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ORIGINAL ARTICLE

Inland river terminal lake preservation: determining basin scale and the ecological water requirement

Jianhua Si · Qi Feng · Tengfei Yu · Chunyan Zhao

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Abstract Inland lakes are a major water resource for arid regions. Determining basin scale is therefore an important indicator of variability for water resources in such regions. The goal of this study was to ascertain the appropriate Juyan Lake basin scale and its minimum ecological water requirement for the lake's continued preservation. This was accomplished in three parts. First, an analysis was carried out on the inflow of the lower reach of Heihe River and any subsequent water surface area change to Juyan Lake. Second, an optimum Juyan Lake basin scale was determined by establishing existing relationships between reservoir capacity and lake area, water level and lake area, and variation in lake area during different times of the year. Third, the ecological water requirement of the lake was determined. Results showed that the decrease in surface runoff and ceased flow of the channel resulted in the drying up of the terminal lake of Heihe River. It was determined that 35.6 km^2 is the most stable Juyan Lake surface area, and 0.55×10^8 m^3 is the minimum replenishment quantity in which to maintain Juyan Lake throughout the year without it drying up.

Keywords Inland lake · Ecological water demand · Juyan Lake · Heihe River · Water diversion

J. Si · Q. Feng · T. Yu · C. Zhao
Alax Desert Eco-hydrology Experimental Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

J. Si (✉) · Q. Feng · T. Yu · C. Zhao
Gansu Hydrology and Water Resources Engineering Center, Lanzhou 730000, China
e-mail: jianhuas@lzb.ac.cn

Introduction

Variation in water resources is a primary factor that influences ecohydrological processes, land use and land cover change, and sustainable development in arid regions (Feng and Cheng 1998; Xiao et al. 2005; Xiao and Cheng 2006; Yang et al. 2005). Being a vital water resource component for arid regions (Cui et al. 2005), change in scale (size, quantity, and level) of inland lakes is also an important indicator of environmental variability change (Ma et al. 2010). Impacts from anthropogenic activity and climate change over recent decades have transformed inland lakes in a number of ways, including lake recession, decline in water levels, water pollution, etc. (Feng and Cheng 1998). Over the past half century, 243 lakes (~8 %) have disappeared in China, an approximate loss of five natural lake systems per year (Ma et al. 2010), which has caused great concern globally (Yao et al. 2012; Song et al. 2014).

Juyan Lake is a typical terminal lake system that is part of the lower reach of Heihe River, northwestern China (Fig. 1). According to historical records, it was once a renowned lake, garrisoned by the empire between the Han and Yuan dynasties (Zhao 1986). With the rise in socioeconomic development and the population growth that occurred over time, Juyan Lake has gradually decreased to 800 km^2 and has even dried up at times within the past 3,000 years (Zhu et al. 1983). This has led to serious environmental degradation (Gong 2005; Wang and Cheng 1998). In order to restore the ecosystem, the Chinese government has instigated and carried out a series of water regulation projects and policies, including the ecological water conveyance project (EWCP) (Guo et al. 2009). EWCP considered the question whether the water level of Juyan Lake was an important index for the success of their initiative at Heihe River, but they only took into account a

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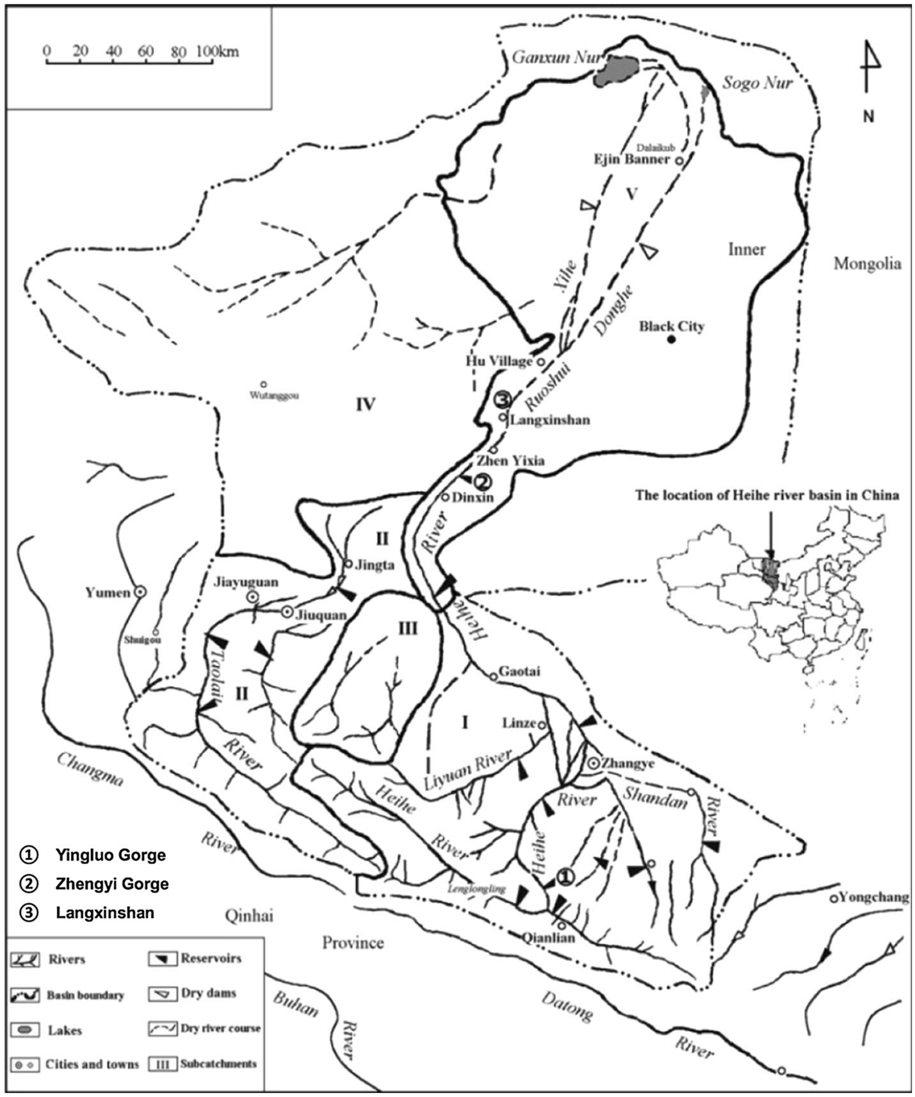

Fig. 1 Heihe River Basin Map

small section of the basin for use for irrigation. Scholars have long debated how to best use the available water from Juyan Lake. A conflict has arisen between economic water use in the middle reach and ecological water use in the lower reach (Jiang and Liu 2010). Other scholars believe there is an urgent need to designate the lake solely for irrigation (Gong et al. 1998). Accordingly, the following questions regarding the lake must be addressed: Do Juyan Lake water levels need to be maintained at all? If so, what would be the appropriate scale of the lake to satisfy ecological needs? Moreover, how much water volume is required to maintain a basin scale that satisfies the needs of the surrounding ecological environment?

Previous studies for the ecological water demand was focus on oasis (Zhao et al. 2007) or natural vegetation (Ye et al. 2010) in the inland river basin of arid regions, China, and rarely involve lakes in the area. For the Juyan Lake, most of studies focused on its environmental evolution (Zhu et al. 1983; Gong et al. 2002; Zhang et al. 2004; Wen et al. 2005), change of ecosystem structure and function (Xiao et al. 2005; Wang et al. 2011a, b), and the influence of water regulation on vegetation surrounding the Juyan Lake (Si et al. 2005; Jiang and Liu 2010; Wang et al. 2011a, b); however, few studies have focused on its scale and the minimum ecological water requirement. The primary objective of this study was therefore to determine the appropriate Juyan Lake basin scale (area, quantity, and level) and ecological water requirement. Results from this study will help to provide a scientific basis for further water regulation project and the improved restoration of the ecosystem in the lower reach of Heihe River.

Materials and methods

Description of study area

Heihe River is the second longest inland river in China, spanning an area of 0.14 million km^2 with a total length of

821 km. The river originates on the north slope of the Qilian Mountains and flows through Qinghai Province, Gansu Province, and the Inner Mongolian Autonomous Region. Upstream above Yingluo Gorge marks the perimeter of its upper reach; Yingluo and Zhengyi gorges mark the boundary of its middle reach; and downstream of Zhengyi Gorge marks the boundary of its lower reach (Fig. 1) (Feng et al. 2004). The length of the lower reach of Heihe River is 333 km, and the drainage area is 80,400 km^2. Heihe River is divided into east and west junctions downstream at the Langxinshan diversion. It then flows into East Juyan Lake and West Juyan Lake, respectively (Wen et al. 2005). The Ejin oasis that formed around the eastern and western junctions of the river in the interior of the Gobi desert has been an important ecological defense against sandstorms in northwestern China (Si et al. 2005).

The study was carried out at East Juyan Lake, located in the lower reach of the Heihe River Basin, northwestern China. The geographic coordinates of the study site are between lat 101°11′31–101°19′07″N and long 42°15′25–42°20′00″E (Fig. 1). The climate of the region is extremely arid with an average annual precipitation rate of 37.4 mm, greater than 75 % of which falls between June and August, during the growing season. Pan evaporation (3,390.3 mm) is greater than precipitation by an approximate magnitude of 90. Mean temperatures of 27 °C (July) and −11.7 °C (January) were calculated from Ejin weather station data originally obtained between 1,959 and 2011. Apart from precipitation, water from the Heihe River and its resultant groundwater provide the main water sources in which to sustain local residents and surrounding ecosystems (Yu et al. 2013).

Ecological water conveyance project (EWCP)

In order to increase water supplies and avoid ecosystem deterioration in the lower reach of Heihe River, the Chinese government has invested a total of 2.352 billion Yuan since 1999 for the ecological water conveyance project (EWCP) of the Heihe River Basin. With regards to the water diversion curve relationship, it was calculated that when the multiyear average water volume of the Yingluo Gorge reaches 1.58 billion m^3, the Zhengyi Gorge would discharge 0.95 billion m^3 to the lower reach, discharging 0.09 billion m^3 to Dingxin and 0.06 billion m^3 to Dongfeng counties, respectively, ensuring that the ecological water supply of the whole basin reaches 0.73 billion m^3 (Jiang and Liu 2010). With the uniform regulation of water resources has been underway since the end of 1999, and water usage in the middle reach of Heihe River has reduced water delivered to the lower reach (Si et al. 2005). After 12 years under such water regulation initiatives, the spatiotemporal distribution of water resources has changed dramatically in the lower reach of Heihe River.

Methods

Determining terminal basin scale

Determining terminal lake area before the 1930s taken from literature (Zhu et al. 1983; Gong et al. 2002), terminal lake area calculation between the 1940s and the 1960s using 1:50 thousand topographical maps (Liu 1992), and lake area calculations began in the 1970s using remote sensing imagery during different periods of time (1975, 1982, 1986, 2006 and 2010) as well as field investigations have been employed to ascertain Juyan Lake area and any change in distribution range.

Calculating the lake ecological water demand

The ecological water demand (EWD) was the least water amount required to maintain the structure and the function of the special eco-system (Yan et al. 2003), and thus for the lake which was defined by the water demand necessary for a natural lake system to maintain and restore its normal ecological system functions and environmental values to benefit human resource needs as determined by Liu and Yang (2002), which includes both itself and the existing environmental water demand (i.e., the eco-environmental water demand) (Liu and Yang 2002). The ecological water demand of the lake (W) in this arid inland river basin was then calculated as follows (Wei et al. 2004; Cui et al. 2005; Cui et al. 2009):

$$W = W_v + W_p + W_i + W_g \quad (1)$$

where W_v is the water demand of lake water surface evaporation; W_p is the water demand of aquatic plant evapotranspiration; W_i is the water demand of the lake itself; and W_g is the water demand of lake seepage.

$$W_v = Q_E - Q_r \quad (2)$$

where W_v is the water demand of lake water surface evaporation (10^8 m^3); Q_E is the evaporation taking place in the lake (10^8 m^3); and Q_r is the precipitation inflow into the lake (10^8 m^3).

$$Q_E = E_w \times A \quad (3)$$

$$Q_r = P \times AQ_r = P \times A \quad (4)$$

where A is the lake area (km^2); E_w is lake water surface evaporation (mm); and P is the unit area of precipitation (mm).

$$W_p = \int_0^{t_1} ET_m dt \quad (5)$$

where t_1 is the time length of the calculation, and ET_m is aquatic plant evapotranspiration (mm). At present, there are basically no aquatic or floating plants in Juyan Lake. The water demand of aquatic plant evapotranspiration therefore plays a negligible role compared to the water demand of lake water surface evaporation. After the reconstruction of aquatic plant communities is finally ascertained, the water demand of aquatic plant evapotranspiration should be calculated according to actual real world requirements.

$$W_i = A \times h/T \quad (6)$$

where h is lake water depth (m). T is the lake exchange rate, the ratio of lake inflow volume and the annual runoff of outflow from the lake. Given that no outflow presently takes place in Juyan Lake, annual outflow runoff was replaced by lake water surface evaporation. Between 2002 and 2012, annual mean lake inflow volume and lake water surface evaporation were 0.33×10^8 and 1.38×10^8 m^3, respectively. Then, the average T was calculated as 0.24.

$$W_g = \gamma \times A \quad (7)$$

where γ is the lake seepage coefficient (0.45), and A is lake area (km^2).

Results

Runoff variation in the lower reach of Heihe River

Annual runoff variation observed by the main hydrological stations located in the Heihe River Basin is provided for in Fig. 2. Data from the Yingluo Gorge station showed multiyear average runoff to be 16.0×10^8 m^3 between 1944 and 2012, and 0.0453 was the slope of the annual runoff trend line. Inter-annual variability of runoff showed a decreasing trend in the Zhengyi Gorge station between 1954 and 2012 where 10.21×10^8 m^3 was the multiyear average runoff, −0.0445 was the slope of the annual runoff trend line, and 5.79×10^8 m^3 was the average interval of water consumption. For the Langxinshan station where an overall decline in runoff took place between 1990 and 2000, 0.134 was the slope of the annual runoff trend line between 1990 and 2012, and 3.77×10^8 m^3 was the multiyear average runoff. Since 2000, the Langxinshan station observed an increase of 5.29×10^8 m^3 in average runoff, a significant increase of 1.52×10^8 m^3 when compared to the time before the reduction in water delivered to the lower reach took place (1999–2000).

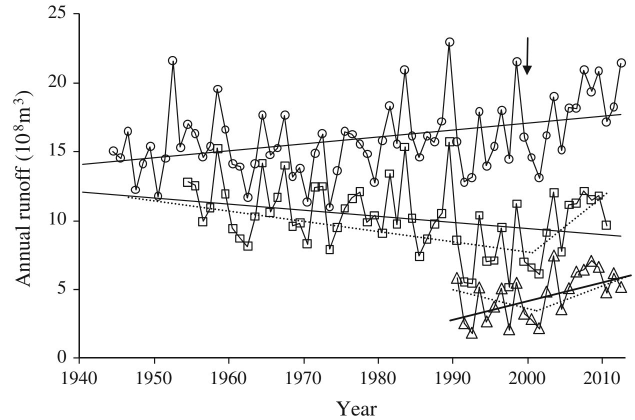

Fig. 2 Variation in annual runoff taken from Heihe River Basin's main hydrological stations. *Circles*, *squares*, and *triangles* denote runoff from Yingluo, Zhengyi, and Langxinshan stations, respectively. *Solid lines* denote *trend lines* while *dotted lines* denote *trend lines* before and after water diversion. The *arrow* denotes the start of water diversion during a particular year

Variation in East Juyan Lake area

According to historical records (Zhu et al. 1983; Gong et al. 2002), the amount of water flowing from Heihe River into the Ejin River exceeded 15.0×10^8 m^3. In the 1930s, the area of water in East Juyan Lake spanned 120 km^2. Since the 1940s, however, during a time when great changes took place in the hydrological processes of Heihe River, inflow into Ejin River was drastically reduced. For example, river courses shortened and terminal lakes receded or even dried up altogether (Table 1). The East Juyan Lake was the region most affected by such water regulations. Water first arrived in East Juyan Lake on July 17, 2002, after 13 years of continuous water diversion transfer from the middle reach of the Heihe River. Lake area subsequently expanded with this water diversion transfer. A detailed description is provided in Table 1 that shows the area of East Juyan Lake reached a maximum of approximately 42.7 km^2 in 2011 compared to 23.8 km^2 in 2002.

Determining the stability of East Juyan Lake area

An increasing trend in reservoir capacity and lake area of East Juyan Lake took place between 2004 and 2012. This trend exhibited a 0.48×10^8 m^3 multiyear average reservoir capacity and 36.5 km^2 multiyear average lake area. Maximum reservoir capacity (0.88×10^8 m^3) and maximum lake area (42.7 km^2) was attained in October 2011. The trend in variation in East Juyan Lake corresponded to the combined association between reservoir capacity and lake area (Fig. 3). Correlation analysis showed that a significant logarithmic relationship existed between reservoir

Table 1 Inflow from the lower reach of Heihe River and changes in water surface area of East Juyan Lake

Time	R (10^8 m^3)	Q (10^8 m^3)	A_L (km^2)	Data origins
1930s	>15.00		120.0	Sun Peishan, etc., Hydrogeologic Study on western of Inner Mongolia Plateau, Science Press, 1964
1940s	13.49		58.4	Calculated from 1/50,000 topographic maps
1950s	12.33		53.3	Calculated from 1/50,000 topographic maps
1960s	10.52		35.5	Calculated from 1/50,000 topographic maps
1970s	10.52		33.0	Calculated from 1975 satellite imagery
1980s	9.68		23.6	Calculated from 1982 satellite imagery
1990s	3.47		dried-up	Field investigation
2000	2.98		dried-up	Field investigation
2001	2.18		dried-up	Field investigation
2002	4.837	0.493	23.8	Field investigation
	7.456			
	3.549			
	5.084			
	6.291			
	6.427			
	7.064			
	6.632			
	4.779			
	6.174			
	5.167			
2003	7.46	0.425	31.5	Field investigation
2004	3.55	0.522	35.7	Field investigation
2005	5.08	0.368	33.9	Field investigation
2006	6.29	0.691	38.6	Field investigation
2007	6.43	0.597	39	Field investigation
2008	7.06	0.547	40.5	Field investigation
2009	6.63	0.567	42	Field investigation
2010	4.78	0.480	41.4	Field investigation
2011	6.17	0.880	42.7	Field investigation
2012	5.17	0.622	42.3	Field investigation

R denotes inflow into Ejin Oasis from the main stem of Heihe River; A_L denotes water surface area of East Juyan Lake; and Q denotes the flow of water quantity into East Juyan Lake

capacity and lake area in East Juyan Lake [$y = 10.516\ln(x) + 45.8$ ($R^2 = 0.965$)]. This implies that lake area gradually achieved steady state after the trend in

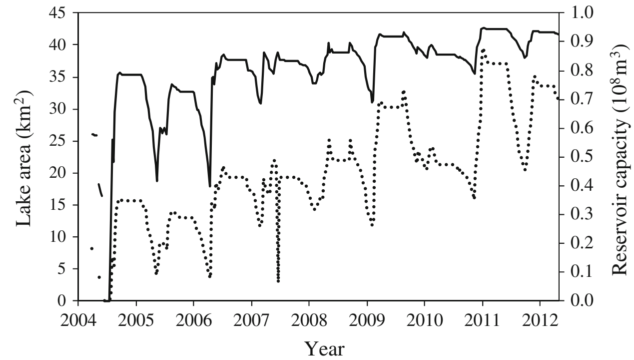

Fig. 3 Variation in reservoir capacity and area of East Juyan Lake between 2004 and 2012. The *solid line* denotes East Juyan Lake area while the *dotted line* denotes East Juyan Lake reservoir capacity

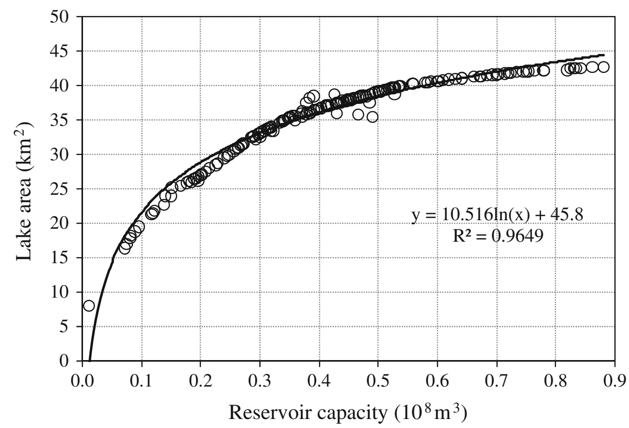

Fig. 4 Relationship curve between East Juyan Lake reservoir capacity and area

variation was rapidly increased by means of an increase in water flow into East Juyan Lake. The slope of the curve decreased, however, when a reservoir capacity greater than 0.355×10^8 m^3 was attained. That is to say, lake area become relatively stable with an increase in reservoir capacity, i.e., achieving a lake area of 35.6 km^2 (Fig. 4).

The relationship curve between water level and water area of East Juyan Lake showed that lake area gradually achieved steady state after its trend in variation rapidly increased with an increase in lake water levels. Lake area rapidly increased further when water levels exceeded 1,000 m. That is to say, water began to outflow into the surrounding area when water levels reached a particular height at a lake area of 35.6 km^2 (Fig. 5). Remote sensing image vectorization results showed that the most obvious zone of change in East Juyan Lake area took place in the southeast where flows spread quickly with rising water levels, owing to the fact that topography is relatively low in that particular area of the lake (Fig. 6).

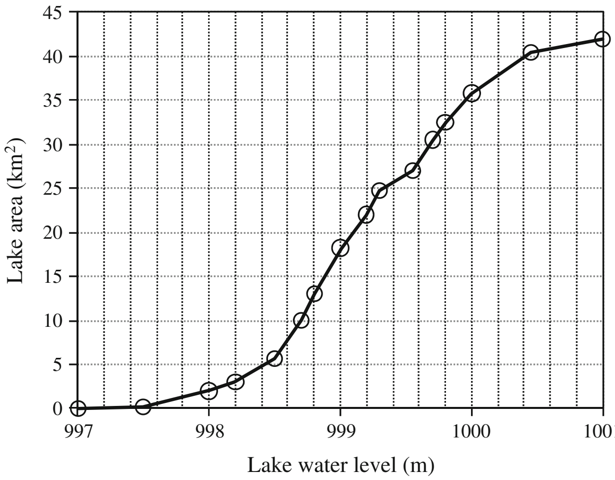

Fig. 5 Relationship curve between East Juyan Lake water level and area

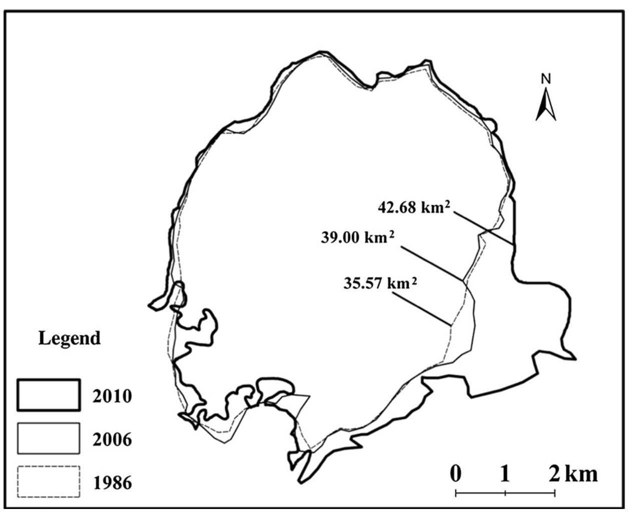

Fig. 6 Variation in East Juyan Lake area during different time periods

Ecological water requirement of East Juyan Lake

Results showed that W was 2.15×10^8 m^3. Among these variables, W_v, W_i, and W_g were 1.36×10^8, 0.24×10^8, and 0.55×10^8 m^3, respectively, and W_v, W_i, and W_g accounted for 64, 10, and 26 % of total W, respectively. The EWD during winter months cannot be considered within the ecological water supplement. This is due to the fact that the lake would be in a frozen state since temperatures would be below 0 °C and vegetation would be in its dormant stage from November to the following March. Given that, the minimum EWD was 1.19×10^8 m^3, and the maximum EWD was 1.80×10^8 m^3 between April and October. If lake area is calculated in accordance to the suitable lake area (35.6 km^2) determined by this study, the minimum EWD would be 1.05×10^8 m^3, and the maximum EWD would be 1.54×10^8 m^3 between April and October. If a groundwater supply of 0.5×10^8 m^3 is also taken into account, then a minimum replenishment quantity of 0.55×10^8 m^3 should be maintained in East Juyan Lake to prevent the lake from drying up throughout the year.

Discussion

The slope of the annual runoff trend line for the Yingluo Gorge station was 0.0453 between 1944 and 2012. This implies that Yingluo Gorge annual runoff has increased due to seasonal increases in water by way of snowmelt deriving from the Tibetan Plateau (Song et al. 2014). However, the interannual variability of runoff showed a decreasing trend in the Zhengyi Gorge station between 1954 and 2012, the slope of the annual runoff trend line being −0.0445. This implies that water consumption increased in the middle reach of Heihe River and increasing trends have grown more pronounced since the 1990s. Under conditions of increasing water consumption in the middle reach of Heihe River, it was found that annual runoff showed a decreasing trend in the lower reach before 2000 where −0.337 was the slope of the annual runoff trend line, annual runoff increased after the implementation of the water diversion project, and 0.221 was the slope of the annual runoff trend line after 2000. As a result of the water extraction that took place in the upper and middle reaches of Heihe River in the past 60 years to supply water for industrial and agricultural usage, flow into Zhengyi Gorge has rapidly decreased even though no significant change has been observed in Yingluo Gorge (Fig. 2), and less water entered into the lower reach of Heihe River. Owing to the lack of water in the lower reach, Ejin oasis became seriously desertified, lakes dried up, and water quality deteriorated. Subsequently, the carrying capacity of pastures declined sharply and large areas of vegetation disappeared altogether (Wang et al. 2011a, b; Si et al. 2005; Guo et al. 2009; Jiang and Liu 2010).

Historical records and field dating have shown that Juyan Lake was originally a very large lake. According to ^{14}C dating, water surface area of Juyan Lake around 3,000 years ago was 800 km^2 (Zhu et al. 1983). It fragmented into East Juyan Lake and West Juyan Lake over time due to decreased inflow. Within the past 100 years water surface area of both lakes has gone through continuous change in response to anthropogenic generated variations in water inflow. The decrease in surface runoff and the cease in channel flow resulted in the drying up of the lakes at the terminus of the Heihe River. For these reasons,

Table 2 Most up-to-date data on the ecological water requirement of East Juyan Lake (2012)

Month	P (mm)	E_w (mm)	A (km^2)	W_v ($10^8 m^3$)	W_i ($10^8 m^3$)	W_g ($10^8 m^3$)	W ($10^8 m^3$)
1	0.33	36.13	42.5	0.02	0.02	0.00	0.04
2	0.23	69.10	42.5	0.03	0.02	0.01	0.06
3	1.23	181.64	42.5	0.08	0.02	0.02	0.12
4	1.38	343.53	42.1	0.14	0.02	0.05	0.21
5	2.86	493.70	41.1	0.20	0.02	0.08	0.30
6	6.01	552.17	40.2	0.22	0.02	0.10	0.33
7	9.96	554.94	38.9	0.21	0.02	0.10	0.33
8	7.96	486.33	38.7	0.19	0.02	0.09	0.29
9	4.22	342.73	40.9	0.14	0.02	0.05	0.21
10	2.56	202.65	42.2	0.08	0.02	0.03	0.13
11	0.45	90.40	42.0	0.04	0.02	0.01	0.07
12	0.26	39.59	42	0.02	0.02	0.01	0.04
Total	37.44	3,392.92		1.36	0.24	0.55	2.15

P is precipitation (mm); E_w is lake water surface evaporation (mm); A is lake area (km^2); W_v is the water demand of lake water surface evaporation (10^8 m^3); W_i is the water demand of the lake itself; W_g is the water demand of lake seepage; and W is the ecological water demand of the terminal lake within the arid inland river basin

Juyan Lake became the focus of intense water regulation. Since the 1940s, for example, great changes have taken place in the hydrological regimes of Juyan Lake. The continuous intensification in water utilization in the oasis located in the middle reaches of Heihe River resulted in drastically reduced discharge to the lower reach (Zhou and Yang 2006). This not only directly influenced the quantity and quality of water resources, but also destroyed the area's natural ecological balance and led to deterioration of the ecological system in the lower reach. In the worse cases, river courses have shortened, and terminal lakes have receded or dried up altogether (Liu 1992).

The lower reach of Heihe River has been designated an area of critical water shortages in China. As a result, the Chinese government has spent heavily in the comprehensive management of the Heihe River Basin. For example, specialized agencies responsible for water diversion have been instigated whose purpose is to solve the critical problem of water shortages in the lower reach of the Heihe River. Water shortages in the lower reach are highly disproportionate. Water flows directly into the former East Juyan Lake, which for all intents and purposes vanished decades earlier. In fact, water diversion should fully serve the lower reach. East Juyan Lake should only be considered as a means of water storage during times of flooding of the Heihe River and as an indicator to determine lower reach groundwater levels. However, EWCP believes the area surrounding East Juyan Lake is an important index of Heihe River water diversion. Therefore, the question that must be addressed is: What is the specific area of East Juyan Lake that must be maintained? This study used correlations between reservoir capacity and lake area of East Juyan Lake (Fig. 4), water level and area of East Juyan Lake (Fig. 5), and variation in area of East Juyan Lake during different periods (Fig. 6) to determine the appropriate East Juyan Lake basin scale. It was concluded that 35.6 km^2 is the most stable lake area size for preservation.

The ecological water demand of the terminal lake is the runoff that flows into the lake in order to maintain or restore ecosystem balance and health of the lake and to fit the various service functions the ecological system requires. This comprises the water demand of lake water surface evaporation, the water demand of aquatic plant evapotranspiration, the water demand of the lake itself, and the water demand of lake seepage. The water demand of lake water surface evaporation accounted for 64 % of the ecological water demand of the terminal lake (Table 2); therefore, water quantity consumption is primarily the result of lake water surface evaporation in this particular arid inland area. The minimum ecological water demand of the lake should therefore guarantee supplemental lake water surface evapotranspiration.

For East Juyan Lake, this study has determined two thresholds for the ecological water demand. The first is the maximum ecological water demand of the lake. If the flow into the lake exceeds maximum ecological water requirements, lake water will diffuse from the bank and lead to flooding. The second is the minimum ecological water demand of the lake. If it is less than the optimum value, the structure and function of the lake ecosystem will be irreversibly damaged. Therefore, guaranteeing water resource allocation and sustainable utilization must take place to determine the minimum ecological water demand of the lake ecosystem.

Conclusions

To protect lake ecosystems from receding, this study focused on quantitative analysis of the correlation between changes in inland lake surface area and human activity over extended time scales. The primary objective of this study was to determine the appropriate East Juyan Lake basin scale and its ecological water requirement. Results showed that the decrease in surface runoff and cease of channel flow resulted in the drying up of the Heihe River terminal lake, 35.6 km^2 is the most stable lake area for preservation, and 0.55×10^8 m^3 is the minimum replenishment quantity required to maintain East Juyan Lake throughout the year without drying up. These results are useful in the protection of such arid lake ecosystems and the planning and rational use of water resources for such inland river basins.

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