Water-level regulation for freshwater management of Bosten Lake in Xinjiang, China

Yusufujiang Rusuli, Lanhai Li, Fadong Li and Mamattursun Eziz

ABSTRACT

The Bosten Lake is the largest inland freshwater lake of China, in which water level and salinity fluctuate due to the imbalance between inflows and outflows under climate change and anthropogenic activities. This paper employed system dynamics as an effective methodology to grasp the regulation rules for sustainable freshwater management of the Bosten Lake. Results show the following. (1) Changing of lake water salinity is not only affected by the salinity of water entering and leaving, but is mostly a result of water exchange rate (WER) and the lake level fluctuation. (2) According to the estimated regime of lake level regulations, it is attested that surface water inflow must be larger than outflow about $10.6 \times 10^8$ m$^3$ every year. Thus, the Bosten Lake can keep its normal water level. (3) A nonlinear equation was fitted between WER and average salinity of the Bosten Lake. This equation quantifies that when WER equals, or is larger than, 7, the Bosten Lake can be kept as a freshwater lake at all times.

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Key words | Bosten Lake, freshwater, lake level, salinity, salt balance, SD-model, water balance

INTRODUCTION

Freshwater is characterized by having less than 1 g/l concentrations of dissolved salts and other total dissolved solids (TDS). According to USGS (1984), dissolved salts in water with 1–3 g/l are defined as slightly saline water, 3–10 g/l as moderately saline water, 10–35 g/l as very saline water and more than 35 g/l as brine water. TDS commonly is used as a ‘watchdog’ of environmental change. High TDS levels affect many forms of aquatic life (Shuter et al. 1998). TDS effects are more prominent in arid and semi-arid regions, and in some places the water is so saline that it has become unfit for use (Weber-Scannell & Duffy 2007). Studies of Lake Qaroun in Lebanon (Ali et al. 2000), Lake Mono in California (Herbst 1992), Aral Sea in central Asia (Benduhn & Renard 2004) and Lake Okeechobee in South Florida (Vedwan et al. 2008) have shown that water salinity is directly influenced by the rise and fall of lake levels. At a result, lake level fluctuations lead to a series of ecological changes and environmental evolutions, by means of fluxes of matter and energy (Venkatesan et al. 2011). Untimely or drastic water level variations have undesirable effects for biota, the ecosystems and humans (Bond et al. 2008). In arid regions, water resource is an important factor for economic and social development as well as the stability of the ecosystem. Sustainable freshwater management of lakes in arid lands where evapotranspiration is greater than precipitation is becoming an important scientific interest under environmental change.

Bosten Lake, located in the arid region of northwest China, is the largest inland freshwater lake in China. Drastic changes in water level of Bosten Lake since the 1980s have led to a considerable loss of biomass, consequently endangering the habitat of various wild species (Walker & Yang 1993). Some studies focusing on Bosten Lake include models for water and salt balance (Cheng 1995; Brunner 2005; Rusuli et al. 2015) and combined influences of climate variation and human activities (Guo et al. 2015). The studies used to estimate potential contributions of natural and socio-economic factors to variations in the water level and salinity of the lake. Quantitative assessment of the dynamic relationships between lake level and water salinity has not been considered in sustainable freshwater lake management. The relationship
between lake fluctuation and dynamics of water salinity needs to be fully investigated at a systematic level.

System dynamics (SD) is an approach to understanding the behavior of complex systems over time, and deals with internal feedback loops while keeping track of the whole system response (Ahmad & Simonovic 2000). SD differs from other approaches to study complex systems, due to the use of stocks, flows, feedback loops, nonlinearity and time delay. These elements help in understanding how seemingly simple systems display dynamic complexity and nonlinearity (Forrester 1971). This investigation took the Bosten Lake as a case study and the coupled SD model of water and salt balance was used to assess the internal relationships between lake water level and salinity for sustainable freshwater lake management.

**MATERIALS AND METHODS**

**Study area**

The Bosten Lake is located in the Bayin’gholin Mongol Autonomous Prefecture, Xingjian Uyghur autonomous region, China. The lake is the lowest point of the Yanqi Basin. It receives all rivers flowing through the basin. It has a single outflow, the Konqi River. The Bosten Lake is divided by a natural dam into two parts, called ‘large lake’ and ‘little lake’. The average water depth of the large lake is 8.1 m with the deepest point of the lake at 17 m below the water surface, and corresponding water surface area approximately 1,000 km² when its level is about 1,048 m above sea level (ASL). The lake receives water inflow from a catchment area of 56,000 km², and several rivers in the Yanqi Basin flow into the lake (Figure 1).

The Kaidu River is the most important tributary to the lake, accounting for about 83% of its average annual water inflow, and other rivers (including Huangshui River, Qingshui River, Ushaktal River) contribute about 17% of the inflow (Table 1). Results of a study by Brunner (2005) demonstrate that the exchange of ground water between the Bosten Lake and its aquifer is negligible. The Kaidu River flows into the Konqi River through the Bosten Lake. The ‘little lake’ is a complex channel network, overgrown by thick reeds. Between 1958 and 1988, the level of the large lake dropped from 1,049 to 1,045 m ASL and annual mean salinity increased from 0.56 g/l in 1958 to the highest
The decreasing water level with an increase in salinity of the lake led to a considerable loss of biomass, consequently endangering the habitat of various wild species. In the 1990s, there was an increase of water from the watersheds into the lake, which reduced lake salinity to 1.17 g/l and improved the lake environment. Due to water conflict between water demand and supply of upstream and downstream agricultural area, the lake level dropped rapidly to about 1,045 m ASL in 2013 and the lake salinity shot up again. This issue has drawn widespread attention from government and scholars. Meanwhile, an argument was brought forward on whether or not it was possible to keep the Bosten Lake as a freshwater lake under the future climate change and human pressure.

### Methods

The coupled SD model for water and salt balance of Bosten Lake is investigated in STELLA platform. The first step in the modeling process was to develop a basic generic structure of the model to capture the key individual storage and flow interactions. The coupled SD model consists of lake water volume stock and salt amount stock (the rectangles in Figure 2). As shown in Figure 2, water volume stock includes water entering components (surface water inflow, ground water inflow, drainage water and precipitation) and water leaving components (surface water outflow, seepage from lake, evaporation and transpiration). Salt amount stock not only includes the transported salt amount with entering and leaving water components, but also salt amount with precipitation, TDS, lake sedimentation and the salt amount from the lake bed.

According to Bosten Lake’s water cycle system, the two stocks of SD model are connected at third water allocation station and at the Tashdian water station (Figure 1). The Kaidu River east diversion through the large lake and the Kaidu River west diversion through the little lake flow into the Konqi River. There is a so-called Jiefangyiqu canal, which flows into the Konqi River directly from Kaidu River.

### Model formulations

The water balance model is the base of salt balance model, because most salt is transported by water flows. With the exception of the salt from atmosphere (including salt through dust storm, precipitation and TDS), salt sedimentation amount on the lake bed and soluble salt mass entered from

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**Table 1 |** Main meteorological and hydrological factors of Bosten Lake between 1983 and 2012

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Average value</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall (mm)</td>
<td>83.00</td>
<td>16.00</td>
<td>143.70</td>
<td>31.70</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>1,745.60</td>
<td>1,089.90</td>
<td>2,120.00</td>
<td>295.10</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>8.76</td>
<td>-26.80</td>
<td>38.80</td>
<td>12.27</td>
</tr>
<tr>
<td>Kaidu River east division (10⁸ m³)</td>
<td>14.97</td>
<td>8.38</td>
<td>35.92</td>
<td>5.21</td>
</tr>
<tr>
<td>Kaidu River west division (10⁸ m³)</td>
<td>7.64</td>
<td>4.74</td>
<td>12.85</td>
<td>1.92</td>
</tr>
<tr>
<td>Huanghai River (10⁸ m³)</td>
<td>2.05</td>
<td>0.61</td>
<td>4.71</td>
<td>1.27</td>
</tr>
<tr>
<td>Qinghai River (10⁸ m³)</td>
<td>0.75</td>
<td>1.36</td>
<td>0.41</td>
<td>0.29</td>
</tr>
<tr>
<td>Drainage water inflow (10⁸ m³)</td>
<td>1.53</td>
<td>1.65</td>
<td>0.55</td>
<td>1.03</td>
</tr>
<tr>
<td>Tashdian water station (10⁸ m³)</td>
<td>15.43</td>
<td>10.99</td>
<td>26.11</td>
<td>4.83</td>
</tr>
<tr>
<td>Lake water level (m ASL)</td>
<td>1,046.58</td>
<td>1,044.99</td>
<td>1,048.69</td>
<td>1.05</td>
</tr>
<tr>
<td>Average salinity of the large lake (g/l)</td>
<td>1.27</td>
<td>0.97</td>
<td>1.87</td>
<td>0.32</td>
</tr>
</tbody>
</table>
the lake bed into the water body are also considered as main components which affect salt balance of the lake.

**Water balance equation**

According to water balance theory, the large lake’s water balance equation can be written as:

$$V_t^1 = Q_t^1 + [(R_t^1 + R^x_t + I_t^1 + D_t^1 + P^t A_t^1) - (O_t^1 + E^t A_t^1 + T^t A_t^1 + S_t^1)]$$

(1)

where $V_t^1$ is water volume of the large lake at time $t$, $Q_t^1$ is the water amount of the large lake at initial time, $R_t^1$ is the water inflow of Kaidu River east division to the large lake at time $t$, $R^x_t$ is the total inflow of other rivers to the large lake at time $t$, $I_t^1$ is the ground water inflow to the large lake at time $t$, $D_t^1$ is the drainage water inflow to the large lake at time $t$, $P^t$ is the precipitation amount at time $t$, $A_t^1$ is the large lake area at time $t$, $O_t^1$ is the water outflow through Xibeng station from the large lake at time $t$, and $S_t^1$ is the seepage from the large lake at time $t$.

The equation of the little lake water balance is a little different from that of the large lake water balance due to its individual input–output flows. Unfortunately, there are no accurately observed data of Dawut station, which is the single outlet of the little lake’s surface water. In this circumstance, the outflow amount of surface water from the little lake can be estimated by the following equation:

$$O_t^2 = R_t^2 - O_t^1 - R_t^1$$

(2)

where $O_t^2$ is the surface water outflow from the little lake at time $t$, $R_t^2$ is the total runoff of Konqi River at Tashdian station, and $R_t^1$ is the water amount of Jiefangyiqu canal from Kaidu River at time $t$. Then, in the same way of the large lake’s water balance equation, we can write the little lake’s water balance equation as:

$$V_t^2 = Q_t^2 + [(R_t^2 + I_t^2 + D_t^2 + P^t A_t^2) - (O_t^2 + E^t A_t^2 + T^t A_t^2 + S_t^2)]$$

(3)

where $V_t^2$ is water volume of the little lake at time $t$, $Q_t^2$ is the water amount of the little lake at initial time, $R_t^2$ is the water inflow of Kaidu River west division to the little lake at time $t$, $I_t^2$ is the ground water inflow to the little lake at time $t$, $D_t^2$ is the drainage water inflow to the little lake at time $t$, $A_t^2$ is the little lake area at time $t$, and $S_t^2$ is the seepage from the little lake at time $t$.

**Reeds area estimation**

The growth of reeds in Bosten Lake area lies on the salinity, and the hydrological and nutrimental situation of wetlands (Liu 2004). The reeds area, which is extracted from Landsat images of the research area, has a big correlation with the average lake level in the previous year (Rusuli et al. 2015). The reeds area estimation functions for the large and little lake are as follows:

$$B_t^1 = 5.9611 + \frac{29.64472}{1 + 10^{1.04667675 - 0.63577}}$$

$$R^2 = 0.95$$

(4)

$$B_t^2 = 269.38875 + \frac{16.84145}{1 + 10^{1.04732795 - 0.795781}}$$

$$R^2 = 0.99$$

(5)

where $B_t^1$ and $B_t^2$ are the reeds area of the large and little lake at time $t$, respectively, $H_t^{1-1}$ and $H_t^{2-1}$ are the average level of the large and little lake in the previous year, respectively.

**Salt balance equation**

Because most salt mass is transported by water input and output flows, the salt balance equation is derived from the water balance Equations (1) and (3). Therefore, the equation of the large lake salt balance is written as:

$$S_t^1 = S_t^0 + [(R_t^1 C_t^1 + R_t^x C_t^0 + I_t^1 C_t^d + D_t^1 C_t^d + S_t A_t^1)$$

$$\quad - (O_t^1 C_t^1 + S_t A_t^1 + S_t^1 B_t^1 + S_t^1 C_t^d)]$$

(6)

where $S_t^1$ is total salt amount in the large lake at time $t$, $S_t^0$ is initial salt amount in the large lake, $C_t^1$ is the salinity of Kaidu River at Boransumul station at time $t$, $C_t^d$ is the average salinity of other rivers into the large lake, $C_t^d$ is the salinity of the ground water into the large lake, $C_t^d$ is the average salinity of drainage into the large lake, $S_t^1$ is the salt amount on the per lake area from atmosphere (which
includes salt from dust storm, precipitation and TDS), $C_t^x$ is the salinity of the outflow from the large lake at time $t$, $S_t^x$ is the sedimentation amount on the per large lake bed area at time $t$, $S_t^s$ is the lost amount of salt with per reeds area, and $C_t^s$ is the salinity of the seepage.

Actually, the little lake consists of 16 separated lake-lets and their connecting canals network. The wetlands among these lake-lets are covered mainly with reeds. There is not accurately observed morphometric data on the little lake. Therefore, under the limited data situation, according to water balance model, the little lake’s salt balance equation is written as:

$$S_t^2 = S_0^2 + [R_t^2 C_t^f + I_t^2 C_t^g + D_t^2 C_t^d + S_t^a A_t^2] - (O_t^2 C_t^da + S_t^1 A_t^2 + S_t^s C_t^s)]$$

(7)

where $S_t^2$ is total salt amount in the little lake at time $t$, $S_0^2$ is the initial salt amount in the little lake, $C_{tda}$ is the mean salinity of the little lake at time $t$, and it is considered that the mean salinity of the little lake is equal to the water salinity at the Dawut station.

### Results

#### Model calibration and validation

Model calibration is the evaluation and adjustment of model’s parameters and constants to fit the simulated results with real data for all state variables (Rykiel 1996). Parameters are selected from a range of feasible values, then tested in the model, and adjusted until a satisfactory agreement between predicted and observed variables is obtained (Li & Simonovic 2002; Li et al. 2010). Model validation has to consider both model’s behavior and structure (Ruth & Hannon 1997) as it is necessary to test the structure of the model, including correct conceptions, with rational internal logics. Tests of model’s behavior evaluate adequacy of behavior generated by the structure (Forrester 1971), including behavior reproduction, behavior prediction, and so on. According to the research objectives, the large lake level and its average salinity are selected as key variables for validation of SD models’ behavior and structure of water and salt balance from 1983 to 2012. The simulated results fit historical data quite well (Figure 3). The ratio of the root mean square error (RMSE) to the standard division of measured data (RSR) is chosen to evaluate the performance of SD model of water and salt balance during calibration.

$$RMSE = \sqrt{\frac{1}{n} \sum_{t=1}^{n} (X_t^{obs} - X_t^{cal})^2}$$

(8)

Figure 3 | Comparison of observed and simulated average salinity and level of the Bosten Lake.

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**The data**

Historical flow, TDS values and 171 pairs of lake volume-level and volume-area curve data (Figure 1) were provided by the Water Resources Bureau of Bayin’gholin Mongol Autonomous Prefecture in Xinjiang. Meteorological data were acquired from Bagrash weather station and Dahekou weather station, which are located around the Bosten Lake (Figure 1). The average annual, extreme, minimum and maximum values, standard deviation of main meteorological and hydrological factors are as shown in Table 1.

Other components’ data were collected from literature sources. For example, the average annual salt amount with precipitation is $0.03 \times 10^5$ ton, and salt from sandstorms on the lake is 1.966 kg/s (Cheng 1995). The salt-amount per lake area per year from the atmosphere is estimated at 0.153 kg/m²/a (Zhao 2005). The sedimentation rate on the large lake’s bed is about 1.3 kg/m²/a (Zhang et al. 2004). The estimated conversion coefficient of actual evaporation vs. potential evaporation between is 0.44 to 0.62, and the salt amount from the lake bed varied between 0.9 and 1.2 kg/m²/a (Rusuli et al. 2015).
where STDEV\(_{\text{obs}}\) is standard deviation of observed lake level or average salinity of lake water, \(X^{\text{obs}}_t\) and \(X^{\text{cal}}_t\) are the observed and simulated lake level or average salinity of lake water at time \(t\), respectively. \(X^{\text{mean}}_t\) is the observed average value of lake level or average salinity.

The calculated RMSE error and RSR are 0.26 and 0.04 for lake level, respectively; the calculated RMSE error and RSR are 0.06 and 0.03 for lake average salinity, respectively. According to Moriasi et al. (2007), the evaluation results of lake level and average water salinity of the Bosten Lake can be judged as ‘very good’.

Estimation of lake level regulation rules

Lakes are dynamic systems that are sensitive to changes of local climatic and non-climatic variables under anthropogenic pressure in the surrounding landscape. Surface water inflow (\(Q_{\text{in}}\)), and surface water outflow (\(Q_{\text{out}}\)) and over-lake evaporation are the most sensitive factors which influences Bosten Lake level fluctuations (Rusuli et al. 2015). Over-lake evaporation among them is a factor affected by the climate and physiography of the water body, its surroundings and the lake’s open water surface area. In this study, the man-controlled \(Q_{\text{in}}\) and \(Q_{\text{out}}\) are proposed to grasp the rules of Bosten Lake level fluctuation. Other variables, such as climate and physiography, are recognized as constant, and open water surface area of the Bosten Lake is a dependent variable of water balance controlled by \(Q_{\text{in}}\) and \(Q_{\text{out}}\). According to existing records, \(Q_{\text{in}}\) varied between \(8.38 \times 10^8\) m\(^3\) and \(35.92 \times 10^8\) m\(^3\), while \(Q_{\text{out}}\) varied between \(5.90 \times 10^8\) m\(^3\) and \(17.50 \times 10^8\) m\(^3\) in the same period. In order to obtain corresponsive lake levels in different situations, coupled dynamics model for water and salt balance of the lake was circulated from \(0 \times 10^8\) m\(^3\) to \(36 \times 10^8\) m\(^3\) with one time step through changing \(Q_{\text{in}}\) and \(Q_{\text{out}}\), respectively. The nonlinear relationships as a surface plot among \(Q_{\text{in}}\), \(Q_{\text{out}}\) and lake level are shown in Figure 4 (left). This result proved that for every different value (\(\Delta Q\)), there is an equilibrium point of lake level (L) at a different period of time. This means that if \(\Delta Q\) is invariable regardless \(Q_{\text{in}}\) and \(Q_{\text{out}}\) changed in any rate, L reaches a stable level sometime. Moreover, the simulation results demonstrate that the SD model of water and salt balance fits only for the situation: \(\Delta Q\) is between \(2 \times 10^8\) m\(^3\) and \(12 \times 10^8\) m\(^3\). When \(\Delta Q\) is less than \(2 \times 10^8\) m\(^3\), the Bosten Lake will begin to disappear gradually. Conversely when \(\Delta Q\) is more than \(12 \times 10^8\) m\(^3\), floods will happen in Bosten Lake area. According to the nonlinear relationship between \(\Delta Q\) and L, the following function is built:

\[
L = 1,028.67345 + 22.68242 \left( \frac{0.10318}{1 + 10^{(0.25457-\Delta Q)/0.73692}} + \frac{0.89682}{1 + 10^{(4.79722-\Delta Q)/0.10965}} \right) R^2 = 0.99
\]  

This study estimated regulation rules for the Bosten Lake according to the characteristics of water levels...

Figure 4 | The nonlinear relationships among \(Q_{\text{in}}\), \(Q_{\text{out}}\) and lake level (left); variation of average salinity and \(\Delta Q\) vs. normal water level of Bosten Lake (right) between 1983 and 2012.
which have been studied by Xia et al. (2003) and the results are shown in Table 2. From Table 2 it is obvious that when $\Delta Q$ is guaranteed about $10.60 \times 10^8$ m$^3$ every year, the Bosten Lake can keep its normal water level. Thus, the Bosten Lake and its ecosystem will be regulated harmoniously. As shown in Figure 4 (right), during 1983 and 1993, $\Delta Q$ was almost less than normal water level. Correspondingly, average salinity of the Bosten Lake was also higher than 1.20 g/l. From the middle of 1990s to 2003, the $\Delta Q$ was higher than normal water level, and average salinity decreased gradually. Consequently, the Bosten Lake became a really freshwater lake around the year 2000. However, after 2003, the value of $\Delta Q$ was lower than normal water level. As a result, the trend of average salinity increased slightly. If this situation continues, it then becomes the omen of troublesome history for the Bosten Lake and its ecosystem again.

### Table 2 | Characteristic water levels and corresponding $\Delta Q$ of the Bosten Lake

<table>
<thead>
<tr>
<th>Name of characteristic water level</th>
<th>Characteristic water levels (m ASL)</th>
<th>$\Delta Q$ ($10^8$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood level</td>
<td>1,048.30</td>
<td>11.70</td>
</tr>
<tr>
<td>Upper water level for flood control</td>
<td>1,048.00</td>
<td>11.30</td>
</tr>
<tr>
<td>Normal water level</td>
<td>1,047.50</td>
<td>10.60</td>
</tr>
<tr>
<td>Level of dead water level</td>
<td>1,045.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Limit dead water level</td>
<td>1,044.50</td>
<td>7.50</td>
</tr>
</tbody>
</table>

### Optimal lake level for salinization control

Coupled water and salt balance model of the Bosten Lake demonstrated that the change in water salinity is not only a result of water level fluctuation, but a result of the complex interaction among many variables including the salt quantity drained into the lake, water and salt quantity discharged out of the lake, and so on. According to the model it is discovered that the most sensitive parameter to the lake salinity is $Q_{out}$, and the next place is $Q_{in}$ and over-lake evaporation. On all accounts, these three factors are the most important for Bosten Lake’s water and salt balance.

Whether the Bosten Lake can be kept as a freshwater lake depends on water exchange rate (WER). WER is the rate between lake water volume and exchanged water ($Q_{in} - Q_{out}$) in a special time period. A lake’s salinity decreases when the WER or level of the lake increases. WER refers to the replacement of lake water and is related to average residence time, i.e., WER is high when average residence time is low. The high WER along with low-salinity water coming as inflow decreases water salinity in lakes. This study finds out that there is a big correlation between WER and average salinity of the lake which is shown in Figure 5 (left). According to the relationship between WER and average salinity, the answer of the question can be found out, i.e., when WER is equal to or larger than 7, the Bosten Lake will be kept as a freshwater lake (average salinity is equal to or less than 1 g/l). Except that, Figure 5 (left) demonstrates that high WER is propitious to decrease water salinity.
Accordingly, the equation which can meet the condition of freshwater lake (WER is equal to or larger than 7) concerned with \( Q_{\text{in}} \) and objective lake water level (L) is given as follows:

\[
Q_{\text{out}} = Q_{\text{in}} + 0.746357 \left( \frac{177.04395}{7 + 7 \times 10^{(1.047.90441 - L) \times 10.0441}} \right) \tag{11}
\]

If the objective water level (L) is definite, according to the value of \( Q_{\text{in}} \), the \( Q_{\text{out}} \) can be calculated by Equation (11). Equation (11) can provide us with the information of the potential possibility of the lake that can afford how much surface water to the downstream area accordingly \( Q_{\text{in}} \).

**DISCUSSION**

Although the model simulation has been verified on water and salt balance in different fluctuation periods of Bosten Lake, uncertainty may still exist in the simulation processes due to parameter estimation. The estimated conversion coefficient of actual evaporation vs. potential evaporation and salt amount from the lake bed (Rusuli et al. 2015) was used. This may lead to some uncertainty. The exchange of ground water between the Bosten Lake and its aquifer may influence the water level, but it is small (Brunner 2005). In order to represent the influence of ground water exchange, this study has regarded it as a constant. In addition to the model structure, input data were may be another source of uncertainty. Meteorological data as evaporation and precipitation were obtained from two gauges located at west part of the Bosten Lake, which might not be sufficient for a large water surface.

According to the model’s calculations, the annual surface water outflow and unproductive water lost are \( 8.45 \times 10^8 \) m\(^3\) and \( 11.48 \times 10^8 \) m\(^3\) from 1983 to 2012, respectively. To keep Bosten Lake as a freshwater lake with normal water level considering water demand of downstream area, Equation (11) and Figure 5 implies that the annual surface water inflow must be larger than about \( 17 \times 10^8 \) m\(^3\). However, because of increasing water demands due to socioeconomic development in the Bosten Lake area, it is a challenge to keep the Bosten Lake level above the normal water level. Climate change probably will aggravate the situation, and will require a reduction in human water consumption. Therefore, through modern water conservation technologies and water use polices, it is possible to keep the Bosten Lake and its ecosystem within a good quality. In contrast, Bosten Lake might result in shrinking or disappearance altogether.

**CONCLUSIONS**

In this paper, a coupled SD model of the Bosten Lake was developed to grasp the sustainable freshwater lake management rules. The model was able to simulate the historic lake level and its salinity satisfactorily. The following conclusions can be drawn:

1. The controlled surface water inflow and outflow of the lake cause the imbalanced situation of the lake water. The change in lake water salinity is not only affected by the salinity of water entering and leaving, but also the lake level fluctuation and WER.
2. According to the estimated rules of lake-water-level regulations, if the normal lake level with 1,047.5 m ASL is regarded as the best choice for the Bosten Lake and its ecosystem, it is attested that surface water inflow must be larger than outflow, about \( 10.6 \times 10^8 \) m\(^3\) every year. Thus, the Bosten Lake can keep its normal water level.
3. The change in salinity is mostly related to water inflow to the lake, and the next place is water outflow and over-lake evaporation. Among them the evaporation which is determined by open-water surface area is as dependent variable of the difference between inflow and outflow. The nonlinear equation between WER and average salinity reveals that when WER is equal to or larger than 7, the Bosten Lake can be kept as a freshwater lake at all times.

As an overall conclusion to this study, one can state that ways for the sustainable freshwater lake management of the Bosten Lake exist. At the meantime, it is irrefragable that there is a big challenge between the progressively water demand of socioeconomic development and sustainable freshwater management for the Bosten Lake.
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