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Ecological Water Demand Estimations for Desert Terminal Lake Survival under Inland River Water Diversion Regulation

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Abstract: Desert terminal lakes are important signals to discern ecological degradation crises, particularly in arid areas where an artificial project of ecological water diversion has designated a quota of river water to prevent lake body shrinkage and protect the ecosystem. Knowledge of the minimum ecological water demand (EWD) is thus necessary to ensure the basic health of lake ecosystems. This study analyzed the spatiotemporal evolution of water boundaries using Landsat satellites data via remote sensing technology from 2002 to 2017 in East Juyan Lake, an inland desert terminal lake of the Heihe River in northwest China. The minimum lake water demand was determined using two estimation methods: the lake-evaporation-oriented EWD method and the minimum water level method. In the latter method, both lake topography (using water-level area curves) and biological survival demands (using bighead carps as indicators) were considered to derive the minimum lake EWD. Water diversion to the lake over the past 15 years has increased the lake's area, but there are still marked intra-annual seasonal variations. The annual minimum lake water demand was suggested to be 54×10^6 m^3/year by comparing the different methods; however, it was not satisfied, and the lake survival was endangered when the occurrence frequency of the annual runoff in the Zhengyixia hydrological station exceeded 65%. This study offered promising directions for inland lake water resource management.

Keywords: lake area; water diversion; ecological water demand (EWD); minimum water level; inland river

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1. Introduction

Lakes are important territorial freshwater resources, with many functions of regulating river runoff, providing water sources for agriculture, industry, and domestic development, and improving the regional ecological environment [1,2]. Due to changing climate and rapid development of human society, lakes in inland hyper-arid areas face a variety of problems, such as area shrinkage and ecological degradation [3,4]. To address the aquatic ecosystem crisis brought about by a shrinking lake, it is necessary to determine the minimum EWD of lakes [5,6]. Below this threshold, lake ecosystems will be severely damaged.

Lake EWD refers to the water demand to conserve the basic structure and important functions of the lake wetland ecosystem [7,8]. In recent decades, EWD investigation has mainly concerned on river ecosystem, researching the hydrology, hydraulics, ecology, and holistic methods [9,10]. To study the EWD of lakes, the primary methods are the water balance method, the minimum water level method, the function setting method, and the water quality target method [11]. Cao et al. [12] determined the optimal EWD and water level of Baiyangdian Lake according to its ecosystem service value. By studying four natural lakes in the Mediterranean Sea, Petriki et al. [13] found that the hydrological and ecological methods should be combined to evaluate the ecological water regime of lakes. Maihemuti et al. [14] established a lake water balance model and explored the complex nonlinear connections in the lake water level, volume, and boundaries.

East Juyan Lake (101°12′ E–101°19′ E, 42°10′ N–42°20′ N) is an inland terminal lake [15] of the Heihe River. Due to the continuous increase in industrial and agricultural water use in the upstream and midstream regions, East Juyan Lake had dried up six times, it completely dried up in 1992, and the oasis shrank [16,17]. In order to avoid the continuous deterioration of the downstream ecological environment, the national government implemented an ecological water diversion regulation on the mainstream Heihe River in 2000 [18]. In July 2002, East Juyan Lake received water from the upper Heihe River for the first time. East Juyan Lake is in the shape of "a shallow dish", yielding problems, such as a large water surface area, shallow water depth, and high evaporation [19]. Therefore, it is important to determine a minimum EWD that can ensure the continued survival of East Juyan Lake [20].

The primary goals of this study were as follows: (1) to analyze the spatiotemporal tendencies in the water boundaries of East Juyan Lake from 2002 to 2017 using Landsat data, which can help identify the impacts of ecological water diversion regulation on the lake conservation; (2) to estimate the minimum EWD using both hydrological and ecological methods from the three perspectives of lake evaporation, lake topography, and biological impacts, which have been rarely explored before in this typical but significant desert terminal lake; and (3) despite long-term benefits of artificial water diversion, to determine the minimum condition of annual water diversion to maintain the lake alive based on the minimum EWD estimations. This study is expected to provide references for lake management and inland river regulation of ecological water diversion projects in arid areas.

2. Study Area and Materials

2.1. Study Area

East Juyan Lake is situated 44 km north of the city of Ejina Banner and is the terminal lake of the Heihe River, China (Figure 1a). This study area has an extremely dry climate and fragile ecological environment, heavily depending on the water supply from the Heihe River that springs from the Qilian Mountains. At present, there are about 20,000 permanent residents in Ejina Banner, who depend on the Heihe River and local groundwater for more than 97% of their water [21].

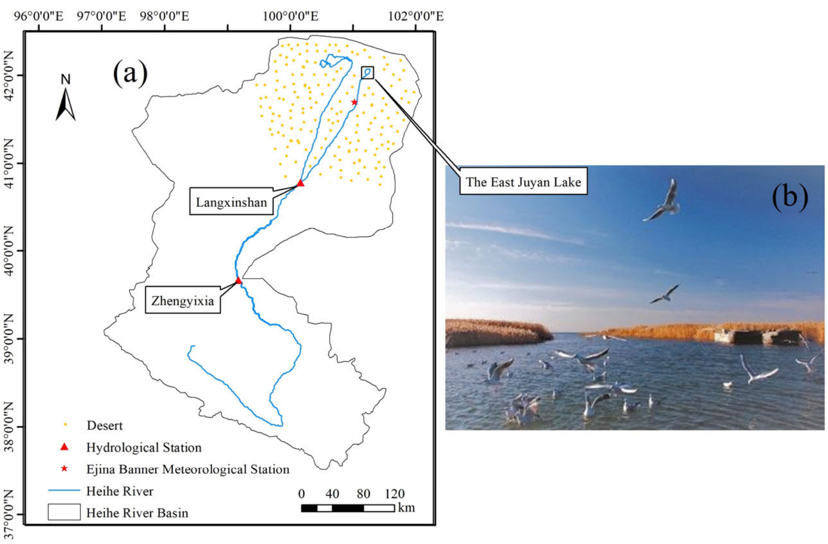

Figure 1. Study area: (**a**) the location of East Juyan Lake and (**b**) a photograph taken in East Juyan Lake.

Ejina Banner has a continental arid climate, with little precipitation and high evaporation [22] and is a typical hyperarid area. According to the calculations by averaging the observed meteorological data of Ejina Banner over years 2002–2017, the annual average precipitation was only 35.0 mm, the annual average temperature was 8.6 °C, and the annual average reference evaporation was approximately 3500 mm, which was one hundred times greater than the annual average precipitation. A project was constructed in the Heihe River basin in 2002, which delivers runoff water to the downstream area between the Zhengyixia and Langxinshan hydrological stations. The downstream Heihe River includes the two tributaries: the West River and the East River at the Langxinshan site, and the East River flowed into East Juyan Lake in the desert regions. Currently, a number of bird habitats are found in the center of East Juyan Lake, marking the gradual improvement of the ecological environment and the continuous enrichment of biodiversity (Figure 1b).

2.2. Data Source

This study was conducted primarily using Landsat remote sensing data and local meteorological observations. The Landsat series of satellite remote sensing images can accurately describe the seasonal fluctuations in lake water surfaces [23]. The Landsat series of satellites includes a total of eight satellites, and the sensors on the Landsat satellites include a multispectral scanner (MSS), a thematic mapper (TM), and so on [24]. Landsat 5, 7, and 8 were used to obtain remote sensing image data of East Juyan Lake from 2002 to 2017. Simple geometric correction and registration preprocessing were performed on the remote sensing images. The polygonal area of the lake was generated by the visual interpretation method. The lake area was calculated using GIS technology to project 128 images by selecting monthly scenes in January and from April to November. The glacial period is from December to March each year. The quality of the selected images was well controlled with no cloud cover over the study area. The item attributes and band information of the selected satellites are shown in Table 1. Landsat data can be freely obtained from online data sharing from NASA (http://glovis.usgs.gov/) (accessed on 20 August 2021).

Table 1. Properties of each item of the Landsat satellite.

System	Launch Time	Sensor	Cycle	Resolution	Number of Bands
5	1984	MSS/TM	16 days	80/30	7
7	1999	ETM+	16 days	Panchromatic 15/Multispectral 30	8
8	2013	OLI	16 days	Panchromatic 15/Multispectral 30	9

Observation data of various meteorological factors, including precipitation and evaporation, were collected from the Ejina Banner meteorological station from 2002 to 2017. The Ejina Banner meteorological station is located southwest of the oasis in Ejina Banner at 41.95° N, 101.07° E. The weather station describes the climate conditions of East Juyan Lake to some extent.

3. Methods

3.1. Lake Evaporation Estimations

East Juyan Lake is a closed lake, and the loss of lake water by evaporation corresponds to the highest share of water consumption [25]. The sum of the lake leakage, groundwater flows, and precipitation recharge in the study area was less than 1% of the evaporation [8] and was thus ignored. The lake water demand mainly offsets water consumption from evaporation.

The lake evaporation is mainly controlled by the lake area, atmospheric pressure, temperature, wind speed, and saturated vapor pressure lock [26]. According to previous studies, Li et al. [27] used the Penman–Monteith method to calculate the evaporation of East

Juyan Lake; Liu et al. [28] calculated the lake evaporation in the lower Heihe River using E601 pan evaporation. In this study, the empirical formula in Equations (1)–(4) adopted by [20,29] was used to calculate the lake evaporation, which is suitable for data-lacking areas, and the results were compared with those estimated from [27,28].

$$E = E_a \cdot A \tag{1}$$

Here, A is the lake area (km^2) obtained by the interpretation of Landsat satellite imagery and arranged in descending order to acquire area values under the 50%, 75%, and 95% percentiles for the period of 2002–2017. E_a is the water surface evaporation per unit area (mm/d), which is further estimated by Equation (2).

$$E_a = \left[0.1 + 0.24\left(1 - U^2\right)^{0.5}\right](e_0 - e_{150})V^{\left(\frac{0.85V}{v+2}\right)} \tag{2}$$

Here, U is the relative humidity, V is the local wind speed (m/s), e_0 is the saturation vapor pressure (hPa), and e_{150} represents the saturated vapor pressure at 1.5 m above the lake surface (hPa). e_0 can be expressed as $e_{0\text{water}}$ at the water surface and determined by Equation (3).

$$e_{0water} = 6.11 \times 10^{\frac{7.45t}{235+t}} \tag{3}$$

Here, t is the lake surface temperature (°C). When the lake freezes, e_0 can be expressed as $e_{0\text{ice}}$ and determined by Equation (4).

$$e_{0\text{ice}} = 6.11 \times 10^{\frac{9.5t}{265+t}} \tag{4}$$

3.2. Minimum Water Level Method

The minimum water level method [30] estimates the water demand of lakes by determining the minimum water level and area. The ecological water level is the minimum water level required to sustain the health and basic functions of the lake ecosystem without serious degradation. Therefore, the lake area A (km^2) corresponding to this minimum water level was taken in the extreme case of 95% percentiles. Considering the basic characteristics of the lake, the formula for calculating the minimum lake volume W (10^6 m^3/year) needed to meet ecological processes is:

$$W = (H_{min} - H) \cdot A \tag{5}$$

where H_{min} is the minimum ecological water level elevation (m), and H is the lake bottom elevation (m) with consideration of the inapparent impacts of sediment deposition.

In this study, the two commonly used estimation methods of lake minimum ecological water level were used: the lake morphology analysis method and the biological minimum space requirement method.

3.2.1. Lake Morphology Analysis

The lake morphology method [31] considers that the lake water and topography subsystems are the most basic parts of the lake ecosystem. To maintain a healthy lake ecosystem, the lake water level and morphometry, which are closely associated with changes in lake areas, must not be severely degraded. Lake water level is an indicator reflecting the fluctuation in the lake hydrological and topographic systems, and the lake area is an indicator reflecting the lake functions. Because of the nonlinearity between the water level and the area of lake surface, when the water level varies, the reduction in the lake area could be different for each unit of reduction in the lake water level.

The first-order derivative of the function that water level changes with lake area can indicate the fluctuation degree of water level under the impacts of varying lake area, i.e., the slope of the function curve of Equation (6). When the lake area decreases by one unit, both the lake volume and the corresponding water level will decrease. When the curve slope reaches its maximum, the corresponding water level is considered to reach its greatest change with lake area. This sensitive water level to lake area is usually a relatively low value that could cause negative influences on local biological habitat, species diversity, and desert eco-tourism resources [25] and is thus artificially set to be the target minimum water level in this method. The second-order derivative can represent the concavity and convexity of the fitting functions for water-level area curves $f(\cdot)$. When the second-order derivative in the domain is 0, the corresponding value is the extreme or inflection point in the domain of the first-order derivative [14,32]. The formula is as follows:

$$H_0 = f(A_0) \tag{6}$$

$$\frac{d^2 H_0}{d{A_0}^2} = 0 \tag{7}$$

where A_0 is the lake area (km^2), and H_0 is the lake water level elevation (m).

3.2.2. Biological Space Minimum Requirement Method

The lake water level is used as an indicator of the living space of lake organisms. The ecological water level depends on the living space demand of various biological species in the lake. The biological minimum space requirement method [32] uses an aquatic organism as the indicator from the perspective of the minimum biological demand for living space to determine the minimum ecological water level of the lake. Among many species, fish are a commonly used indicator to reflect the situation of an aquatic ecosystem given the advantage of their sensitivity to low water levels and their representability of other types of organisms [31,32]. Therefore, this method describes the biological space minimum requirement by taking the minimum ecological water level of fish as the baseline. The minimum water depth required by the fish plus the elevation of the lake bottom elevation is the minimum ecological water level [33], which is expressed as follows:

$$H_{min} = H_1 + H \tag{8}$$

where H_1 is the water depth (m) threshold for fish to survive in the study area. According to the comprehensive considerations of both natural water level data [18] and previous environmental flow records monitored by the local ecological conservation center [21,25], H_1 was chosen from the water depth interval of 1.50 m~2.00 m which meet the survival needs of fish and most other aquatic organisms in the East Juyan Lake.

4. Results and Discussion

4.1. Temporal Tendencies in Lake Areas

The inter-annual water surface area of the East Juyan Lake showed an obvious uptrend (Figure 2a). The lake almost dried up briefly from June to August in 2003. Since 2004, East Juyan Lake has not dried again. In 2002 and 2003, the water surface area of East Juyan Lake was primarily affected by the amount of water diverted to the lake and did not show marked periodic changes. After 2004, the lake area began to change regularly. The area of the lake changed from 17.33 km^2 in 2002 to 64.80 km^2 in 2017, with an average annual increase of 2.97%. The maximum lake area appeared in 2017 at 70.11 km^2, and the minimum value appeared in 2004 only 10.8 km^2, while the multiyear average area was 45.72 km^2. The three different tendencies in lake areas appeared over time. The marked upward trend was from 2002 to 2005; then, the trend was smaller from 2005 to 2016, and there was a major uptick in 2017. Between 2011 and 2015, the average lake area was maintained at approximately 54 km^2, and the average annual water inflow into the lake during this period (68×10^6 m^3/year) increased markedly compared with the previous period from 2002 to 2010 (52×10^6 m^3/year). However, the inter-annual variation in the wetland area after 2010 was small, and the overall growth rate was only 0.64 km^2/year. In general, the current annual water inflow can only maintain the existing area to avoid marked shrinkage.

In terms of the monthly changes in lake areas (Figure 2b), The ice period lasts from November to March, and the lake area remains stable. After April, the area of the lake begins to decrease, reaches its smallest value in the year from July to August and reaches its highest value between October and November. After summer, the weather gradually becomes warmer, the evaporation on the water surface increases, and the upstream water does not flow into the desert terminal lake. At this time, the area of the lake gradually decreases. After autumn, the upper reaches releases water, and the lake area begins to increase.

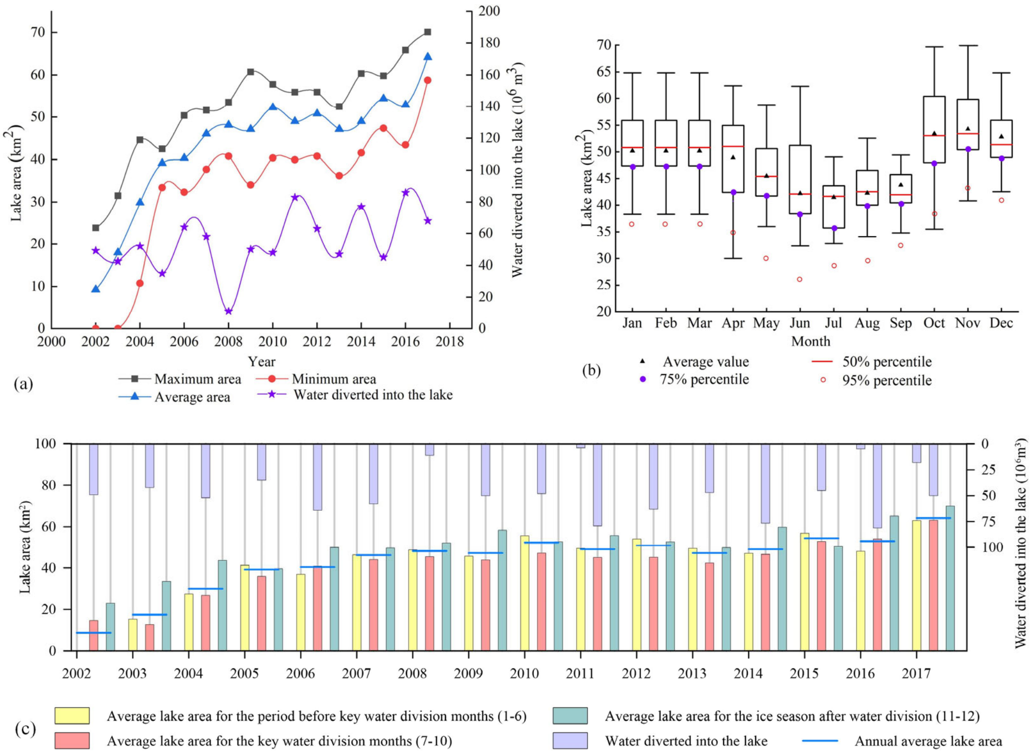

Figure 2. (**a**) Annual variations of the lake area in the East Juyan Lake and water diverted into the lake from the Heihe River, (**b**) monthly variations of East Juyan Lake area (Box-Whisker plot), and (**c**) periodical changes in the lake area and water diverted into the lake, with a whole calendar year divided into the three time periods: the period before key water division months (1–6), key water division months (7–10), and ice season after water division (11–12).

The response of the lake areas to the water diverted into the lake was quite affected by the scale of the continuous implementation of the ecological water diversion. The lake area expanded rapidly with runoff into the lake, which was sensitive to the inflow water volume. In some years, the amount of water diverted to the lake was inversely proportional to the lake area, which indicated that there was a lag time between water diversion and lake area change. Figure 2c helps illustrate the time-lag effects by presenting the periodical variations of the lake area and water diverted into the lake, with a whole calendar year divided into the three time periods: the period before key water division months (1–6), key water division months (7–10), and ice season after water division (11–12). For example, the inflow in 2004 increased to 52×10^6 m^3/year, which represented the expansion of the annual average lake area in 2005. The possible reason might be that most water entering the lake from the Heihe River is during July to October when the critical water division plan starts and meanwhile compensates for large lake evaporation loss. The lowest lake area during July to September in a year gradually increased and reached the highest value of lake area until the annual key water diversion period was completed in October (Figure 2b). Then, in November, the inflow begins to freeze, and lake evaporation decreases as the weather becomes cold [21] with little reduction in lake area. Therefore, despite long-term benefits of artificial water diversion increases, an increase in the lake area was not obvious after a whole calendar year, and risks of lake survival always existed.

4.2. Spatial Variations in Lake Boundaries

From the perspective of the overall shape of the lake (Figure 3), East Juyan Lake did not dry up throughout the successive years since 2004, and its southern boundary expanded markedly. In 2009, the boundary expansion on the east and west sides of the lake was larger. In 2013, the lake boundaries were generally unchanged. In 2017, the shape of the lake remained basically fixed, and the southern boundary expanded marginally. In the early stage of water inflow because the lake was dry before, the difference between the largest and smallest areas of the year was large, and there were marked spatial shape differences. With the continuous implementation of ecological water diversion projects, the intra-annual largest area and the smallest area gradually increased, and the small temporary lake was found in the south, in the recent years, during the high-water levels from 2014 to 2017.

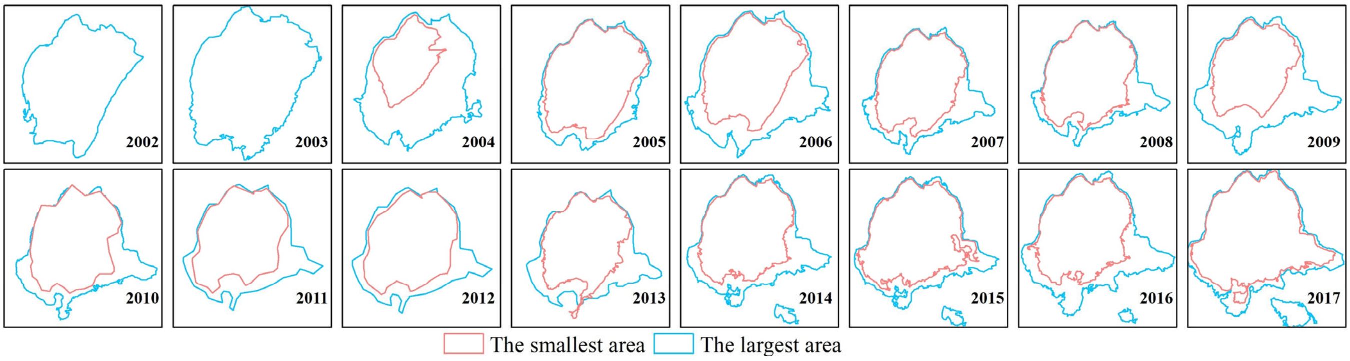

Figure 3. The intra-annual largest area and the smallest area of East Juyan Lake.

4.3. EWD Estimation Results

4.3.1. EWD by Lake Evaporation

According to the water surface area calculated under the 50%, 75%, and 95% percentiles for East Juyan Lake, the corresponding lake evaporation water consumption and EWD are shown in Table 2.

Table 2. The EWD by lake evaporation in East Juyan Lake under different percentiles.

Percentile (%)	Lake Area (km^2)	EWD by Lake Evaporation (10^6 m^3)		
		(1)	(2)	(3)
		Based on Empirical Formula	Based on E601 Pan Evaporation	Based on Penman–Monteith Formula
50	47.88	77	75	78
75	44.40	71	69	72
95	34.60	54	54	56

The lake evaporation results estimated based on the empirical formula were between and similar to those converted from the E601 pan evaporation and the Penman–Monteith formula. In the case of 50%, maintaining a lake surface area of 47.88 km^2 required an EWD of 77×10^6 m^3/year. In the case of 75%, maintaining a lake surface area of 44.40 km^2 required an EWD of 71×10^6 m^3/year. In the case of 95%, to maintain the lake surface area of 34.60 km^2, the EWD was 54×10^6 m^3/year.

4.3.2. Minimum Water Level Method Considering the Lake Morphology

The nonlinear connection in the water level and the surface area of East Juyan Lake is shown in Figure 4, from which the minimum ecological water level of the lake can be calculated.

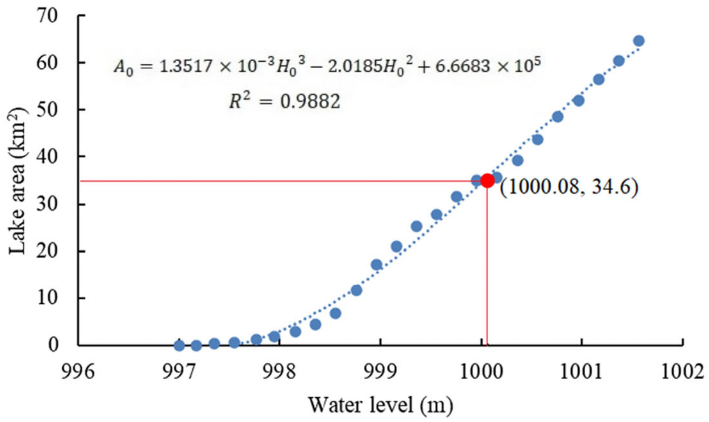

Figure 4. The fitting results for scatters of the water level and surface area of East Juyan Lake.

The lake water level (H_0) and the surface area (A_0) was fitted as follows:

$$A_0 = 1.3517 \times 10^{-3} H_0{}^3 - 2.0185 H_0{}^2 + 6.6683 \times 10^5 \quad (9)$$

By solving Equation (9), the minimum ecological water level $H_{\min}$ elevation of East Juyan Lake was 1000.08 m, and the lake bottom elevation H was 997.00 m. Based on the minimum water level method, when the multiyear average area of East Juyan Lake was 34.60 km^2, the EWD was calculated to be 106.57 $\times$ 10^6 m^3/year in combination with Equation (5).

4.3.3. Minimum Water Level Method Considering the Biological Space Minimum Demand

Bighead carps (*Aristichthys nobilis*) were listed as a protected fish species in East Juyan Lake and were thus selected as the representative fish indicator in this study. In line with the findings in the previous reference [33], who compared the water change cycle method and ecological evolution method, the lowest ecological water level for East Juyan Lake was chosen to be 1.75 m, which was also consistent with the actual survey of the local wetland conservation center [21,25]. Using the minimum water level method based on the biological space minimum demand, the EWD was calculated to be 61 $\times$ 10^6 m^3/year.

4.4. Comparison of Different Methods

The minimum EWD values for the three different methods are summarized from the highest to the lowest as follows: 106.57 $\times$ 10^6 m^3/year from the lake morphology method, 61 $\times$ 10^6 m^3/year from the biological minimum space requirement, and 54 $\times$ 10^6 m^3/year from the lake evaporation.

The basic principle of the empirical formula is to establish the empirical fitting-curves between the evaporation and the meteorological elements observed on the ground in the absence of measured data. The lake morphology method determined the ecological water level by studying the fitting of the water level and area that belonged to a semiempirical method. This method showed the advantage in less requirement of detailed ecological data and containing more specific lake information. The disadvantage of this method was that it did not reflect the seasonal changes, with a lack of ecosystem mechanisms. This method is suitable for small lakes with low and relatively stable water levels and no marked environmental pollution. The biological minimum space requirement method belongs to the category of the habitat method and has advantages in the ecological mechanism of lake-related organisms, but the difficulty is in obtaining the required biological data.

Compared with the other two methods, lake evaporation has a more complete theoretical system and has been widely verified to give a good estimation agreement with observation measurements [34,35]. Therefore, using the lake evaporation method, the annual minimum EWD of East Juyan Lake was suggested to be 54 × 10^6 m^3/year. Some comparative results were previously reported. For example, Zhang et al. [36] adopted the water mass balance model to simulate the impact of ecological water transfer on East Juyan Lake and found that the annual water inflow should be, on average, maintained at 61 × 10^6 m^3/year to maintain an annual average lake area, which was lower than the estimated EWD of 77 × 10^6 m^3/year at the 50% scenario (Table 2). Li et al. [37] indicated that the minimum annual evaporative water consumption in East Juyan Lake was 58 × 10^6 m^3/year, which was close to the results of 54 × 10^6 m^3/year at the 95% scenario (Table 2) in this study.

The dynamic lake changes are primarily reflected by variations in lake surface areas or water levels. Compared with manual monitoring methods, remote sensing technology has overcome the difficulties in field investigation and inconsistencies in data. In recent years, Landsat has often been used in lake area extraction [24,38]. Therefore, lake area data obtained from Landsat imagery in this study could be reliable.

4.5. Lake Survival Risk Based on Minimum Lake Water Demand

The annual mean runoff values of the Zhengyixia and Langxinshan hydrological stations were 1.17 × 10^9 m^3/year and 0.65 × 10^9 m^3/year (Figure 5), respectively. In the period of 2002–2010, only 33% of the annual runoff from the two hydrographic stations exceeded the multiyear average annual runoff, while during the period 2011–2017, 71% of the annual runoff volume exceeded the multiyear average value. Therefore, the Heihe River was recently in its water-abundant period and enabled the delivery of sufficient water for the ecological restoration in East Juyan Lake. The annual average precipitation, another water source in East Juyan Lake, was only 34.15 mm and was generally stable. Thus, the water supply from local precipitation could be negligible.

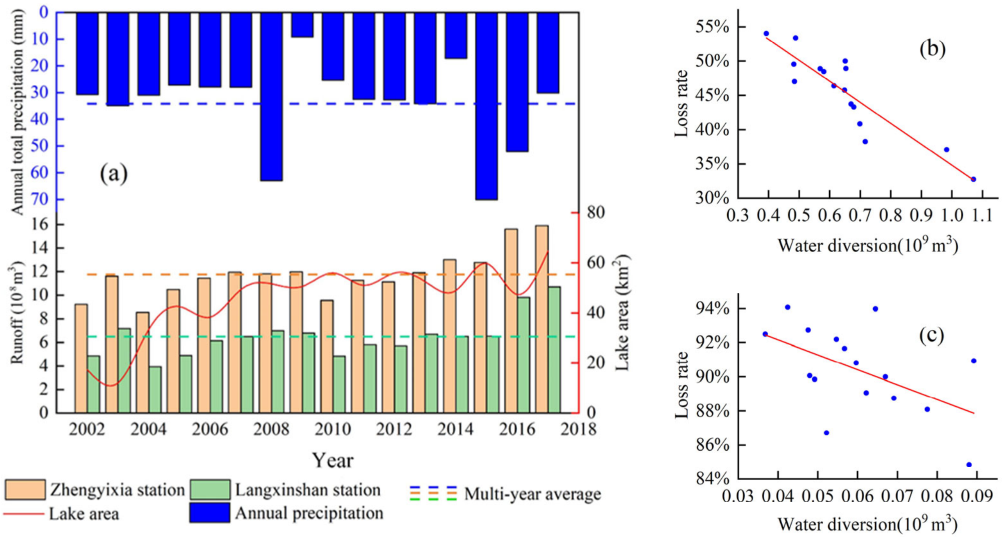

Figure 5. (**a**) Changes in runoff, precipitation, and area trends. The relationship between the quantity and the loss rate of water diversion for (**b**) Zhengyixia and Langxinshan hydrological stations and (**c**) Langxinshan hydrological stations and East Juyan Lake.

The average loss rate, which included water delivery losses and water withdrawal in the study area, decreased from the highest at 54% to 32% from 2002 to 2017 with the gradual increase in the water delivery volume from the Zhengyixia to the Langxinshan sections. In the section from Langxinshan to East Juyan Lake, the loss rate increased to an average of 90%, and the minimum loss rate was 85%, largely due to the intense regional evaporation. Although the water delivery continued to increase, the loss rate was still high. The currently wider lake water boundaries were demonstrated to be attributed to the more abundant incoming water under inland river water diversion regulation. Thus, with the change in the hydrological cycle, once the probability of dry or continuous dry weather increases, the favourable inflow conditions to keep East Juyan Lake from drying up no longer exist, and the risk of drying up East Juyan Lake likely remains high.

To ensure the minimum EWD of 54×10^6 m^3/year for the survival of East Juyan Lake, the incoming water from the Langxinshan hydrological station would be at least 460×10^6 m^3/year, which was estimated by adding both the maximum water delivery losses and maximum water withdrawal in the river-flowing regions between the Langxinshan station and East Juyan Lake for the period 2002–2017. Then, the annual runoff of Zhengyixia station (as the first controlled hydrological station in the downstream Heihe River) should discharge at least 930×10^6 m^3/year to satisfy this requirement of 460×10^6 m^3/year in the Langxinshan station, according to the well-fitting relationship between the annual runoff of Zhengyixia and Langxinshan stations from 1980 to 2017 ($R^2 > 0.96$) (Figure 6a). In other words, when the runoff frequency in the Zhengyixia station exceeded 65%, the East Juyan Lake might encounter again the danger of drying up, as shown by the Pearson-III type probability distribution curve (Figure 6b), which has been proved to be suitable in hydrological frequency analysis for most watershed in China [39].

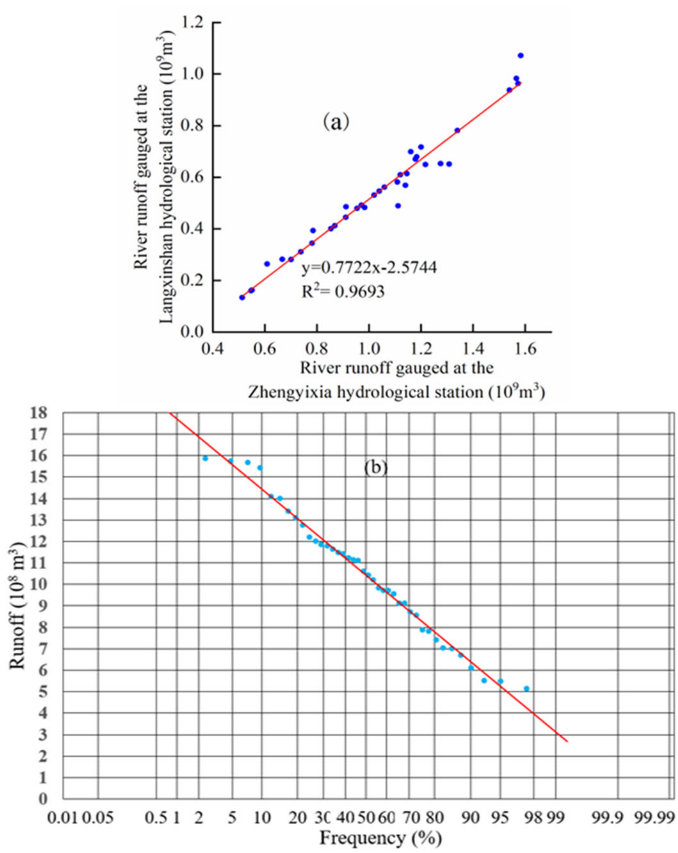

Figure 6. (**a**) The relationship between Zhengyixia and Langxinshan hydrological station. (**b**) The runoff frequency curve of Zhengyixia hydrological station.

5. Conclusions

This study used Landsat series data as a primary information source, combined local meteorological data, and comprehensively used geographic information technologies to analyze the spatiotemporal tendencies in water boundaries of East Juyan Lake over decades. Using hydrological and ecological methods, the minimum EWD of East Juyan Lake was estimated. Since 2002, under river water diversion regulation for East Juyan Lake, the lake area has been increasing. In 2017, the lake area had reached 70 km^2 and exhibited marked seasonal changes. The lake area was the largest during the period of October to November and the smallest from July to August. The shape of the lake continued to change over time and was still expanding. Based on the results of the lake evaporation methods used, the minimum EWD of East Juyan Lake was suggested to be 54×10^6 m^3/year. When the frequency of runoff discharge from the Zhengyixia hydrological station exceeds 65% based on a Pearson-III type probability distribution fitting, the discharged water from the Zhengyixia station could not satisfy the minimum water demand of 460×10^6 m^3/year in the downstream Langxinshan station, and finally, the East Juyan Lake might dry up again.

In addition, how to coordinate the ecological needs around East Juyan Lake and maintain the health of its ecosystem are key problems that must be addressed. Future research should couple the interactions between the ecological and hydrological factors and social factors to explore the impact of different inflow schemes on ecological restoration.

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