Long-term Environmental Dynamics of the Lake Bosten Catchment: Implications for Freshwater Resource Management in NW China

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Abstract

Arid and semiarid regions account for ~ 40% of the world's land area. Rivers and lakes in these regions provide sparse, but valuable, water resources for the fragile environments; and play a vital role in the development and sustainability of local societies. During the late 1980s, the climate of arid and semiarid northwest China dramatically changed from "warm-dry" to "warm-wet". Understanding how these environmental changes and anthropogenic activities affect water quantity and quality is critically important for protecting the aquatic ecosystem and determining the best use of freshwater resources. Lake Bosten is the largest inland freshwater lake in NW China and has experienced inter-conversion processes between freshwater and brackish status. Herein, we explored the long-term water level and salinity trends in Lake Bosten from 1958 to 2019. During the past 62 years, Lake Bosten's water level and salinity exhibited "W" and "M" patterns. Partial least squares path modeling (PLS-PM) suggested that the decreasing water level and salinization during 1958–1986 were mainly caused by anthropogenic activities, while the variations in water level and salinity during 1987–2019 were mainly affected by climate change. The transformation of anthropogenic activities and climate change is beneficial for sustainable freshwater management in Lake Bosten Catchment. Our findings highlight the benefit of monitoring aquatic environmental changes in arid and semi-arid regions over the long-term for the purpose of fostering a balance between socioeconomic development and ecological protection of the lake environment.

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Key Points:

- During 1958–2019, Lake Bosten's water level and salinity exhibited a "W" and "M" pattern, respectively
- Climatic mutation from "warm-dry" to "warm-wet" occurred during the late 1980s in the upstream mountain areas of Lake Bosten catchment
- The climatic mutation and the transform of anthropogenic activities facilitate sustainable freshwater management in NW China

Abstract

Arid and semiarid regions account for ~ 40% of the world's land area. Rivers and lakes in these regions provide sparse, but valuable, water resources for the fragile environments; and play a vital role in the development and sustainability of local societies. During the late 1980s, the climate of arid and semiarid northwest China dramatically changed from "warm-dry" to "warm-wet". Understanding how these environmental changes and anthropogenic activities affect water quantity and quality is critically important for protecting the aquatic ecosystem and determining the best use of freshwater resources. Lake Bosten is the largest inland freshwater lake in NW China and has experienced inter-conversion processes between freshwater and brackish status. Herein, we explored the long-term water level and salinity trends in Lake Bosten from 1958 to 2019. During the past 62 years, Lake Bosten's water level and salinity exhibited "W" and "M" patterns. Partial least squares path modeling (PLS-PM) suggested that the decreasing water level and salinization during 1958–1986 were mainly caused by anthropogenic activities, while the variations in water level and salinity during 1987–2019 were mainly affected by climate change. The transformation of anthropogenic activities and climate change is beneficial for sustainable freshwater management in Lake Bosten Catchment. Our findings highlight the benefit of monitoring aquatic environmental changes in arid and semi-arid regions over the long-term for the purpose of fostering a balance between socioeconomic development and ecological protection of the lake environment.

1. Introduction

Sustainable utilization and regulation of water resources is a major research focus of the global environmental scientific community, especially with respect to inland arid and semiarid regions (Deng & Shi, 2014; Peng et al., 2020; Ragab & Prudhomme, 2002; Rosa et al., 2019). In China, arid and semi-arid regions account for ~ 52.5% of the national territorial area. These regions are primarily supported by oasis economies and irrigation agriculture, where inland rivers and lakes provide sparse, but valuable, freshwater resources for societal use, agriculture, and the fragile ecological environments. Over the last six decades, rapid development of irrigation agriculture and artificial oasis economies have resulted in many inland rivers being over-exploited, which is drastically compromising sustainable societal and economic development (Deng & Shi, 2014).

Central Asia is located further from the oceans than any landmass on Earth, and thus comprises one-third of the world's arid region. As such, rivers and lakes are the major source of freshwater for communities living in the oases (Bai et al., 2011). The rivers and/or lakes within each oasis form a separated catchment. Of particular concern is the Lake Bosten Catchment, a typical watershed that contains River Kaidu and Lake Bosten—the largest inland freshwater lake in northwest China. The Lake Bosten Catchment lies in the center of the Eurasian continent and is characterized by an inland desert climate. Within this catchment, water supply is the top ecological function and provides the highest ecosystem service value (Mamat et al., 2021); but it is also affected by climate change and anthropogenic activities. Since 1987, northwest China has experienced an abrupt climate shift from "warm-dry" to "warm-wet" conditions (Lu et al., 2021; Peng & Zhou, 2017; Shi & Zhang, 1995; Shi et al., 2003). In addition, population growth has modified the scale of agricultural activity and the patterns associated with it. Recent evidence suggests that both climate change and anthropogenic activities affect the River Kaidu's runoff (Chen et al., 2013; Liu et al., 2017); agricultural and wetland environments (Jiang et al., 2020);

and Lake Bosten's area, water level (Dai et al., 2020; Gao & Yao, 2005; Rusuli et al., 2016; Yao et al., 2018), water quality, and salinity (Ba et al., 2020; Liu & Bao, 2020). Due to the combined impact of climate change and anthropogenic activities, dramatic changes in water level and salinity have resulted in the freshwater Lake Bosten transitioning into an oligo-saline lake, which hampers regional ecological security (Tang et al., 2020). However, the long-term variation patterns associated with climate, water resources, and anthropogenic activities, and their quantitative impacts on water level and salinity dynamics in Lake Bosten are still not fully understood.

Herein, long-term historical time series data are used to provide a brief overview of Lake Bosten's water level and salinity dynamics over the past 62 years. Climate change trends (particularly air temperature and precipitation) in the mountain and oasis areas are then respectively explored. Next, the quantity of water resources and how they were utilized throughout different historical periods are investigated and discussed in detail. Subsequently, anthropogenic factors, such as population, sown area of crops (SAC), water consumption, and the primary industry's gross domestic product (GDP), are systematically presented. Finally, the impacts of climatic and anthropogenic factors on Lake Bosten's water level and salinity dynamics throughout different historical periods are quantitatively determined using partial least squares path modeling (PLS-PM). The causes, impacts, and implications of these environmental dynamics are also discussed. This study provides the first extensive examination of long-term aquatic environmental changes in Lake Bosten and sheds new light on sustainable freshwater resource management in arid and semiarid regions.

2. Materials and methods

2.1 The study area

The Lake Bosten Catchment is located in the central Xinjiang Uygur Autonomous Region, northwest China, and covers an area of 4.39×10^4 km^2 (Figure 1). The River Kaidu originates in the snow and glacier covered southern Tianshan Mountains, flows through the small and big Yulduz (ground elevation: 2400~2700 m) and Yanqi Basins (ground elevation: 1031~1200 m), and eventually discharges into Lake Bosten (Ba et al., 2020). This river has a total length of 560 km and exhibited an average annual runoff of ~ 35×10^8 m^3 from 1960–2009 (Chen et al., 2013). The Baolangsumu (BLSM) diversion gate divides the River Kaidu's water into two branches: the eastern branch (eBLSM), which flows into the large lake area occupied by Lake Bosten; and the western branch, which flows into the reed-covered lake wetlands that occupy a small surface area of ~ 300 km^2. As the sole perennial river, it supplies 86.2% of the water delivered to Lake Bosten annually. The seasonal Huangshuigou and Qingshui rivers supply another 7.2% and 2.9%, respectively (Zhong, 2008). In addition, 26 artificial agricultural drainage channels flow into Lake Bosten and its surrounding wetlands (Figure 1).

Previously, Lake Bosten (86°19′–87°28′ E and 41°46′–42°08′ N) was the largest inland freshwater lake in China. It is characterized by a surface area of 1064 km^2 (1047 m above sea level), mean depth of 7 m, maximum depth of 16 m, and total water volume of 73×10^8 m^3. Historically, the lake maintained natural outflow conditions until 1981, when an artificial pumping station was built at the southwest corner of Lake Bosten. A second artificial pumping station followed in 2008 (Gao & Yao, 2005). Since then, the lake water has been pumped out through artificial channels to the River Kongque, where it provides valuable water resources for irrigation, economic development, and the ecology along the lower River Tarim (Liu & Bao, 2020; Yao et al., 2018; Ye et al., 2009).

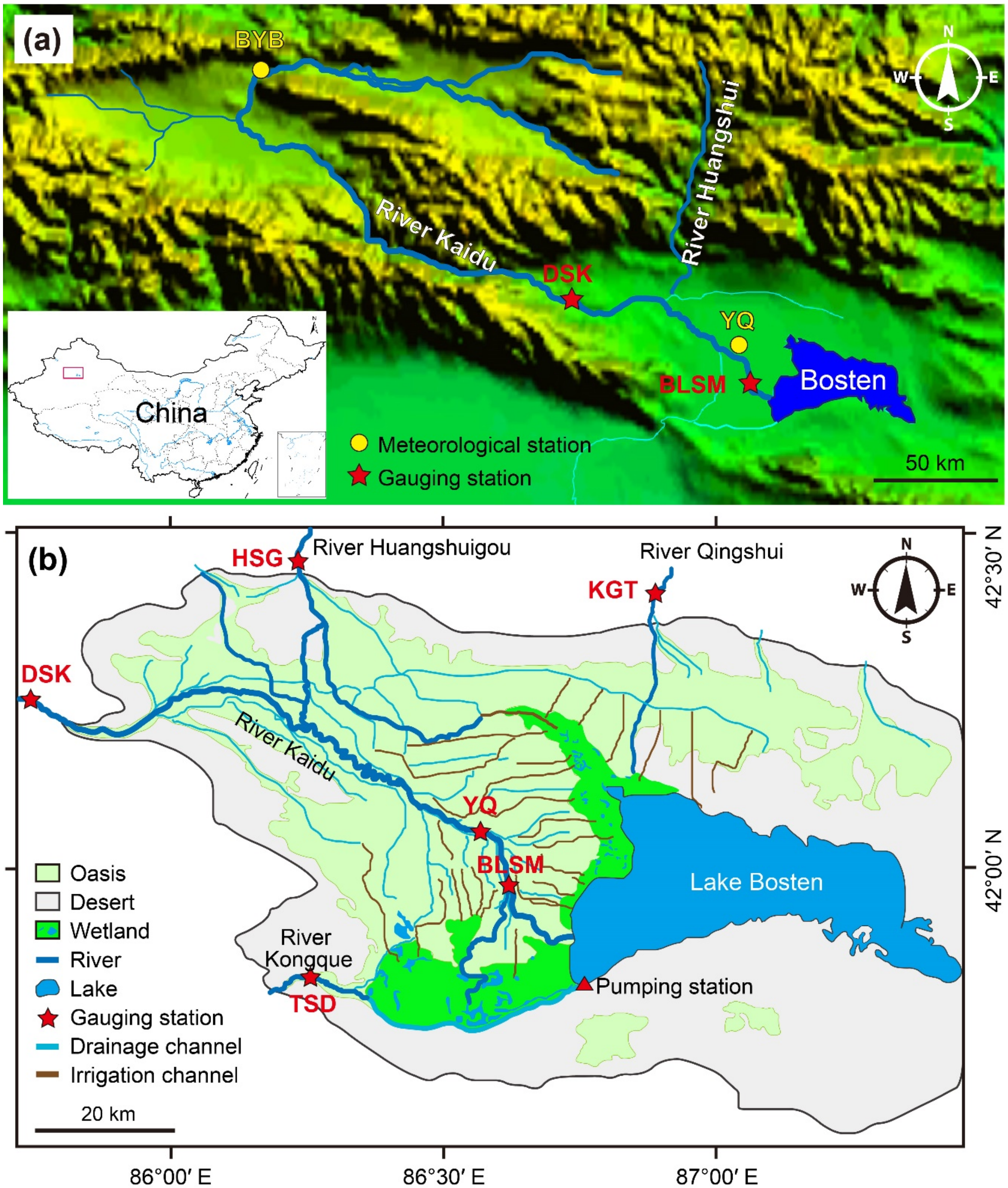

Figure 1. (a) Lake Bosten Catchment, and **(b)** artificial irrigation and drainage channels around Lake Bosten. Abbreviations of meteorological and gauging stations: BYB, Bayanbulak; YQ, Yanqi; DSK, Dashankou; BLSM, Baolangsumu; HSG, Huangshuigou, KGT, Keerguti; TSD, Tashidian.

2.2 Data sources

Lake Bosten's annual water level (averaged from monthly data) and total dissolved solids (TDS) data (1958–2019) were obtained from the Environmental Protection Bureau of Bayingol Mongolian Autonomous Prefecture. Daily meteorological data for the years 1958–2020 came from two stations (Figure 1), i.e., Bayanbulak (BYB, elevation: 2459 m) and Yanqi (YQ, elevation: 1057 m), were provided by the China Meteorological Data Service Center (http://data.cma.cn/). The annual river's annual runoff from Dashankou (DSK) gauging station, lake inflow from the eBLSM, outflow from the River Kongque at Tashidian (TSD) station, and outflow from the pumping stations (PS) located in southeast corner of Lake Bosten were obtained from the Xinjiang Tarim River Basin Management Bureau. Anthropogenic activity data were acquired from the Water Conservancy Bureau and Statistical Yearbook of the Bayingol Mongolian Autonomous Prefecture (Table 1).

Table 1 Data sources on water level and total dissolved solids in Lake Bosten, climate, runoffs, and anthropogenic activities in Lake Bosten Catchment.

Data type	Lake/Station name	Year	Data provider
Water level	Lake Bosten	1958−2019	Environmental Protection Bureau of Bayingol Mongolian Autonomous Prefecture
Total dissolved solids (TDS)	Lake Bosten	1958−2019	
Climatic data	Bayanbulak (BYB)	1958−2020	China Meteorological Data Service Center (http://data.cma.cn/)
	Yanqi (YQ)		
Runoff	Dashangkou (DSK)	1958−2019	Xinjiang Tarim River Basin Management Bureau
	East Baolangsumu (eBLSM)		
	Tashidian (TSD)		
	Pumping station (PS)		
Anthropogenic activity data	Yanqi Basin	1958−2019	Water Conservancy Bureau and Statistical Yearbook of Bayingol Mongolian Autonomous Prefecture

2.3 Data processing

The non-parametric Mann–Kendall (MK) test is widely used for detecting monotonic climatic and hydrological time series trends (Hamed, 2008; Mann, 1945; Salehi et al., 2020; Shadmani et al., 2012), and thus was used in this study to investigate hydro-meteorological data trends. It's important to note that autocorrelation or serial correlation must be applied over successive time intervals prior to looking for trends, as they can increase the chances of significant trends being detected (Hamed & Rao, 1998; Yue et al., 2002). Therefore, autocorrelation detection was performed before applying the MK test, during which *acf()* and *pacf()* functions in R were used to compute the autocorrelation and partial autocorrelation, respectively. For the data influenced by autocorrelation, a modified MK test was performed using the "*modifiedmk*" package v1.5.0 in R (Patakamuri et al., 2020). In this case, the variance correction approach was applied (Yue & Wang, 2004) to eliminate the influence of autocorrelation on the test. The trend's magnitude (i.e., linear rate of change) was calculated using Sen's slope method.

Spearman rank correlations among the variables were calculated using the "*PerformanceAnalytics*" package v1.5.3 in R 3.6.1 (https://www.r-project.org) and the RStudio 1.4.1717 platform. PLS-PM was performed to explore the direct and indirect effects of climatic and anthropogenic factors on water level and TDS in Lake Bosten before (1958–1986) and after (1987–2019) the climatic shift year (Henseler et al., 2017). PLS-PM were run in the "*plspm*" package v0.4.7, following the procedure described by Sanchez (2013).

3. Results

3.1 Long-term water level and salinity dynamics in Lake Bosten

From 1958–1987, Lake Bosten's annual water level depicted a fluctuating downward trend (Figure 2), during which time the water level decreased from 1048.0 to 1045.0 m and the water volume decreased from 84.1 to 53.7 × 10^8 m^3. In contrast, from 1987–2002, the annual water level dramatically increased at a rate of 23 cm/year, ultimately reaching1048.7 m, the highest value ever recorded. Congruently, the water volume soared to 92.6 × 10^8 m^3. This increase was followed by a rapid period of decrease (2003–2013), where the lowest annual water level recorded was 1045.1 m. A continuously increasing water level has been observed since 2014, with 1047.9 m, measured in 2019, being the highest water level recorded during this period.

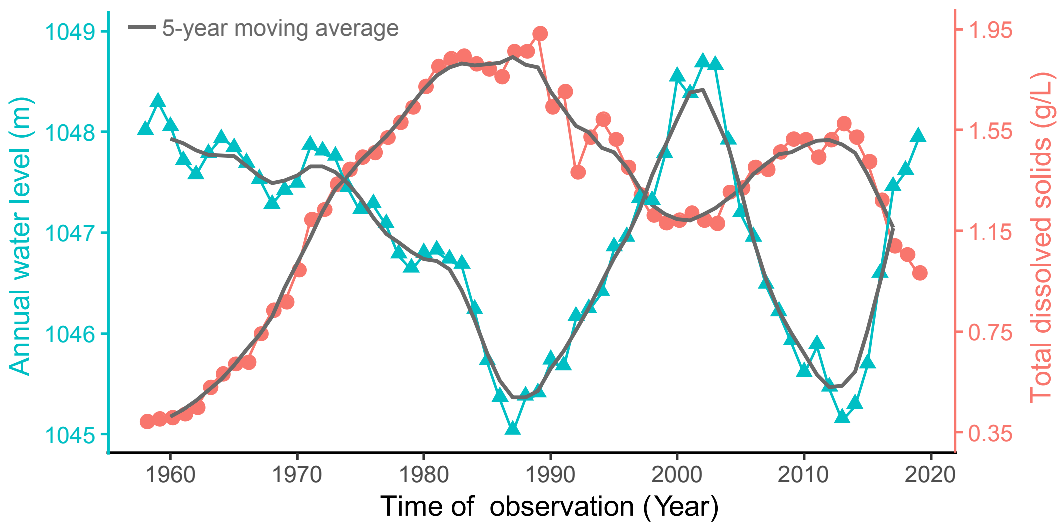

Figure 2. Variations in total dissolved solids (TDS, circle) and water level (triangle) in Lake Bosten over the past 62 years (1958–2019).

Over the past 62 years, Lake Bosten's annual TDS (i.e., salinity) concentration exhibited an opposite trend as compared to its water level (Spearman correlation $\rho = -0.70$, $p < 0.001$; Supplementary Materials Figure S1). From 1958–1989, the salinity in Lake Bosten rapidly increased from 0.39 g/L to 1.93 g/L (Figure 2). In 1971, Lake Bosten's salinity exceeded 1 g/L, thus demarcating the point when it evolved from a freshwater inland lake to an oligo-saline lake. Between 1990 and 2003, the salinity depicted a fluctuating downward trend, yet the lowest recorded value remained > 1 g/L. From 2004–2013, the salinity increased, reaching 1.57 g/L by the end of this period. In recent years, the salinity has been dramatically decreasing, with the lowest recorded value, measured in 2019, being < 1 g/L. When considered together, the data show that over the past 48 years, Lake Bosten has evolved back into a freshwater lake.

3.2 Long-term climatic factor dynamics in the Lake Bosten Catchment

3.2.1 Air temperature dynamics

The MK trend test indicated that from 1958 to 2020, the annual air temperatures, in both the mountain area (BYB Station) and oasis area (YQ Station), showed a significant increasing trend, with rates of increase being equal to 0.14 °C and 0.31 °C per 10 years, respectively (Table 2). In BYB, the mean annual air temperature was –4.56 °C from 1958–1986, and –3.96 °C from 1987–2020 (Figure 3a). In YQ, the annual air temperatures increased linearly from 1958–2020, and depicted a mean value of 8.71 °C. Over the last 34 years, the trend showed significant (p < 0.01) acceleration, and exhibited an average annual air temperature of 9.18 °C (Figure 3b).

Table 2 The non-parametric Mann–Kendall tread test of annual air temperature, precipitation, and runoff in the Lake Bosten Catchment. BYB, Bayanbulak; YQ, Yanqi; DSK, Dashankou; eBLSM, east branch of Baolangsumu; TSD, Tashidian; PS, artificial pumping station. Significance levels: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Item	Station	Corrected Z_c	Sen's slope
Temperature	BYB	3.30**	0.014
	YQ	6.39***	0.031
Precipitation	BYB	2.47*	0.660
	YQ	0.62	0.131
Runoff	DSK	3.82***	0.122
	eBLSM	5.72***	0.166
	TSD	4.32***	0.088
	PS	9.77***	0.167

3.2.2 Precipitation dynamics

With respect to the entire study period (1958–2020), annual precipitation in the mountain area showed a significant increasing trend (mean = 284 mm) with an increase rate being equal to 6.6 mm every 10 years. In contrast, the oasis area depicted a nonsignificant increasing trend (Table 2). In the mountain area, annual precipitation exhibited a significant linearly decreasing trend (p < 0.01) between 1958–1986, while a significant linearly increasing trend (p < 0.05), with an increase rate being equal to 2.1 mm per year, was observed after 1987 (Figure 3c). In the oasis area, the average annual precipitation during the long-term time series (1958–2020) was 76 mm, and no significant linear trend (p > 0.05) was detected in either period of 1958–1986 or 1987–2020 (Figure 3d).

3.3 Long-term runoff dynamics in the Lake Bosten Catchment

Significant increasing annual runoff trends were observed at the River Kaidu DSK and eBLSM inflow stations, where the measured runoff equaled 0.122 and 0.166 × 10^8 m^3/year, respectively (Table 2). A similar trend was recorded at the TSD and PS outflow stations, where the measured runoff equaled 0.088 and 0.167 × 10^8 m^3/year, respectively. At DSK, the mean annual runoff was 32.9 × 10^8 m^3 from 1958–1986, and 38.1 × 10^8 m^3 from 1987–2019 (Figure 4). The lowest and highest annual runoff values at DSK were recorded in 1986 (24.7×10^8 m^3) and 2002 (57.1×10^8 m^3), respectively. Accordingly, the annual water volume that flowed into Lake Bosten from the eBLSM station showed a similar trend. The annual runoff measurements at eBLSM and DSK were significantly correlated (Spearman $\rho = 0.86$, $p < 0.001$; Figure S1). From 1958–1986, the runoff at eBLSM measured 10.5×10^8 m^3; yet the years 1987–2019 marked a 70% increase in runoff to 17.9×10^8 m^3. At the TSD station, the highest annual outflow (mean value = 25.8×10^8 m^3) was recorded between 2000 and 2003, a value that was 2.1 times higher than the 12.0×10^8 m^3 recorded during the 1958–1986 period. Recent years (2013–2019) have shown a rapidly increasing annual outflow trend that parallels the rapid inflow increase from eBLSM (Figure 4). From 1981, when construction began on PS, to 1986, the outflow from Lake Bosten increased to 9.1×10^8 m^3. During the following period, i.e., 1987–1998, the outflow maintained a mean value of 7.7×10^8 m^3. In response to the rainy period from 1999–2002, the outflow from PS showed an increasing trend from 2004–2019, during which time the mean value equaled 11.2×10^8 m^3 (Figure 4). After the climate abruptly changed in1987, an anomalously high increasing annual runoff rate was observed at the DSK and eBLSM stations, while a lagging increasing trend was exhibited at the TSD and PS stations (Figure S2).

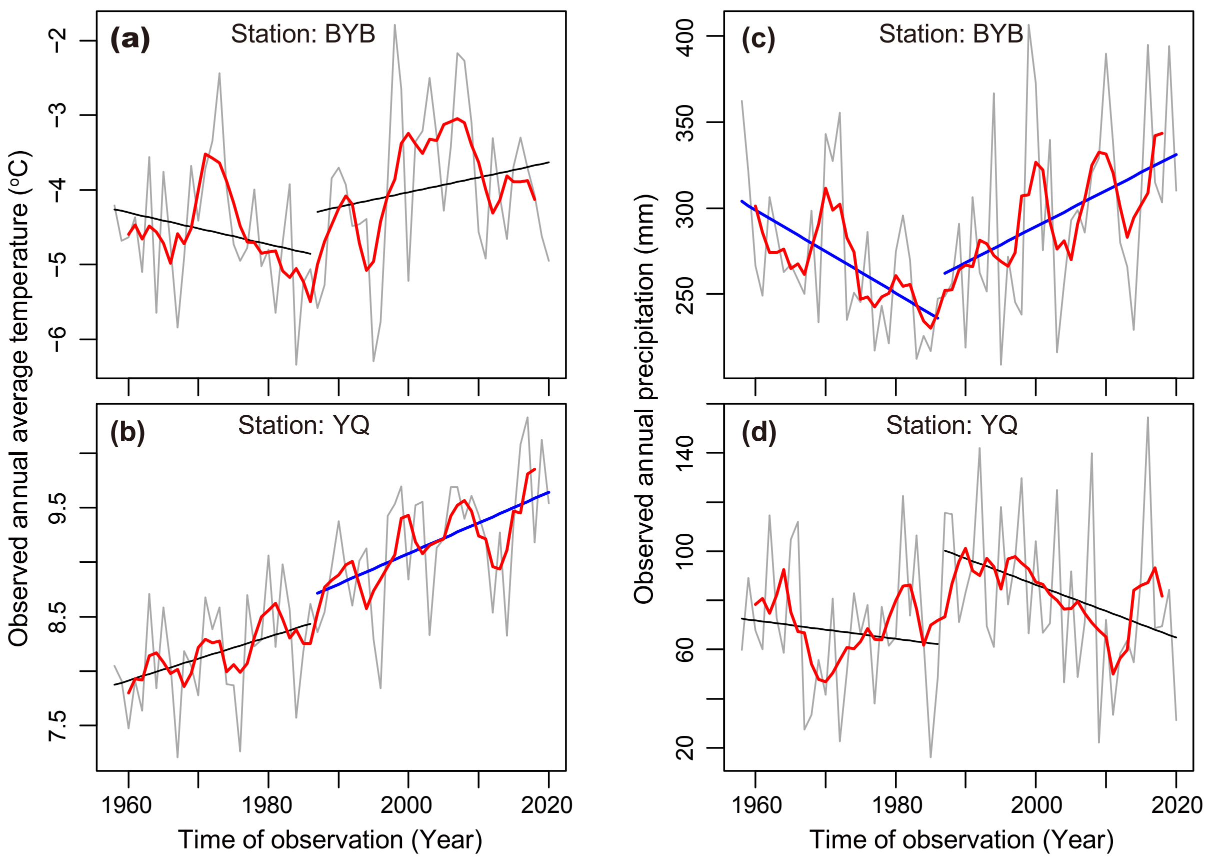

Figure 3. Historical time series data (grey curves), 5-year moving average (red curves), and annual average temperature and precipitation linear trend (black and blue lines) in Bayanbulak (BYB) and Yanqi (YQ) stations from 1958–1986 and 1987–2019, respectively. The black and blue lines represent nonsignificant ($p > 0.05$) and significant ($p < 0.05$) linear trends during each period, respectively.

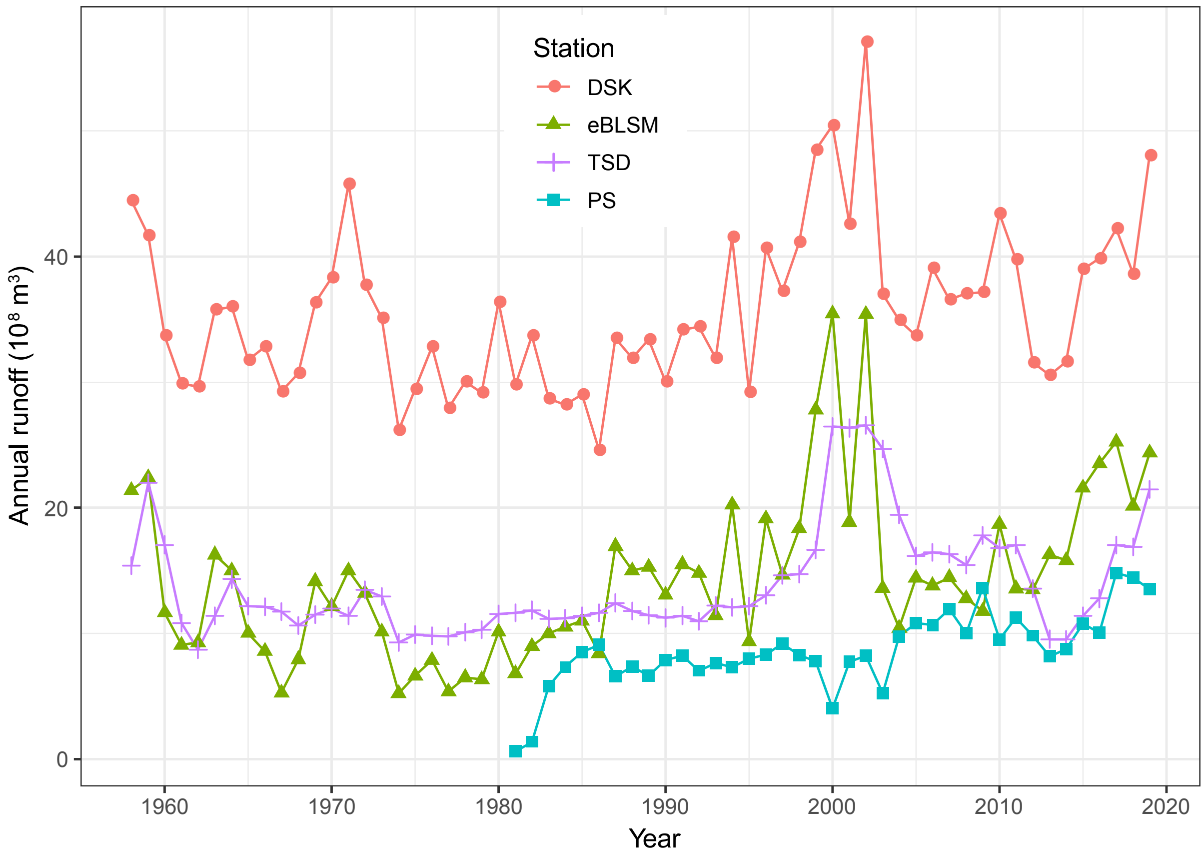

Figure 4. Annual runoff at Dashangkou (DSK), east branch of Baolansumu (eBLSM), and Tashidian (TSD) stations from 1958–2019. Outflow through the pumping station (PS) at the southwest corner of Lake Bosten from 1981–2019.

3.4 Long-term anthropogenic factor dynamics in the Lake Bosten Catchment

In 1958, the Lake Bosten Catchment's population was ~ 100,000 (Figure 5a). Beginning in 1964, the population rapidly increased, reaching ~ 370,000 by 1985. While the population continued to grow over the next 30 years, starting in 1987, the rate of increase slowed relative to the previous period. The population peaked at ~ 500,000 from 2011–2014; and since then has decreased to ~ 420,000, as measured in 2019.

From 1958–2015, the SAC increased ~ 5.6-fold from 24.6 × 10^3 hm^2 in 1958 to 137.2 × 10^3 hm^2 in 2015 (Figure 5b). In recent years, the SAC has steadily decreased, totaled 128.4 × 10^3 hm^2 in 2019. Overall, the SAC was significantly correlated with population (Spearman $\rho = 0.77$, $p < 0.001$; Figure S1).

Water consumption in the YQ Basin over the past 62 years was calculated by evaluating the difference in runoff values between the DSK and BLSM stations. As shown in Figure 5c, water consumption doubled from1958–1978, demonstrating a sharp increase. Since then, water consumption has declined and a mean runoff level of 12.8 × 10^8 m^3 was maintained from 1987–2019; excepting a small period from 2003–2011, where runoff levels were slightly higher at 15.2 × 10^8 m^3.

Primary industry's GDP gradually increased from 1958–1986. Following this period, the increase rate dramatically accelerated and peaked in 2017 with a value of 6967 million RMB yuan (Figure 5d). Over the past 60 years (1958–2017), primary industry's GDP in the Lake Bosten catchment increased ~ 934 times; and was positively correlated with population (Spearman $\rho = 0.63$, $p < 0.001$; Figure S1) and the SAC (Spearman $\rho = 0.96$, $p < 0.001$; Figure S1).

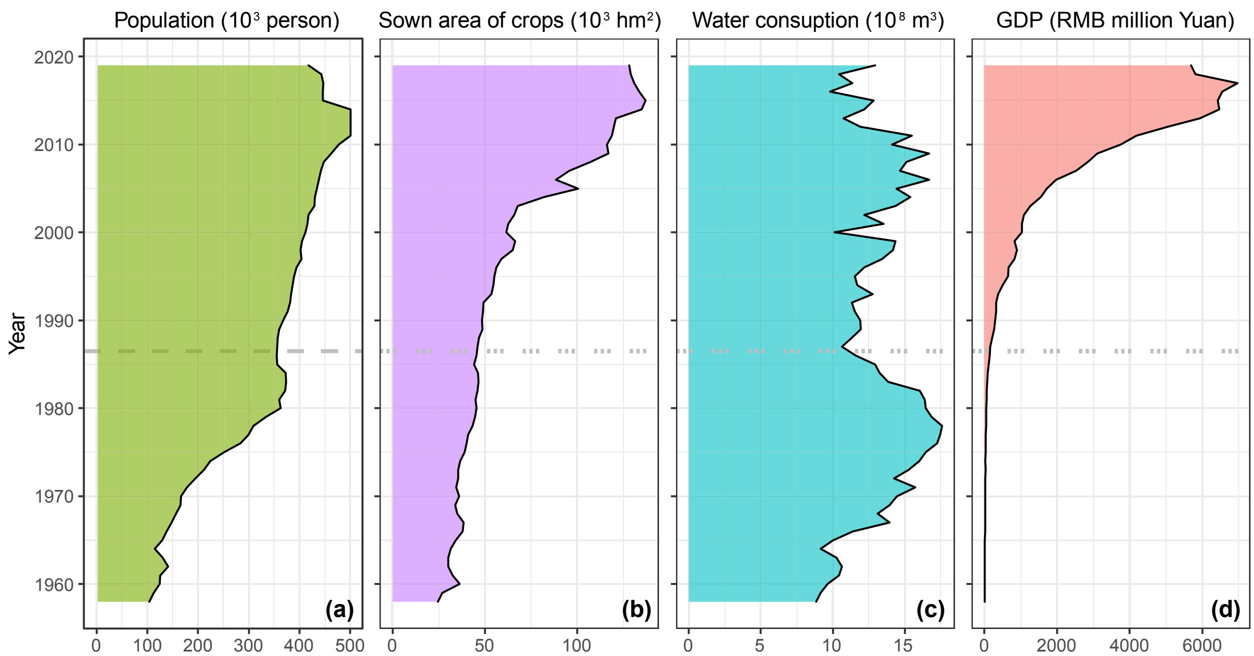

Figure 5. Variations in **(a)** population, **(b)** sown area of crops (SAC), **(c)** water consumption, and **(d)** gross domestic product (GDP) of the primary industry in the River Kaidu catchment during 1958–2019.

3.5 Effects of climatic and anthropogenic factors on water level and TDS in Lake Bosten

PLS-PM results showed that both the water level and TDS in Lake Bosten were affected by different mechanisms, depending on the period (Figure 6). From 1958–1986, water level was primarily negatively affected by anthropogenic activities ($R^2 = -0.83$, $p < 0.001$) and weakly positively affected by runoff from DSK ($R^2 = 0.17$, $p < 0.05$) due to the climate within the BYB during that period. During that same period, 1958–1986, only anthropogenic activity had significant, positive direct effects on TDS ($R^2 = 0.98$, $p < 0.001$). However, from 1987–2019, only the DSK runoff showed significant, positive direct effects on water level ($R^2 = 0.68$, $p < 0.001$), while both the DSK runoff ($R^2 = -0.63$, $p < 0.001$) and anthropogenic activity ($R^2 = -0.41$, $p < 0.05$) exhibited significant, negative direct effects on water level. When considering the whole study period, climate in mountain area (BYB) had significant direct effects on the DSK runoff, yet local climate (YQ) showed no significant effects on water level or TDS (Figure 6).

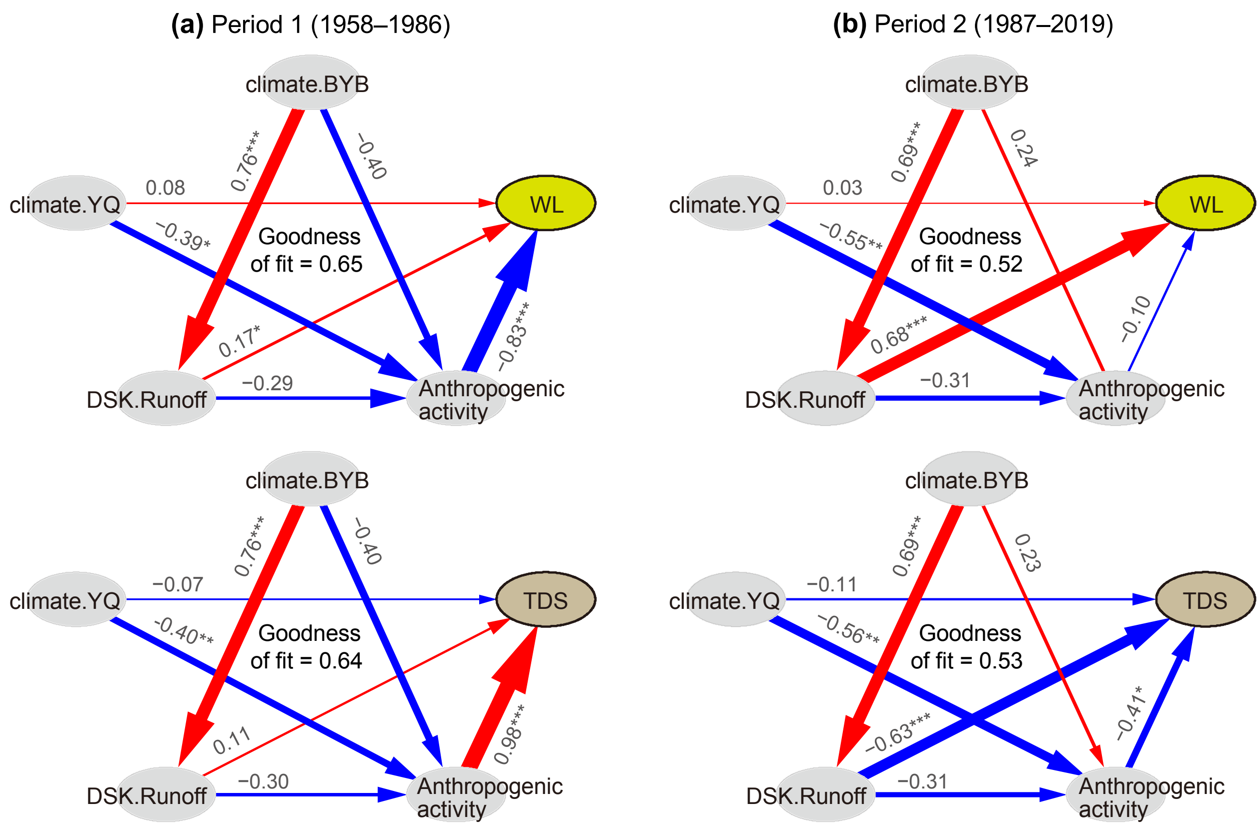

Figure 6. Partial least squares path model (PLS-PM) showing the direct and indirect effects of climate and anthropogenic factors on water level (WL) and total dissolved solids (TDS) in Lake Bosten during the two periods of **(a)** 1958–1986 and **(b)** 1987–2019. Climate.BYB and climate.YQ represent climatic factors (precipitation and air temperature) in the Bayanbulak and Yanqi meteorological stations, respectively. DSK.Runoff represents the runoff at the Dashangkou gauging station, which is rarely affected by anthropogenic activity and herein is considered an indirect climate factor. Anthropogenic activity factors include population, SAC, water consumption, and GDP of the primary industry in the Lake Bosten Catchment, as well as outflow through the artificial pumping station at the southwest corner of Lake Bosten. Larger path coefficients are shown as wider arrows and red and blue colors indicate positive and negative effects, respectively. Path coefficients and coefficients of determination (R^2) were calculated using 999 bootstraps. The significance levels are indicated by * ($p < 0.05$), ** ($p < 0.01$) and *** ($p < 0.001$). Goodness of fit is a measure of the model's overall predictive power.

4. Discussion

4.1 Impacts of climatic and anthropogenic factors on Lake Bosten's water level

In general, the water level in a lake is primarily controlled by the quantity of water input and output, including water that is gained or lost due to local precipitation and evaporation, respectively. However, in the YQ Basin where Lake Bosten resides, the average annual precipitation was only 76 mm (Figure 3d). Furthermore, due to the decreased mean wind speed and sunlight hours, as well as increased mean humidity (Figure S3), evaporation in the YQ Basin depicted a declining trend (Chen et al., 2013; Xia et al., 2003). As such, total runoff, which is regulated by climate, is the main water level determinant. However, it's important to note that anthropogenic activities regulate the quantity of runoff from the River Kaidu that makes it to Lake Bosten, and therefore is also a major determinant in the lake's water level.

Total runoff in the River Kaidu is monitored at DSK station and is primarily determined by upstream precipitation and temperature (affect the quantity of glacier melt runoff). Results from this study demonstrate that air temperature and precipitation in the upstream River Kaidu area have increased significantly over the past 63 years (Table 2, Figure 3), a trend that is especially pronounced since the abrupt climatic change that began in 1987. This continuous increase in air temperature and precipitation directly impacts the quantity of runoff generated. Previous studies have demonstrated that higher air temperature leads to an increase in the amount of glacier melt water (Farinotti et al., 2015; Sun et al., 2010). For example, Sun et al. (2010) found that the glacier covered area in the Lake Bosten Catchment's mountainous regions diminished 40% from 1984–2000. Moreover, the significantly enriched precipitation in the mountain area since 1987 has increased the quantity of runoff that passes through DSK on its way to the YQ Basin (Figures 3 and 4), which in turn has increased inflow to Lake Bosten through eBLSM (Figure 4).

The PLS-PM results showed that from 1958–1986, Lake Bosten's water level was mainly affected by anthropogenic activity (Figure 6a). During this period, the YQ Basin underwent a rapid population increase that was accompanied by large-scale cultivation (Figure 5). Water consumption, 87% of which was attributed to agricultural irrigation (Xia et al., 2003), increased from 8.83×10^8 m^3 in 1958 to 17.58×10^8 m^3 in 1978; and thus, runoff to DSK decreased accordingly. Because agricultural irrigation starts in May, Lake Bosten's water level decreased in spring and remained relatively stable through the summer, despite that fact that precipitation and the runoff into the River Kaidu are highest during the summer season (Figure S4). Environmental changes resulting from the intense agricultural activity are evident in land use remote sensing data (Mamat et al., 2021) and Lake Bosten's sedimentary record (Zhang et al., 2012). Therefore, the amplified anthropogenic activity during this period was the dominant factor impacting water level decline in Lake Bosten.

In contrast, the PLS-PM results showed that from 1987–2019, Lake Bosten's water level was most significantly affected by the runoff in DSK, as opposed to anthropogenic activity (Figure 6b). Despite the fact that the SAC increased ~ 3-fold (Figure 5b) due to natural grassland and wasteland reclamation (Wang et al., 2015), water consumption remained relatively stable during this period (Figure 5c). This phenomenon may be partially attributed to stricter water resource regulations and use of water-saving irrigation patterns, which resulted in the irrigation quota decreasing from 25,200 m^3/hm^2 in the 1960s to 9,075 m^3/hm^2 in 2002 (Xia et al., 2003). Another possible explanation is the increase in groundwater exploitation that has taken place over the past 60 years. Prior to 2000, the volume of groundwater exploitation was $< 1.25 \times 10^8$ m^3. That value increased to 6.92×10^8 m^3 by 2011 and has remained $> 5 \times 10^8$ m^3/year up to the present (Wu et al., 2018; Zhang et al., 2021b). These data suggest that in general, agricultural activities during this period did not have an evident negative effect on water level fluctuations. However, a sharp water level decline was observed from 2003–2013 (Figure 2), during which time annual runoff in the River Kaidu had shifted from high to normal flow. Over the course of these 10 years, water input that entered the lake through eBLSM remarkably decreased (Figure 4, Figure S5); while water output through the pumping stations dramatically increased (Figure 4, Figure S2). Thus, the 2003 – 2013 water level decline is mainly attributed to hydraulic regulation activities.

4.2 Impacts of climatic and anthropogenic factors on TDS in Lake Bosten

Prior to the 1960s, Lake Bosten was composed of freshwater that was characterized by a TDS < 0.4 g/L (Figure 2). By 1971, it had evolved into an oligo-saline lake that reached peak TDS in the late 1980s. The PLS-PM results showed that from 1958–1986, the TDS in Lake Bosten was significantly and positively affected by anthropogenic activity (Figure 6a). During this period, ~ 22×10^3 hm^2 of agricultural land was newly cultivated. Furthermore, > 20 main irrigation channels, with a combined total length of 594 km were built; as were 26 main drainage channels, with a combined total length of 552 km (Guo, 2011). Because > 73% of the newly cultivated land contained salinized soil (Xia et al., 2003), a large amount of freshwater was harvested from the River Kaidu for the purpose of salt-leaching (Figure 5c). As a result, from 1963–1982, ~ 2.6×10^8 m^3 of agricultural wastewater containing 52.9×10^4 t salt was discharged into Lake Bosten on a yearly basis (Xia et al., 2003). Thus, the large-scale agricultural cultivation, which subsequently produced a gargantuan amount of salty wastewater discharge, was primarily responsible for the salinization of Lake Bosten.

The PLS-PM results showed that from 1987–2019, Lake Bosten's TDS was significantly and negatively affected by both the runoff in DSK and anthropogenic activity (Figure 6b). During this period, climate change increased precipitation in the upstream mountain areas (Shi et al., 2003), resulting in higher amounts of freshwater inflow into Lake Bosten, and the subsequent decline in TDS. In addition, anthropogenic activities, such as decreasing consumption of freshwater in the YQ Basin (Figure 5c) and increasing the amount of outflow through the pumping stations (Figure 4), aided the decline of TDS in Lake Bosten. Since 1981, when the east pumping station was put into operation, water with high TDS has been pumped out. In response, Lake Bosten ceased accumulating salt and is currently undergoing desalinization (Wang et al., 2009).

4.3 Implications for future catchment regulations

Results from this study showed that the water level decline and rapid increase in TDS that occurred in Lake Bosten between 1958 and 1986 were mainly caused by anthropogenic activity in general, and agricultural expansion specifically. In contrast, variations in water level and TDS from 1987–2019 primarily resulted from a combination of climate change and transitioning to lower consumption water resource utilization practices and regulation patterns. It is important to acknowledge that these findings may be somewhat limited by the restricted parameters that were considered as contributors to climate change and anthropogenic activities when PLS-PM was performed. Although the importance of climate change and anthropogenic activities on water level and TDS in Lake Bosten still needs to be quantitatively analyzed, the relative importance of both factors throughout different historical periods provides deep insight into their impact on variations in water level and TDS in Lake Bosten over the past 62 years.

At the end of 1980s, the climate in the Lake Bosten Catchment abruptly changed to warm-wet (Shi et al., 2003; Zhang et al., 2021a), which was beneficial for stabilizing the water level and desalinating Lake Bosten. However, there are still great uncertainties concerning how long this climate pattern will last. Moreover, meltwater from glaciers and snow is not sustainable long-term, as the glacier cover in the River Kaidu's mountainous regions is shrinking in response to the increasing air temperature. In addition, the onset of this warm-wet climate increased the frequency and intensity of extreme precipitation events and flooding over short time scales or local spatial scales (Huang et al., 2020; Lu et al., 2021; Ning et al., 2021; Yao et al., 2022), which will affect water level fluctuations and lake ecosystem stability. Finally, detailed studies are required to determine what water level is suitable considering sustainable economic development and freshwater resource availability (Rusuli et al., 2016).

From 1958–1986, over-exploitation of freshwater resources for agricultural irrigation caused Lake Bosten to undergo both a rapid water level decline and salinization. While the situation has significantly improved since 1987 when a series of changes were implemented, climate change and anthropogenic activity have introduced several additional issues that impact sustainable freshwater management in the Lake Bosten Catchment. Thus, policymakers should consider the uncertainty of long-term climatic change patterns, what constitutes reasonable agricultural acreage, input and output of water and salt, and optimal groundwater exploitation. As such, future studies need to be conducted that take these issues into account.

5. Conclusions

The annual water level exhibited a "W" pattern, while that of TDS depicted an "M" pattern during the past 62 years (1958–2019). Significant increasing trends of annual air temperature and precipitation were recorded in the upstream mountain areas of Lake Bosten Catchment, especially in the late 1980s. Accordingly, runoff in the River Kaidu, as well as inflow to and outflow from Lake Bosten increased significantly. The decreasing water level and salinization experienced by Lake Bosten from 1958–1986 were mainly caused by anthropogenic activities, while the variations in water level and TDS from 1987–2019 were mainly affected by climate change. After the late 1980s, freshwater consumption from River Kaidu remained relatively stable due to implementation of water saving irrigation technologies and groundwater exploitation. Considered together, these results suggest that the water environmental conditions have been improving, as evidenced by the fact that Lake Bosten transitioned back into a freshwater lake after being oligo-saline for 48 years. These findings have vital implications for sustainable freshwater management in arid and semi-arid regions given the uncertainty associated with future environmental change scenarios. The next challenge is to investigate how to determine an appropriate agricultural scale given the local freshwater resources and the changing environmental conditions.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

XT designed the research. XT, GX, JH, JZ, and GG performed the research. XT, GX, JD, KS, and YH analysed the data. XT wrote the manuscript with the help of all authors. GX, JD, and KS participated in the discussion and modification.

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