Relationship between Water Surface Area of Qingtu Lake and Ecological Water Delivery: A Case Study in Northwest China

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Abstract: Qingtu Lake is located between Tengger Desert and Badain Jilin Desert, Gansu Province, Northwest China. It is the terminal lake of Shiyang River. In recent years, Qingtu lake has maintained a certain area of water surface and vegetation by artificial water conveyance. It is of great significance in preventing the convergence of the two deserts and restraining the trend of ecological deterioration of Shiyang River Basin. The relationship between the water surface area and the ecological water conveyance have not been thoroughly investigated. This study analyzed the spatial and temporal distribution of water surface area of Qingtu Lake and surrounding reeds by interpreting remote sensing data; the change of water surface area under the influence of meteorological factors and water conveyance by linear regression; the water conveyance to maintain current water surface area by water balance method, as well as the reasonable ecological water delivery in high flow year, normal flow year and low flow year by the means of analyzing the upstream inflow and water consumption in Minqin Basin. The results showed that there is a significant correlation between the water surface area of Qingtu Lake, evaporation and ecological water conveyance, and the minimum and maximum water surface areas generally appear before and after water delivery, indicating that the ecological water delivery and evaporation are the two main factors affecting the water surface area change of Qingtu Lake. The result calculated by linear regression indicated that the ecological water delivery volume to maintain current water surface area of Qingtu Lake is \(3.146 \times 10^7\) m\(^3\)/yr, while the value was \(3.136 \times 10^7\) m\(^3\)/yr calculated by water balance method. These two results are similar and can be verified with each other. Reasonable ecological water conveyance of Qingtu Lake in high flow year, normal flow year and low flow years were \(4 \times 10^7\) m\(^3\)/yr, \(3.2 \times 10^7\) m\(^3\)/yr and \(2.3 \times 10^7\) m\(^3\)/yr, respectively.

Keywords: surface area of Qingtu lake; evaporation; water balance; reasonable ecological water conveyance

1. Introduction

Qingtu lake, located between Tengger Desert and Badain Jilin Desert, is the terminal lake of Shiyang River in Gansu Province, China. As an ecological barrier between the two deserts, Qingtu Lake is of great significance in preventing the convergence of deserts and restraining the trend of ecological deterioration in the basin. According to the historical records, the water area of Qingtu Lake during the Western Han Dynasty was 4000 km\(^2\). Due to climate change, it was 400 km\(^2\) during the Ming Dynasty and the Qing Dynasty [1]. At the beginning of liberation, the water surface area of Qingtu Lake was 70 km\(^2\) [2]. In modern times, due to the influence of human activities, such as increase of upstream water consumption and establishment of Hongyashan Reservoir, the amount of water entering the lake was greatly reduced and the area of water surface sharply shrunk. By 1959, Qingtu Lake was completely dried up, which led to the convergence of Badain Jilin Desert and Tengger Desert, and the rapid deterioration of the ecosystem [3]. Since 2010, the local government has carried out targeted treatment on the above problems by...
means of artificial ecological water conveyance. Qingtu Lake has formed seasonal water surface and the surrounding ecological environment has improved obviously [4].

Ecological water conveyance is a unique way of ecological restoration under manual intervention, which was only successfully implemented in Tarim River Basin in China [5]. At present, relevant studies mainly focus on the change of groundwater level [6–9], vegetation types [5], plant physiological mechanism and the change of regional ecosystem [10,11]. For example, Wang, Y.J. and Guo, Y.H. used remote sensing interpretation and transfer matrix of land use to analyze the characteristics of the oasis of Lower Tarim River before and after the ecological water conveyance [12]. Deng, M.J. et al. systematically analyzed and evaluated the change of ecological environment of the Lower Tarim River after ecological water conveyance through continuous dynamic monitoring and sample survey [13]. In a word, the purpose of the ecological water conveyance of Tarim River is to restore the ecosystem along the river, and the way is to transport water along the natural river.

Different from Tarim River, the purpose of ecological water conveyance of Qingtu Lake is to restore the water surface of the lake and the surrounding ecology, and the way is to transport water through the artificial channel. Current research on Qingtu Lake mainly includes the impact of ecological water conveyance on ecological environment, the effect of water surface formation on the distribution of regional typical vegetation, the change of groundwater level and paleoclimate [1,14,15]. Zhao, J. et al. inverted vegetation coverage using multi-stage Landsat images of Qingtu Lake and analyzed the relationship between vegetation coverage and ecological water conveyance and climatic factors [3]. Liu, S.J. et al. analyzed the diversity of plant species along the shore of Qingtu Lake and the time-space changes of plant species as well as their relationship with groundwater level through four years of positioning observation [4]. Chen, Z.R. et al. carried out statistical analysis on water surface and vegetation type by object-oriented classification remote sensing method [2].

Nevertheless, the existing studies mainly focus on the vegetation change in Qingtu Lake area, but few on water surface, which is an important factor to prevent deserts convergence. Meanwhile, the time series of many studies were often discontinuous, which can not reveal the changing trend of lake surface with high temporal resolution. In addition, most of the correlations were based on statistical analysis, and there was a lack of research on further validation. In this study, we analyzed the influencing factors of water surface area and determined the reasonable ecological water conveyance.

2. Study Area

Minqin Basin is located in the downstream of Shiyang River Watershed of Gansu Province (see Figure 1), covering a total area of about 4800 km². It is one of the typical desert oases in China. The annual precipitation is approximately 110 mm and annual evaporation is more than 2600 mm [16]. The surface water resources of Minqin Basin mainly depends on the discharge of Hongyashan Reservoir in the upstream. The water supply to the reservoir mainly includes natural water from Shiyang River, water diversion from Jingdian Phase II Minqin Water Diversion Project and water diversion from Liangzhou District. Jingdian Phase II Minqin Water Diversion Project, which has been put into service since 2001, conducts water of the Yellow River to Minqin County through water conveyance canal. The total length of the canal is about 260 km. The water passes through Jingtai County and Gulang County of Gansu Province, crosses the Tengger Desert, discharges into Shiyang River from the outlet of Minqin Water Diversion Project (shown in Figure 1), and then flows into Hongyashan Reservoir via natural river. Water Diversion Project from Liangzhou District has transferred water from Xiying River Reservoir in Liangzhou District to Minqin since 2006. The reservoir water is transported through water conveyance channel of Xiying River and flows into Shiyang River from the project water outlet (shown in Figure 1), then flows through Caiqi Section and enters Hongyanshan Reservoir. All three parts flow into Hongyashan Reservoir and is supplied to Minqin Basin under artificial control.
River from the project water outlet (shown in Figure 1), then flows through Caiqi Section and enters Hongyanshan Reservoir. All three parts flow into Hongyashan Reservoir and is supplied to Minqin Basin under artificial control.

Figure 1. Canal distribution of the Minqin County.

Shiyang River in the basin, the only surface water which entered the study area, has been transformed into the main artificial irrigation channel for Oasis Irrigation. Thus, there is no natural surface runoff in Minqin basin. The surface water is supplied to all parts of the basin through a dense network of diversion canals. The distribution of diversion canals is shown in Figure 1. Yuejin Canal is the first main channel, running through the whole study area from southwest to northeast. The secondary main channels which branched out from Yuejin Canal connect different zones of the study area. Additionally, many branch irrigation ditches further dense the canal network. All the canals are seepage prevented, so the leakage can be neglected. Basically, the utilization rate of water resource of each main canal is more than 70% (data obtained from Minqin Water Authority).

In addition to the canal diversion, there was also a large amount of groundwater exploitation in Minqin Basin in the past, which led to a series of eco-environmental problems, such as vegetation degradation and land desertification. In recent years, a strict management of water resource has been implemented by the local government and the amount of groundwater exploitation decreased to about $8.5 \times 10^7$ m$^3$/yr [17]. Since 2010, the downward trend of groundwater level in Minqin Basin has been slowed down.

Qingtu Lake, the terminal lake of Shiyang River Basin, is located in northeast of Mingqin Basin, at the junction of Tengger Desert and Badain Jilin Desert (see Figure 1). Its unique geographical location makes it to be an ecological sensitive area. Its climate is typical temperate continental arid desert climate. The soil type is dominated by Sand and loam sand [18] and the vegetation type is typical desert vegetation, mainly Nitraria sibirica, while reed is dominant around the lake [19].

3. Materials and Methods

3.1. Analytical Methods

The water resources supply-demand system of Minqin Basin is shown in Figure 2, all surface water resources (natural water from Shiyang River, water diversion from Jing-dian Phase II Minqin Water Diversion Project and water diversion from Liangzhou District.)
are supplied to Minqin Basin through Hongyashan reservoir. Groundwater in the basin is also one of the water supply sources. Part of water resources can meet the water demand in the basin, and the other part can be used as ecological water to restore the ecology of Qingtu lake. The ecological water conveyance is mainly conducted through agricultural irrigation canal in Minqin Basin during non-agricultural irrigation period. Additionally, it is forbidden to exploit groundwater in the area of Qingtu Lake.

Figure 2. Water supply flow chart of Minqin Basin.

In this study, we interpreted the multi-period continuous data of the surface area of Qingtu Lake using remote sensing images from 2010 to 2019. Based on the analysis of the images, the relationship between the surface area of Qingtu lake, meteorological factors and water conveyance was revealed by means of statistical analysis. Meanwhile, the mechanism of the change of the surface area of Qingtu Lake was further discussed and the ecological water conveyance was determined by the method of water balance analysis. The methods are as follows:

(1) Identification of Vegetation and Water Surface Area

The identification of vegetation and water surface area was based on multi-spectral Lansat remote sensing images from 2010 to 2019. In remote sensing identification, water can be characterized by penetration of visible light and strong absorption of infrared and vegetation can be characterized by strong absorption of the light of wavelength near 700 nm and strong reflection the light of wavelength of over 700 nm. Therefore, samples were selected by NDVI (normalized difference vegetation index) and MNDWI (modified normalized difference water index), which are defined as [20,21]:

\[
\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + \rho_{\text{Red}}}
\]

\[
\text{MNDWI} = \frac{\rho_{\text{Green}} - \rho_{\text{MIR}}}{\rho_{\text{Green}} + \rho_{\text{MIR}}}
\]

where \(\rho_{\text{Green}}\) and \(\rho_{\text{Red}}\) are the green band and the red band in the remote sensing image, separately; \(\rho_{\text{MIR}}\) and \(\rho_{\text{NIR}}\) represent the mid-infrared and the near-infrared bands [22]. On this basis, the area of water surface and reed of Qingtu Lake were identified.

(2) Correlation and Multiple Regression Analysis

The coefficient of correlation between the change of Qingtu-lake surface area and possible factors (meteorological factors and artificial water conveyance) were calculated by correlation analysis. After determining the main influencing factors of the change of lake surface area, the empirical formula between the change of water surface and influencing factors was obtained by multi-linear regression analysis.
(3) Water Balance Analysis

Based on water balance, the reasonable ecological water conveyance (meeting the ecological demands of Qingtu Lake while not occupying water use of upstream area) for maintaining the water surface area of Qingtu Lake was determined. For Qingtu Lake, the recharge includes artificial water conveyance and precipitation, the discharge includes evaporation and infiltration to groundwater. The annual water budget can be expressed as:

\[ \Delta Q_L = Q_C + Q_P - \Delta Q_{L-G} - Q_E \]  

(2)

In Formula (2), \( \Delta Q_L \) is the change of lake surface area; \( Q_C \) is the volume of ecological water conveyance into Qingtu Lake; \( Q_P \) is the volume of precipitation; \( \Delta Q_{L-G} \) is the exchange volume between water of the lake and groundwater during the water balance period, which can be obtained by calculating the variation of groundwater reservoir; \( Q_E \) is the volume of evapotranspiration, including evaporation for free water surface and transpiration for area covered by reeds. The units of the above items are \( 10^4 \text{ m}^3/\text{yr} \).

Evapotranspiration includes vegetation transpiration and water surface evaporation, which can be calculated by the following formula:

\[ Q_E = S_w \cdot E \cdot \alpha + S_v \cdot \gamma \]  

(3)

In Formula (3), \( S_w \) is the area of water surface, \( \text{m}^2 \); \( E \) is the evaporation data measured by small evaporators (evaporating dish with 20 cm diameter), \( \text{m} \); \( \alpha \) is the ratio of evaporation value of large water surface to small evaporator, which is 0.6 [23]; \( S_v \) is the area of reed, \( \text{m}^2 \); \( \gamma \) is the water consumption of reed, \( \text{m} \). The reeds grow well in the study area, and \( \gamma \) could be calculated by 60% of the potential evaporation [24]. The growth season of reeds in arid regions of Northwest China is from May to October [25] and the other months were treated as no evapotranspiration. The treatment methods for the area of water surface and reed are as follows: according to the linear variation, the result of remote sensing interpretation was calculated to the daily area.

Precipitation and groundwater variations are calculated as follows:

\[ Q_P = P \cdot S_w \]  

(4)

\[ \Delta Q_{L-G} = \Delta h \cdot \mu \cdot S \]  

(5)

In Formulas (4) and (5), \( P \) is the precipitation data, \( \text{m} \); \( \Delta h \) is the variation of groundwater level, which can be obtained from the observation wells of Qingtu Lake. \( \mu \) is specific yield, and its empirical value is 0.10 as the sedimentary type of the lake region is mainly lacustrine sediment of arid area and the lithology is dominated by silt and sandy clay [26].

3.2. Data Sources

3.2.1. Meteorological Data

Meteorological data were collected from the daily climatic data set of China Ground International Exchange Station on China Meteorological Data Network (http://data.cma.cn/ accessed on 19 January 2021), in which evaporation is counted by small-scale (20 cm diameter) and E-601 evaporator. The data used in this study were mainly evaporation and data of Minqin Station from 2010 to 2019. However, there are only evaporation data measured by small evaporators in the freezing period from January to April and from October to December, and only evaporation data measured by E-601 evaporator from May to September. The two evaporation data can not be combined for statistical analysis due to the difference between the two evaporation instruments. Therefore, the two evaporation data were converted into the same sequence for subsequent research. Xie, W.Y. et al. found that it is more reasonable to convert E-601 evaporation into small evaporator evaporation in Minqin area for research [27], and the conversion coefficient of each month is shown in Table 1. The converted meteorological data are shown in Table 2.
Table 1. Evaporation coefficient converted from E-601 to small evaporator.

| Time       | May | June | July | August | September |
|------------|-----|------|------|--------|-----------|
| Conversion coefficients | 0.540 | 0.562 | 0.590 | 0.593 | 0.601 |

Table 2. Situation of ecological water conveyance of Hongyashan Reservoir and evaporation of Minqin Station from 2010 to 2019.

| Water Conveyance Year | Water Discharge from Hongyashan Reservoir (Q, 10^4 m^3) | Water Inflow to the Lake (Qt, 10^4 m^3) | Qt/Q | Evaporation (mm) | Period of Water Conveyance |
|-----------------------|----------------------------------------------------------|----------------------------------------|------|-----------------|---------------------------|
| 2010                  | 1290                                                     | 909.98                                 | 71%  | -               | 9.1–10.20                 |
| 2011                  | 2160                                                     | 1282.18                                | 59%  | -               | 9.2–10.24                 |
| 2012                  | 3000                                                     | 2100.33                                | 70%  | 2528.96         | 7.31–11.25               |
| 2013                  | 2000                                                     | 1399.69                                | 70%  | 2624.72         | 8.2–11.5                 |
| 2014                  | 3300                                                     | 2324.97                                | 70%  | 2583.27         | 6.9–11.4                 |
| 2015                  | 2833                                                     | 1983.00                                | 70%  | 2775.71         | 8.17–11.5               |
| 2016                  | 3358                                                     | 2335.00                                | 70%  | 2586.10         | 7.30–11.3               |
| 2017                  | 3830                                                     | 2400.00                                | 63%  | 2576.10         | 8.1–11.21               |
| 2018                  | 3180                                                     | 2207.52                                | 69%  | 2543.00         | 8.6–11.6                |
| 2019                  | 3100                                                     | 2154.88                                | 70%  | 2689.74         | 8.1–10.30               |

3.2.2. Remote Sensing Data

The remote sensing data used in the study were Landsat-5, Landsat-8 satellite and Gaofen-2(GF-2) satellite remote sensing data for multiple periods from 2010 to 2019, downloaded from the data sharing system (http://ids.ceode.ac.cn/ accessed on 20 March 2019), and have been geometrically and atmospherically corrected [28].

3.2.3. Water Conveyance and Water Consumption Data

The data of ecological water conveyance, reservoir discharge and water consumption of Minqin Basin from 2010 to 2019 were provided by Minqin Water Authority (shown in Table 2). Water demand in Minqin Basin includes agricultural irrigation, industrial requirement, domestic consumption and ecological demand.

Agricultural irrigation is the main water requirement in Minqin Basin. The water allocation for agricultural irrigation accounts for around 61–63% of the total water allocation after 2014 [29]. Table 3 shows water demand for agricultural irrigation in Minqin Basin in 2019 is 2.34 × 10^9 m^3/yr. With the closure of agricultural machinery wells, the cultivated land in Minqin Basin has been unchanged since 2014. Thus, this amount of water demand can be used as a stable agricultural water demand in a certain period.

Table 3. Water Requirement for agricultural irrigation in Minqin Basin.

| Irrigation Area | Area of Water Distribution [30] | Irrigation Quota (m^3/mu) [31] | Agricultural Water Consumption (10^4 m^3/yr) |
|-----------------|---------------------------------|---------------------------------|---------------------------------------------|
| Dam area        | 257,777                         | 400                            | 10,300                                      |
| Quanshan area   | 111,325                         | 415                            | 4600                                        |
| Lake area       | 186,269                         | 453                            | 8500                                        |
| Total           | 555,371                         | -                              | 23,400                                      |

Note: mu = 666.67m^2.
Domestic water consumption is closely related to population and urbanization rate. As can be seen from Table 4, it is estimated that the total domestic water consumption in Minqin Basin is around $1.036 \times 10^7$ m$^3$/yr.

Table 4. Domestic water demand in Minqin Basin.

| Items                      | Population (10$^4$ P) [30] | Quota (L/P•d) [32] | Water Consumption (10$^4$ m$^3$/yr) |
|----------------------------|----------------------------|--------------------|-----------------------------------|
| Rural water supply         | 15.6                       | 40                 | 227.76                            |
| Urban water supply         | 5.59                       | 75                 | 153.03                            |
| Urban public               | -                          | -                  | 200.00                            |
| Poultry and livestock      | -                          | -                  | 606.00                            |
| Total                      | 21.19                      | -                  | 1186.79                           |

Note: P = people.

The actual industrial water consumption in the basin is about $4.29 \times 10^6$ m$^3$/yr [33], while the industrial water allocation in Minqin County is $4.525 \times 10^7$ m$^3$/yr. Based on the guarantee of industrial water consumption and the actual development of regional industry, the excess industrial water distribution can be optimized and allocated among various industries in the region [30]. Therefore, the water demand for industrial planning of Minqin County in 2020 is $2.218 \times 10^7$ m$^3$/yr [29].

The total ecological water demand in Minqin Basin is around $5.523 \times 10^7$ m$^3$/yr [30].

In summary, the total water demand in the basin is $3.23 \times 10^8$ m$^3$/yr (Table 5).

Table 5. Basic water requirements of Minqin Basin (Unit: 10$^4$ m$^3$/yr).

| Category       | Agriculture | Industry | Domestic | Ecology | Total   |
|----------------|-------------|----------|----------|---------|---------|
| Water demand   | 23,369      | 2218     | 1187     | 5523    | 32,297  |

3.2.4. Groundwater Depth Data

The data of groundwater depth were recorded from observation wells located in Qingtu Lake (shown in Figure 1). The data are shown in Table 6.

Table 6. Groundwater depth of Qingtu Lake.

| Year | Groundwater Depth (m) |
|------|------------------------|
| 2012 | 3.60                   |
| 2013 | 3.48                   |
| 2014 | 3.32                   |
| 2015 | 3.20                   |
| 2016 | 3.14                   |
| 2017 | 2.99                   |
| 2018 | 2.94                   |
| 2019 | 2.92                   |

3.3. Principles of Determining Ecological Water Demand

Since Qingtu Lake is the terminal lake of Shiyang River, the following principles should be followed when determining the reasonable ecological water conveyance:

1. In order to guarantee the ecological environment of Qingtu Lake and meet the water demand of social and economic development of Minqin Basin, the water inflow from the upper Shiyang River and the water consumption of Minqin Basin should be taken into account.

2. The amount of groundwater can be adjusted manually in high and low flow years. Therefore, reasonable ecological water conveyance should be discussed on the basis
of multi-year dynamic water balance in Minqin Basin. The amount of groundwater exploitation can be appropriately reduced in high flow year due to abundant water resources, while the amount of groundwater exploitation can be properly increased in low flow year to meet the water demand in the basin and the ecological water transport demand of Qingtu Lake.

3. The average annual groundwater exploitation should be controlled at the specified exploitation and the multi-year average ecological water conveyance should be not less than the water volume required to maintain a certain area of water surface.

4. Results and Discussion

4.1. Composition and Change of Ecological Water Conveyance

The situation of inflow of Minqin Basin is shown in Figure 3, the designed volume of water diversion of Jingdian Phase II of Minqin Water Diversion Project is $6.1 \times 10^7$ m$^3$/yr. With the construction of water conservancy facilities and the improvement of water supply capacity, the water supply shows a steady increase trend. Its volume was basically maintained at $8.3 \times 10^7$ m$^3$/yr after 2011. Since 2006, the water delivery volume from Liangzhou District has been generally stable at $1.34 \times 10^8$ m$^3$/yr. In the 1960s, the water inflow of Shiyang River was abundant, up to $6 \times 10^8$ m$^3$/yr. However, the water inflow of Shiyang River decreased year by year with the aggravation of human activities, such as population growth, cultivated land expansion and agricultural development. In 2004, the river and Hongyashan Reservoir dried up. Since the beginning of comprehensive management of Shiyang River, the inflow of the river has gradually increased, reaching $3.85 \times 10^7$ m$^3$/yr in 2018.

![Figure 3. Situation of inflow and inter-annual variation in Minqin Basin from 1956–2019 (data provided by Minqin County Water Bureau).](image_url)

The plan of ecological water conveyance from Hongya Reservoir to Qingtu Lake has been implemented since 2010. As shown in Table 2, the amount of ecological water conveyance shows an increasing trend in general. After 2014, the amount of ecological water conveyance was basically above $3 \times 10^7$ m$^3$/yr. The actual amount of water entering Qingtu Lake is around 70% of the ecological water out of the reservoir. There are three irrigation periods in Minqin: spring irrigation (from March to April), summer irrigation (from June to July) and autumn-winter irrigation (from October to November). In order to avoid the peak period of summer irrigation, the ecological water conveyance to Qingtu Lake is generally carried out from August to October.
4.2. Variation of Area of Qingtu Lake Water Surface and Reed

The water surface and reed area of Qingtu lake were interpreted by multi period remote sensing data from 2011 to 2019. Part of interpretation results are shown in Figure 4, which are the annual maximum areas; the seasonal water surface of Qingtu Lake was completely dry in 1959, has appeared since the beginning of ecological water conveyance in 2010; the water surface area continued to expand from 2011 to 2018. The water surface area in 2011 was 5.18 km$^2$, reached 13.43 km$^2$ in 2018, which is 2.6 times larger than the value in 2011. The area of reed also increased year by year, showing regular changes: first, it distributed in a small area along the water conveyance channel to the lake, then distributed in succession along the channel and around the water, and finally developed to the northwest of the water surface. We should note that the expansion of reed is not limited to the above areas. In the eastern part far from the water surface, the reed also developed in pieces gradually.

![Figure 4. Area changes of water surface and reed in the same period from 2011 to 2018.](image)

A variation curve of interpreted water surface areas is shown in Figure 5. Considering the relative completed data of 2013–2018, the period of increasing trend of water surface coincided with the period of water conveyance: the water surface area increases with the progress of water conveyance and decreases as soon as the water conveyance is finished. Therefore, the water surface area at the end of water conveyance is defined as the maximum water surface area ($S_{max}$) of the year. $S_{max}$ interpreted by remote sensing are shown in Table 7.
4.3. Change of Water Surface Area under the Influence of Multiple Factors

The period from the beginning of ecological water conveyance under the last year to the beginning of ecological water conveyance under current year is defined as a water conveyance year. In order to study the synergistic effects of artificial water conveyance and meteorological factors on the change of surface area, the statistics of evaporation, precipitation, water conveyance and the corresponding lake surface area variation under different water conveyance year are shown in Tables 2 and 7. It can be seen from Table 2 that the actual water inflow into the lake is around 70% of the ecological water conveyance.

Linear regression method was used to analyze the correlation between the change of water surface area and evaporation as well as water conveyance. The relationship was obtained as Formula (6), its R^2 reached 0.94.

\[
S_{\text{max}}^i = 0.704S_{\text{max}}^{i-1} + 0.210Q_i - 0.425E_i + 1058.32 \quad (6)
\]

In Formula (6), \(Q_i\) is the volume of water inflow to the lake in the \(i\) water conveyance year, \(10^{4}\) m\(^3\). \(E_i\) is the evaporation in the \(i\) water conveyance year, mm; \(S_{\text{max}}^i\) and \(S_{\text{max}}^{i-1}\) are the maximum surface area in the \(i\) water conveyance year and the \((i - 1)\) water conveyance year, \(10^{4}\) m\(^2\).

According to the evapotranspiration data from 1960 to 2018, the average annual evapotranspiration in the study area is 2643 mm. Taking this value into Formula (6), the result showed that the water surface area could be maintained at 13.43 km\(^2\) (the maximum water surface area in 2018) when the water inflow to the lake is about \(2.202 \times 10^7\) m\(^3\)/yr. Formula (6) is a linear fitting formula based on existing data. Considering the topographic factors, the influence of evaporation will increase with the expansion of water surface and wetland area, and Formula (6) will no longer be applicable. Therefore, extrapolation is only carried out within a certain range of water surface area. Figure 6 shows the extrapolation results, indicating the water inflow into the lake required to keep the water surface area of 14 km\(^2\) is \(2.284 \times 10^7\) m\(^3\)/yr, to maintain the water surface area of 15 km\(^2\) and 16 km\(^2\) are \(2.424 \times 10^7\) m\(^3\)/yr and \(2.565 \times 10^7\) m\(^3\)/yr; within a certain range, the additional water inflow to the lake required for enlarging the water surface area of 1 km\(^2\) is \(4.503 \times 10^6\) m\(^3\)/yr.

Table 7. Maximum area of water surface of Qintu Lake from 2010 to 2018.

| Water Conveyance Year | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|-----------------------|------|------|------|------|------|------|------|------|------|
| \(S_{\text{max}} (10^6\ m^2)\) | 3    | 5.18 | 6.87 | 7.7  | 10.95| 10.23| 10.86| 13.3 | 13.43|
4.4. Basic Ecological Water Conveyance Based on Water Balance

The water surface area of Qingtu Lake is constantly changing. It is not enough to analyze the change of lake surface mathematically only by using the evaporation data. To verify the result of regression analysis and further understand the mechanism of change of the water surface area of Qingtu Lake, we employed the water balance method to reveal the change of lake surface area.

Taking the water conveyance year as an equilibrium period, the equilibrium and variation of water surface area of each year is shown in Table 8. Table 8 shows that except for 2015, the regional water balance is positive equilibrium during 2010 to 2018. Correspondingly, the area change values are positive except 2015. It also can be seen in Table 8 that all equilibrium items and lake surface area from 2017 to 2018 are relatively stable. Therefore, according to the balanced situation, the equilibrium state ($\Delta Q_L = 0$) could be basically reached and the current lake area around 13.43 km$^2$ could be basically maintained when the ecological water inflow into the lake is not less than $2.195 \times 10^7$ m$^3$/yr. The results of water balance analysis ($2.195 \times 10^7$ m$^3$/yr) and regression analysis ($2.202 \times 10^7$ m$^3$/yr) are close enough to verify each other.

![Figure 6.](image-url)

**Figure 6.** Ecological water conveyance corresponding to different water surface area. Note: point on the dotted line represents the actual surface area and water inflow into the lake (can be found in Table 2). Point on the solid line represents the speculated surface area and water inflow into the lake. Dotted line is not monotonically increasing because the points on the dotted line represent the actual volume of water conveyed and the maximum water surface area reached. The maximum water surface area can be achieved is not only related to water conveyance, but also affected by evaporation. However, in the solid-line section, the evaporation used in the calculation is average values of multiple years, ignoring the influence of evaporation variation.

### Table 8. Water balance and surface area of Qingtu Lake in a water conveyance year.

| Water Conveyance Year | Q_{FW} (10^4 m^3/yr) | Q_{EV} (10^4 m^3/yr) | Q_{P} (10^4 m^3/yr) | $\Delta Q_{L-G}$ (10^4 m^3/yr) | Q_{C} (10^4 m^3/yr) | $\Delta Q$ (10^4 m^3/yr) | $S_{max}$ (10^6 m^2) | $\Delta S$ (10^6 m^2) |
|-----------------------|----------------------|----------------------|---------------------|-------------------------------|-------------------|---------------------|---------------------|---------------------|
| 2010                  | —                    | —                    | —                   | —                             | —                 | 909.98              | —                   | —                   |
| 2011                  | 53.74                | 169.06               | 4.38                | 36.00                         | 1282.18           | 1027.76             | 5.18                | 5.18                |
| 2012                  | 203.42               | 416.40               | 24.00               | 2100.33                       | 1027.76           | 1468.82             | 6.87                | 1.69                |
| 2013                  | 545.05               | 663.16               | 24.00               | 1399.69                       | 190.40            | 190.40              | 7.70                | 0.83                |
| 2014                  | 841.65               | 790.58               | 24.00               | 2324.97                       | 2335.00           | 2335.00             | 10.95               | 3.25                |
| 2015                  | 849.96               | 1230.15              | 24.00               | 2010.33                       | 1180.58           | 1180.58             | 10.23               | 0.72                |
| 2016                  | 801.62               | 1116.87              | 24.00               | 2335.00                       | 2335.00           | 2335.00             | 10.86               | 0.63                |
| 2017                  | 932.09               | 1233.34              | 4.00                | 2649.00                       | 2649.00           | 2649.00             | 13.30               | 2.44                |
| 2018                  | 1036.09              | 1180.58              | 4.00                | 2207.00                       | 2207.00           | 2207.00             | 13.43               | 0.13                |

Note: $Q_{SW}$ is water surface evaporation; $Q_{EV}$ is vegetation transpiration; $Q_{P}$ is precipitation; $\Delta Q_{L-G}$ is the exchange volume between lake water and groundwater; $Q_{C}$ is water inflow to the lake; $\Delta Q$ is equilibrium difference; $S_{max}$ is the maximum water surface area of the lake in a water conveyance year; $\Delta S$ is the variation of water surface area; “-” means no data.
4.5. Analysis of Reasonable Ecological Water Conveyance

4.5.1. Analysis of Surface Water Supply and Groundwater Exploitation

Surface water supply in Minqin Basin is provided by natural water from Shiyang River, water diversion from Jingdian Project and water diversion from Liangzhou District. Table 4 shows the inflow prediction of Minqin Basin. Referring to the multi-year changes of natural water from Shiyang River after 2000, we chose the water inflow at 75%, 50% and 25% of coming frequency as the incoming water in high, normal and low flow year, respectively. Water diversion of Jingdian Project and water diversion from Liangzhou District took their average water volume in recent years. The predicted runoff of Caiqi Section is obtained by combining the above three sources. According to the long-term actual observation data, the water conveyance efficiency between Caiqi Hydrological Station and the outlet section of Hongyashan Reservoir is 0.859, according to which the annual outflow of Hongyashan Reservoir is converted, as shown in Table 9.

Table 9. Forecast of inflow situation in Minqin Basin (Unit: 10⁴ m³/yr).

| Item                                | High Flow Year | Normal Flow Year | Low Flow Year |
|-------------------------------------|----------------|------------------|---------------|
| Water Diversion of Jingdian Project | 8300           | 8300             | 8300          |
| Water Diversion from Liangzhou District | 13,400         | 13,400           | 13,400        |
| Natural Water from Shiyang River    | 12,500         | 9600             | 6600          |
| Predicted Runoff of Caiqi Section   | 34,200         | 31,300           | 28,300        |
| Outflow of Hongyashan Reservoir     | 29,400         | 26,900           | 24,300        |

Besides the inflow water from Hongyashan Reservoir, groundwater exploitation is also the water source of Minqin Basin. Since the beginning of comprehensive management of Shiyang River, groundwater exploitation in Minqin Basin greatly reduced and maintained at about 9.9 × 10⁷ m³/yr with the increase of water inflow and the implementation of measures such as closing wells. The available exploitation of groundwater in Minqin Basin should be kept at 8.6 × 10⁷ m³/yr [31].

4.5.2. Determination of Reasonable Ecological Water Conveyance

Based on above analysis and principles in Section 3.3, the ecological water conveyance under different level years were calculated, as shown in Table 10—in a normal flow year, the total water resources, including outflow of Hongyashan Reservoir and groundwater exploitation, can meet the water demand of the basin. The maximum ecological water conveyance can meet the water demand for maintaining the current surface area of Qingtu Lake (i.e., 3136 × 10⁴ m³/yr). In low flow year, the water output of Hongyashan Reservoir is insufficient. The total water resources will be not enough to meet the water demand of the basin and Qingtu Lake if the groundwater is exploited in accordance with available groundwater exploitation. Therefore, the groundwater exploitation should be increased to 1.03 × 10⁸ m³/yr, which is 1.2 times of the available exploitation. In high flow year, the outlet water volume of Hongyashan Reservoir is abundant. Surface water should be used instead of groundwater to supplement the excessive exploitation of groundwater in low flow year. Therefore, the groundwater exploitable volume is 6.9 × 10⁷ m³/yr. In this case, on the premise of satisfying water consumption in the basin, the maximum ecological water conveyance is also sufficient to maintain the current water surface area of Qingtu Lake. Reasonable ecological water conveyance volume in high, normal and low flow years is 4 × 10⁷ m³/yr, 3.2 × 10⁷ m³/yr and 2.3 × 10⁷ m³/yr, respectively.
Table 10. Scale of water resources supply and demand and reasonable ecological water conveyance in different level years (Unit: $10^4$ m$^3$/yr).

| Level Year         | Outflow of Hongyashan Reservoir | Groundwater Exploitation | Water Demand of Minqin Basin | Reasonable Ecological Water Conveyance |
|--------------------|---------------------------------|--------------------------|------------------------------|---------------------------------------|
| Low flow year      | 24,300                          | 10,300                   | 32,300                       | 2300                                  |
| Normal flow year   | 26,900                          | 8600                     | 32,300                       | 3200                                  |
| High flow year     | 29,400                          | 6900                     | 32,300                       | 4000                                  |

In general, the average annual groundwater exploitation in the basin is controlled at $8600 \times 10^4$ m$^3$/yr, and the annual average ecological water delivery is $3.167 \times 10^7$ m$^3$/yr, which can meet the ecological water requirement of Qingtu lake to maintain the current water surface area (i.e., $3.136 \times 10^7$ m$^3$/yr). In addition, the analysis in Section 3.2.3 shows that the actual industrial water consumption in the basin is far less than the planned water consumption, and the excess water can also be appropriately allocated as ecological water delivery.

4.6. Discussion

In fact, the water balance is mainly the balance between water inflow to the lake and evapotranspiration, while the precipitation and the groundwater variations only account for a small proportion. Other studies on Qingtu Lake also show the above conclusions. The result of groundwater equilibrium calculation by Feng et al. showed that the main discharge way of groundwater in Qingtu lake is evapotranspiration [34]. Precipitation has little influence on the water characteristics of Qingtu Lake [35], which also shows to some extent, that precipitation has little effect on the water balance in the study area.

The reasonable ecological water volume in the above analysis is an ecological water volume that maintains the current lake surface area (at least not decrease) in different levels years. Due to the lack of detailed topographical and water depth data of Qingtu Lake, it is difficult to predict the change of water surface area with ecological water conveyance in a larger range. However, the altitude of Qingtu lake is 1292–1310 m, and its terrain is relatively flat [36]. Zalong Wetland in China is also a relatively flat wetland. Its water surface area enlarged with the increase of water storage in a power function (i.e., as the impoundment increased, the same amount of water formed a larger water surface area and a shallower impoundment depth) [37]. It means that the surface area formed by water of the same volume increases and so does the amount of evaporation. Related studies shown that reed growth in dryland wetlands is highly correlated with wetland inundate situation [38]. The enlargement of water surface area will promote the growth of reeds, and then increase the transpiration of vegetation. Therefore, the cost of maintaining water surface area will be greater. The critical groundwater depth for reed growth is 1.15 m [39]. If the groundwater depth is too small, the surface soil will be salinized, which is not conducive to the growth of reed. Therefore, the water surface area should not be too large to prevent groundwater level from exceeding the critical value caused by excessive recharge to groundwater.

5. Conclusions

(1) Ecological water conveyance and evapotranspiration are the two main factors affecting the change of water surface area of Qingtu Lake. The period of increase of water surface area coincides with that of water conveyance, and the minimum and maximum area appear basically before and after water conveyance.

(2) Evaporation is intense in arid area of Northwest China and the influence of water surface evaporation can not be ignored with the increase of water surface area. The regression model established in this study can basically reflect the change of surface area of Qingtu Lake under the influence of ecological water conveyance and evaporation. The results show that the maximum water surface area can be basically maintained at 13.43 km$^2$ when the water inflow into the lake is $2202 \times 10^4$ m$^3$/yr (i.e., the ecological water...
volume is $3146 \times 10^4 \text{ m}^3/\text{yr}$; within a certain range, the lake surface area will increase by 1 km$^2$ for every additional $4.503 \times 10^6 \text{ m}^3/\text{yr}$ of ecological water conveyance.

(3) Water balance shows that the water surface area can be maintained at about $13.43 \text{ km}^2$ when the ecological water conveyance of Qingtu lake is $2.195 \times 10^7 \text{ m}^3/\text{yr}$, which is not significantly different from the result of regression analysis.

(4) Through the analysis of surface water inflow and groundwater exploitation, the reasonable ecological water conveyance to Qingtu Lake is determined as follows: it is $2.3 \times 10^7 \text{ m}^3/\text{yr}$, $3.2 \times 10^7 \text{ m}^3/\text{yr}$, and $4.4 \times 10^7 \text{ m}^3/\text{yr}$ in low, normal, and high flow year, respectively.

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