Theor Appl Climatol
DOI 10.1007/s00704-014-1126-y

ORIGINAL PAPER

Investigation of the dramatic changes in lake level of the Bosten Lake in northwestern China

Mengjing Guo · Wei Wu · Xiaode Zhou · Yongmin Chen · Jing Li

Received: 10 October 2013 / Accepted: 6 February 2014

Abstract Bosten Lake, located in the arid region of northwest China, is the largest inland freshwater lake in China. Water resources in Bosten Lake are of great importance for the regional drinking water supply, agricultural irrigation, and economic development of Xinjiang province. In this study, the dynamics of the lake level in Bosten Lake were investigated from 1956 to 2010. We found that the lake level experienced three different periods of change due to the combined influences of climate variation and human activities. Generally, the lake level has shown a significant downward trend since the first observation started in 1956 and dropped to its lowest level in 1987. Thereafter, the lake level presented a continuous upward trend and rose to its highest value in 2002. Then, the level decreased dramatically from 2002 to 2010. A water balance model and the climate elasticity method were used to estimate the reasons for the lake level changes of Bosten Lake. The results showed that an increase in lake evaporation led to the continuous decrease in lake level from 1958 to 1987. Then, human-controlled lake outflow and increasing lake inflow together led to the increase in lake level from 1988 to 2002. During 2003 to 2010, the emergency project of transferring water to Tarim River led to the increase in lake outflow, while the lake inflow obviously decreased because of a decrease in precipitation. These factors resulted in a sharp decrease in the lake level from 2003 to 2010. The changes in lake level indicate changes in available water resources from Bosten Lake. This reason for the analysis of the change in lake level in this study is to support the water resources management of Bosten Lake.

1 Introduction

Arid and semi-arid lakes are important inland ecosystems; they provide vital sources of water for plants' and animals' survival and development (Bai et al. 2011; Coops et al. 2003; Lioubimtseva and Henebry 2009; Parisopoulos et al. 2009). In general, lakes in arid areas are highly sensitive to the effects of climate change and human activities. Therefore, they can serve as an important indicator to reflect the regional environmental change on a timescale of years to hundreds of years (Gibson et al. 2006b; Li and Morrill 2013). The variability in lake water quantity is directly reflected in the fluctuations of lake level. A sustained decrease in lake level can lead to the diminishing of lake wetlands, degradation of vegetation, and damage to biodiversity and fishery resources, while extremely high levels will bring about the submerging of farmland, soil salinization, and growth of flood risk. Therefore, it is crucial to understand the trends in lake level and to quantitatively evaluate the effects of the natural and anthropogenic environment and planning (Delju et al. 2013; Parisopoulos et al. 2009).

Many studies have been conducted to investigate the variation of lake level, for example, at the Great Lakes in America and Canada (Lenters 2001; Quinn 2002), Lake Neusiedl in Austria (Soja et al. 2013), Lake Tana on the Ethiopian plateau (Kebede et al. 2006), and Lake Victoria, which is shared by Uganda, Kenya, and Tanzania (Swenson and Wahr 2009). However, most of these studies focused on humid areas, and less attention has been paid to arid lakes.

Bosten Lake, the largest inland lake in China, belongs to the inland arid area. It provides valuable but limited water

---

M. Guo (✉) · W. Wu · X. Zhou
State Key Laboratory Base of Eco-Hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an, Shaanxi, China
e-mail: guomengjing263@163.com

Y. Chen
Xinjiang Environmental Protection Academy of Science, Urumqi 830011, China

J. Li
Northwest Hydro Consulting Engineers, CHECC, Xi'an, Shaanxi, China

resources for regional drinking water supply, agricultural irrigation, and economic development (Huang et al. 2009; Zuo et al. 2006). In addition, the lake also plays an importance role in flood control, fish production, and wildlife breeding.

Under the effects of climate change and human activities (Liu et al. 2013b), the Bosten Lake basin experienced significant changes, for example, increasing temperature and precipitation (Fengqing et al. 2005; Ling et al. 2012), decreasing evaporation (Xu et al. 2010; Chen et al. 2009), dam construction, and land use change (Gregory 2006; Labat et al. 2004; Lioubimtseva and Henebry 2009). These factors have caused three dramatic fluctuations of the lake level over the past 50 years. To be specific, the lake level has shown a significant downward trend since 1956 and dropped to its lowest level in 1987. Thereafter, the lake level presented a continuous upward trend and reached a peak in 2002. Then, the level began to decline dramatically from 2002 to 2010. Fluctuations in lake level of as much as 3.7 m took place during just 15 years in this large-scale natural lake. This is a very unusual phenomenon in terms of lake level variation in lakes in nearby regions. For example, the Aral Sea has shrunk steadily since the early 1960s, and its level has fallen by 23 m over the past decades (Micklin 2007). Balkhash Lake and Ebinur Lake also showed continuous decreases in lake level, while Alakol Lake and Issyk-Kul have shown no obvious changes since the 1950s (Ma et al. 2007; Romanovsky 2002).

The long-term variations of lake level involve various factors, including changes in lake inflow, outflow, evaporation, and water diversion (Deus et al. 2013; Sun et al. 2012; van Oel et al. 2013). Which is the most important driving factor? The answer to this question is very important for regional water resources management and planning for Bosten Lake. However, few works in the literature have reported on the variability of the lake level and the causes of dramatic fluctuation.

The purposes of this study are to reveal the unusual phenomenon of dramatic variability of Bosten Lake level and to find out the main driving factors causing the phenomenon. To achieve this objective, firstly, the temporal and spatial variability of the lake water budget factors (inflow, outflow, and storage) is investigated. Then, the contributions of various factors to the lake fluctuations are analyzed based on the climate elasticity method and water balance equation. Finally, we quantitatively assess the effects of various water budget factors on lake level fluctuations in different periods. The finding can enhance our understanding of the impacts of climate change and human activities on the lake shrinkage or expansion in arid areas.

2 Study area and data

2.1 Study area

Bosten Lake (41° 56′ N–42° 14′ N; 86° 40′ E–87° 26′ E) is located in the south of Xinjiang Uygur Autonomous Region, an arid area in the northwest of China, between Tianshan Mountains and Taklimakan Desert (Fig. 1). The lake is the largest inland freshwater lake in China. It is about 55 km long and 25 km wide, covering a lake area of more than 1,000 km^2, with maximum and average water depths of 17 and 8.2 m, respectively (Cheng 1995). The total storage capacity is 8.8 km^3, and the mean residence time of lake water is 4.8 years (Lee 2010). The climate of the Bosten Lake basin is principally influenced by westerlies throughout the summer season and characterized by a high evaporation rate and low precipitation. The mean annual air temperature of the lake region is about 6.3 °C, potential evaporation is as high as 2,000 mm, and the mean annual precipitation is only about 70 mm (Mischke and Wünnemann 2006; Wünnemann et al. 2006).

The lake is an open catchment lake which lies at the end of Kaidu River and the beginning of Kongque River, and the total lake basin area is about 56,000 km^2. The lake inflow mainly comes from Kaidu River, which contributes about 95 % of the total water inflow (Gao and Yao 2005; Limei et al. 2013; Mischke and Wünnemann 2006). The lake kept natural outflow states at all times in history until an artificial construction pumping station was built in 1983. Since then, the lake water has been pumped to recharge the Kongque River via a channel.

2.2 Data use

The distribution of meteorological and hydrological stations in the lake basin is shown in Fig. 1. Monthly mean lake level data were obtained from the Xinjiang Environmental Protection Academy of Science. Annual lake inflow and outflow data were taken from the Baolangsumu (BLSM) and Tashidian (TSD) hydrological stations. The annual precipitation and pan evaporation records were collected from Xinjiang Meteorological

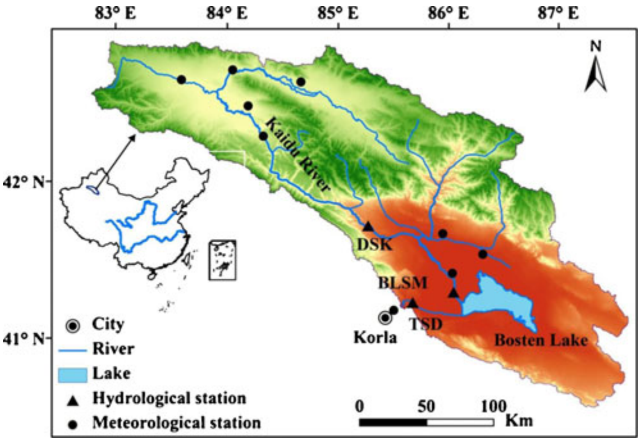

Fig. 1 The study area. *DSK* represents the hydrological station of Dashankou; upstream of the station is a mountain area and downstream is a plain area. *BLSM* represents the hydrological station of Baolangsumu, which is the nearest station to Bosten Lake; *TSD* represents the hydrological station of Tashidian, which is the outlet gauging station of the lake

Bureau and Xinjiang Hydrology Bureau. Pan evaporation cannot represent the actual evaporation from the lake surface. In general, pan evaporation is larger than actual lake evaporation under the same climatic conditions. Traditionally, the actual lake evaporation is estimated using the pan evaporation multiplied by a conversion coefficient (Liu et al. 2011a, b). The conversion coefficient of Bosten Lake is set to 0.47, which was determined by Xia et al. (2003). In the upper catchment, the annual streamflow of Kaidu River was acquired from Dashankou (DSK) hydrological station, and daily meteorological data were provided by Xinjiang Meteorological Bureau. All of these data cover the time span between 1956 and 2010.

3 Methods

3.1 Water balance and model

A well-established water balance often leads to a better understanding of a hydrological system (Lenters 2001). The basic strategy relies on estimation of total water input to the lake as the amount of lake inflows and direct precipitation on the lake surface and estimation of total water output from the lake as the amount of lake outflow and evaporation from the lake surface, using lake level records to characterize storage changes (Gibson et al. 2006a). As Bosten Lake is an open catchment lake, the annual hydrologic water balance equation for the lake can be expressed as:

$$\Delta S = Q_{\text{in}} + P_{\text{L}} - Q_{\text{out}} - E_{\text{L}} \pm G \pm \text{error} \tag{1}$$

where ΔS is the variation in lake water storage (km^3), P_{L} is the precipitation on the lake surface (km^3), Q_{in} is the inflow to the lake (km^3), E_{L} is the evaporation from the lake surface (km^3), Q_{out} is the outflow from the lake (km^3), and $G\pm$error is the residual of the water balance calculation, which mainly consists of the measurement errors and net groundwater exchange. Due to the high complexity of the groundwater exchange process, it is very difficult to quantitatively estimate the net groundwater exchange around the lake. Moreover, the volume of water exchange between the lake and groundwater is very small compared with the other water balance factors (Cheng 1995). Thus, it is reasonable to consider the groundwater flow as a residual as part of the lake balance model.

3.2 Climate elasticity method

Climate change and human activities are regarded as the two most important drivers of changes in watershed streamflow (Liu et al. 2012, 2013a). In this paper, climate variability refers primarily to the variation of precipitation and evaporation. The impacts of human activities on the Bosten Lake inflow refer to the direct water consumption upstream and indirect runoff response to land use change. In this study, the climate elasticity method (Gibson et al. 2006a; Sankarasubramanian et al. 2001; Zheng et al. 2009) is used to quantitatively separate the impacts of climate change and human activities on variation in streamflow into Bosten Lake.

For a given catchment, the change in streamflow between the different periods (ΔQ) can be regarded as

$$\Delta Q = \Delta Q_{\text{C}} + \Delta Q_{\text{H}} \tag{2}$$

where ΔQ_{C} and ΔQ_{H} are changes in streamflow due to climatic variation and human activities, respectively. The change in streamflow impacted by climatic variation (ΔQ_{C}) can be approximately estimated as follows (Arora 2002; Dooge et al. 1999):

$$\Delta Q_{\text{C}} = \Delta Q_P + \Delta Q_{E_0} = (\varepsilon_P \Delta P/P + \varepsilon_{E_0} \Delta E_0/E_0)Q \tag{3}$$

where ΔQ_P and ΔQ_{E_0} are the contributions of changes in P and E_0 to change in Q, respectively. ΔP and ΔE_0 are the changes in P and E_0, respectively. ε_P and ε_{E_0} are the climate elasticity of streamflow to P and E_0, respectively. The following equation, based on the Budyko hypothesis (Budyko 1969), can be used to calculate ε_P and ε_{E_0} :

$$\varepsilon_P = 1 + \frac{\phi F'(\phi)}{1 - F(\phi)}, \text{ and } \varepsilon_P + \varepsilon_{E_0} = 1 \tag{4}$$

where ϕ is taken as a function of the aridity index ($\phi = E_0/P$). In some literatures, many forms of $F(\phi)$ and $F'(\phi)$ have been presented by using the Budyko hypothesis of water and energy balance. The formula of Zhang et al. (2001) is used in this paper, which can be expressed as

$$\begin{cases} F\ \ (\phi) \ = \ (1+\omega\phi) \ / \ (1+\omega\phi+1/\phi) \\ F'(\phi) = \left(\phi^{-2} + 2\omega\phi^{-1} + \omega - 1\right)/(1+\omega\phi+1/\phi)^2 \end{cases} \tag{5}$$

where $F(\phi)$ is a function of ϕ and $F'(\phi)$ is the derivative of $F(\phi)$ with respect to ϕ. ω is the plant-available water coefficient related to vegetation type (Zhang et al. 2001), which is a key model parameter for hydrological sensitivity and the analysis method. Zhang et al. (2004) suggested that ω should be set to 2.0 for forest and 0.5 for pasture. However, real catchment cover is far more complex than a single vegetation type. Thus, the parameter is often calibrated by comparing long-term annual actual evapotranspiration calculated by using Zhang's curve and the water balance equation.

4 Results and analysis

4.1 Long-term changes in lake level

The variability of observed annual lake level from 1956 to 2010 is shown in Fig. 2. Overall, lake level did not vary along

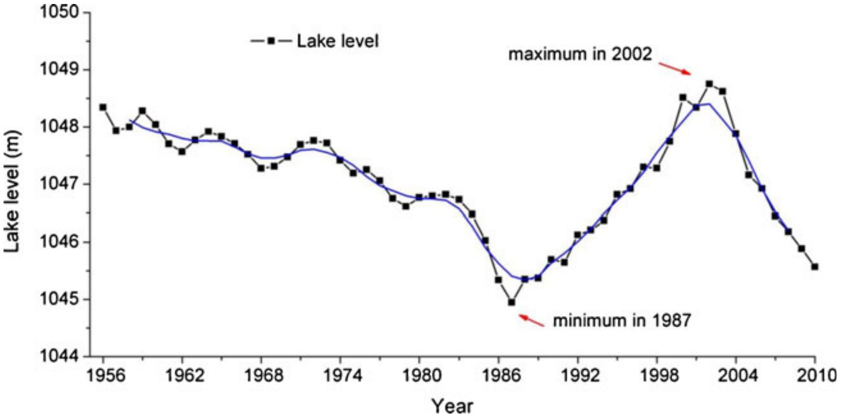

Fig. 2 Variation of the annual lake level from 1956 to 2000. The *blue line* shows the 5-year moving average

a simple linear trend. There are two obvious abrupt changes in the trend of lake level. The first took place in 1987 and the second in 2002. In correspondence with the abrupt changes, the time series is divided into three periods: 1956–1987 (period I), 1988–2002 (period II), and 2003–2010 (period III). The lake level in period I presented a significant decreasing trend and dropped from 1,048.34 m in 1956 to 1,044.73 m in 1987. Thereafter, the lake level showed a continuous upward trend and reached a peak of 1,049.33 m in 2002, having risen by 4.6 m in just 15 years. Afterwards, the level began to decline dramatically. By 2010, the observed lake level was only 0.6 m higher than the record minimum (in 1987). In addition, the fluctuation of lake level was growing in intensity, with the average rate of change during the three periods being −0.11, 0.31, and −0.47 m/a, respectively.

The surface area and water storage of the lake underwent a similar pattern of variability from 1956 to 2010 (Table 1). During these 55 years, the lake level rose during 24 years and fell during 31 years, which account for 43 and 67 % of the total years, respectively.

4.2 Variation of the hydro-climatic factors in the lake

The hydro-climatic conditions are probably the most important determinants of the maintenance of the natural hydrologic system of the lake. From the point of view of lake water balance, the hydro-climatic conditions involve the lake inflow, lake outflow, precipitation, and evaporation on the lake surface. Together, they compose the inputs and outputs of the lake water circulation system and determine the increase or decrease of water storage.

Lake inflow (Q_{in}) mainly comes from Kaidu River, which contributes about 95 % of the total water input. The observed annual runoff from the station of BLSM is used to analyze the variability of lake inflow from 1956 to 2010. The fluctuation characteristics of lake inflow seem to be highly consistent with the lake level variation (Fig. 3a). The average lake inflows in the three periods are 2.04, 2.71, and 2.17 km^3/a, respectively (Table 2).

With the pumping station, which began operation in 1983, the lake level can be controlled by human management. It is clear that there was a remarkable difference after the commencement of operation of the pumping station (Fig. 3b). The change of outflow tended to stabilize more after 1983. The average outflows from the lake in the three periods were 0.99, 1.54, and 1.83 km^3/a, respectively (Table 2).

Figure 3c shows the variation in annual P_{L} from 1956 to 2010. The series of annual P_{L} fluctuated intensely. The annual averages in the three periods were 68.79, 97.30, and 86.56 mm, respectively (Table 2).

Due to global warming, the average temperature in Bosten Lake basin showed a significant upward trend (Ling et al. 2012). The mean annual E_{L} of Bosten Lake was 955.96 mm, ranging from 692.25 to 1,315.27 mm. The average values of evaporation in the three periods were 955, 1,021, and 838 mm/a, respectively (Fig. 3d and Table 2).

Table 1 The rising/falling lake surface area, lake level and lake water storage summary in different periods

Period	Lake level		Lake area		Lake storage		Number of rising/falling years
	Change (m)	Average rate (m/a)	Change (km^2)	Average rate (km^2/a)	Change (km^3)	Average rate (km^3/a)	
I: 1956–1987	−3.61	−0.11	−313	−9.78	−3.79	−0.12	12/20
II: 1988–2002	4.60	0.31	418	27.86	4.82	0.32	12/3
III: 2003–2010	−3.76	−0.47	−348	−43.50	−3.98	−0.50	0/8
1956–2010	−2.77	−0.05	−258	−4.69	−2.89	−0.53	24/31

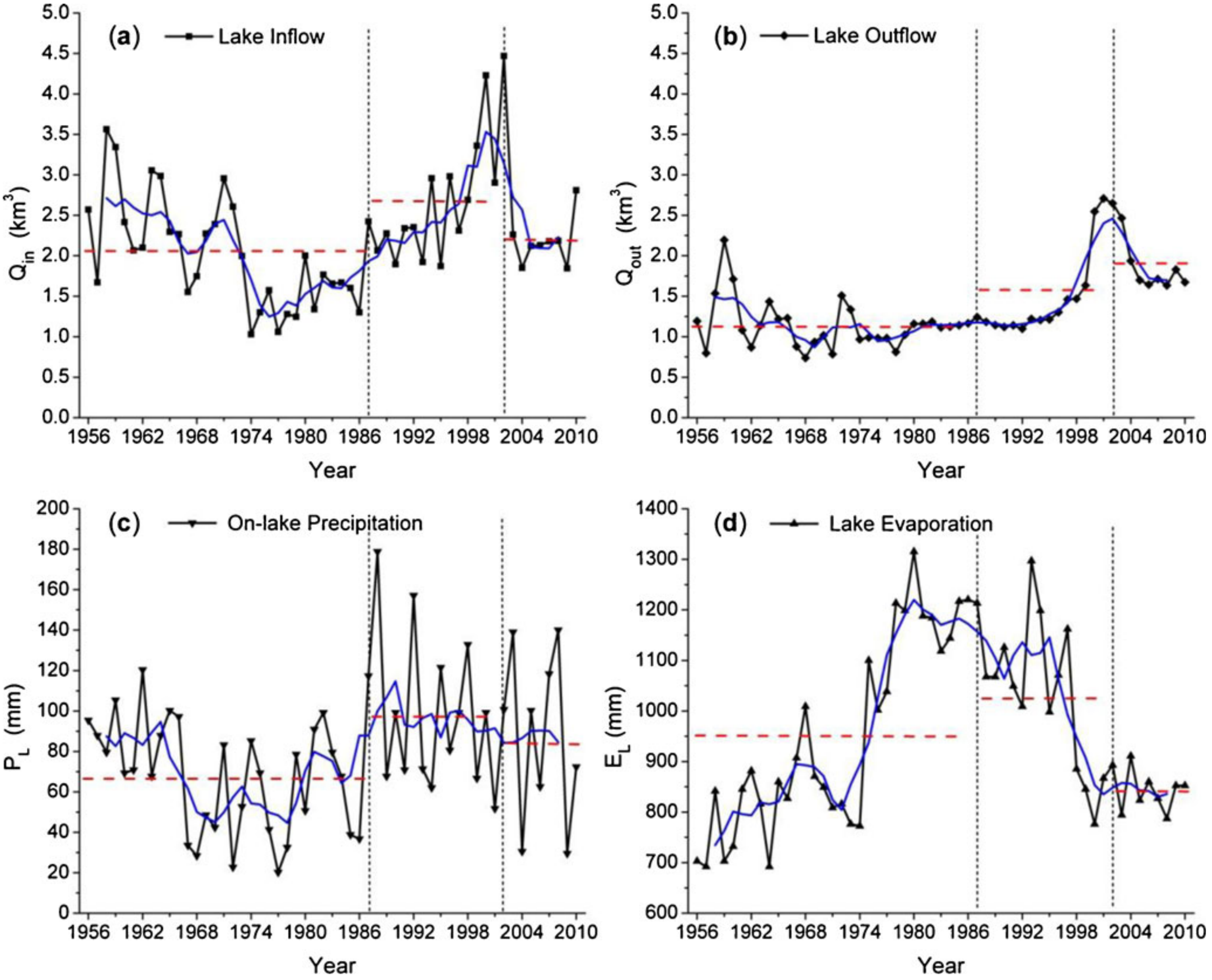

Fig. 3 Variation of annual **a** lake inflow to the lake, **b** lake outflow from the lake, **c** precipitation on the lake surface, and **d** evaporation from the lake surface during the period 1956–2010. The *black vertical dotted line* represents the dipartite period in 1987 and 2002 based on the observed lake level. The *blue line* shows the 5-year moving average, and the *red horizontal dotted lines* represent the averages of corresponding periods

4.3 Causes of the dramatic changes in lake level

4.3.1 Analysis of contributions to lake level fluctuations

Usually, the causes of lake level fluctuations may be attributed to climatic variation and/or anthropogenic factors (Coops et al. 2003; Li et al. 2007). Long-term variation of the lake level was carefully analyzed through water balance studies as shown in Fig. 4. Approximately 95 % of the total water input to the lake comes via the Kaidu River, with a small fraction of water input coming from precipitation (5 %), while lake outflow via the Kongque River and evaporation from the lake contribute 57

Table 2 Hydro-climatic conditions statistics of the three periods

Period	Lake inflow			Lake outflow			Precipitation			Evaporation		
	Q_{in} (km^3)	Δ (km^3)	%	Q_{out} (km^3)	Δ (km^3)	%	P_L (mm)	Δ (mm)	%	E_L (mm)	Δ (mm)	%
I: 1956–1987	2.04	–	–	0.99	–	–	68.79	–	–	954.92	–	–
II: 1988–2002	2.71	0.67	32.8	1.54	0.55	55.5	97.30	28.51	41.4	1,020.88	65.96	6.9
III: 2003–2010	2.17	−0.54	−19.9	1.83	0.29	18.8	86.56	−10.74	−11.0	838.44	−182.44	−17.9
Mean annual	2.23	–	–	1.35	–	–	79.15	–	–	955.96	–	–

Change (Δ) means the difference in hydro-climatic variables between periods I, II, and III; the relative change (%) is the ratio between Δ and the mean value in periods I and II

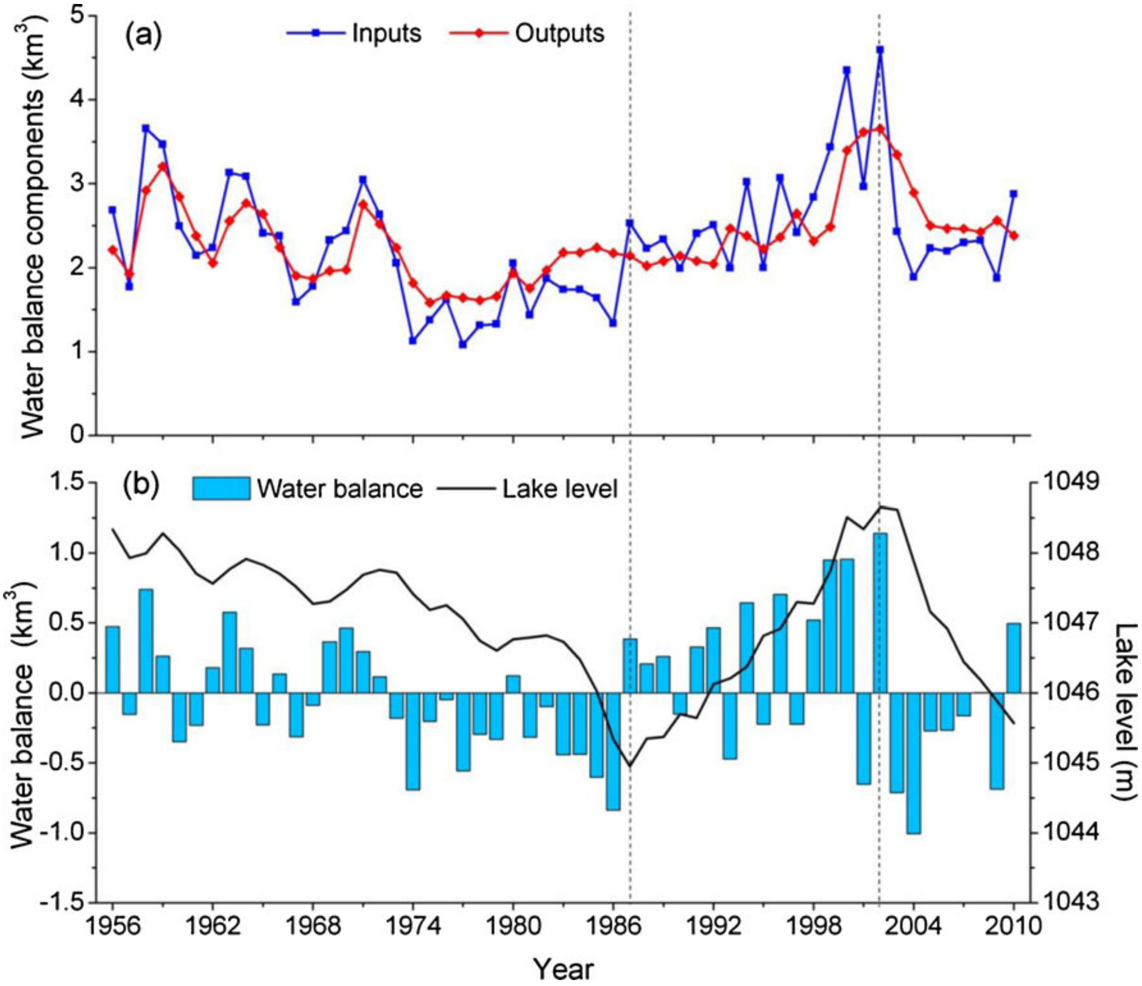

Fig. 4 Fig. 1 variation of annual **a** water inputs and outputs and **b** water balance of Bosten Lake from 1956 to 2010

and 43 % of the total water output from Bosten Lake, respectively (Table 3). This indicates that the water balance of Bosten Lake is dominated by throughput of lake water entering via the Kaidu River and exiting via the Kongque River and loss by evaporation from the lake. The annual average lake inflow, precipitation, lake outflow, and evaporation are 2.23, 0.09, 1.35, and 1.02 km^3, respectively. In the case of water volume, the total water input minus the total water output yields a negative water balance value (−0.06 km^3). This means that decreased lake water storage caused the lake level to decline by 2.77 m between 1956 and 2010 overall. However, the lake level did not vary along a simple linear trend during the 55 years, but changed abruptly after 1987 and 2002. The cause of the dramatic variation of lake level will be discussed in detail later for each of these three periods.

Based on the results of water balance analysis, we can infer that lake inflow is the most important factor for lake water inputs and also influences the fluctuations of lake level.

Table 3 Water balance summary (km^3) in different periods. The bracketed values indicate the percentage of total input or output represented by average yearly volumetric flux

Period/year	Inputs		Outputs		Water balance	Q_{out}/Q_{in} (%)	E_L/Q_{in} (%)
	Inflow (Q_{in})	Precipitation (P_L)	Outflow (Q_{out})	Evaporation (E_L)	$Q_{in}+P_L-Q_{out}-E_L$		
I: 1956–1987	2.04 (95 %)	0.08 (5 %)	0.99 (46 %)	1.18 (54 %)	−0.12	45	60
II: 1988–2002	2.71 (95 %)	0.10 (5 %)	1.54 (59 %)	1.08 (41 %)	0.28	52	41
III: 2003–2010	2.17 (95 %)	0.09 (5 %)	1.83 (67 %)	0.88 (33 %)	−0.45	78	40
Mean annual	2.23 (95 %)	0.09 (5 %)	1.35 (57 %)	1.05 (43 %)	−0.68	60	47

However, the series of annual lake inflow variations is affected by many factors such as precipitation, evaporation, and human consumption. Therefore, in order to further analyze the potential causes, the climate elasticity method was employed to estimate the impacts of climate factors on streamflow for the Kaidu River. The annual streamflow data from DSK hydrologic station at the upper reaches of the Kaidu River during 1956 to 2010 were used because there is very little human disturbance in the uninhabited natural area (Chen et al. 2013; Xu et al. 2008).

Table 4 shows the coefficient of climate elasticity of annual streamflow to precipitation (ε_P) and potential evaporation (ε_{E_0}). The values of ε_P and ε_{E_0} are 1.3 and −0.3, respectively. This implies that a 10 % increase in precipitation would result in a 13 % increase in streamflow and that a 10 % increase in potential evaporation (E_0) would result in a 3 % decrease in streamflow. This means that the annual streamflow is more sensitive to changes in precipitation than to changes in E_0. The impacts of climate variation on streamflow were estimated by using precipitation and E_0. The results revealed that a 36.19-mm increase in precipitation led to a 0.48-km^3 increase in streamflow in period II, while a 35.9-mm decrease in E_0 resulted in an increase in streamflow of only 0.04 km^3. Therefore, climate change (precipitation and E_0) led to 0.52 km^3 of the increase in streamflow, whereas human activities led to only 0.03 km^3 of the increase in streamflow in period II. Similarly, in period III (2003–2010), an increase in precipitation of 31.65 mm led to a 0.42-km^3 increase in streamflow, while a 7.9-mm decrease in E_0 resulted in an increase in streamflow of only 0.01 km^3. The changes in precipitation and E_0 together led to a 0.43-km^3 increase in streamflow, whereas human activities led to a 16.6 % increase in streamflow. It is clear that in periods II and III, the main factor influencing the increase in streamflow was increased precipitation, which contributed 86.3 and 81.6 % of the increased streamflow in these two periods, respectively.

As a result, climate changes were responsible for 93.7 and 83.4 % of the annual streamflow variability and human activities accounted for 6.3 and 16.3 % during periods II and III, respectively. The impacts of climate changes on streamflow were considerably larger than impacts of human activities, and it could be inferred that the variation of the streamflow could be mainly attributed to climate changes. Figure 4b shows the relationship between annual lake inflow (measured by BLSM hydrologic station) and streamflow (measured by DSK hydrologic station) from 1956 to 2010. They were positively correlated with R^2=0.87 from 1956 to 2010, indicating that the variation in annual lake inflow into Bosten Lake was consistent with the variation of streamflow. So, we can infer that lake inflow was correspondingly sensitive to climate changes.

4.3.2 Quantifying the separate effects of hydro-climatic factors in the three periods

In period I (1956–1987), the annual lake level was a total decrease of 3.61 m, with a variable amplitude of 1,048.34–1,044.73 m; however, there were shorter periods of signs of recovery during this time (Fig. 5b). Tan et al. (2004) reported that the lake level of Bosten Lake varies in the range from 1,047.5 to 1,048.5 m under natural conditions and seldom exceeds 1,049 m unless the 100-year flood occurs in a single year. Water control of both lake inflow and outflow was a natural process from 1960 to 1982 (Zhao et al. 2007). Therefore, in this natural process, the outflow volume of the lake was sensitive to the lake inflow. The trend of the annual lake outflow variations was consistent with the variations in the annual lake inflow (Fig. 3a, b), which indicated that a higher lake inflow brings a higher lake outflow and vice versa. The rising or falling of the lake level corresponds to the years with positive or negative water balance, respectively (Fig. 4b). There was an indication that the peaks in the rise of the lake level corresponded to higher lake inflow and outflow but lower lake evaporation (e.g., 1959, 1964, and 1972), and vice versa: the peaks in the fall of the lake level corresponded to lower lake inflow and outflow (e.g., 1957, 1962, and 1968). The mean evaporation losses (E_L/Q_{in}) were close to 60 %, and mean throughput (Q_{out}/Q_{in}) was close to 45 % between 1956 and 1982, which can be inferred that lake evaporation mainly caused the decline of the lake level. Moreover, from 1983 to 1987, the lake level presented a sharp trend of decline compared with the previous trend, because the only surface outlet of Bosten Lake was controlled by the pumping station in 1983 and Q_{out}/Q_{in} went up to 61 %. As noted previously, in period I, the variation

Table 4 Quantifying the impacts of climate change and human activities on streamflow for the Kaidu River during the three periods

Period	ε_P	ε_{E_0}	Q	ΔQ	ΔQ_P		ΔQ_{E0}		ΔQ_C		ΔQ_H	
			km^3	km^3	km^3	%	km^3	%	km^3	%	km^3	%
I: 1956–1987	1.3	−0.3	3.29	–	–	–	–	–	–	–	–	–
II: 1988–2002			3.85	0.56	0.48	86.3	0.04	7.4	0.52	93.7	0.03	6.3
III: 2003–2010			3.80	0.51	0.42	81.6	0.01	1.8	0.43	83.4	0.09	16.6

ΔQ means the change in streamflow between the three periods; the relative change (%) is calculated by $\Delta Q_P/\Delta Q$, $\Delta Q_{E_0}/\Delta Q$, $\Delta Q_C/\Delta Q$, and $\Delta Q_C/\Delta Q$

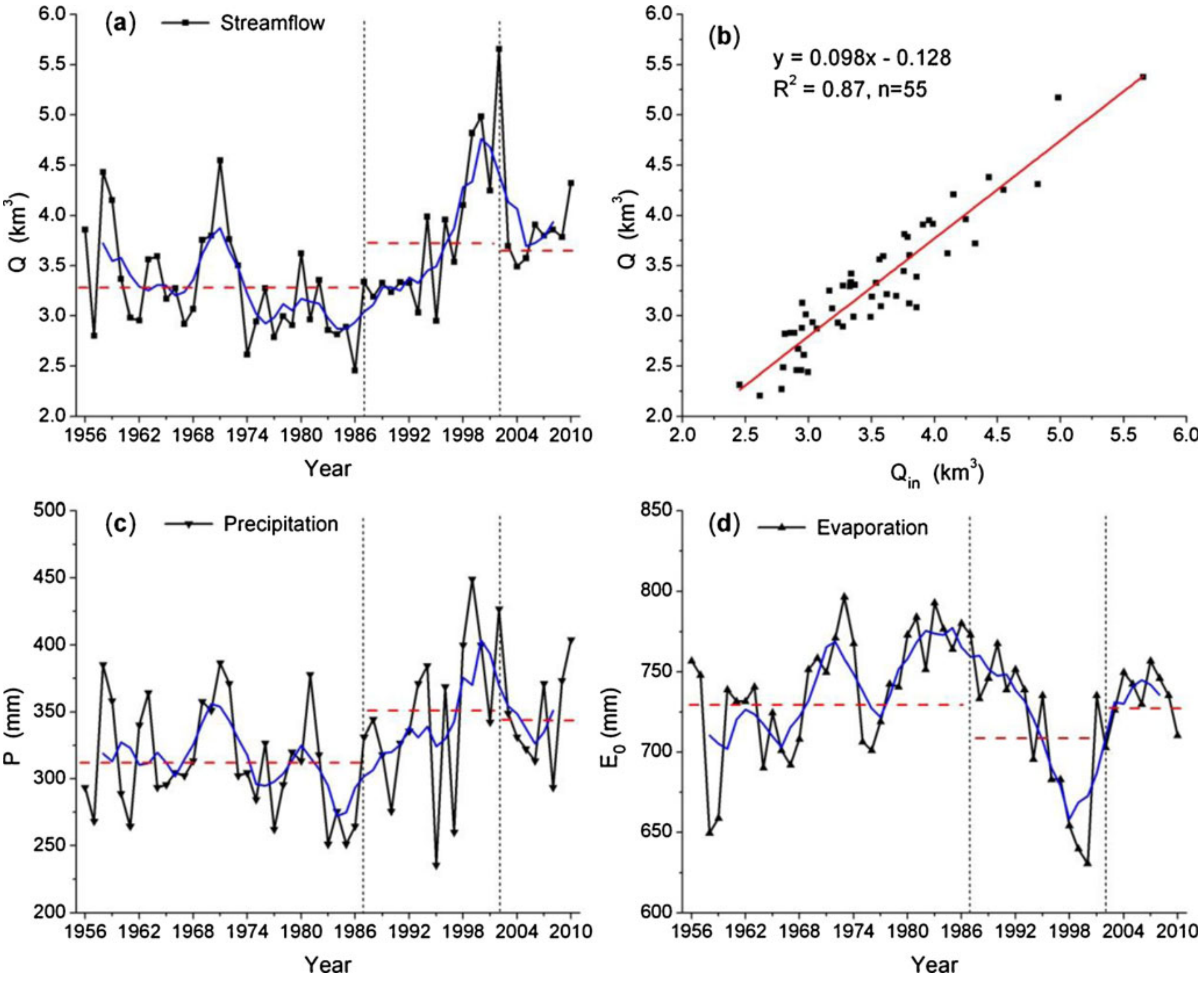

Fig. 5 Variation of annual **a** streamflow of the Kaidu River upstream, **c** precipitation on the lake surface, and **d** potential evapotranspiration from 1956 to 2010. **b** The relationship between annual streamflow and lake inflow from 1956 to 2010. The *black vertical dotted line* represents the dipartite period in 1987 and 2002 based on the observed lake level. The *blue line* shows the 5-year moving average, and the *red horizontal dotted lines* represent the averages of corresponding periods

in annual lake level showed an undulating decreasing trend; the mean total water input and output were 2.12 and 2.18 km^3, respectively, and the decline of lake level was dominated by lake evaporation, which accounted for 54 % of the total water output.

The trend of the annual lake level fluctuations was an almost linear rise or fall in the periods II and III, unlike in period I (Fig. 5b). This alternation can be attributed to the anthropogenic factors which we mentioned above. In period II (1988–2002), the remarkably increased lake inflow, stabilized lake outflow, and decreased lake evaporation resulted in a recovery of the lake level. Compared to period I, mean $Q_{\mathrm{out}}/Q_{\mathrm{in}}$ and $E_{\mathrm{L}}/Q_{\mathrm{in}}$ decreased to 52 and 41 %, respectively. In period II, the mean total water input was 2.81 km^3, which exceeded total water output by 0.28 km^3, so the lake level increased by 4.6 m. In order to save the ecological environment of the lower reaches of Tarim River, an emergency project of transferring water to it through the Kongque River is being constructed. Since 1999, the lake outflow of Bosten Lake has been increased and was 1.64, 2.55, and 2.71 km^3 in 1999, 2000, and 2002, respectively. But, at the same time, due to climate change, the Kaidu River entered the wet season and the corresponding lake inflow went up to 3.36, 4.23, and 4.47 km^3, respectively. The mean $Q_{\mathrm{out}}/Q_{\mathrm{in}}$ was close to 51 %, and the mean $E_{\mathrm{L}}/Q_{\mathrm{in}}$ was close to 24 % in the years of 1999, 2000, and 2002; therefore, the lake level was higher than 1,049 m in 2002, entirely due to artificial factors.

In period III (2003–2010), climate change led to decreases in lake inflow and lake evaporation, while the continuous transfer of water to Tarim River caused an increase in lake outflow. In this period, the mean annual lake inflow was 2.17 km^3 and the mean annul lake evaporation and lake outflow were 0.88 and 1.83 km^3, respectively. Compared to period II, the lake inflow and lake evaporation decreased by 0.54 and 0.2 km^3, respectively, while the lake outflow increased by 0.29 km^3. For period III, the mean value of Q_{out}/Q_{in} was close to 78 %, and the mean value of E_L/Q_{in} was close to 40 %. As in the case of the decline in the lake inflow, in period III, the amount of water delivered to the lower reaches of Tarim River still did not decrease, which led to the sharp decline of the lake level.

5 Discussion

There were some uncertainties in the analysis of the effects of climatic variation on streamflow of Kaidu River using the climate elasticity method. The major sources of uncertainty might arise from the limitations of the method, hydro-meteorological data, and the framework of the method. Firstly, the climate elasticity method is only suitable for analyzing the streamflow responding to climatic variation at the annual timescale (Wang et al. 2012). It cannot be used to analyze the monthly or seasonal time step. However, the streamflow can be influenced by changes in other precipitation characteristics, such as seasonality, intensity, and concentration, and the relationship between streamflow and precipitation may vary in the different months due to the fluctuation of the climate system during the year in the monsoon climate zone. Secondly, the hydro-climatic observation data used for the method were from a limited number of meteorological stations, which could not really represent a large region. In addition, precipitation and evaporation impacted each other and were not totally independent (Liu et al. 2012). Finally, the framework of the climate elasticity method used to estimate the proportional contribution of the influence of climatic variation on streamflow is based on the assumption that human activities are independent of climate change (Zheng et al. 2009). However, the effects of climate variability and human activities interact with each other, even in the baseline period, and they are not readily separable. Therefore, although climatic variation and human activities are interrelated, they will not substantially change the conclusion that climatic variation is the main reason for the change in streamflow.

The mean annual error of the lake water balance is −0.01 km^3 between 1956 and 2010, but it is tiny compared to each water balance component. The source of this error can be attributed to the estimated lake evaporation, which is related to the pan evaporation by a pan-to-lake coefficient, or to the fact that the net groundwater flux is assumed to be negligible. In addition, direct measurements of actual lake evaporation are generally not easy (Abtew 2001), and pan evaporation is generally larger than actual lake evaporation because the wind and thermal regimes of pans and lakes are usually markedly different (Winter 1981). Therefore, the relationship between pan evaporation and actual lake evaporation is complex. Although errors exist in measuring and estimating hydrologic components, the calculated annual water balance of Bosten Lake was very close to the observed annual lake storage, indicating that the results of the water balance calculation are reliable (Fig. 6).

6 Conclusions

Bosten Lake, the largest inland freshwater lake in China, presented three dramatic fluctuations of lake level over the past 50 years. This is an unusual phenomenon considering the trends of lake level in nearby regions. In this study, we described in detail the changes of lake level from 1956 to 2010 and analyzed the main causes of the dramatic changes in the lake. We found that lake inflow contributed 95 % of the total water input to the lake, while precipitation accounted for only 5 %. The lake outflow is an important water balance component and accounted for 57 % of the total water output from the lake. Evaporation over the lake surface contributed 43 % of the water loss from the lake. However, the causes leading to dramatic fluctuations in lake level were different in each period. In period I, the lake level showed a continuously declining trend from 1958 to 1987 due to the increase of lake evaporation. In period II, the lake level rose rapidly by 4.6 m from 1988 to 2002 because the lake outflow was controlled by humans and the lake inflow increased at the same time. In period III, the emergency project of transferring water to Tarim River led to increased lake outflow, while the lake inflow obviously decreased at the same time due to a reduction in precipitation, and these factors resulted in the lake level decreasing sharply by 3.76 m from 2003 to 2010. Dramatic fluctuations of lake level will bring about many harmful

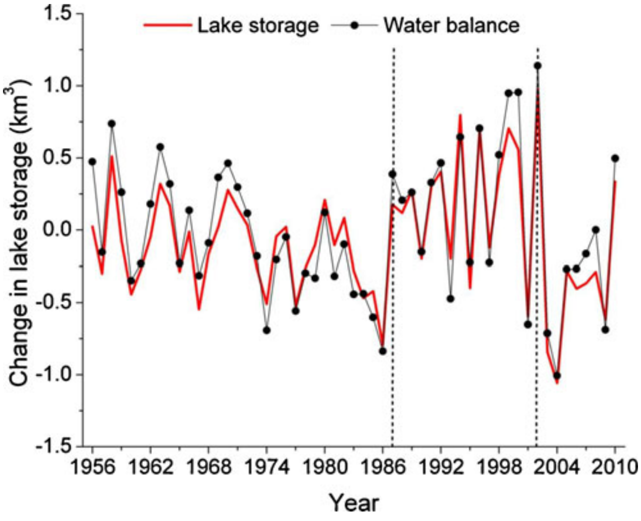

Fig. 6 Calculated annual water balance results of Bosten Lake compared with the actual changes in annual lake storage from 1956 to 2010

impacts on the regional eco-environment, economy, and society. Hence, future research should focus on the quantitative analysis of the relationship between the lake level and the health of the ecological system and the development of an effective scheme of lake storage management.

Acknowledgments This work was supported by the National Basic Research Program of China (No. 2012CB723201).

References

Abtew W (2001) Evaporation estimation for Lake Okeechobee in south Florida. J Irrig Drain Eng 127:140–147

Arora VK (2002) The use of the aridity index to assess climate change effect on annual runoff. J Hydrol 265:164–177

Bai J, Chen X, Li J, Yang L, Fang H (2011) Changes in the area of inland lakes in arid regions of central Asia during the past 30 years. Environ Monit Assess 178:247–256

Budyko MI (1969) The effect of solar radiation variations on the climate of the earth. Tellus 21:611–619

Chen Z, Chen Y, Li B (2013) Quantifying the effects of climate variability and human activities on runoff for Kaidu River Basin in arid region of northwest China. Theor Appl Climatol 111:537–545

Chen Y, Xu C, Yang Y, Hao X, Shen Y (2009) Hydrology and water resources variation and its responses to regional climate change in Xinjiang. Acta Geograph Sin 64:1331-1341 (in Chinese)

Cheng Q (1995) Research on Bosten Lake. Hehai University Press, Nanjing (in Chinese)

Coops H, Beklioglu M, Crisman TL (2003) The role of water-level fluctuations in shallow lake ecosystems—workshop conclusions. Hydrobiologia 506:23–27

Delju A, Ceylan A, Piguet E, Rebetez M (2013) Observed climate variability and change in Urmia Lake Basin, Iran. Theor Appl Climatol 111:285–296

Deus D, Gloaguen R, Krause P (2013) Water balance modeling in a semi-arid environment with limited in situ data using remote sensing in Lake Manyara, East African Rift, Tanzania. Remote Sens 5:1651–1680

Dooge J, Bruen M, Parmentier B (1999) A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. Adv Water Resour 23:153–163

Fengqing J, Cheng Z, Guijin M, Ruji H, Qingxia M (2005) Magnification of flood disasters and its relation to regional precipitation and local human activities since the 1980s in Xinjiang, Northwestern China. Nat Hazards 36:307–330

Gao H, Yao Y (2005) Quantitative effect of human activities on water level change of Bosten Lake in recent 50 years. Sci Geogr Sin 25: 305–309 (in Chinese)

Gibson J, Prowse T, Peters D (2006a) Hydroclimatic controls on water balance and water level variability in Great Slave Lake. Hydrol Process 20:4155–4172

Gibson J, Prowse T, Peters D (2006b) Partitioning impacts of climate and regulation on water level variability in Great Slave Lake. J Hydrol 329:196–206

Gregory K (2006) The human role in changing river channels. Geomorphology 79:172–191

Huang X, Chen F, Fan Y, Yang M (2009) Dry late-glacial and early Holocene climate in arid central Asia indicated by lithological and palynological evidence from Bosten Lake, China. Quat Int 194:19–27

Kebede S, Travi Y, Alemayehu T, Marc V (2006) Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. J Hydrol 316:233–247

Labat D, Goddéris Y, Probst JL, Guyot JL (2004) Evidence for global runoff increase related to climate warming. Adv Water Resour 27: 631–642

Lee X (2010) Characteristics and distribution of low molecular weight organic acids in the sediment porewaters in Bosten Lake, China. J Env Sci 3:328–337

Lenters JD (2001) Long-term trends in the seasonal cycle of Great Lakes water levels. J Gt Lakes Res 27:342–353

Li Y, Morrill C (2013) Lake levels in Asia at the Last Glacial Maximum as indicators of hydrologic sensitivity to greenhouse gas concentrations. Quat Sci Rev 60:1–12

Li X-Y, Xu H-Y, Sun Y-L, Zhang D-S, Yang Z-P (2007) Lake-level change and water balance analysis at Lake Qinghai, west China during recent decades. Water Resour Manag 21:1505–1516

Limei L, Jinfeng Z, Jianping Z (2013) Water balance of Lake Bosten using annual water-budget method for the past 50 years. Arid Land Geogr 36:33–40 (in Chinese)

Ling H, Xu H, Fu J, Zhang Q, Xu X (2012) Analysis of temporal-spatial variation characteristics of extreme air temperature in Xinjiang, China. Quat Int 282:14–26

Lioubimtseva E, Henebry GM (2009) Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations. J Arid Environ 73:963–977

Liu X, Luo Y, Zhang D, Zhang M, Liu C (2011a) Recent changes in pan-evaporation dynamics in China. Geophys Res Lett. doi:10.1029/2011GL047929

Liu X, Zheng H, Zhang M, Liu C (2011b) Identification of dominant climate factor for pan evaporation trend in the Tibetan Plateau. J Geogr Sci 21:594–608

Liu X, Liu C, Luo Y, Zhang M, Xia J (2012) Dramatic decrease in streamflow from the headwater source in the central route of China's water diversion project: climatic variation or human influence? J Geophys Res. doi:10.1029/2011JD016879

Liu X, Dai X, Zhong Y, Li J, Wang P (2013a) Analysis of changes in the relationship between precipitation and streamflow in the Yiluo River, China. Theor Appl Climatol 114:183–191

Liu X, Zhang D, Luo Y, Liu C (2013b) Spatial and temporal changes in aridity index in northwest China: 1960 to 2010. Theor Appl Climatol 112:307–316

Ma M, Wang X, Veroustraete F, Dong L (2007) Change in area of Ebinur Lake during the 1998–2005 period. Int J Remote Sens 28:5523–5533

Micklin P (2007) The Aral sea disaster. Annu Rev Earth Planet Sci 35: 47–72

Mischke S, Wünnemann B (2006) The Holocene salinity history of Bosten Lake (Xinjiang, China) inferred from ostracod species assemblages and shell chemistry: possible palaeoclimatic implications. Quat Int 154:100–112

Parisopoulos G, Malakou M, Giamouri M (2009) Evaluation of lake level control using objective indicators: the case of Micro Prespa. J Hydrol 367:86–92

Quinn FH (2002) Secular changes in Great Lakes water level seasonal cycles. J Gt Lakes Res 28:451–465

Romanovsky V (2002) Water level variations and water balance of Lake Issyk-Kul. In: Lake Issyk-Kul: its natural environment. Springer, pp 45-57.

Sankarasubramanian A, Vogel RM, Limbrunner JF (2001) Climate elasticity of streamflow in the United States. Water Resour Res 37: 1771–1781

Soja G, Züger J, Knoflacher M, Kinner P, Soja A-M (2013) Climate impacts on water balance of a shallow steppe lake in Eastern Austria (Lake Neusiedl). J Hydrol 480:115–124

Sun S, Chen H, Ju W, Song J, Zhang H, Sun J, Fang Y (2012) Effects of climate change on annual streamflow using climate elasticity in Poyang Lake Basin, China. Theor Appl Climatol 112:169–183

Swenson S, Wahr J (2009) Monitoring the water balance of Lake Victoria, East Africa, from space. J Hydrol 370:163–176

Tan Y, Li Y-A, Jiang F-Q, Wang Y-J, Hu R-J (2004) Analysis on the restoration of water level of the Bosten Lake in Xinjiang after 1987 [J]. Arid Land Geogr 3:315–319 (in Chinese)

van Oel PR, Mulatu DW, Odongo VO, Meins FM, Hogeboom RJ, Becht R, Stein A, Onyando JO, van der Veen A (2013) The effects of groundwater and surface water use on total water availability and implications for water management: the case of Lake Naivasha, Kenya. Water Resour Manag 27:3477–3492

Wang W, Shao Q, Yang T, Peng S, Xing W, Sun F, Luo Y (2012) Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. Hydro Process 27(8):1158–1174

Winter TC (1981) Uncertainties in estimating the water balance of lakes. JAWRA – J Am Water Resour Assoc 17:82–115

Wünnemann B, Mischke S, Chen F (2006) A Holocene sedimentary record from Bosten Lake, China. Palaeogeogr Palaeoclimatol Palaeoecol 234:223–238

Xia J, Zuo Q, Shao M (2003) Theory, method and practice on water resources sustainable utilization in Bosten Lake. Chinese Science and Technology Press, Beijing (in Chinese)

Xu J, Chen Y, Ji M, Lu F (2008) Climate change and its effects on runoff of Kaidu River, Xinjiang, China: a multiple time-scale analysis. Chin Geogr Sci 18:331–339

Xu C, Chen Y, Yang Y, Hao X, Shen Y (2010) Hydrology and water resources variation and its response to regional climate change in Xinjiang. J Geogr Sci 20(4):599–612

Zhang L, Dawes W, Walker G (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res 37:701–708

Zhang L, Hickel K, Dawes W, Chiew FH, Western A, Briggs P (2004) A rational function approach for estimating mean annual evapotranspiration. Water Resour Res. doi:10.1029/2003WR002710

Zhao J-F, Qin D-H, Nagashima H, Lei J-Q, Wei W-S (2007) Analysis of mechanism of the salinization process and the salinity variation in Bosten Lake. Adv Water Sci 18:475–339 (in Chinese)

Zheng H, Zhang L, Zhu R, Liu C, Sato Y, Fukushima Y (2009) Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. Water Resour Res. doi:10.1029/2007WR006665

Zuo Q, Dou M, Chen X, Zhou K (2006) Physically-based model for studying the salinization of Bosten Lake in China. Hydrol Sci J 51:432–449