The Long-Time Variation of Lake in Typical Desert Area and Its Human and Climate Change Causes: A Case Study of the Hongjian Nur

Lei Zhou, Yinuo Zhu, Mingyi Du, Siyu Wang, Congcong He, Ting Luo, Jianjun Wu, Jun Zhang, and Kun Yang

***Abstract*—The change of inland lake area has a great impact on human life, ecological environment, and animal and plant habitats. But, the systematic and quantitative research on the long time change of water area and its human activity and climate change causes is very difficult. Here, taking the largest and youngest natural inland freshwater lake Hongjian Nur (HJN) in China as the study object, the long-term changes of water surface area of natural lakes and artificial reservoirs were retrieved. The impact of climate change on the change of HJN lake area is analyzed from the point of view of overall meteorological water shortage. The results showed that the natural lake area continued to decrease for 19 years from 1996 to 2015. On the contrary, the area of the reservoirs increased continuously. The determination coefficient of reservoir area and natural lake area is 0.357, which indicates that the impoundment of reservoirs has a significant impact on the decrease area of natural lake. The drought period for 13 years before 2011 also has a direct impact on the water area reduction of the lake. The future 1–2 years drought period or the transition from drought to humidity will threaten the maintenance of the existing water volume. Historical impact of multisource precipitation changes on the HJN water area proved the important influence of precipitation on the change of lake area. It is concluded that human activities and climate change will be the key constraints for maintaining ecological balance in lakes in the desert.**

***Index Terms*—Geographic information systems, lakes, remote sensing, water, wavelet transform.**

I. Introduction

LAKES play an important role in ecological environment and regulating the climate in inland water shortage and desert areas [1]. It is important to study the change of surface area of HJN lake and analyze its possible driving factors for protecting the habitat of larus relictus and maintaining the biodiversity and ecological function of HJN lake [2], [3].

The common water extraction methods based on remote sensing include single-band method, multiband spectrum-photometric method, image classification method, and water body extraction index [4]–[6]. Among them, the water body extraction index has the characteristics of reliable monitoring accuracy and high calculation efficiency [7], [8]. At present, more water body extraction indices have been developed to monitor water area and its change by enhancing the contrast between water body and land [9]–[11]. The construction principle of the index model is various [12], [13]. According to different geomorphological conditions in different regions, different index models can be constructed. But the idea of building these models is similar.

At present, the most widely applied water body extraction indices include normalized difference water index (NDWI) and modified normalized difference water index (MNDWI) [14], [15]. However, the latter index model only considers vegetation factors, but neglects soil and building factors. Because soil and buildings have very similar spectral characteristics that the reflectivity in green band is higher than that in near-infrared band with water, the calculated values of soil and buildings are also positive when water body information is extracted by using this index, which can easily cause confusion and noise [6]. Later, the water index (referred to here as the WI2006) has been validated in the result of water extraction in different backgrounds around the world [16]. On this basis, linear discriminant analysis classification (LDAC) is used to determine the coefficient of the best training area classification at first. The improved water index (WI2015) has a good application effect in water extraction [17]. Automated water extraction index (AWEI) has a simple calculation principle and high accuracy, which is widely used in water extraction under complex background all over the world, and the experimental results show that AWEI can extract the spatial distribution of water effectively [18]. Monitoring the change of water area is an important basis for investigating the causes of its variation.

The change of the area of lake in desert area is mainly influenced by natural and human factors [19]. Many researchers analyzed the impact of human activities and climate change on the area of lake in desert region [20]–[22]. The possible

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influencing factors of surface area change of lake include climate change, irrigation water, ecological environment construction, water and drainage for coal mining, water source exploitation, and so on. When analyzing the influence of climate factors, most of the studies are based on the analysis of the correlation of precipitation, temperature, and water surface area, which cannot reflect the impact of water shortage in the basin as a whole on the water surface area of HJN lake Basin [23].

Developed by meteorologist Palmer, Palmer drought index (PDSI) is a measure of dryness based on precipitation and temperature [24]. The index is based on the supply–demand model of soil moisture, and the "supply" is calculated relatively directly, but the "demand" is complicated because it depends on many factors—not only temperature and soil moisture, but also evaporation and recharge rate, which are difficult to measure directly. PDSI can be used to measure the overall extent of water shortage in an area. The revised PDSI model constructed by Chinese researchers is an authoritative method for assessing the overall water shortage in the study area [25], [26]. It is of great significance to study the implicit periodicity of PDSI in order to master the meteorological pattern and predict its future change trend [27]. The wavelet analysis proposed by Morlet has multiresolution property in frequency and time domain. It can clearly reveal the various change periods hidden in the time series and reflect the change trend of the system in different time scales to estimate the future trend of the data series [28]. Because the change of climate characteristics caused by precipitation has a multitime scale and is continuous, the continuous wavelet transform using complex Morlet wavelets is a robust tool to analyze the change characteristics of years of PDSI time series [29]. However, there are few studies on the correlation analysis between the variation period of PDSI and the area of surface waters.

Generally speaking, there is a lack of systematic and quantitative research on the change of surface area of HJN lake and its causes. Due to the different data sources and discontinuous time, the monitoring data and results analysis of the area change of HJN lake are quite different. From the point of view of overall meteorological water shortage, the systematic study on the causes of surface area change is insufficient. We attempt to address the mentioned problems with two main objectives. First, using Landsat data from 1984 to 2017, this article uses AWEI water body extraction index to accurately retrieve the changes of water surface area of natural lakes and artificial reservoirs in the basin, which reveals the correlation between man-made water conservancy and storage project and the changes of water surface of HJN lake. Second, the impact of climate change on the surface area change of HJN lake is analyzed from the point of view of overall meteorological water shortage of the basin.

II. Study Area and Data

A. Study Area

Located in the border area of Shenmu County, Shanxi Province, and Ejin Horo Banner, Inner Mongolia, close to Mu Us Desert, Hongjian Nur (HJN) lake is the largest and youngest natural inland freshwater lake in desert areas of China, which holds the title of "desert pearl" in China [22]. Besides, HJN lake is also the largest breeding ground and habitat of the world's larus relictus, and 80% of the world's larus relictus breeding population lives in HJN lake [30]. Therefore, the wetland environment of HJN lake is of great significance to the protection of the habitats of larus relictus [31]. Since 2017, HJN lake has become a national nature reserve in China because of the importance of its ecological environment and function [32], [33]. As an oasis in desert, HJN lake plays an important role in water conservation, windbreak, sand fixation, and biodiversity maintenance. It is also an important source of water for production and living, irrigation, and animal husbandry of the surrounding residents, and has an important ecological status [34]. The study area lies in 39°04′∼39°08′N, 109°50′∼109°56′E, and the total area of the HJN lake Basin is about 1444 km^2. Because it is situated in the north of China's inland area and adjacent to the desert with small rainfall, large evaporation, and sparse vegetation, the ecological environment in this area is very fragile. The change of water volume in the basin caused by climate change and human activities has seriously damaged the local ecological environment. In recent years, the survival environment of the larus relictus has been threatened and the number of them has decreased due to the decrease of water volume in the HJN lake area. The area is an erosive hilly terrain on the plateau with a continental monsoon climate, which means the temperature difference there is large, while the precipitation is little. Administratively, HJN lake is located at the junction of two provinces in China, which crosses the middle of the lake. The two provinces implement different administrative measures in their own jurisdiction. As a result, they can neither uniformly supervise human activities nor carry out effective environmental impact assessment before the implementation of the engineering project. Geographical location and administrative regionalization aggravate the damage and impact of human activities on this ecologically fragile area, making the task of ecoenvironmental protection in the study area more arduous.

B. Data

1) Landsat Data: Because of the appropriate spatial and temporal resolution, Landsat satellite data with spatial resolution of 30 m and 16-d revisit period were selected to extract the water area of HJN lake. Landsat satellite data include Landsat 4,5 TM, Landsat 7 ETM+, and Landsat 8 OLI data from 1984 to 2017, mainly downloaded from the GLOVIS database[1] of the United States Geological Survey (USGS). Considering the 16-d revisit period of Landsat satellite data and TM images are more susceptible to weather, such as clouds, rain, and fog in summer, we selected up to eight TM images over a 4-month window to ensure high-quality images in the study area can be obtained during the period. Furthermore, this period is basically HJN's abundant water period and the lake area in that period will not change much. Combining these two factors, we chose June to September as the window period to select TM images. The original download data are L1T product (Level 1T), and the error of the data after geometric correction is less than

[1] [Online]. Available: http://glovis.usgs.goc

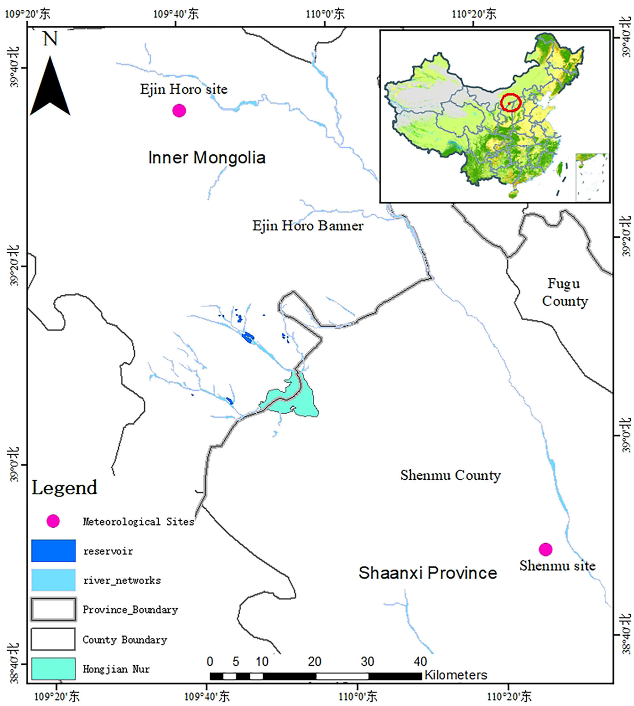

Fig. 1. Study area.

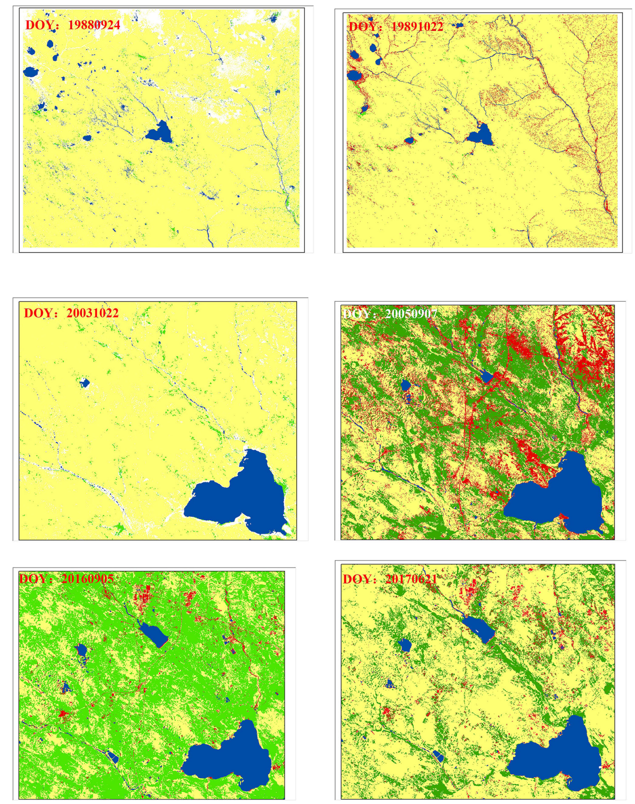

Fig. 2. Remote sensing monitoring results of changes in HJN Lake and its surrounding water systems in typical years.

0.4 pixels. We use the Landsat ecosystem distribution adaptive processing System (LED APS) software to convert the DN value of each pixel in the image into surface reflectance. For clouds and shadows in images, we use a newly developed algorithm F-mask to remove them [35]. Landsat ETM + airborne scanning corrector (SLC) malfunctioned on 31 May 2003, resulting in strip loss in later data. All pixels affected by clouds, shadows, and SLC-off are removed, and only good-quality observations (clear-sky observations) are used for subsequent research. The processed data were used to retrieve the water area and its changes in the HJN lake.

2) Meteorological Data: The daily dataset (V3.0) of China's surface climate data used in the study was obtained from the China National Meteorological Information Center[2]. The dataset contains daily data of atmospheric pressure, temperature, precipitation, evaporation, relative humidity, wind direction, wind speed, illumination hours, and 0 cm geothermal elements of 699 basic weather stations in China since January 1951. The dataset stores meteorological data of the whole country in subelements, and each monitoring element is stored as a file per month. In this study, the temperature and precipitation data of two stations (Fig. 1) in the study area are extracted. The Ejin Horo site locates at 39°35′N, 109°40′E, and its altitude is 1328.2 m. The Shenmu site locates at 38°49′N, 110°26′E, and its altitude is 940.3 m. During the data reorganization process, we repeatedly detect and control the quality of the observed data, and supplement the multiday missing data in November 1968. The average values of two adjacent years were used to replace the missing data. Finally, the temperature and precipitation data of the 1961–2016 time series were obtained and used to calculate the PDSI series of the two stations in the study area.

[2][Online]. Available: http://data.cma.cn/data/

This article attempts to analyze the characteristics of climate change in HJN lake watershed from multiple perspectives using multisource data and to determine the results of climate change in the study area by checking the correlation and consistency of the data. The annual observation data of rain gauge installed in the lake area from 1956 to 2010 were obtained and compared with the monitoring data of national meteorological stations in the study area.

3) Data From Global Precipitation Climatology Centre (GPCC): The long time series precipitation data series product (1901–2010) from GPCC was used to derive the historic water yield in HJN watershed [36]. The GPCC dataset is gauge-analysis products derived from quality-controlled station over the world. Its full data reanalysis product is suitable for total precipitation analysis in HJN watershed. The product avoided the error caused by various systematic gauge measuring errors as much as possible. Therefore, the precipitation product from GPCC has high accuracy related to the measurement. The products used in this article are daily with 0.5×0.5 spatial resolution.

III. Methodology

A. *Extraction of Water Surface Area by Water Body Extraction Index Method*

The AWEI index is developed using the corresponding relationship between the water body extraction index value and the proportion of water body in mixed pixels. AWEI can quantitatively estimate the submerged area because of its higher classification accuracy and more stable discrimination threshold at the land–water boundary. The expression of AWEI is as follows:

$$\mathrm{AWEI} = 4 \times (\rho_{\mathrm{band2}} - \rho_{\mathrm{band5}}) - (0.25 \times \rho_{\mathrm{band4}} + 2.75 \times \rho_{\mathrm{band7}}). \quad (1)$$

In the formula, ρ is the reflectivity of the corresponding band of Landsat TM/ETM+ image. AWEI value is calculated from the reflectivity of each band of Landsat image. Utilizing the AWEI index programmed based on interactive data visualization solution (IDL), water body and nonwater body can be distinguished by K-means clustering algorithm.

In this study, the deep learning framework of recurrent neural network (RNNs) was used to classify the land use/cover types. AWEI index is used to distinguish water body from nonwater body by K-means clustering algorithm to assist the accuracy of surface feature detection. Then, the results of land use/cover types and the results of water body detection from AWEI were combined to do water area change detection analysis.

B. PDSI as the Precipitation Deficit Index

Based on the principle of water balance, PDSI defines "climate suitable precipitation" as water demand and uses the difference between it and actual precipitation to define the water profit and loss status of the study area. PDSI can not only consider the current water supply and demand situation, but also consider the effect of preliminary dry and wet condition and its duration on the current drought situation. It has a clear physical meaning and is an index that can objectively, reasonably, and quantitatively describe the water profit and loss situation.

The first step of PDSI is to calculate the suitable precipitation per month according to the principle of water balance and to calculate the water deficit combined with the actual monthly precipitation. Therefore, the suitable precipitation for a certain month is calculated as follows:

$$\hat{P} = \widehat{ET} + \hat{R} + \widehat{RO} - \hat{L}. \quad (2)$$

Among them, $\widehat{ET}$, $\hat{R}$, $\widehat{RO}$, and $\hat{L}$ represent evapotranspiration, soil water supplement, yield, and soil water loss under suitable climatic conditions, respectively. This formula means that precipitation under suitable climatic conditions within a month needs to provide water that is "used" to evapotranspiration, supplement soil moisture, and generate runoff. In addition, soil moisture will also "appropriately" lose part to evapotranspiration, runoff generation, and other directions, so the demand for precipitation will be a little bit less, and therefore the corresponding soil moisture loss under suitable climate conditions needs to be subtracted. Utilizing python programming tools, PDSI can be calculated after calculating the parameters using a simple two-layer soil hydrological model. Water profit and loss are calculated by the following formula:

$$d = P - \widehat{P}. \quad (3)$$

In the formula, d is the water profit and loss, and P is the actual precipitation. PDSI value was obtained by revising and standardizing d, which represents water profit and loss.

C. Multiscale Morlet Wavelet Transform Method

Complex Morlet wavelet transform can simultaneously give the phase and amplitude information of time series changes, which can be used to determine the period of PDSI sequence and the overall change range of total dryness and humidity such that

$$\int_{-\infty}^{+\infty} \Psi(t)\, dt = 0 \quad (4)$$

$$w_f(a, b) = |a|^{-\frac{1}{2}}\, \Delta t \sum f(k\Delta t)\, \bar{\Psi}\left(\frac{k\Delta t - b}{a}\right). \quad (5)$$

The wavelet variance function var (f) is the integral of the modulus square value of the wavelet coefficients on the time scale a, which can reflect the main period of PDSI sequence and the oscillation intensity of different time scales. In this study, the scale of a is set to 1–32 years, and the change of the wavelet coefficients and the module square of wavelet coefficients is analyzed year by year. The calculating method is as follows:

$$\mathrm{var}(f) = \int |w_f(a,b)|^2\, db. \quad (6)$$

The contour maps of the real part of wavelet coefficients can reflect the variation of PDSI sequence at different time scales and its distribution in time domain. The wavelet coefficient is positive, which means that it is in a wet period, otherwise it is in a dry period. The modulus square value of the wavelet coefficients is equivalent to the energy spectrum of wavelet, which can analyze the oscillation intensity of different periods. The larger the value, the stronger the periodicity of its corresponding scales. In order to ensure the reliability of original data sequence analysis by wavelet transform, the PDSI sequence of 56 years from 1961 to 2016 was expanded by mirror image method for 4 years before and after expansion, and the PDSI sequence after expansion was 64 years. 32-year-scale Morlet wavelet transform is applied to the extended data series. Finally, the original 56-year wavelet transform results are extracted and analyzed.

IV. Results

A. Area of Wetland Waters in HJN Lake Watershed

The surface area changes of HJN lake and its surrounding water systems were extracted by AWEI. The results in typical years are shown in the Fig. 2.

From the results of remote sensing monitoring, the changes of the surrounding water system and the water area of HJN lake have a good correlation. In 1988 and 1989, the area of water system around HJN lake was abundant, and the surface area of HJN lake did not change significantly.

In 2003, although the area of water system around HJN lake was insufficient, it could still clearly identify the river area, and the area of HJN lake did not change significantly. In 2005, it can be clearly found that Zazak Reservoir began to impound water, and the water area of it increased year by year. From 2005 to 2017, the water requirement of the reservoirs around HJN lake multiplied year after year. Besides Zazak Reservoir, more and more reservoirs were constructed. For example, reservoirs in the upstream of Manggaitu River and so on. With the increase

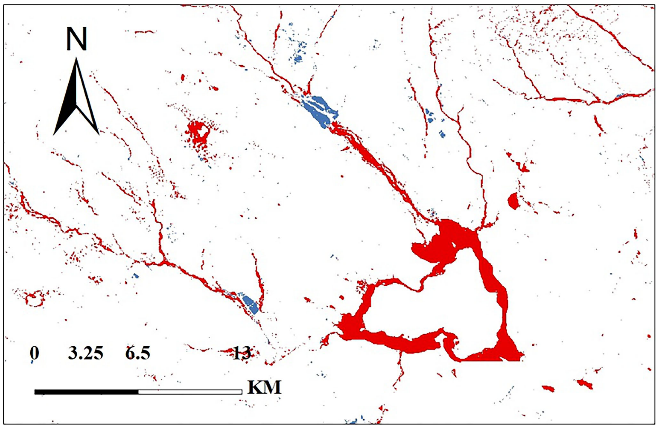

Fig. 3. Differences of water area between 1992 and 2015 in HJN Watershed. The blue area is increased water area and the red area is the decreased water area.

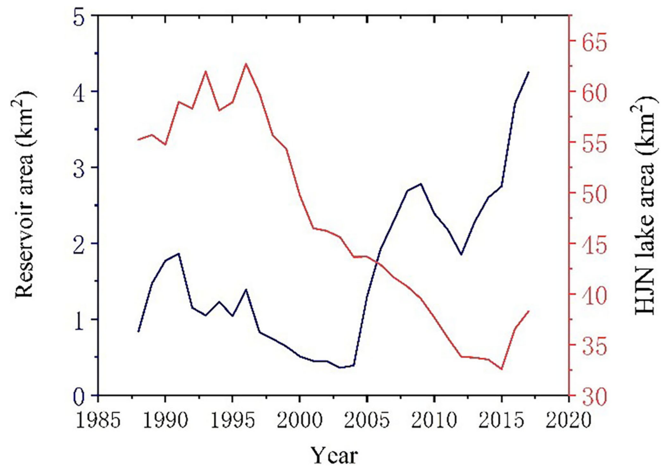

Fig. 4. Changes in lake area and reservoir area of HJN Lake Basin during 1988–2017 (km^2).

of upstream water interception volume, the upstream channels of HJN lake basically disappeared, and the area of lake water surface also decreased year by year. It can be seen that the throttling of the reservoirs and ponds in upper reaches of HJN lake has obvious effects on the water volume of HJN lake. The difference maps of water area of the water systems around HJN lake in 1992 and 2005 intuitively reflect the influence of upstream closure on water volume in the lake area (Fig. 3).

It can be seen from the above figure that there was no obvious change in the area of the lake and reservoirs before 1996, and the area of HJN lake continued to increase. In 1996, the area of HJN lake reached its historical maximum (62.72 km^2). At the same time, the area of the reservoirs increased first and then decreased, and the maximum area of the reservoirs was 1.86 km^2 in 1991. From 1996 to 2015, the surface area of HJN lake continued to decrease for 19 years. In 2015, the surface area of HJN lake decreased to 32.58 km^2, about half of the area in 1996, which greatly affected the surrounding ecological environment. During the same period, the area of the reservoirs increased continuously, and only decreased slightly from 2009 to 2012. The area of the reservoirs was 2.75 km^2 in 2015, an increase of 0.89 km^2 over 1991. With the increase of precipitation, the area of HJN lake increased and the area of reservoirs continued to increase from 2015 to 2017. The area of reservoirs reached 4.25 km^2 in 2017, the largest in history, more than twice that in 1991. The determination coefficient of reservoir area and lake area is 0.357, and the correlation is obvious, which indicates that the impoundment of reservoirs in HJN lake watershed has a significant impact on the decrease of HJN lake area.

Utilizing the lake area estimated by GPS survey of local HJN protection and management organization, we compared the HJN lake area extracted in this article with it and calculated the correlation coefficient between them. The calculated result shows that $R = 0.93$ ($P < 0.1$), indicating that the HJN area extracted by the method used in this study has a high reliability.

B. Analysis of Water Shortage in HJN Lake Watershed

HJN lake watershed is a typical inland watershed. The monthly PDSI series considering total precipitation and evapotranspiration is an effective measure of the surplus and deficiency of water quantity in this area. The annual average of PDSI series of two meteorological stations in Ejin Horo Banner and Shenmu County from 1961 to 2016 is shown in the Fig. 5.

From the annual average of PDSI series of the two stations, the PDSI series of the two stations has obvious fluctuation during the research period, and the fluctuation of Ejin Horo Banner is more intense than that of Shenmu. The PDSI of Shenmu Station was relatively low for 13 years from 1998 to 2011, which indicated that the station was in a historical drought period. The PDSI value of Ejin Horo Banner in this period was also on the low side as a whole, and the rainfall was relatively abundant only in 2002–2005. The low PDSI of the two stations indicates that the HJN lake Basin was in a relative drought period for 13 years before 2011, which has a direct impact on the water surface reduction of the HJN lake. In 2011–2016, PDSI for the two stations had an increasing trend, which indicates that HJN watershed was in a relative wet period. As a result, the area of HJN lake increased slightly in 2016–2017 (Fig. 4). By further analyzing the implied periodicity of PDSI series with the method of wavelet transform (Fig. 6), we can determine the current meteorological period of HJN lake and predict its future trend.

According to the results of multiscale wavelet transform, the contour map of the real part of wavelet coefficients is drawn [Fig. 6 (a)], and the result shows that the Ejin Horo Banner has obvious periodicity in the scale of 15–20 years. The contour map of the modulus square value of the wavelet coefficients [Fig. 6 (b)] reflects the energy aggregation of wavelet period, and the result shows that PDSI series in Ejin Horo Banner has a significant 15- to 20-year period in the 70 s, 80 s, and 2000. The curves of wavelet variance [Fig. 6 (c)] further confirms that the main period of PDSI in Ejin Horo Banner is 19 years. Therefore,

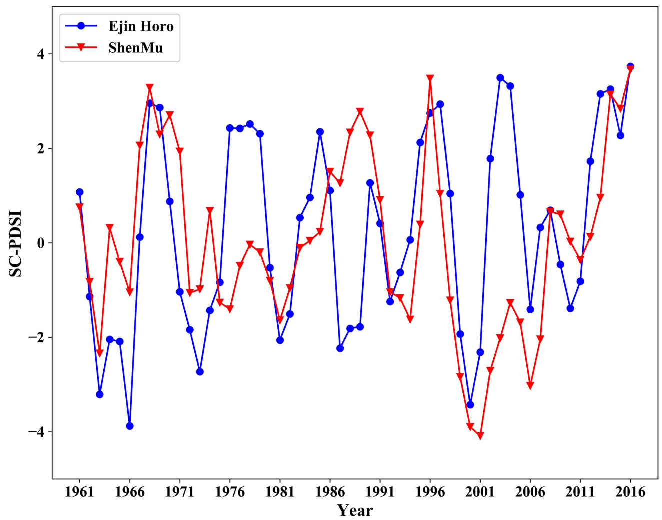

Fig. 5. PDSI annual average sequence of Ejin Horo and Shenmu sites.

we extracted a 19-year-scale trend map of the real part of the periodic variation of the wavelet coefficients [Fig. 6(d)]. According to the trend forecast of 19-year cycle change, 2009–2014 will be a wet period at the Ejin Horo Banner Meteorological Station, and 2014–2019 may be a period from abundant rainfall to drought, which will threaten the maintenance of existing water in HJN lake.

In order to verify the prediction made above, we calculated the PDSI value of Ejin Horo Banner from 2009 to 2018. As shown in the Fig. 7, 2009–2014 is a relatively wet period. The PDSI value has decreased as a whole since 2014, indicating that 2014–2019 is a period from abundant rainfall to drought, and the drought is especially serious in 2015. In addition, the figure shows that the drought continued from 2009 to 2010. Then, the study area entered a long-wet period from 2010 to 2014. The average PDSI value in 2010–2014 was 1.45, 0.28 more than that in 2014–2018, which further illustrated that the study area has changed from abundant precipitation to drought since 2014. Overall, the actual verification results are consistent with the prediction.

From the results of wavelet transform of overall PDSI data series from 1961 to 2016, the surplus and deficiency of water quantity in Shenmu Station showed apparent periodicity, but this periodicity is different from that of Ejin Horo Banner Station. Shenmu Station not only has periodicity on the scale of 15–20 years, but it also has obvious periodicity on the longer time scale (32 years) [Fig. 8(a)]. Around 1990–2005, 15–20 year was the most significant cycle of the station [Fig. 8(b)]. The main period of Shenmu Station is 19 years from the curves of wavelet variance [Fig. 8(c)]. Forecasting the trend of change according to the 19-year main cycle, 2007–2012 belongs to the drought period of Shenmu Station, and 2012–2016 is a transition period from drought to abundant rainfall, which has lasted for 4 years. In the next 1 to 2 years, there will be a turning point from drought to humidity, then it will enter another dry spell.

The periodic analysis of these two stations shows that the meteorological conditions of the HJN lake Basin will be in the period of drought or the transition from drought to humidity in the next 1 to 2 years, which will threaten the maintenance of the existing water quantity. Therefore, more effective precautionary measures need to be taken.

C. *Historical Impact of Precipitation Change on the Water Area of Watershed*

From the analysis of Fig. 9, it can be seen that the precipitation of HJN lake watershed fluctuated obviously from 1960 to 1969, but the total precipitation was obviously higher than that in the previous 60 years, which was the formation period of HJN lake. During that period, the area of lake surface increased year by year, and reached a maximum in 1969. It indicates that there is a good correlation between typical flood years or extreme floods and drought fluctuation years and the formation period of HJN lake before 1969. During the stable period of HJN lake from 1969 to 1999, there were no meteorological precipitation events different from the normal fluctuation, which was an important condition for maintaining the relative stability of HJN lake. After 2000, especially after 2006, HJN lake was in the shrinkage period and also in a long drought period. The precipitation cycle was abnormal, and the influence of meteorological conditions was quite obvious. After 2006, the precipitation gradually increased. However, dam impoundment, coal mining, and other human factors in addition to precipitation also have a significant impact on the lake area in years when precipitation has not changed much. In these years, the correlation coefficient between lake area and precipitation is influenced by other factors. This may explain why precipitation increased a bit in during 2006 and 2009, but the lake area continued to decline. This is evidenced by the significant increase in water storage in upstream reservoirs during the same period (Fig. 4). When precipitation increases significantly, the impact of other factors on the lake area becomes less pronounced. The precipitation increased greatly from 2012 to 2016 and approached the highest level of nearly 100 years in 2016, which makes the water area of HJN lake increase to the highest level since 2012 although the reservoir area continued to increase. In this period, Pearson correlation of precipitation and lake area is 0.83, and the P value is 0.08, which further indicates that the significant increase of precipitation in 2012–2016 has a strong relationship with the increase of the HJN lake area during the same period.

V. Discussion

This article synthetically uses multisource data to analyze the change of century-long meteorological conditions from different angles and contrast changes in water area to explore the reasons. Our conclusion is based on the observation data from the two meteorological sites. GPCC and the other dataset are mainly used for validating the correlation and the consistency of the precipitation data. The percentage of precipitation anomaly of the three data sources was counted respectively, and the corresponding relationship between precipitation changes and the area of HJN lake was compared and analyzed. Moreover,

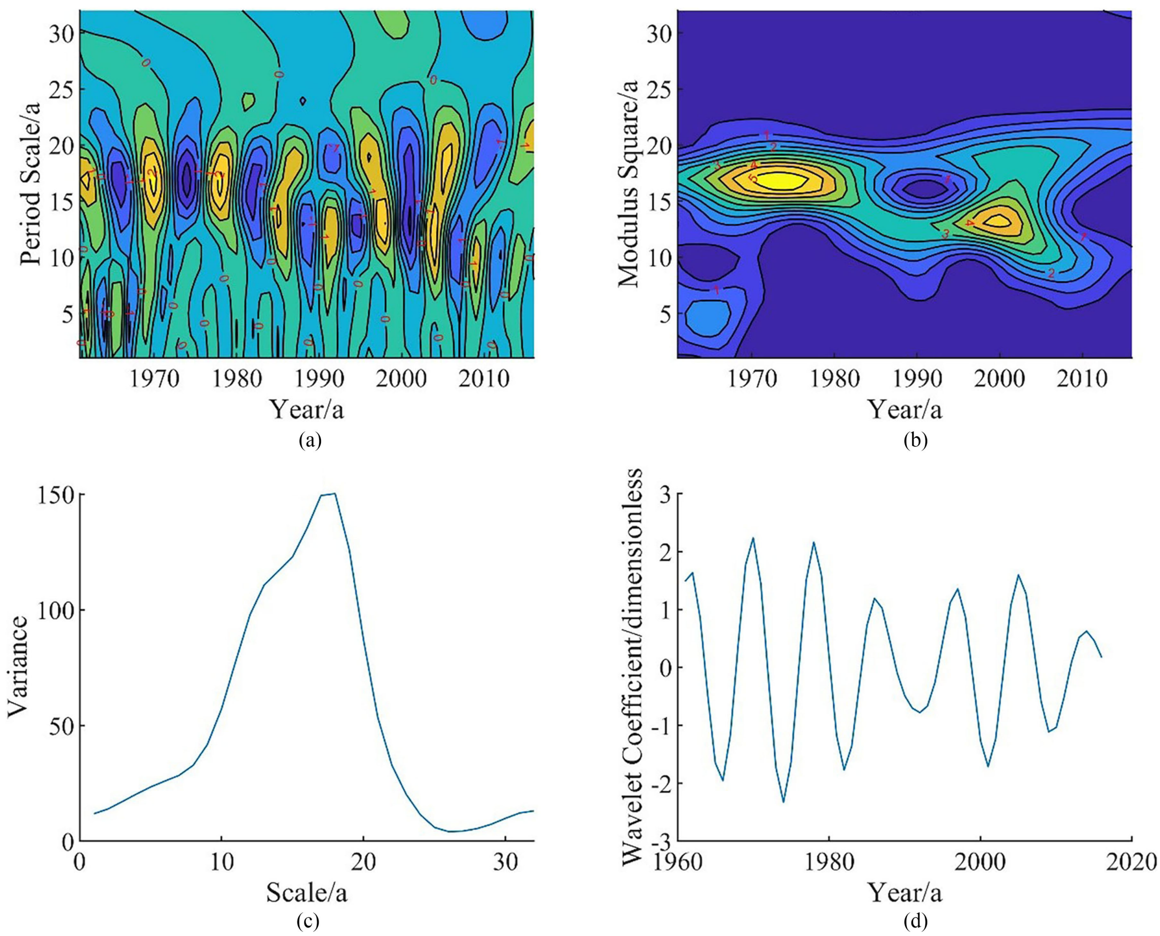

Fig. 6. Wavelet transform results of PDSI sequence for Ejin Horo site.

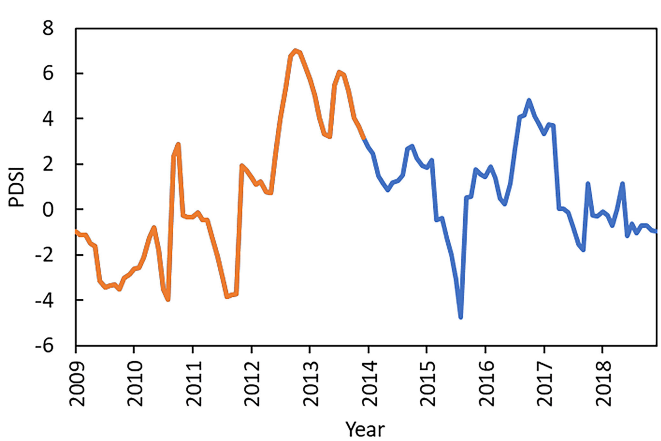

Fig. 7. PDSI variation curve of Ejin Horo Banner from 2009 to 2018.

the reasons for the change of the surface area of HJN lake were explored from the meteorological point of view. From Table I, it can be seen that although the sources of years of precipitation data series are different, there is a very significant correlation among the data, and the data results are consistent. Fig. 4 shows the surface area variation curve of HJN lake, which is consistent with previous studies [37], [38]. After calculation and verification, there is a correlation between the significant increase of precipitation in 2012–2016 and the increase of the HJN lake area during the same period and the prediction of drought cycle in HJN lake basin is reliable.

TABLE I
UNITS FOR MAGNETIC PROPERTIES

	Ejin Horo	Shenmu	Rain gauge	GPCC
Ejin Horo	1			
Shenmu	0.711**	1		
Rain gauge	0.783**	0.740**	1	
GPCC	0.922**	0.703**	0.748**	1

**significant at 0.01 level; *significant at 0.05 level.

In this study, we focus on the impact of precipitation on the surface area of HJN. In addition to precipitation, coal mining, poor management, and other man-made reasons may also have a great impact on the change of HJN lake area. However, these factors are difficult to quantify and there is a lack of data. In the future, we will continue to study the causes of water area changes of HJN lake by combining other factors.

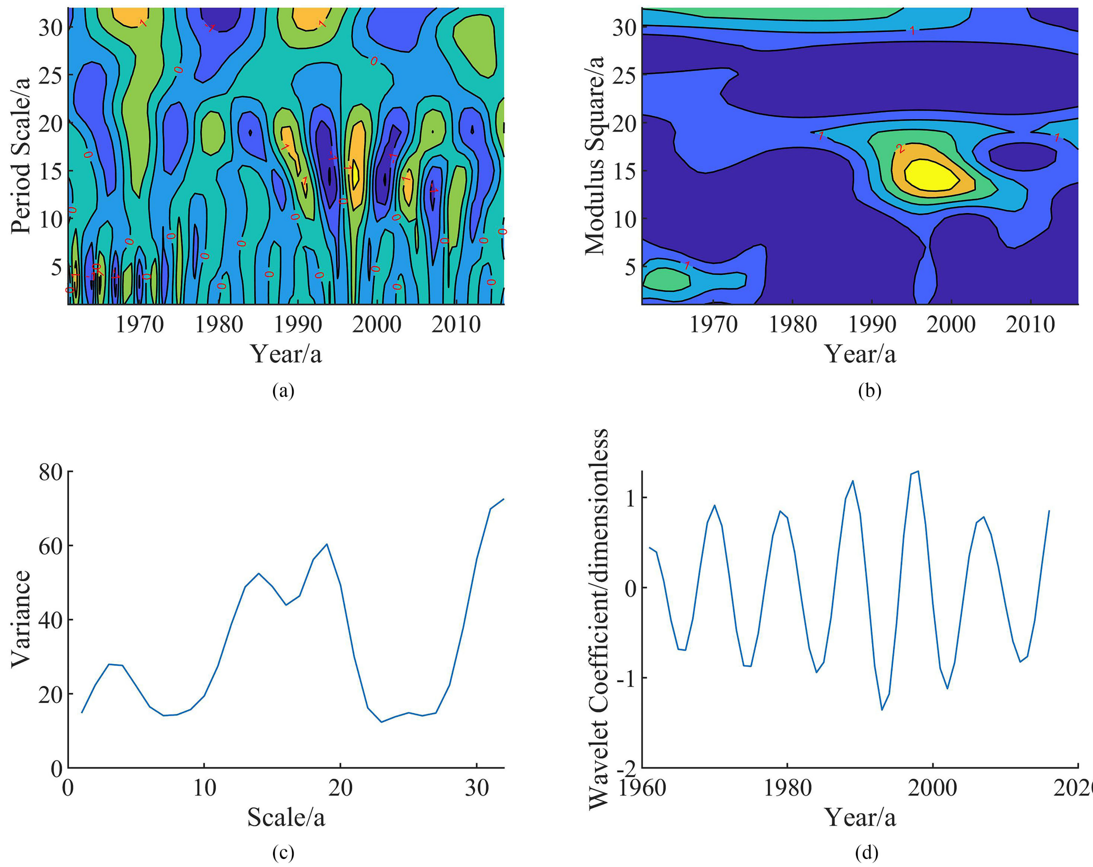

Fig. 8. Wavelet transform results of PDSI sequence for Shenmu site.

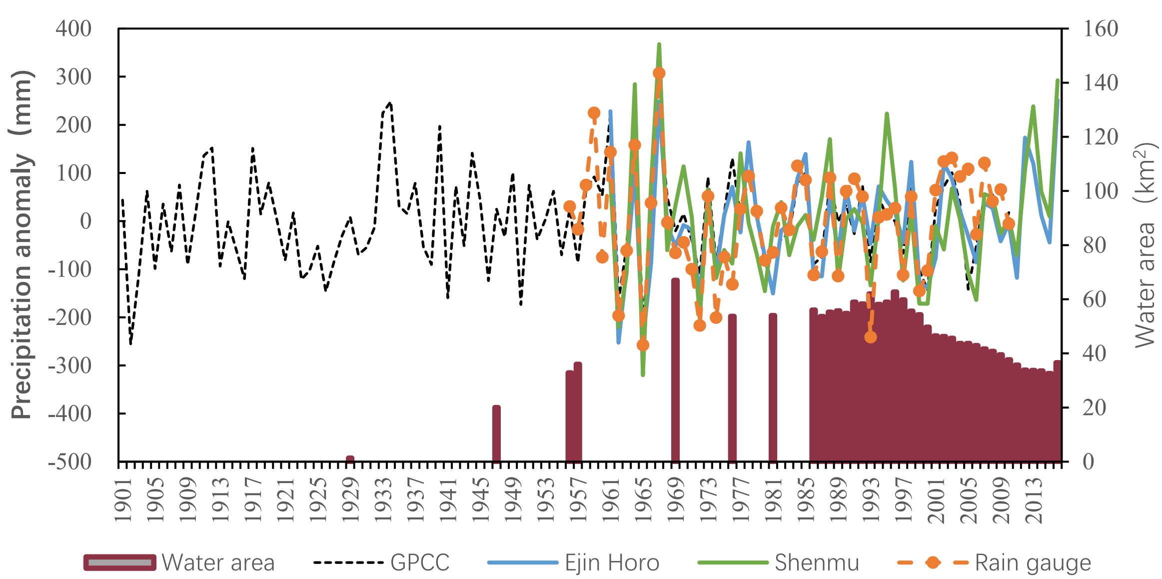

Fig. 9. Relationship between precipitation anomaly of HJN and its water area. HJN water area data before 1988 comes from the records of Shenmu county.

VI. Conclusion

Using Landsat data, the surface area and spatial distribution of HJN lake and its surrounding water systems during 1984 to 2017 were accurately extracted based on AWEI. From the results of remote sensing detection, there is a good negative correlation between the changes of water systems around HJN lake and the changes of HJN lake water area. With the increase of upstream water interception, the upper reaches of HJN lake basically disappeared, and the water surface area of the lake decreased correspondingly year by year. Therefore, the throttling of the reservoirs and ponds in upper reaches of HJN lake, which is used to meet the needs of human life and irrigation water, has a significant impact on the water reduction of HJN lake. The periodic variation of monthly PDSI considering total precipitation and evapotranspiration is consistent with the change of the area of HJN lake in history. Based on the continuous Morlet wavelet transform analysis of PDSI sequences for the two stations, it is found that there is a 15 to 20-year cycle of the overall wet and dry change in the HJN lake watershed, and the main cycle of the PDSI series of both the two stations is 19 years. Using 19-year cycle as the main cycle, we can predict that the meteorological conditions in the HJN lake Basin will be in a period of drought or a period of transition from drought to humidity, and the water surface area will probably be further reduced in the next 1 to 2 years, thus maintaining the existing ecological environment face greater pressure. The historical series of precipitation in the past 100 years are also well correlated with the formation and area change of HJN lake. The consistency analysis result of multisource meteorological observation data proves the reliability of the above results.

It can be concluded that the change of surface area of HJN lake in recent 20 years is the comprehensive results of human activities and climate change. The increase of throttling in upstream reservoirs and ponds caused by human mining, domestic water uses, and irrigation has a strong correlation with the decrease of the area of HJN lake. HJN lake has been upgraded to be a China's National Nature Reserve in 2017. However, the intensification of human activities, the increase of water demand, and the periodic reduction of precipitation caused by climate change will continue to put pressure on the ecological environment protection in this area. This study is helpful to have a thorough grasp of water surface change of HJN lake. The conclusion of the analysis of the reasons for the change of water surface provides a reference and basis for the formulation of ecological environment protection measures of lake in desert area in northern China in the future.

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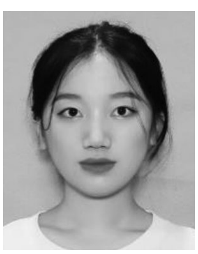

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