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Hui Yue (✉ 13720559861@163.com)

Xi'an University of Science and Technology

Ying Liu

Xi'an University of Science and Technology

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Water Balance and Influence Mechanism Analysis: A Case Study of Hongjiannao Lake, China

Hui Yue^{1, 2*}, Ying Liu¹

¹Xi'an University of Science and Technology, College of Geomatics, Xi'an, 710054, China

²Key Laboratory of Mine Geological Hazards Mechanism and Control, Xi'an, 710054, China

*13720559861@163.com

Abstract Hongjiannao groundwater exchange was the largest desert freshwater lake in China (57.25 km² in 1986). However, it shrank sharply over the past 34a (1986-2019), with the smallest lake area 31.41 km² in 2015. The objective of this study was to use the Landsat images, ASTER GDEM V2 data, and meteorology and statistics data, in combination with the water balance model to calculate the dynamics of water balance elements, quantify and characterize the interannual variations in lake-groundwater exchanges, and analyzed its influencing factors by using the geographical detector. The results showed that in the stable stage (1986-1997), the average rate of the lake area, water level, and lake volume change was -0.26 km²/a, -0.0483 m/a, and -0.0009 km³/a, respectively. Precipitation, river inflow, and groundwater were 0.0203 km³, 0.0485 km³, and 0.0098 km³, which accounts for the whole input were 25.83%, 61.70%, and 12.47%, respectively, evaporation was 0.0786 km³. In the reduction stage (1998-2015), the average rate of the lake area, water level, and lake volume change was -1.21 km²/a, -0.2422 m/a, and -0.0101 km³/a, respectively. Before 2006, precipitation, river inflow, and groundwater were 0.0154 km³, 0.0475 km³, and -0.0025 km³, respectively; from 2006 to 2009, precipitation, river inflow, and groundwater were 0.0143 km³, 0.0334 km³, and 0.0058 km³, respectively; after 2009, precipitation, river inflow, and groundwater were 0.0139 km³, 0.0199 km³, and 0.0085 km³, respectively. Evaporation decreased from 0.0714 km³ to 0.0480 km³ from 1998 to 2015. In the growth stage (2016-2019), the average rate of the lake area, water level, and lake volume change were 1.38 km²/a, 0.27 m/a, and 0.0088 km³/a, respectively. Precipitation, river inflow, and groundwater were 0.0209 km³, 0.0005 km³, and 0.0373 km³, which accounts for the whole input were 46.63 %, 52.12 %, and 1.25 %, respectively, evaporation was 0.0187 km³. Compared with the stable stage, groundwater in the growth stage reduced from 12.47 % (0.0098 km³) to only 1.25 % (0.0005 km³). From 1998 to 2004, Hongjiannao Lake experienced continuous losing conditions (discharge from the lake to groundwater), with a variable exchange volume of up to -0.01582 km³ in 1999. Through geographical detector analysis, it was found that temperature was the dominant factor from 1988 to 1997, while human factors were the dominant factors from 1998 to 2015.

Keywords Water Balance; Lake area; Water level; Lake volume change; Geographical detector; lake-groundwater exchange

1. Introduction

Inland lakes are an important part of water resources in arid or semi-arid regions, which has an important impact on the balance of the local ecosystem and human production and life (Sheng et al., 2016; Gal et al., 2016; Zhang et al., 2017; Yang et al., 2020). In recent years, due to the impact of climate change and human activities, the area of some lakes in northern China has shrunk or disappeared (Ma et al., 2011; Liu et al., 2013; Yang and Lu, 2015; Liu and Yue, 2017). It is a very important and forward-looking work to analyze the evolution and genesis of inland lakes in arid and semi-arid regions and to evaluate the impact of climate change and human activities on lakes, which has guiding significance for the rational development and utilization of lake resources in arid and semi-arid areas.

Hongjiannao Lake is located at the junction of Shaanxi and Inner Mongolia in the arid and semi-arid regions of Northwest China. It is currently the largest desert freshwater lake in China, which plays an indispensable role in regulating the local climate, maintaining the balance of water resources, and biodiversity. Hongjiannao Lake is formed by wind erosion depression. Before lake formation, it is a marsh with less water. Around 1929, due to the increase of water accumulation, the depression became a lake. In the 1930s, the lake area was only 1.3 km² and gradually expanded to 20 km² in 1947. In the middle and late 1950s, due to the dredging of surrounding wetlands for reconstruction, the lake area continued to expand. From the 1970s to the 1990s, the lake area was stable at about 60 km² (Tang et al., 2003; Shen et al., 2005; Yin et al., 2008). Since the 1990s, Northern Shaanxi has suffered from continuous drought and lake evaporation has increased. Meanwhile, Shendong Mining Area, China's largest coal production base, started large-scale coal mining in the northeast of Hongjiannao Lake, which is only 20-30 km away from the lake. The continuous development of the coal mining project has a great impact on the groundwater supply for Hongjiannao Lake. In 2015, the area of Hongjiannao Lake has been reduced to its lowest level of 31.41 km², and the continuous reduction of the lake has resulted in the continuous deterioration of the ecological environment (Yue and Liu, 2019a; Yue and Liu, 2019b). Therefore, it is necessary to monitor the variations of Hongjiannao Lake and to analyze its responses to climatic and anthropogenic factors, to provide a scientific reference for rational coal mining exploitation and protection of water resources, as well as regional sustainable development in the arid and semi-arid area of Northwest China.

Various studies have been put forward to analyze the changes of the lake area, water level, and lake volume and the dynamics to climate change and human activities by using remote sensing techniques and hydrological models (Ma et al., 2014; Liang, 2019; Liang and Yan, 2017; Yan et al., 2018; Wang et al., 2018a; Zhao et al., 2018; Liang and Li, 2019; Yue and Liu,

2019). Indeed, Hongjiannao Lake has been largely neglected in hydrological research, as it receives less attention and lacks management compared with large lakes and reservoirs which have traditionally been managed and monitored. Hongjiannao Lake does not have enough hydrological information to assess and to understand its hydrological processes, because it does not have any hydrometeorological gauging stations surrounded by. Therefore, estimating the water balance and its components is a necessary precondition for this challenge. Many of the water balance components (surface runoff and lake-groundwater exchanges) are difficult to estimate directly even at the local scale and are often assumed to be in the residuals of the water balance equation (Kampf and Burges, 2010; Faso et al., 2015; Huang et al., 2018; Guevara-Ochoa et al., 2020).

Previous studies have focused primarily on variations in the lake area and water volume by using remote sensing data. Comprehensive and systematic analysis of long-term continuous variations hydrological process of Hongjiannao Lake on quantitative analysis based on water balance is still lacking. Therefore, the objectives of this study were as follows: (1) based on the hydrogeological model of Hongjiannao Lake, we calculated the dynamics of water balance elements, including precipitation, evaporation, lake volume change, river inflow, and runoff change; (2) to quantify and characterize the interannual variations in lake-groundwater exchanges based on water balance model ; (3) to comprehensively explore the dominant factors affecting the lake area, water level, and water volume change of Hongjiannao Lake in terms of NDVI (Normalized Difference Vegetation Index), sheep population (SP), human population (HP), the industrial output value (GVIO), annual average temperature (AT) and precipitation (AP).

2. Materials and methods

2.1 Study area

2.1.1 Hongjiannao Lake

Fig. 1. The spatial schematic diagram for Hongjiannao Lake and Hongjiannao Basin

Hongjiannao Lake is located at the junction of Shenmu County, Shaanxi Province, and Yijinholo Banner of Inner Mongolia, and adjacent to the Mu Us Desert in the West (Fig.1). The geographical coordinates are 109°42'-110°54' E and 39°13 '-39°27' N. Hongjiannao Lake is the largest desert freshwater lake in China, known as the “Pearl of the desert”. Hongjiannao Lake is also a National Nature Reserve of China and the world’s largest breeding ground for relict gulls and black storks under the national level I key protection.

2.1.2 Hongjiannao Basin

Hongjiannao Basin is located in the lake basin with high around and low in the middle. The northwest and northeast are undulating mountains and gentle hills. In the southwest and southeast, the surface watershed is composed of aeolian dunes. The highest point is located in the western watershed, with an altitude of 1510 m, and the lowest point is located in Hongjiannao Lake, with an altitude of 1223 m. In the north, the terrain fluctuates greatly, and in the East, there are relatively gentle dunes and beaches. The area of Hongjiannao Basin is about 1400 km², including Xinjie Town, Taigesumu Town, Erlintu town, and Zhongji town. Xinjie town and Taigesumu town were merged into Zhasake town in 2005.

2.1.3 Watershed system

Hongjiannao Lake is a closed inland lake, which is mainly supplied by precipitation, river runoff, and groundwater. Before 2000, the runoff supply of Hongjiannao Lake came from Donghulusu River, Zhasake River, Qibosu River, Erlintu River, Malian River, Haolai River, and Songdaogou River, among which Manggaitu River, Zhasake River, and Qibosu River were the three rivers with the largest flow in the basin. In 2000, Malian River had no surface runoff and flows into Hongjiannao Lake. In 2005, the establishment of Zhasak reservoir was 6 km away from Hongjiannao Lake blocked the Zhasak River. Since then, Zhasak River had no water supply to Hongjiannao Lake. In 2009, the Inner Mongolia Autonomous Region intercepted Manggaitu River and established a reservoir, which interrupted the runoff supplement of Manggaitu River to Hongjiannao Lake. At present, the largest runoff supply source of Hongjiannao lake is Qibusu River (Table 1).

2.2 Data

2.2.1 Landsat images

In this paper, 359 Landsat images including Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper (ETM+), and Landsat-8 Operational Land Imager (OLI), were used to extract the lake area of Hongjiannao Lake. The path/row was 127/033 and the time was from 1986 to 2020. The images were obtained from the United States Geological Survey (USGS) Earth Explorer (<https://earthexplorer.usgs.gov/>).

2.2.2 ASTER GDEM V2 data

ASTER GDEM V2 data was released by the National Aeronautics and Space Administration (NASA) and the Ministry of Economy, Trade, and Industry (METI) on October 17, 2011. The spatial resolution is 30m (confidence 95%) and the vertical accuracy is 20 m (95% confidence level). ASTER GDEM V2 data covered the global latitude of 83° north to 83° south, which covered more than 99% of the earth's land surface. Compared with aster GDEM V1, which can recognize more than 12 km² lakes at most, GDEM V2 can recognize more than 1 km² lakes. In this study, ASTER GDEM V2 data was used to obtain the water level of Hongjiannao Lake from 1986 to 2020.

2.2.3 MODIS data

The MODIS product used in this paper was MODIS NDVI product MOD13Q1, which was often used in large-scale vegetation coverage study. The temporal resolution is 16 days, the spatial resolution is 250 m × 250 m. The path/row was h26v05 and the time series was from 2000 to 2018. The images were obtained from the National Aeronautics and Space Administration (NASA) (<https://search.earthdata.nasa.gov/search>). We used the MODIS

Projection Tool (MRT) to preprocess MOD13Q1 products in batches, and the Maximum Value Composite (MVC) method to get the monthly data set of MOD13Q1 products.

2.2.4 Meteorology and statistics data

The annual average temperature (AT), precipitation (AP), and evaporation data of Hongjiannao Lake from 1986 to 2019 were all from Shenmu County (110°28'E, 31°49'N) and Yijinhuluo Banner (109°44'E, 39°34'N) Meteorological station, the data is downloaded from China Meteorological Data Network (<http://data.cma.cn/>).

The four datasets (1988-2015) were used for geographical detector analysis: the normalized vegetation index NDVI (Normalized Difference Vegetation Index), sheep population (SP), human population (HP), and the industrial output value (GVIO) come from the papers of Yue and Liu (2019a), and Liang et al (2017). The water used for irrigated livestock husbandry used to calculate the changes in the water volume of the Hongjiannao Basin was obtained by referring to the data and the statistical yearbook and socioeconomic development bulletin of Shenmu County and Yijinhulo Banner.

2.3 Water balance calculation

2.3.1 Water balance model

The hydrology of the water balance model is controlled by an input-storage-output process, which can be expressed by the following water balance model (all components in km³/annual):

$$Q_{River} + P_{Lake} + Q_{Groundwater} = E_{Lake} \pm \Delta V \quad (1)$$

Where ΔV is the volume change of the lake, Q_{River} is surface runoff into the lake, P_{Lake} is lake precipitation, E_{Lake} is lake evaporation, $Q_{Groundwater}$ is groundwater recharge, which indicates the difference between the inflow and outflow of groundwater.

This paper studies the relationship between groundwater recharge and lake volume change. Therefore, the formula of Hongjiannao water balance for many years can be expressed as:

$$Q_{Groundwater} = E_{Lake} \pm \Delta V - Q_{River} - P_{Lake} \quad (2)$$

2.3.2 Lake area extraction: LA

We used the Deeply Clear Water Extraction Index (DCWEI) (Yue and Liu, 2019b) to extract the lake area, DCWDI can be expressed as:

$$DCWEI = \sqrt{\rho_{Red}^2 + \rho_{NIR}^2} \quad (3)$$

where ρ_{Red} and ρ_{NIR} are the reflectance of the red and NIR bands, respectively.

2.3.3 Water-level derivation: WL

We used the waterline method combined with the ASTER GDEM V2 image and the Landsat image to obtain the Hongjiannao Lake boundary to calculate the multi-year water level of Hongjiannao Lake. Firstly, we used Landsat Image and DCWEI to extract the boundary

(waterline) of Hongjiannao Lake from 1986 to 2020. Secondly, the DEM within the lake boundary is extracted by superimposing the obtained Lake boundary in different periods on ASTER GDEM v2. Thirdly, calculate the arithmetic average value of the DEM within the lake boundary, which was the lake water level. Finally, the water level of Hongjiannao Lake from 1986-2011 and 2017-2020 was obtained through the waterline method and the DEM data (Fig. 2).

Hongjiannao Lake continued to shrink after 2011. By January 2016, the area had reached the minimum level, and it had been rising since then. In January 2017, it reached the level of 2011. However, due to the inability to find ASTER GDEM data of the minimum elevation period in 2016, the water level of Hongjiannao Lake from 2012 to 2016 was obtained by fitting the relationship model between area and water level. We used a scatter plot to fit the area water level data from 1986 to 2011 (the equation is $y=0.2078x+1199.4$, $R^2=0.9947$, where x is the area and y is the water level). Then, substituting the area data from 2012 to 2016 into the equation, the water level data for this period was calculated.

Fig. 2. Water-level derivation (a) Different periods of shoreline superimposed on DEM; (b) DEM extraction by lake boundary on August 2nd, 1986.

2.3.4 Lake volume variation: ΔV

The volume algorithm proposed by Taube (2011) was used to calculate the lake volume change. The calculation formula can be expressed as:

$$\Delta V = \frac{1}{3} (WL_1 - WL_0) \times (LA_0 + LA_1 + \sqrt{LA_0 \times LA_1}) \quad (4)$$

Where ΔV is the volume change of the lake, WL_0 and LA_0 are the initial water level and area of each lake during the study period, WL_1 and LA_1 are the water level and area data during the study period. In the calculation of volume, the area data closest to the time of each period water level data acquisition was selected.

2.3.5 Lake precipitation and evaporation: P_{Lake} and E_{Lake}

Annual precipitation and evaporation over the lake water surface area were based on the pan

data (Ikebuchi et al., 1988; Abtew, 2001). The ratio of lake evaporation to pan evaporation of Φ 20 cm small evaporating dish to E601 large evaporating dish is 0.85, the conversion coefficient of evaporation from E601 evaporating dish to large water area (Lake, etc.) is 0.9 and 0.91. Therefore, this study assumes that the annual pan coefficient is 0.905 as the conversion coefficient (Fu et al., 2004; Lowe et al., 2009). Therefore, the conversion coefficient of Φ 20cm evaporating dish to large area water area is $0.85 \times 0.905 = 0.769$.

$$P_{\text{Lake}} = \text{precipitation} \times LA \quad (5)$$

$$E_{\text{Lake}} = \text{evaporation} \times LA \times 0.769 \quad (6)$$

2.3.6 River inflow: Q_{River}

Hongjiannao Basin is mainly composed of the Hongjiannao Lake area and seven inflow rivers, Zhasake River, Donghulusu River, Qibosu River, Songdaogou River, Erlintu River, Haolai River, and Malian River. According to previous studies and data statistics: Zhasake River, Donghulusu River, and Qibosu River are perennial rivers, the average surface runoff over many years is 0.01247 km^3 , 0.01345 km^3 , and 0.01417 km^3 , respectively. Songdaogou River, Erlintu River, Haolai River, and Malian River are seasonal rivers, the average surface runoff over many years is 0.00109 km^3 , 0.00598 km^3 , 0.00136 km^3 , and 0.00593 km^3 , respectively (Table 1) (Yang, 2014).

Table 1. The rivers runoff of Hongjiannao Basin

No	River	River type	Year	Drainage area (km^2)	River length (km)	Runoff (km^3)
1	Zhasake River	Perennial river	(1986-2006) (2016-2020)	356.0	33.89	0.01247
2	Donghulusu River	Perennial river	(1986-2009)	385.7	30.57	0.01345
3	Qibosu River	Perennial river	(1986-2020)	351.3	20.08	0.01417
4	Songdaogou River	Seasonal river	(1986-2020)	29.3	5.36	0.00109
5	Erlintu River	Seasonal river	(1986-2020)	130.1	6.03	0.00598
6	Haolai River	Seasonal river	(1986-2000)	35.9	17.05	0.00136
7	Malian River	Seasonal river	(1986-2020)	139.2	9.33	0.00593

2.4 Geographical Detector

The geographical detector is a statistical tool used to detect the spatial separation of relevant elements and reveal the driving force behind it (Wang et.al., 2010; Wang et.al., 2016). Based on the theory of spatial differentiation, the dependent variable and different discrete independent variables are detected on the same spatial scale. If the independent variable has an important influence on the dependent variable, the spatial distribution of the two variables is similar. The geographical detector contains four different geographical detectors: risk, factor, ecological, and interaction. In this paper, we used the factor detector and the ecological detector.

The evaluation index of the factor detector is q , which can evaluate the heterogeneity of spatial elements and the explanatory power of detection factors, analyze the interaction between two variables, and find the explanatory power of two variables. The range of q value is 0-1, which indicates the relationship between the independent variable x and dependent variable y . The larger the value, the greater the impact.

$$q = 1 - \sum_{i=1}^m n_i \sigma_i^2 / n \sigma^2 \quad (7)$$

Where $i=1,2,3,\dots,m$ refers to the classification of independent variable x ; n_i is the number of units corresponding to layer i ; n is the total number of units in the study area; σ_i^2 and σ^2 are the variance of Y values in the i layer and the whole region, respectively.

The ecological detector is used to compare the influence of two factors X_1 and X_2 on the spatial distribution of attribute y , which is measured by F-statistics:

$$F = \frac{N_{X1}(N_{X2}-1)SSW_{X1}}{N_{X2}(N_{X1}-1)SSW_{X2}} \quad (8)$$

$$SSW_{X1} = \sum_{n=1}^{L1} N_h \sigma_h^2 \quad (9)$$

$$SSW_{X2} = \sum_{n=1}^{L2} N_h \sigma_h^2 \quad (10)$$

Where: N_{X1} and N_{X2} represent the sample size of $X1$ and $X2$, respectively; SSW_{X1} and SSW_{X2} represent the sum of the intralayer variance of the stratification formed by $X1$ and $X2$, respectively; $L1$ and $L2$ represent the number of variables $X1$ and $X2$, respectively. Among them, if $H_0: SSW_{X1}=SSW_{X2}$ is rejected at the significance level of α , it indicates that there is a significant difference between the two factors $X1$ and $X2$ on the spatial distribution of attribute y . In this paper, α is 95%, “Y” means there is a significant difference, “N” means there is no significant difference.

In this paper, the lake area (LA), water level (WL), and lake volume change (ΔV) of Hongjiannao Lake from 1988 to 2015 are taken as dependent variables “Y”. NDVI, human population (HP), sheep population (SP), the industrial output value (GVIO), annual precipitation (AP), and annual average temperature (AT) are taken as independent variables “X”, and the main driving factors of Hongjiannao Lake are calculated.

3. Results

3.1 Dynamics of water balance elements

3.1.1 Hydrogeological model

The isohydrograph of groundwater shows that the Hongjiannao Lake groundwater system is a closed independent groundwater system with high surrounding and low center (Fig. 3). After the groundwater is replenished by the atmospheric precipitation, it moves from the watershed to the lake along the terrain, and finally discharges into the Hongjiannao Lake, the infiltration of atmospheric precipitation forms phreatic water and shallow confined water, and supplies surface water (Yin et.al., 2008). Therefore, Hongjiannao Lake had water all year-round, with weak seasonal change of water area and high correlation with dynamic change of groundwater (Ma et.al., 2015). As a result of this closed hydrogeological structure, Hongjiannao Lake becomes a concentrated drainage area of groundwater.

Fig. 3. The schematic diagram for the hydrogeological model of Hongjiannao Lake

3.1.2 Precipitation and evaporation

Fig. 4. Precipitation and evaporation for Hongjiannao Lake from 1986 to 2019.

The calculated annual average precipitation and evaporation on the lake water surface showed high variability from 1986 to 2019, but represent similar behavior (Fig. 4). The precipitation ranged from 0.00948 km³ in 2000 to approximately 0.02733 km³ in 1995 with the mean value of 0.01709 km³/year, while the evaporation ranged from 0.03357 km³ in 2016 to approximately 0.08599 km³ in 1997 with the mean value of 0.06528 km³/year. Thus, the evaporation was much greater than the precipitation, it was consistent with the fact that Hongjiannao Lake belonged to an arid and semi-arid climate.

3.1.3 Lake area, water-level and lake volume

Fig. 5. Variations in the lake area, water level, and lake volume change of Hongjiannao Lake from 1986 to 2019.

The calculated annual average lake area, water level, and lake volume change of Hongjiannao Lake in the period of 1986-2019 were shown in figure 5. The lake area ranged from 31.41 km² in 2015 to 57.25 km² in 1986 with a mean value of 44.74 km²/year. The water level ranged from 1206.11 m in 2015 to 1211.25 m in 1986 with a mean value of 1208.73 m. The lake volume change ranged from -0.0085 km³ in 1993 to -0.2242 km³ in 2015 with a mean value of -0.1236 km³/year.

It can be seen that the whole change trend process of Hongjiannao Lake can be divided into different stages. The calculated annual average lake area, water level, and lake volume change showed similar behavior and high variability from 1986 to 2019. To more intuitively represent the stage changes, we divided the whole period of 1986-2019 into three different stages: stable (1986-1997), reduction (1998-2015), and growth (2016-2019). In the stable stage (1986-1997), the lake area changed from 57.25 km² to 54.13 km² with the average rate of change was -0.26 km²/a, the water level changed from 1211.25 m to 1210.67 m with the average rate of change was -0.0483 m/a, lake volume changed from -0.02158 km³ to -0.03173 km³ with the average rate of change was -0.0009 km³/a. In the reduction stage (1998-2015), the lake area changed from 53.13 km² to 31.41 km² with the average rate of change was -1.21 km²/a, the water level changed from 1210.47 m to 1206.11 m with the average rate of change was -0.2422 m/a, lake volume changed from -0.04285 km³ to -0.22425 km³ with the average rate of change was -0.0101 km³/a. In the growth stage (2016-2019), the lake area changed from 31.75 km² to

37.28 km² with the average rate of change was 1.38 km²/a, the water level changed from 1206.18 m to 1207.26 m with the average rate of change was 0.27 m/a, lake volume changed from -0.22227 km³ to -0.18694 km³ with the average rate of change was 0.0088 km³/a.

3.1.4 River inflow and runoff change

From the water balance formula of Hongjiannao Lake, the input included precipitation, river inflow, and groundwater recharge, while the river inflow all come from the seven rivers runoff into the lake (Table 1). In section 3.1.3 we divided the changing trend of the lake area, water level, and lake volume changes into three stages, here we undertake the different stages to analyze the spatio-temporal variation of the seven rivers change in Hongjiannao Basin. In the stable stage (1986-1997) (Fig. 6(1)), seven rivers including Zhasake River, Donghulusu River, Qibosu River, Songdaogou River, Erlintu River, Haolai River, and Malian River, were all inflow into the lake. In the reduction stage (1998-2015) we can further divide it into three periods according to the situation of river cutoff. In 2006, the Zhasake Reservoir was built in the upper reaches of the Zhasake River, which blocked the runoff supply for Hongjiannao Lake. Since then, Zhasake River disappeared from the satellite image. In 2009, an underground reservoir was built in the upper reaches of Donghulusu River to intercept another supply runoff source for Hongjiannao Lake. After 2009, Donghulusu River gradually disappeared on satellite images. Therefore, the reduction stage can be further divided into three periods: (1) 1998-2005 (Fig.6(2)), (2) 2006-2009 (Fig. 6(3)), (3) 2010-2015 (Fig. 6(4)). In 2016, Hongjiannao Lake was promoted to a National Nature Reserve of China, the local government agreed to make an ecological water supplement for Hongjiannao Lake by Zhasake Reservoir each year (Fig. 6(5)). That was the main reason that the curve of the lake area, water level, and lake volume raised when it reached the bottom of the valley in 2015, this trend was consistent with the growth period of the lake in 2016-2019.

Fig. 6. Spatio-temporal variation of rivers change in Hongjiannao Basin

(1) 1986-1997, (2) 1998-2005, (3) 2006-2009, (4) 2010-2015, (5) 2016-2019.

3.2 Lake-groundwater exchanges

Fig. 7. Variations in lake runoff and lake area for Hongjiannao Lake from 1986 to 2019.

Table 2. Lake volume change of Hongjiannao Lake in different periods

Different stages		Lake area (km ²) (LA)	Input (km ³)			Output (km ³)	Lake volume change (km ³ /a) (Δ V)
			Precipitation (P _{Lake})	River inflow (Q _{River})	Groundwater (Q _{Groudwater})	Evaporation (E _{Lake})	
Stable	1986-1997	54.34	0.0203	0.0485	0.0098	0.0786	0.0000
	1998-2005	46.00	0.0154	0.0475	-0.0025	0.0714	-0.0109
Reduction	2006-2009	39.89	0.0143	0.0334	0.0058	0.0671	-0.0136
	2010-2015	33.41	0.0139	0.0199	0.0085	0.0480	-0.0057
Growth	2016-2019	35.18	0.0187	0.0209	0.0005	0.0373	0.0028

Figure 7 showed the annual variation trend of the lake area and the surface runoff by the river inflow. The simulations indicated that the annual average lake area and surface runoff had high consistency, which consistent with the trend of different stages change. Table 2 showed the calculated components of the water balance model for Hongjiannao Lake in three different stages. In the stable stage (1986-1997) the average lake area was 54.34 km², which kept at a high level, the water balance described as lake volume change (ΔV)=0, which means that Precipitation (P_{lake})+River inflow (Q_{River})+Groundwater ($Q_{Groundwater}$)-Evaporation (E_{lake})=0. In this stage, the precipitation accounts for 25.83 % (0.0203 km³) of the input, river inflow accounts for 61.70 % (0.0485 km³) of the input, groundwater accounts for 12.47 % (0.0098 km³) of the input. Groundwater recharge lake in the stable stage with the annual average $Q_{Groundwater}$ =0.0098 km³. In the reduction stage we based on the river inflow situation to analyze the water balance, from 1998 to 2005, the average lake area was 46.00 km², we calculated the lake volume change (ΔV)=-0.0109 km³, according to the water balance: Groundwater ($Q_{Groundwater}$)=lake volume change (ΔV) $\pm$ Evaporation (E_{lake})-Precipitation (P_{lake})-River inflow (Q_{River}), lake recharge groundwater with the annual average $Q_{Groundwater}$ =-0.0025 km³. From 2006 to 2009, the average lake area was 39.89 km², due to the block of the Zhasake River in 2006, the Q_{River} reduced from 0.0475 km³ in 1998-2005 to 0.0334 km³ in 2006-2009, groundwater recharge lake with the annual average $Q_{Groundwater}$ =0.0058 km³, from 2010 to 2015, the average lake area was 33.41 km², due to block of Donghulusu River in 2009, the Q_{River} further reduced to 0.0199 km³, the $Q_{Groundwater}$ =0.0085 km³. In the growth stage (2016-2019), the average lake area increased to 35.18 km², groundwater recharge lake with the annual average $Q_{Groundwater}$ =0.0005 km³, the precipitation accounts for 46.63 % (0.0187 km³), river inflow accounts for 52.12 % (0.0209 km³) of the input, groundwater accounts for 1.25 % (0.0005 km³) of the input. Compared with the stable stage, the groundwater supply in the growth stage reduced from 12.47 % (0.0098 km³) to only 1.25 % (0.0005 km³).

3.3 Annual lake water balance

Figure 8 showed the annually estimated lake-groundwater exchange volumes across Hongjiannao Lake from 1986 to 2019. Most of the time in this period, the lake showed obvious gaining conditions, (i.e., $Q_{Groundwater} > 0$), discharge from groundwater to the lake, with a variable exchange volume of up to 0.03364 km³ in 1993. The annual exchange volumes indicated that the Hongjiannao Lake experienced continuous losing conditions (1998-2004), (i.e., $Q_{Groundwater} < 0$), discharge from the lake to groundwater, with a variable exchange volume of up to -0.01582 km³ in 1999. Unlike the freshwater lake system, (i.e. the Poyang Lake) (Li et al. 2020), the losing condition was not much different from the gaining condition, suggesting

that the groundwater supply for the lake input is a noticeable factor in affecting the lake water balance. Hongjiannao Lake is located in the arid and semi-arid areas in the northwest of China, with scarce rainfall and huge evaporation, groundwater recharge is essential to maintain the lake area.

Fig. 8. Estimated lake-groundwater exchange volume for Hongjiannao Lake from 1987 to 2019.

3.4 Causes of changes in Hongjiannao Lake by using Geographical Detector

From Tables 3, 4, and 5, it can be seen that the single dominant factor affecting the lake area, water level, and water volume change of Hongjiannao Lake from 1988 to 1997 was AT, and q value was 0.973, 0.969, and 0.964 respectively. At this stage, the single dominant factor was temperature. There were significant differences between the temperature and other factors in the changes in the lake area, water level, and water volume change, while there were no significant differences between other factors. Therefore, the change of Hongjiannao Lake from 1988 to 1997 was mainly affected by the natural factor temperature.

Table 3. q values and influence of ecological detector on the lake area from 1988 to 1997

Lake area	NDVI	HP	SP	GVIO	AP	AT
q value	0.878	0.660	0.730	0.662	0.853	0.973
NDVI						
HP	N					
SP	N	N				
GVIO	N	N	N			
AP	N	N	N	N		
AT	Y	Y	Y	Y	Y	

Table 4. q values and influence of ecological detector on the water level from 1988 to 1997

Water level	NDVI	HP	SP	GVIO	AP	AT
q value	0.858	0.643	0.713	0.809	0.730	0.969
NDVI						
HP	N					
SP	N	N				
GVIO	N	N	N			
AP	N	N	N	N		
AT	Y	Y	Y	Y	Y	

Table 5. q values and influence of ecological detector on the lake volume change from 1988

to 1997

lake volume change	NDVI	HP	SP	GVIO	AP	AT
q value	0.859	0.638	0.706	0.814	0.731	0.964
NDVI						
HP	N					
SP	N	N				
GVIO	N	N	N			
AP	N	N	N	N		
AT	Y	Y	Y	Y	Y	

From 1998 to 2015, the single dominant factor of lake area had the strongest impact on GVIO followed by NDVI and SP, with q value of 0.985, 0.96, and 0.944 respectively (Table 6). NDVI and SP had a great influence on the area and there was no significant difference between them. Among the single dominant factors of water level, GVIO was the strongest, NDVI and SP were the seconds, q value was 0.979, 0.972, and 0.897 respectively (Table 7). There were significant differences between GVIO and HP, AP, AT, SP, but no significant differences between GVIO and NDVI. NDVI was the most influential factor among the single leading factors of lake volume change, followed by GVIO and SP, q value was 0.979, 0.97, and 0.897 respectively (Table 8). GVIO and NDVI had the greatest influence on the change of water quantity, and there was no significant difference between GVIO and NDVI, followed by SP, AT, and there was no significant difference between SP and AT. There were significant differences between

GVIO and HP, AP, AT, SP, but there were no significant differences between GVIO and NDVI. Therefore, the change of Hongjiannao Lake from 1998 to 2015 was mainly affected by human factors.

Table 6. q values and influence of ecological detector on the lake area from 1998 to 2015

Lake area	HP	AP	AT	SP	NDVI	GVIO
q value	0.706	0.661	0.732	0.944	0.960	0.985
HP						
AP	N					
AT	N	N				
SP	Y	Y	Y			
NDVI	Y	Y	Y	N		
GVIO	Y	Y	Y	Y	Y	

Table 7. q values and influence of ecological detector on the water level from 1998 to 2015

Water level	HP	AP	AT	SP	NDVI	GVIO
q value	0.502	0.634	0.832	0.897	0.972	0.979
HP						
AP	N					
AT	Y	Y				
SP	Y	Y	Y			
NDVI	Y	Y	Y	Y		
GVIO	Y	Y	Y	Y	N	

Table 8. q values and influence of ecological detector on lake volume change from 1998 to

2015						
lake volume change	HP	AP	AT	SP	NDVI	GVIO
q value	0.406	0.613	0.854	0.878	0.979	0.970
HP						
AP	N					
AT	Y	Y				
SP	Y	Y	N			
NDVI	Y	Y	Y	Y		
GVIO	Y	Y	Y	Y	N	

Notes: Sig. F test: 0.05

5. Discussion

The lake water volume change and precipitation-evaporation volume of Hongjiannao Lake were mainly balanced, and the water level change was small before 1999 (Figure 4 and 5). Since 1999, the area of lake area had shown a linearly decreasing trend, with an average shrinking rate of 1.21 km²/a. Previous studies have shown that the area of Hongjiannao Lake was stable on the whole from 1986 to 1997, with slight fluctuations around 50 km². From 1998 to 2015, the water area decreased to about 30 km² year by year, and the area of Hongjiannao

Lake increased year by year from 2015 to 2019 (Wang et al., 2018; Zhuo et al., 2018; Cheng et al., 2018; Ma et al., 2019). Liu et al. (2015) pointed out that the area of Hongjiannao Lake area fluctuated slightly from 1988 to 1999 and showed a linearly decreasing trend from 1999 to 2015. Zheng et al. (2020) pointed out that the water area of Hongjiannao Lake decreased first and then slowly increased, with the maximum area in 1986 and the minimum area in 2015, and continued to increase steadily from 2016. Yue and Liu (2019a) divided the water level of Hongjiannao Lake into five stages: a shrinking period (1986–1989), a relatively stable period with a high level (1990–1997), a continuously shrinking period (1997–2013), a relatively stable period with a low level (2013–2016), and an expansion period (2016–2018). Li (2020) divided the variation trend of water level in Hongjian into four stages, namely, decline (1986–1989), fluctuating rise (1989–1997), rapid decline (1997–2016), and rise (2016–2020). Yue and Liu (2019a) divided the water quantity change of Hongjiannao Lake into four stages: a shrinking period (1986–1990), a relatively stable period with a high level (1991–1997), a continuous shrinking period (1997–2010), and a slight expansion period (2011–2018). Li (2020) divided the change of water quantity into four stages: decline (1986–1991) - fluctuating rise (1991–1997) - rapid decline (1997–2016) - rising (2016–2020). The above studies are consistent with the variation trend and numerical variation of this study, which indirectly verifies the accuracy of this study.

Previous studies on the causes of the shrinkage of Hongjiannao Lake can be classified into two categories: (1) climate drought (Tang et al., 2003; Liu et al., 2009); (2) irrigation water consumption and upstream closure (Yin et al., 2008; Li et al., 2009). Zheng(2020) believed that the change of water area in Hongjiannao Lake was related to precipitation, air temperature, and other meteorological factors to a certain extent, but it was mainly affected by human disturbance. Liu (2019a) and Li (2020) pointed out that during 1986–1997, the temperature change was the dominant factor underlying the slight decline of the lake area. Liang et al. (2017), Li (2020), and Wang(2018b) found that severe human activity, as well as climate warming, lead to a fast decrease in the area of Hongjiannao Lake in 1999–2015. When considering time lag, the correlation coefficient between climatic factors and human activities significantly increased (Liang and Li, 2019). Yue and Liu (2019a) used a ridge regression method to establish a regression model between lake area, water level, lake volume variations, and influencing factors. The results showed that gradually intensifying human activities were the leading factor during 1998–2015. In this study, we used the factor detector and the ecological detector to access the influencing factors on lake area, water level, lake volume changes, it was novel in

that it exacted the interrelationships between geographic information of Hongjiannao Lake and influencing factors.

An understanding of the magnitude of the dynamics of Hongjiannao Lake's water balance is important for sustainable development not only in the local government management but in the energy policy implementation. Hongjiannao Lake is a typical lake as it is located in arid and semi-arid areas, and the lake-groundwater exchanges cannot observe directly. The volume of river inflow and as well as the volume of runoff change depends on the watershed system of the Hongjiannao Basin. Thus, the uncertainties associated with estimating river inflow and runoff change could contribute to the overestimation or underestimation of these components in water balance.

The results also showed that the calculation of water balance components can be used to better understand the situation of lake-groundwater exchange volumes. Catchment upstream of Zhasake Reservoir in 2006, the hydrological balance varied substantially before 2006 and after 2006, discharged from the lake to groundwater (1998-2005), discharged from groundwater to the lake (2006-2009). In terms of inter-annual hydrological variability, there was a decrease of evaporation by 22.29 % and a decrease of groundwater by 41.18 % in 2016-2019 as compared to 2010-2015 and a 34.53 % increase in precipitation and 5.02 % increase in river inflow.

Besides, the industrial output value (GVIO) was considered to be the dominant factor of water level and water quantity change during 1998-2015. Liang (2017) pointed out that the total industrial output value (GIOV) of Hongjiannao Lake showed an upward trend from 1988 to 2015, and increased rapidly from 1999 to 2015. Hongjiannao is located in an area rich in coal resources and a key development zone, and coal mining is an important factor affecting its ecological environment. The coal chemical industry destroys groundwater resources, leading to a threat to groundwater recharge in Hongjiannao Lake (Liu et al., 2019).

6. Conclusion

Based on an analysis of the Landsat images, ASTER GDEM V2 data, and meteorology and statistics data, we calculated the components of the water balance of Hongjiannao Lake, and estimated annually lake-groundwater exchanges during 1986-2019, and analyzed the potential influencing factors by using the geographical detector.

The results showed that the average annual precipitation was $0.01709 \text{ km}^3/\text{year}$, the average annual evaporation was $0.06528 \text{ km}^3/\text{year}$, evaporation was 3.8 times of precipitation. In the stable stage (1986-1997), the average rate of the lake area, water level, and lake volume change is $-0.26 \text{ km}^2/\text{a}$, -0.0483 m/a , and $-0.0009 \text{ km}^3/\text{a}$, respectively. In the reduction stage (1998-2015),

the average rate of the lake area, water level, and lake volume change is $-1.21 \text{ km}^2/\text{a}$, -0.2422 m/a , and $-0.0101 \text{ km}^3/\text{a}$, respectively. In the growth stage (2016-2019), the average rate of the lake area, water level, and lake volume change are $1.38 \text{ km}^2/\text{a}$, 0.27 m/a , and $0.0088 \text{ km}^3/\text{a}$, respectively.

In the stable stage (1986-1997), precipitation, river inflow, and groundwater were 0.0203 km^3 , 0.0485 km^3 , and 0.0098 km^3 , respectively, which accounts for the whole input were 25.83%, 61.70%, and 12.47%, respectively, evaporation was 0.0786 km^3 . In the reduction stage (1998-2015), before 2006, precipitation, river inflow, and groundwater were 0.0154 km^3 , 0.0475 km^3 , and -0.0025 km^3 , respectively; from 2006 to 2009, precipitation, river inflow, and groundwater were 0.0143 km^3 , 0.0334 km^3 , and 0.0058 km^3 , respectively; after 2009, precipitation, river inflow, and groundwater were 0.0139 km^3 , 0.0199 km^3 , and 0.0085 km^3 , respectively. Evaporation decreased from 0.0714 km^3 to 0.0480 km^3 during 1998-2015. In the growth stage (2016-2019), precipitation, river inflow, and groundwater were 0.0187 km^3 , 0.0209 km^3 , and 0.0005 km^3 , respectively, evaporation was 0.0373 km^3 .

Most of the time in 1986-2019, the lake showed obvious gaining conditions (discharge from groundwater to the lake), with a variable exchange volume of up to 0.03364 km^3 in 1993. From 1998 to 2004, Hongjiannao Lake exhibited continuous losing conditions (discharge from the lake to groundwater), with a variable exchange volume of up to -0.01582 km^3 in 1999.

The geographical detector showed that Hongjiannao Lake was affected by the natural factor temperature from 1988 to 1997, while it was affected by human factors from 1998 to 2015.

Declaration of Competing Interest

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

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Figures

Figure 1

The spatial schematic diagram for Hongjiannao Lake and Hongjiannao Basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Water-level derivation (a) Different periods of shoreline superimposed on DEM; (b) DEM extraction by lake boundary on August 2nd, 1986. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

The schematic diagram for the hydrogeological model of Hongjiannao Lake

Figure 4

Precipitation and evaporation for Hongjiannao Lake from 1986 to 2019.

Figure 5

Variations in the lake area, water level, and lake volume change of Hongjiannao Lake from 1986 to 2019.

Figure 6

Spatio-temporal variation of rivers change in Hongjiannao Basin (1) 1986-1997, (2) 1998-2005, (3) 2006-2009, (4) 2010-2015, (5) 2016-2019.

Figure 7

Variations in lake runoff and lake area for Hongjiannao Lake from 1986 to 2019.

Figure 8

Estimated lake-groundwater exchange volume for Hongjiannao Lake from 1987 to 2019.