized by the large-scale degradation of grassland and woodland and the large-scale expansion of bare land. From 2000 to 2005, the grassland recovered, but the degradation of the woodland continued. From 2005 to 2010, the main change was the further restoration of the grassland, but the water body area shrank significantly and the degradation of the woodland continued. From 2010 to 2015, the grassland slightly degraded, and the woodland and water body area were restored to a small extent. From 2015 to 2018, the various types of land changed little.

Relationships between lake area changes and driving factors

The results of the correlation analysis and gray relational analysis (Tab. 3) revealed that the average annual relative humidity had a significant positive correlation with the lake area ($p<0.01$) and had a higher GRD with the lake area. The lake area exhibited significant negative correlations with the annual evaporation and the average annual temperature ($p<0.01$) and the average annual wind speed ($p<0.05$), but these three driving factors had low GRDs with the lake area. The annual precipitation and annual sunshine duration did not have significant correlations with the lake area ($p>0.05$). RP exhibited a significant positive correlation with the lake area ($p<0.01$) and had a higher GRD with the lake area. LLWE exhibited a significant negative correlation with the lake area ($p<0.01$) and had the highest GRD with the lake area. Based on these results, the changes in LLWE, RP, and the average annual relative

Tab. 2. Area of various land use types in the Huri Chagannao'er watershed from 1990 to 2018.

Year	Land use types					
	Grassland	Cultivated land	Water body	Woodland	Artificial surfaces	Bare land
1990	13639.27 km^2	98.19 km^2	250.78 km^2	244.75 km^2	16.98 km^2	1528.97 km^2
2000	11808.41 km^2	116.81 km^2	241.50 km^2	108.38 km^2	15.44 km^2	3488.40 km^2
2005	12534.93 km^2	121.74 km^2	227.42 km^2	81.79 km^2	14.65 km^2	2798.41 km^2
2010	12755.22 km^2	113.01 km^2	118.99 km^2	67.90 km^2	16.00 km^2	2707.82 km^2
2015	12627.16 km^2	123.39 km^2	132.41 km^2	82.00 km^2	17.72 km^2	2796.26 km^2
2018	12612.37 km^2	123.74 km^2	117.32 km^2	84.26 km^2	19.52 km^2	2821.73 km^2

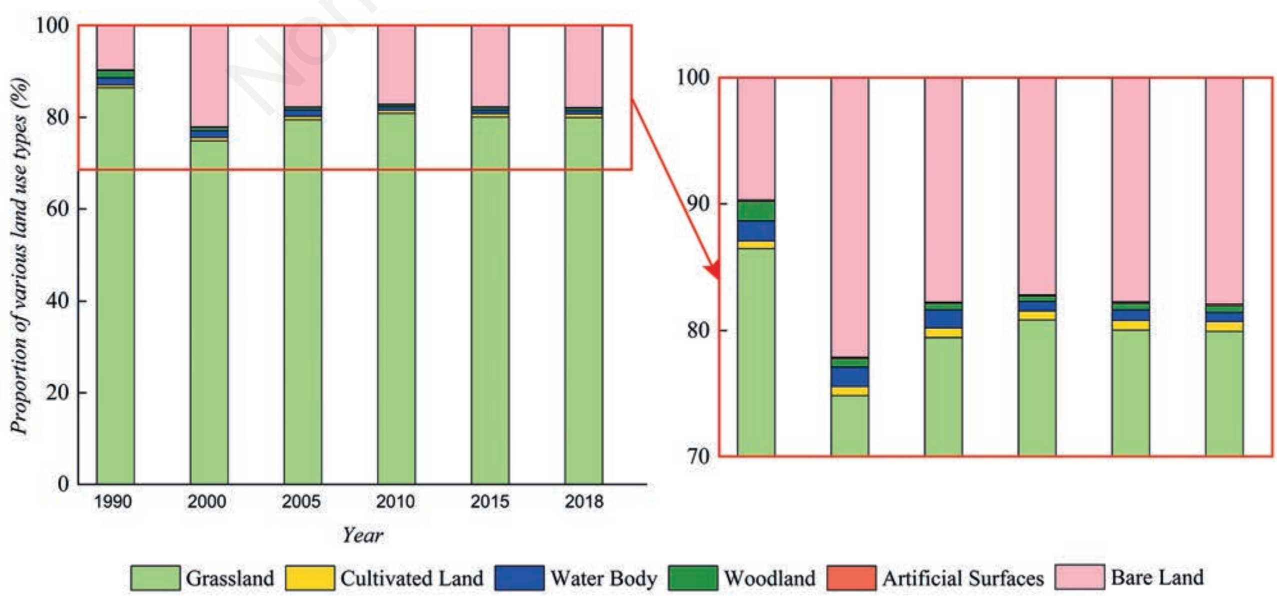

Fig. 6. Land use and land cover changes in the Huri Chagannao'er watershed between 1990 and 2017.

humidity were the most closely related to the changes in the lake area.

Among the meteorological indicators, the annual precipitation and the annual evaporation had strong autocorrelations with RP and LLWE, respectively. Therefore, RP was used to replace the annual precipitation, and LLWE was used to replace the annual evaporation. However, the changes in the average annual temperature, the average annual wind speed, and the annual sunshine duration were not closely related to the changes in the lake area. In summary, the average annual relative humidity was selected as the main research indicator.

Regarding the water balance, the water balance of a lake is mainly determined by NVLW and WCHA. NVLWs were calculated using three indicators: RSR, RP, and LLWE. Therefore, NVLW and WCHA can be used as main research indicators.

In terms of land use, through induction, the grassland, woodland, and water body were classified as natural land, while the cultivated land, artificial surfaces, and bare land were classified as unnatural land. As is shown in Fig. 6 and Tab. 2, through the calculations, it was found that the natural land use greatly decreased in 2000, and the change was relatively stable after some recovery in 2005. According to previous studies (Liu *et al.*, 2002; Karnieli *et al.*, 2013; Yang *et al.*, 2015), the degradation of the grassland and woodland in this region was mainly caused by human activities. Therefore, the land use and land cover changes in the HC watershed should also be used as the main research indicators.

Based on the above results, four indicators were selected: the average annual relative humidity, NVLW, WCHA, and the land use and land cover changes. To unify the data period, only the data from 2008 to 2017 were calculated. The results of the Geodetector are shown in Tab. 4.

DISCUSSION

Main driving factors of lake area change

The following information was gathered and photos were taken during field surveys and visits to HC Lake and its drainage basin. The images were captured on July 19, 2018 (Figs. 7-9).

Before 2000, HC Lake was classified as containing abundant water, with its area being >90 km². The secondary and tertiary industries had developed slowly in the area surrounding HC Lake, and there were basically no large-scale industrial, mining, or tourism enterprises. Human activities consumed low volumes of water, with most of the water being used as drinking water for livestock and residents.

After 2000, the lake area fluctuated drastically, with the western portion of the lake drying up multiple times. The lake and its surrounding areas were subjected to human activities that were designed to enhance economic production with little to no consideration for the sustainable development and use of the water resources. First, most of the small- and large-scale enterprises only focused on economic development while paying no attention to environmental protection, directly using the nearby river water as industrial water. As is shown in Fig. 7, the water intake point in the downstream section of the Gaogesitaiguole River (Fig. 7a), and the water intake point in the upstream section of the Enge'erguole River (Fig. 7b). Water was taken directly from the river at places such as a cement factory on the midstream section of the Gaogesitaiguole River, a coal factory in the downstream section of the Gaogesitaiguole River, a tile factory on the upstream section of the Enge'erguole River, and several mining factories in the drainage basin.

Second, extensive construction of artificial embankments and sluices to intercept and store water for industrial and agricultural production occurred from 2000 to 2015. During this period, the eastern waters of HC Lake were contracted to private fish farmers, and the natural embankment was converted into an artificial embankment with a sluice, which was used to artificially control the water flow to prevent fish from escaping and improve the production of the fish farm (Fig. 8). As shown in Fig. 8a, the artificial embankment and sluice are in the middle of the photo, the area with water on the left is the eastern part of HC Lake, and the right side is the western part of HC

Tab. 3. Correlation coefficients and gray relational degrees between the area of Huri Chagannao'er Lake and the natural driving factors.

Factor type	Driving factor	Correlation coefficient	Gray relational degree
Meteorological indicator changes	Annual precipitation	0.30	0.73
	Annual evaporation	−0.57**	0.65
	Average annual temperature	−0.51**	0.64
	Average annual relative humidity	0.51**	0.75
	Annual sunshine duration	0.27	0.75
	Average annual wind speed	−0.40*	0.67
Water balance changes	Recharge from precipitation	0.81**	0.84
	Loss of lake water through evaporation	−0.96**	0.92

*$p<0.05$ (two-tailed); **$p<0.01$ (two-tailed).*

Lake. As shown in Fig. 8b, the eastern part of HC Lake was converted into a reservoir, which is locally known as the Chagan Reservoir. In addition, the Barun Chagannao'er Lake, another natural lake in this region, was converted into the Enge'er Reservoir and used to provide water for fish farming and nearby agricultural and industrial activities while controlling the water discharge into the lower section of the Enge'erguole River (Fig. 9).

According to the results of the Geodetector (Tab. 4), the factor that had the largest impact on the lake area was WCHA, followed by NVLW, the average annual relative humidity, and finally the land use and land cover changes. In addition, the sum of the q-statistics of the human factors (WCHA and the land use and land cover changes) was greater than that of the natural factors (NVLW and the average annual relative humidity). This shows that the human activities had a greater impact on the lake area change, especially WCHA.

Inland lakes in the typical steppe region of Inner Mongolia have an extremely fragile ecological environment with a very low self-recovery capacity, especially HC Lake, and the lake water is only recharged by precipitation and inland rivers. If the lake's surface replenishment rivers are cut off, the water resources in the drainage basin are over-exploited and used, and/or the lake's water replenishment depends only on precipitation, the lake will soon dry up. The natural embankments between the lakes have played a role in regulating the water level, and they kept the water level in the eastern and western parts of HC Lake relatively stable before 2000, but the artificial embankments broke this balance. The annual flow of the Gaogesitaiguole River is sufficient to cause the lake water

Fig. 7. Industrial and agricultural water collection points on the Gaogesitaiguole River (a) and the Enge'erguole River (b).

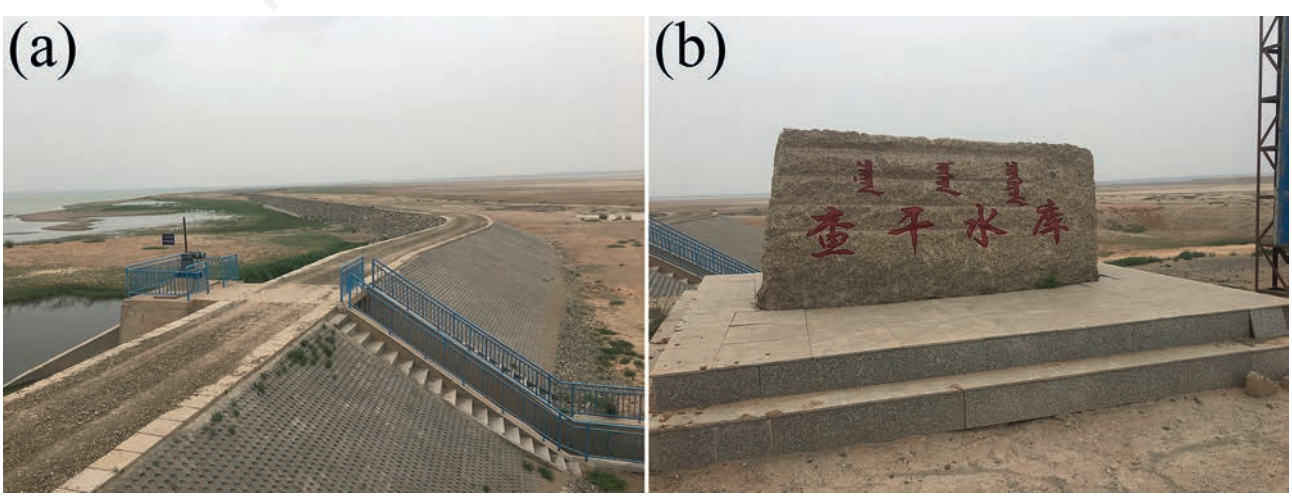

Fig. 8. Artificial sluice in Huri Chagannao'er Lake (a) and the monument of Chagan Reservoir (b).

to overflow the embankment, but the water level of the eastern part of the lake has remained constant for many years. So, where does the water of the Gaogesitaiguole River actually flow? Although the warming and drying of the climate have contributed to a reduction in lake water recharge, the amount of natural water in the drainage basin remains abundant. As a result, the above phenomena in the study area clearly show that the over-exploitation of water resources, excessive WCHA, and inappropriate water interception and storage without scientific planning has seriously disrupted the drainage basin's self-regulation mechanism.

Based on the above analysis, the over-exploitation of the water resources and the increasing intensity of the human activities in the drainage basin are the main reasons for the shrinkage of HC Lake, which have in turn caused other ecological and environmental problems. For a dried-up lake basin, it is impossible to restore the original lake area and water volume even after restoring the surface runoff recharge. Moreover, the precipitation recharge and surface runoff recharge are far from sufficient to compensate for the strong evaporation. The dried-up lake basin formed a large area of saline land, and now this saline land has become the provenance of sandstorms and alkali dust storms (Liu *et al.*, 2015). Currently, the environment in this region is seriously deteriorating, and it has lost its self-recovery ability. Thus, there is an urgent need for ecological environmental restoration and management.

Tab. 4. The q-statistics of the driving factors of the lake area changes.

Driving factor	q-Statistic
Water consumption by human activities	0.40
Natural variation in the lake water	0.33
Average annual relative humidity	0.27
Land use and land cover changes	0.22

Recommendations for lake management and protection

For a dried-up lake basin, even if its surface runoff recharge is restored, it is difficult to restore the original area of the lake under strong evaporation. Therefore, to manage and protect the lake and the entire drainage basin, multiple avenues should be pursued. For example, the management and protection of Juyan Lake in Inner Mongolia, northwestern China, has been very successful (Li *et al.*, 2017). We should learn from the practices implemented at Juyan Lake, and according to the characteristics of HC Lake, a set of suitable management and protection measures should be developed.

First, artificial intervention should be provided to restore the water storage and area of HC Lake, and then, the inappropriate water conservation facilities in the drainage basin should be removed. Currently, the construction of reservoirs, embankments, and sluices, as well as water interception and storage, is highly prevalent in the HC watershed, and they are mainly used for industrial and agricultural production. These inappropriate water conservation facilities have directly resulted in the disappearance of the western part of the lake. Therefore, dismantling these facilities is a crucial step in the restoration of HC Lake. In addition, it is necessary to establish hydrometric stations on the rivers in the drainage basin. In the wet years, the amount of ice-melt and snowmelt in spring and the amount of precipitation in summer are relatively large. The river channels in the steppe are generally shallow and narrow, the river water is prone to break

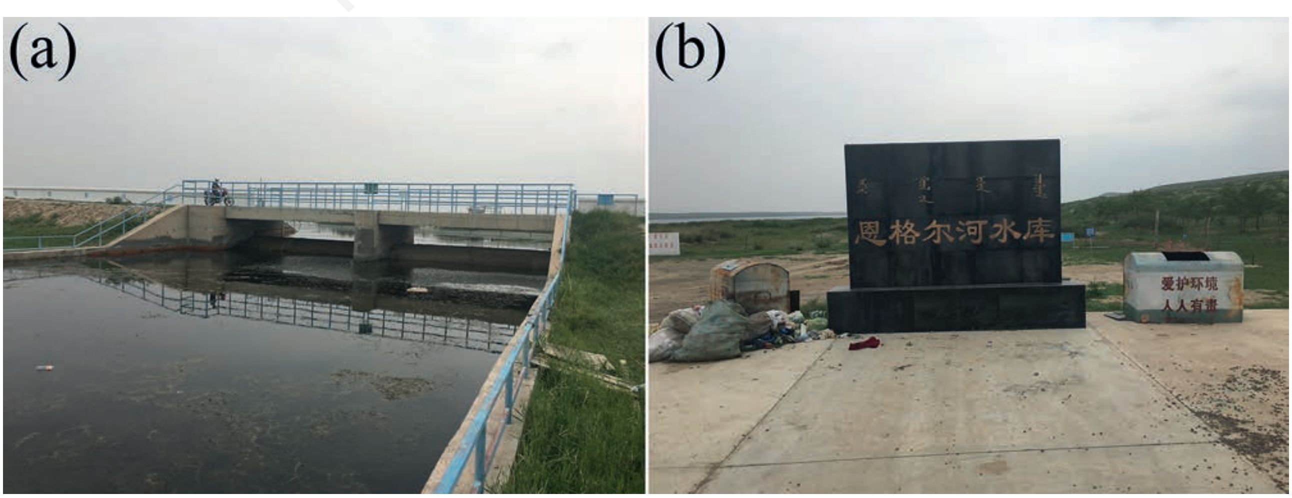

Fig. 9. Artificial sluice in Bahrun Chagannao'er Lake (a) and the monument of Enge'er Reservoir (b).

the embankments and divert its flow routes, and it may even cause floods. The evaporation in this typical steppe region is strong, and the overflowing river water undergoes evaporation into the atmosphere, which easily causes a loss of steppe water resources. Therefore, hydrometric stations should be established on the rivers in the drainage basin to strengthen hydrological monitoring.

Next, WCHA in the HC watershed should be regulated, and different, specific measures should be developed for wet versus dry years. The water resources on the steppe are mostly affected by natural conditions, with the typical steppe climate causing large inter-annual variability in the annual precipitation and thereby the occurrence of wet and dry years. Therefore, it is necessary to strictly regulate WCHA. The amount of industrial and agricultural water use should be specified in accordance with the production scales, and it is necessary to completely prohibit the practice of directly taking surface river water for industrial production and agricultural irrigation. In wet years, excess water can be used for economic production after ensuring the water balance of the entire drainage basin. In dry years, water consumption should be strictly controlled to avoid waste.

Finally, the ecological environment and natural pastures should be protected. In the typical steppe region in Inner Mongolia, the steppe resources and water resources are interdependent, with the natural pastures providing a protective layer for the water resources. Therefore, it is necessary to prohibit steppe cultivation and overgrazing and to ensure highly efficient land-use planning to minimize damage to the natural pastures.

CONCLUSIONS

Between 1988 and 2017, the area of HC Lake exhibited a drastic decreasing trend, with a total decrease of approximately 69.18 km^2 over the 30-year study period. The year 2000 was the important time point when the lake area began to undergo significant changes and after which it underwent four shrinkage and three expansion periods. The shrinkage of the lake area mainly occurred in the western part of the lake, while the area of the eastern part of the lake remained stable.

In recent years, the regional climate has become warmer and drier, with increasing temperature and decreasing precipitation. Although the warming and drying of the climate somewhat promoted the reduction of water recharge to the lake, the amount of natural water in the drainage basin remained abundant. WCHA in the drainage basin was generally high and was far greater than NVLW. In addition, the land use and land cover changes in the HC watershed were characterized by the serious degradation of natural land such as grassland, woodland, and water after 2000.

The results of the correlation analysis, gray correlation analysis, and Geodetector revealed that the factor that had the largest impact on the lake area was WCHA, followed by NVLW, the average annual relative humidity, and finally the land use and land cover changes. The dramatic fluctuations in the lake area and the drying up of the western part of the lake were mainly driven by the human activities, water interception and storage, and excessive exploitation of the water resources. Due to climate change, the regional climate has become warmer and drier, which has also had a certain degree of influence on the lake area changes.

Currently, HC Lake has lost its self-recovery capacity, and the regional ecological balance has been significantly affected. The large, exposed lake basin has become the provenance of sandstorms and salt dust storms, directly threatening the ecological security of northern China and even the entire nation.

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