Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: http://www.tandfonline.com/loi/thsj20

Physically-based model for studying the salinization of Bosten Lake in China

QITING ZUO , MING DOU , XI CHEN & KEFA ZHOU

Physically-based model for studying the salinization of Bosten Lake in China

QITING ZUO[1,2], MING DOU[2], XI CHEN[1] & KEFA ZHOU[1]

1 *Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China*
zuoqt@zzu.edu.cn; zuoqt@sina.com

2 *School of Environment & Water Conservancy, Zhengzhou University, Zhengzhou 450002, China*

Abstract Salinization of lakes in arid areas is a common phenomenon with harmful consequences and must be controlled for the better use of lake freshwater and for the conservation of the environment around lakes. Bosten Lake, located in Xinjiang (western China) and the largest inland freshwater lake in China, now experiences salinization. The salinization of Bosten Lake is studied herein by using a physically-based model. After qualitative analysis of lake salinization, the quantitative model is presented that describes the systems of water quantity–water quality–ecology (WQQE) in an integrated way and that simulates the changing processes of lake salinization in the past. On the basis of the WQQE model, an optimal model was also developed to investigate the best strategy for controlling salinization of the lake in the future. The results demonstrated that the developed models can be used to depict the physical process of salinization of Bosten Lake and to provide meaningful information on how to control this salinization.

Key words arid area; Bosten Lake; China; lake salinization; optimal control model; salinization control; simulation

Un modèle à bases physiques pour l'étude de la salinisation du Lac Bosten en Chine

Résumé La salinisation des lacs en régions arides est un phénomène courant aux conséquences nuisibles, qui doit être contrôlé dans l'optique d'une meilleure utilisation de l'eau douce des lacs et de la conservation des environnements lacustres. Le Lac Bosten, situé dans le Xinjiang (à l'ouest de la Chine) et constituant le plus grand lac d'eau douce de Chine, subit désormais la salinisation. La salinisation du Lac Bosten est étudiée à l'aide d'un modèle à bases physiques. Après une analyse qualitative de la salinisation lacustre, présentation est faite du modèle quantitatif qui décrit les systèmes quantité d'eau–qualité d'eau–écologie (WQQE) d'une manière intégrée et qui simule les processus évolutifs de salinisation lacustre au cours du passé. Grâce au modèle WQQE, un modèle optimal a également été développé afin d'identifier la meilleure stratégie de contrôle de la salinisation du lac pour le futur. Les résultats montrent que les modèles développés peuvent être utilisés pour représenter les processus physiques de salinisation du Lac Bosten et pour produire une information pertinente en vue du contrôle de cette salinisation.

Mots clefs région aride; Lac Bosten; Chine; salinisation lacustre; modèle de contrôle optimal; simulation

INTRODUCTION

Salinization of lakes in arid areas occurs very commonly and some typical examples include Ebinur Lake, the largest saltwater lake in Xinjiang, western China; Sambhar Lake, located in an arid area of Rajasthan, India; the Aral Sea and Balkhash Lake, located in the arid areas of Central Asia; and the Great Salt Lake, the largest lake in Utah, USA. Salinization of lakes in arid areas may be caused by either natural factors, or human activities, or both. Many studies (e.g. Feng & Cheng, 1998; Williams, 1999; Alcocer *et al*., 2000; Zou *et al*., 2002; Migahid, 2003) reveal that the superfluous salts in lake water have done serious damage to the water quality and the health of people and animals, hence limiting efficient utilization of the water resources and jeopardizing the integrity of ecosystems. As lake freshwater in most arid areas is the only water resource on which people, animals and plants rely for existence, it is very important to protect freshwater lakes in arid areas from salinization.

Open for discussion until 1 December 2006

Many studies have addressed salinization problems of lakes in arid areas. These studies have mainly focused on the following aspects:

(a) Qualitative analyses of the causes of salinization and its direct and associated impacts on societies. For example, Williams (1999) discussed in detail the impacts of salinization of lakes, especially in terms of the social, economic and environmental costs, and also the management options.

(b) Simulation of water quantity and water quality for the watersheds where lakes are located. For example, Moharana & Kar (2002) carried out a GIS-based simulation in a watershed in the Thar Desert. Pala (2003) used the conceptual analysis and synthesis of hydrographs (CASH) model to analyse rainfall and runoff data from the Kocadere rural catchment, Turkey. Xia *et al*. (2001a, 2003) developed a coupled hydrology–ecology model to simulate and predict the change of water resources and environment in the Bosten Lake basin. However, there have not been many studies on modelling the physical processes of lake salinization, nor on quantitative methods for controlling lake salinization.

In order to understand the salinization processes of lakes in arid areas and to develop the best strategies to control or reduce the speed of the salinization process, it is necessary to develop a suitable methodology.

Bosten Lake, located in the Bayingolin Mongol Autonomous Prefecture of Xinjiang Uygur Autonomous Region in western China, is the largest inland freshwater lake in China. The water salinity of Bosten Lake has been greater than 1.0 g L^{-1} since the 1970s (up to 1.8 g L^{-1} in the 1980s) and is currently about 1.3 g L^{-1}. The lake has experienced salinization in the past. In this study, a physically-based model is developed that couples water quantity, water quality and ecosystem (WQQE) to analyse the salinization of the lake. Based on the WQQE model, an optimal model for controlling the salinization of the lake is developed to investigate the best management strategies for the control of the salinization of Bosten Lake in the future.

STUDY AREA

Bosten Lake is located within the stream system of the Kaidu and Kongque rivers in the south of Xinjiang Uygur Autonomous Region, an arid area in west China. In fact, it is at the end of the Kaidu River but the beginning of the Kongque River, as shown in Fig. 1(a). Bosten Lake is divided into two parts: the Big Lake and the Small Lake (see Fig. 1(b)). It is 55 km long from east to west and 20 km wide, on average, from south to north, and its average and maximum water depths are 7.5 m and 16.0 m, respectively, when the water level is 1048.5 m a.m.s.l. However, the lake becomes very shallow near the shores. The Bosten Lake basin is deep-dish shaped, with its bottom being quite level (Cheng, 1995).

The study area covers five counties (Yanqi, Hejing, HeSuo, Bohu and Yuli), as well as QuErLe City. The Kaidu River divides the irrigated area in the watershed into an eastern and a western part. Bosten Lake is recharged by the Kaidu, Huangshuigou, and Qingshui rivers, among which only the Kaidu River is perennial. Rising in the west alpine zone covered perennially with snow, the Kaidu River is mainly recharged by glacier snow meltwater, as well as rainfall. The total length of the Kaidu River is

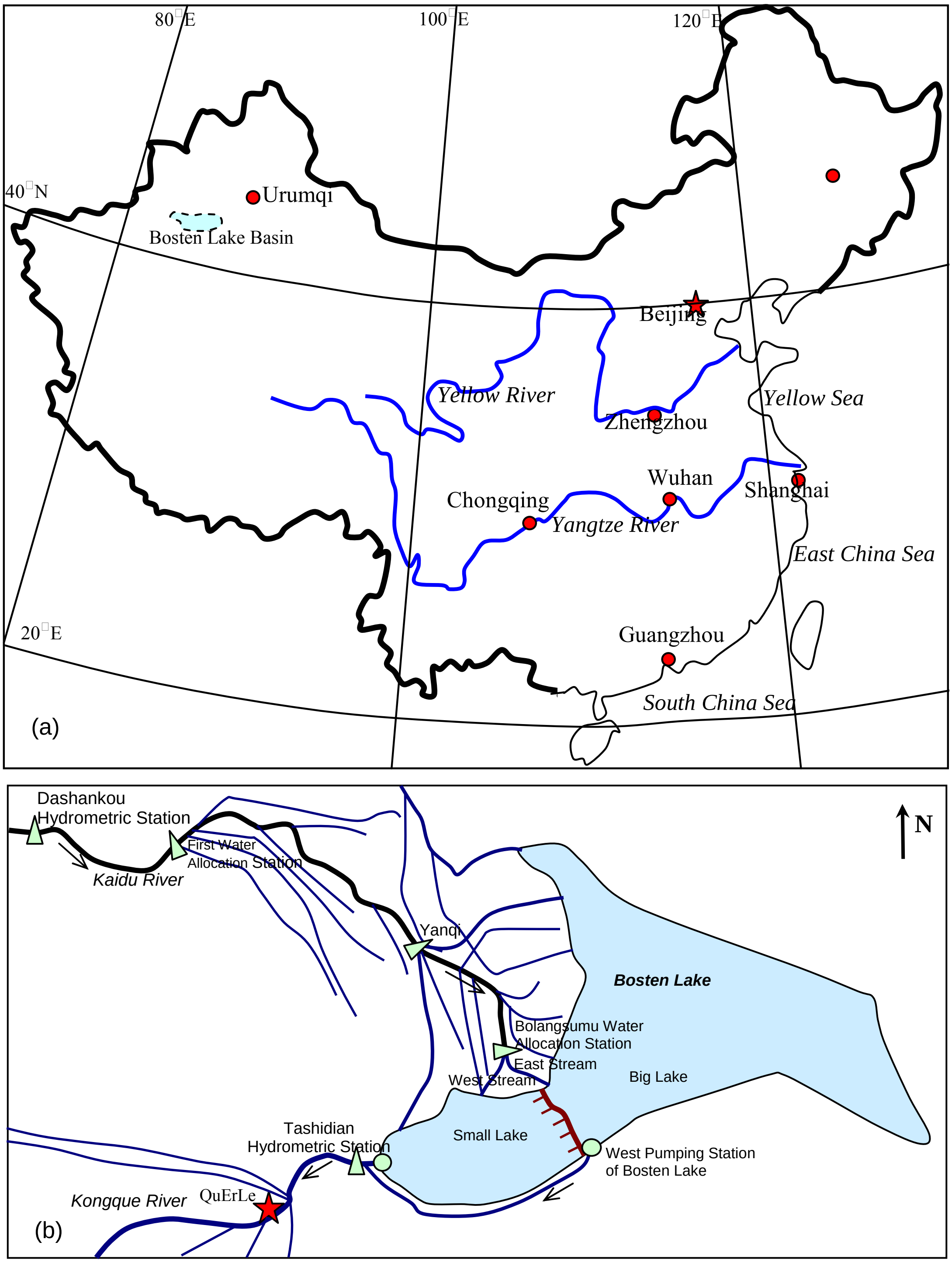

Fig. 1 (a) Location of the study area in China; and (b) schematic illustration of Bosten Lake.

513 km, its catchment area is 2.2×10^4 km^2, and its average annual runoff volume is 3.412×10^9 m^3. One of the major gauging sites is the Dashankou hydrometric station. At the downstream Bolangsumu Water Allocation Station, the Kaidu River bifurcates into East and West streams, which respectively flow into the Big and Small lakes.

As Bosten Lake is the at the end of the Kaidu River, but also at the head of the Kongque River, it has served many functions in the region, such as water supply for industry and the population, flood control, drought relief, environmental conservation in the basin. There is an emerging project of transferring water to the lower reaches of the Tarim River for enhancing the environment. Therefore, it is vitally important to protect Bosten Lake. However, the lake is threatened by salinization due to the large-scale water reclamation in the source areas, excessive exploitation and utilization of water resources, reduction of inflow and increase of salt flux into the lake. It has been found that the water salinity of Bosten Lake increased from 0.6 g L^{-1} in 1958 to 1.87 g L^{-1} in 1988 (Xia *et al*., 2003; Zuo *et al*., 2003).

QUALITATIVE ANALYSIS OF THE SALINIZATION OF BOSTEN LAKE

Bosten Lake has been regarded as a freshwater lake since recorded history (from 600 AD) (Xia *et al*., 2003). The earliest records of water salinity of the lake stem from observations in 1958 by the Xinjiang Comprehensive Investigation Team of the Chinese Academy of Sciences, and the average salinity of lake water then was about 0.6 g L^{-1}. At that time, Bosten Lake was really a freshwater lake. However, since the 1970s, the observed data reveal that the salinity of the lake water has been generally over 1.0 g L^{-1} and Bosten Lake has become a slightly saltwater lake (Xia *et al*., 2003). Water salinity is an important index indicating water quality of lakes in arid areas. When water salinity of a lake is higher than 1.5 g L^{-1}, drinking water supply can be threatened, and the lake water cannot be used for industrial purposes or irrigation when water salinity is higher than 2.0 g L^{-1}.

In the arid region, where Bosten Lake is located, the average annual precipitation is only 68.2 mm, but the average annual potential evaporation rate is as high as 1800–2000 mm. Water salinity can easily increase with the salt accumulation in the lakes due to the high evaporation, even though the mineral content of inflow to the lake is low. Many lakes in arid areas, such as the Ebinur, Aral, and Balkhash, are saltwater lakes. For Bosten Lake, there is a lot of freshwater flow into and out of it, so that it remains a freshwater lake. However, the salinity of the lake increases if its inflow decreases, or the water circulation slows down. Utilization of water resources of the lake is limited along with the increase in water salinity of the lake. Currently, the water quality of Bosten Lake is relatively good because of the interactions of multiple natural factors over the past ten years, as will be discussed later. It is Bosten Lake that sustains the prosperity in the basin and has become the "lifeblood" of the people in the region.

From the many years' monitoring data of Bosten Lake, the average annual values of water salinity of the lake were calculated, as shown in Table 1. The change trend is shown in Fig. 2. Figures 3 and 4 show the annual and inter-annual changes of inflow to Bosten Lake, and the lake water level, respectively. It can be seen in Figs 2–4 that, from 1971 to 1991, the inflow to Bosten Lake (and hence its water level) decreased and at the same time its water salinity increased. However, since 1992, the inflow to the lake has increased greatly, its water level gradually increased, and its water salinity decreased. It is generally considered that the lake salinity decreases when the inflow and water level of the lake increase. However, this may not necessarily be the case in the future: the level and volume of water stored in the lake may increase or decrease,

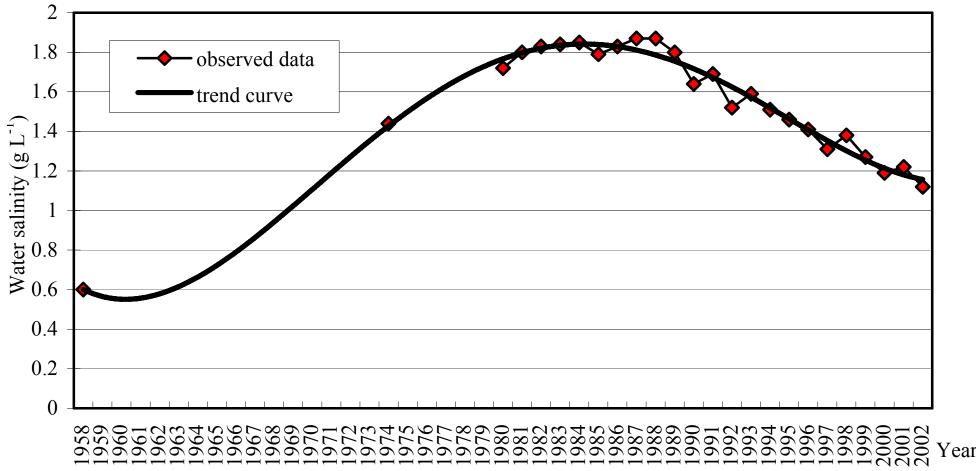

Fig. 2 Average annual water salinity of Bosten Lake.

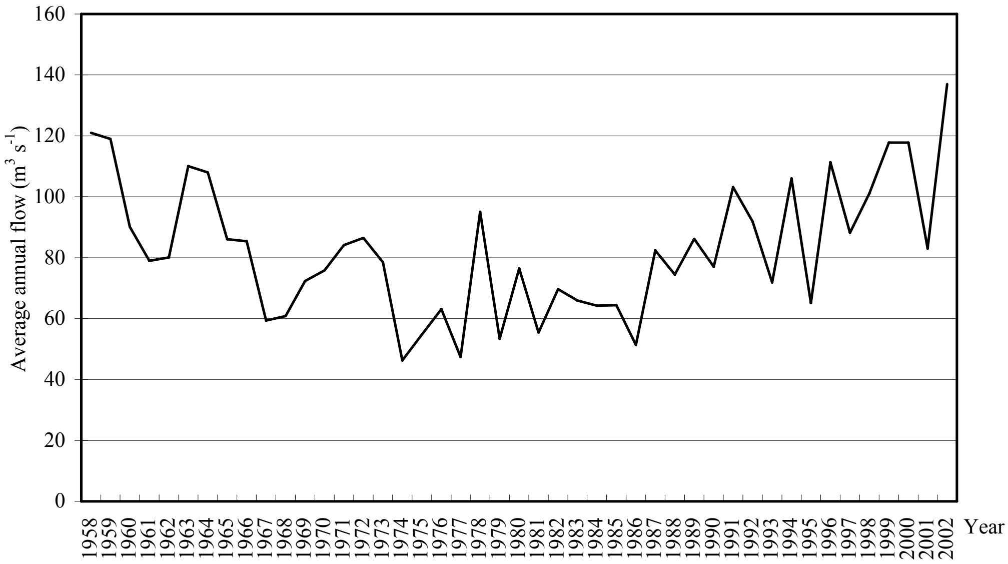

Fig. **3** Average annual flow into Bosten Lake.

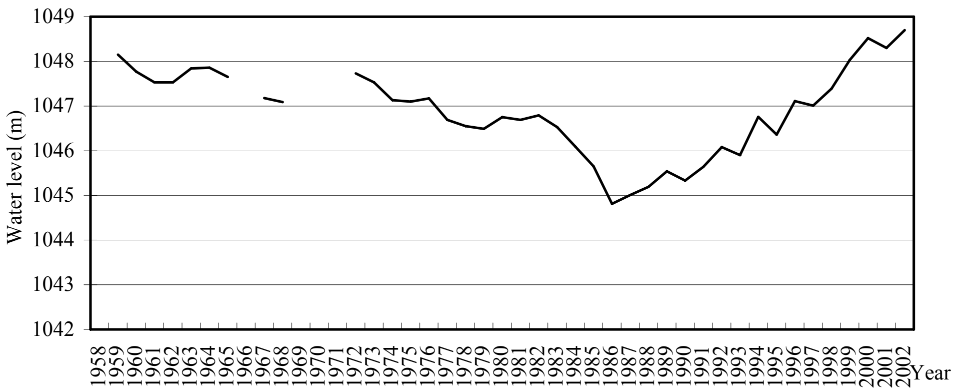

Fig. 4 Water level of Bosten Lake.

Table 1 Average annual values of water salinity in Bosten Lake (g L^{-1}).

Year	Water salinity	Year	Water salinity	Year	Water salinity	Year	Water salinity
1958	0.60	1985	1.79	1992	1.52	1999	1.27
1974	1.44	1986	1.83	1993	1.59	2000	1.19
1980	1.72	1987	1.87	1994	1.51	2001	1.22
1981	1.80	1988	1.87	1995	1.46	2002	1.12
1982	1.83	1989	1.80	1996	1.41		
1983	1.84	1990	1.64	1997	1.31		
1984	1.85	1991	1.69	1998	1.38		

depending on a number of factors. The increase in inflow could lead to an increase in water level if the volume of water discharged from the lake does not grow. The water level may decrease if the volume of water discharged from the lake grows. The reduction in inflow may increase the water level if the volume of water discharged from the lake is strongly reduced; however, the water decreases if the volume of water discharged from the lake increases. Therefore, the increase or decrease in water level is a result of the water balance, being affected not only by inflow, but also by the volume of water discharged from the lake.

Moreover, if the inflow and the water level of the lake increase, but the volume of water discharged from the lake decreases, then the water area of the lake expands, with the result being the increase of evaporation from water surface of the lake. The annual evaporation of Bosten Lake is as high as 1.37×10^9 m^3, consuming about one third of the total inflow into the lake. As time passes, the quantity of accumulated salts in the lake gradually increases, and so does the water salinity. If the inflow and water level of the lake decrease, but the water volume discharged from the lake is maintained, then the water area and the evaporation from water surface of the lake decrease, but the quantity of salts carried away with streamflow from the lake may not be reduced, and the water salinity of the lake decreases. Furthermore, the lake salinity possibly increases with increase in the quantity of salts carried into the lake with streamflow; for example, if the quantity of salts drained from farmlands in the peripheral regions of Bosten Lake increases, so does the water salinity. When the water level of Bosten Lake is high, the groundwater depth beneath the peripheral regions of the lake is shallow, thus the evaporation is high, and the water salinity of the lake will be increased. These give an indication that the increase in water salinity is caused by the decrease in water level of the lake. Lake salinization is affected not only by lake water level (storage capacity), but also by the water circulation capability of the lake and the quantity of salts drained into the lake.

The analysis above reveals that the change in water salinity of the lake is not only related to its water level, but is a result of the complex interaction among many factors. These factors include the salt quantity drained into the lake, the inflow and water level of the lake, water quantity and salt quantity discharged out of the lake, and the quantity of salts carried away by other pathways. The change in water salinity of the lake is simultaneously affected by these factors and is a complicated dynamic process that needs some physically-based models to simulate and explain it.

DEVELOPMENT OF A MODEL TO REPRESENT SALINIZATION OF THE LAKE

From the above analysis, it can be seen that the salinization of Bosten Lake is a complicated dynamic process. In order to improve understanding, it is necessary to develop a physical model to represent the salinization process.

Model of the coupling system of water quantity, water quality and ecology

The model that can simultaneously describe the water quantity, water quality and ecology (WQQE) was developed to represent the change in water salinity in the Bosten Lake basin. The WQQE model includes three parts: water quantity balance, salt quantity balance and ecosystem simulation. The procedures for developing the model are summarized below.

Delineation of the sub-regions for calculation

First, the rivers, lakes (reservoirs) and other landforms are classified. Then, they are further divided into sub-regions, referred to as "calculation sub-regions". The procedures for classifying sub-regions are given in Table 2. The Bosten Lake basin is divided into six calculation sub-regions: the upper and lower sections of the Kaidu River, the irrigated areas on the east and west sides of the Kaidu River, the Big and Small lakes.

Table 2 Classification method of calculation sub-regions.

Category		Calculation sub-regions
River		Classified by water quantity and quality
Lake	Marsh plant area	Classified by vegetation types
	No plant water area	Classified by water quality
Land		Classified by vegetation types, percentage of coverage, physical characteristics

Development of the WQQE model for each calculation sub-region

Model of water quantity This model is developed based on the law of mass conservation, which is summarized as follows: (a) first, all the volumes of inflow and outflow in a calculation sub-region, including diverted water and recycled water, as well as other variables along a river section, are determined during a certain period of time; (b) according to the relationships between the unknown variables and the given variables, the unknown variables are expressed by the approximate functions of the given variables, and are then put into the models. For example, the volume of irrigation-recycled water (Q_{RH}, unknown parameter) is approximately substituted by the volume of diverted irrigation water (Q_{RD}, given parameter): $Q_{RH} = a_1Q_{RD}+a_0$, etc.; (c) the unknown parameters are identified and inserted into the models. According to the calculated multiple correlation coefficients, the regressed results are evaluated and the identified parameters are put into the model. The values of all the water volumes are calculated and checked to see whether or not the calculations can satisfy the law of mass conservation. The model is reckoned to be reliable only when the regressed results are reliable and the calculations can satisfy the law of mass conservation. The model of water quantity can be represented by the water-balance equation. For any time period of length Δt, one can write the water-balance equation as:

$$P + G_{in} + Q_{in} = E + G_{out} + Q_{out} + \Delta S \tag{1}$$

where P is precipitation, G_{in} groundwater inflow, Q_{in} surface water inflow, E evapotranspiration, G_{out} groundwater outflow, Q_{out} surface water outflow, and ΔS the change in all forms of storage.

Model of water quality Similar to the development of the water quantity model, the model of water quality can also be developed based on the law of mass conservation for the salt. For any time period of length Δt, one can write the salt-balance equation as:

$$V_1C_1 + PC_P + G_{in}C_{Gin} + Q_{in}C_{Qin} = G_{out}C_{Gout} + Q_{out}C_{Qout} + V_2C_2 \tag{2}$$

where V_1 and C_1 are, respectively, volume and average water salinity of the lake at the beginning of the calculation period Δt; C_p is average water salinity of precipitation P; C_{Gin} and C_{Qin} are, respectively, average salinity of groundwater inflow G_{in} and surface water inflow Q_{in}; C_{Gout} and C_{Qout} are, respectively, average salinity of groundwater outflow G_{out} and surface water outflow Q_{out}; and V_2 and C_2 are, respectively, volume and average salinity at the end of the time period Δt.

Model of ecosystem The lake ecosystem is complex and thus it is difficult to develop a precise mathematical model to describe it. In this study, an artificial neural network (ANN) model is used to simulate the lake ecosystem. The model has the following characteristics: (a) it can represent the complicated nonlinear relations of ecosystems; (b) the development of the model is mainly based on observed data, and there is no need to carry out further experiments and identify the parameters of the model; (c) it has a powerful learning function, i.e. when the environment of ecosystems is changed, the model can re-learn and monitor the change in ecosystems if the new data are fed into the artificial network as inputs; (d) it is easy to operate; and (e) it can be used to predict the change of output factors of ecosystems when the input factors are changed.

Here, water quantity, water quality and the related variables are taken as the input factors, and the comprehensive index of the environment quality or the index of ecological status (such as the plant distribution area) can be regarded as an output factor. According to the method of ANN model, the "learning mode" should be derived first by learning, and then the output factors of the system can be predicted based on the changed input factors of the system in the future.

The average lake water levels h_1 and h_2 of the present and past years, the average lake water salinities, C_1 and C_2, of the present and past years and a "man-made interference" parameter, μ, are selected as inputs. Reed area, F, and its yield, W, are selected as outputs. The ANN model includes one input layer (five neurons), one hidden layer (six neurons) and one output layer (two neurons). The output F or W, generally represented by $Y(t)$, is assumed to be related to five inputs, using a general nonlinear model structure:

$$Y(t) = f_{\text{non}}[h_1, h_2, C_1, C_2, \mu] + e(t) \quad (3)$$

where $f_{\text{non}}[\ldots]$ is the unknown nonlinear mapping function, and $e(t)$ is the unknown mapping error (to be minimized).

Coupling of sub-models The above three models of water quantity, water quality and ecosystem are correlated and interdependent, and they must be coupled together to simulate and predict the change in the whole system. The basic concept is to proceed with iterative calculations by using the three models for each sub-region until the error is smaller than a requested value. The coupling relationship of the sub-models is illustrated in Fig. 5.

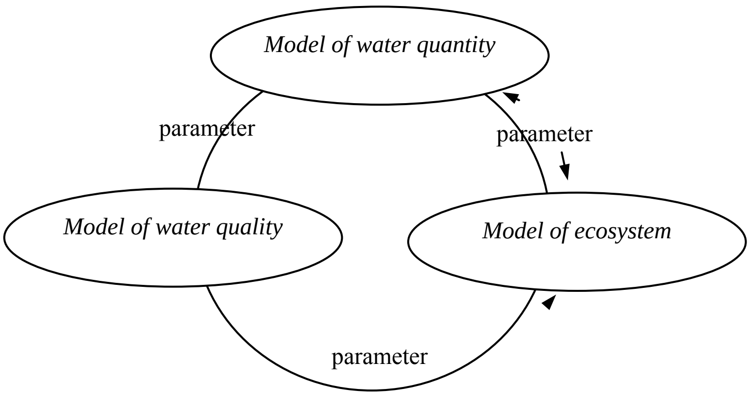

Fig. 5 Coupling relationship of the three sub-models.

Calibration of the WQQE model

The model is constructed for each sub-region first and then combined for the whole system. The model needs to be verified to prove its usefulness for representing the physical process of lake salinization. One of the verification methods is to take the simulated values as input values and put them into the model to verify the regressed results of the main intermediate variables. Another verification method is to evaluate the sensitivity of the system for changes in one or several variables.

Both water quantity and quality were simulated using the above developed model to investigate its applicability for representing the process of lake salinization. The simulation results are illustrated in Figs 6 and 7, respectively, for monthly water quantity and quality in the past. By comparing the simulation results with observations, it can be seen that the model performs well in both water quantity and quality aspects, and that the model can simulate the change in the salinization process of the lake. The relative errors for annual water quantity and quality are 5.09 and 9.21%, respectively. For such a large lake as Bosten Lake, the salinization process is very complicated and has many uncertainties. Taking this into account, the results obtained by the model can be considered satisfactory and the model can be regarded as reasonably representing the physical processes of the lake. The model had been used as a "basin hydro-

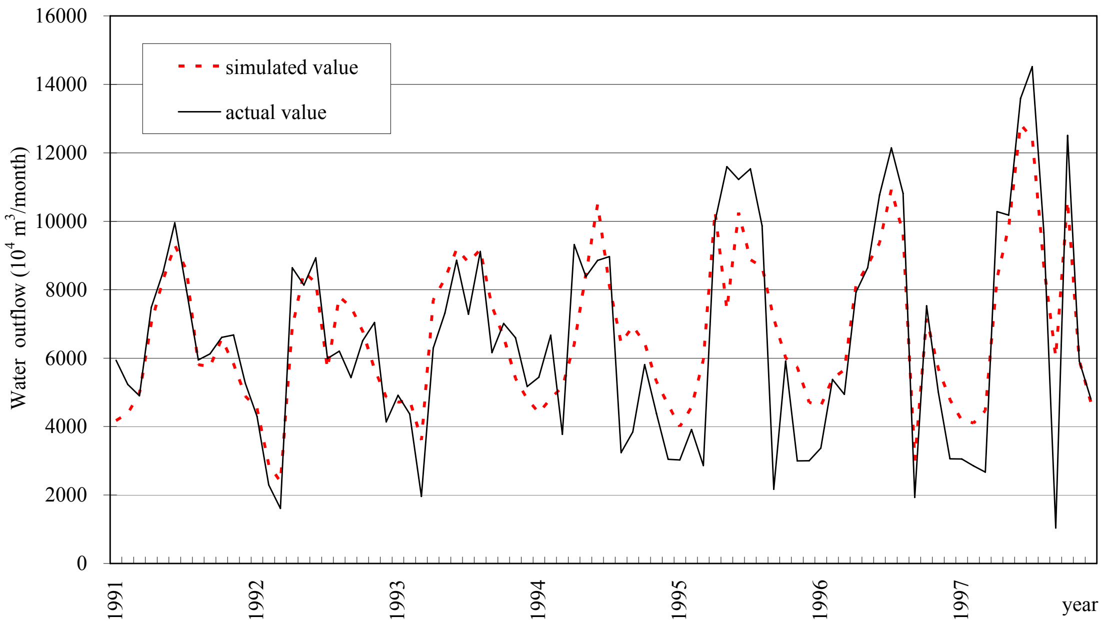

Fig. 6 Comparison of the simulated and observed water outflow of the lake.

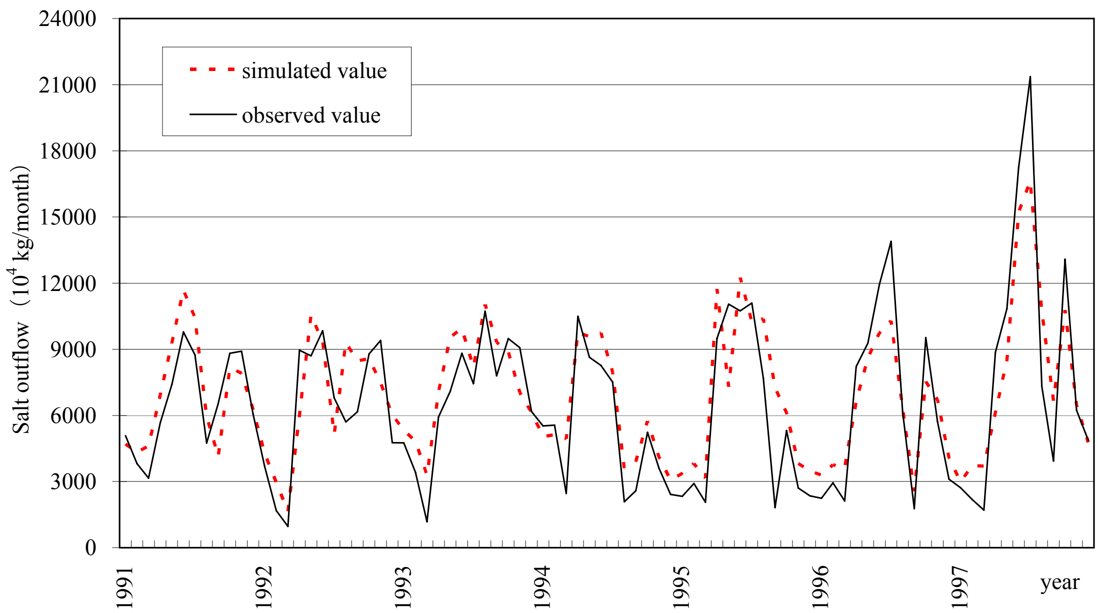

Fig. 7 Comparison of the simulated and observed salt outflow of the lake.

ecosystem model", and included in an optimal model for sustainable water resources management, with satisfactory results (Xia *et al*., 2001b).

Simulated results and discussion

The WQQE model couples the water quantity–water quality–ecosystem together. The relationships between the change in salt content and changes in the other factors are

Table 3 The scenarios of model analysis and corresponding change trend of water salinity.

Scenario	Inflow into the lake	Outflow from the lake	Water level of the lake	Other factors	Change trend of water salinity
1	Normal	Normal	Normal	Normal	Normal
2	Normal	Reduce by 20%	Higher than normal level	Normal	Gradual increase
3	Reduce by 30%	Reduce by 20%	Slightly lower than normal level	Normal	Gradual increase
4	Reduce by 30%	Normal	Lower than normal level	Normal	Gradual decrease

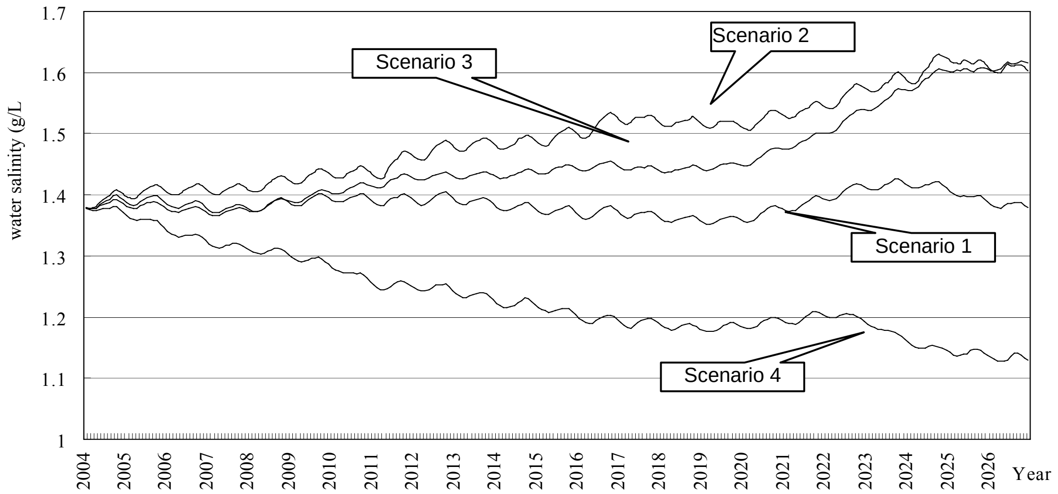

Fig. 8 The change in water salinity in Bosten Lake calculated by the four scenarios.

quantitatively expressed. These relationships can be used as the basis to predict the change in water salinity and to control salinization of the lake. In order to analyse the change in water salinity of the lake with the influencing factors in a clear way, four analysis scenarios are assumed, as presented in Table 3. In Scenario 1, it is assumed that the volumes of inflow and outflow as well as the water level of the lake are similar to the multi-year averages, which are calculated with the time-series trend model (Zuo *et al.*, 2002). In Scenario 2, it is assumed that the volume of outflow of the lake is controlled to increase its water level. In Scenario 3, the volumes of both inflow and outflow of the lake are reduced; and in Scenario 4, the volume of outflow is maintained while reducing the volume of inflow, but the water level decreases.

The water salinity of the lake in 2004 is regarded as the starting point in the calculation. Based on the above four scenarios, the process of change in water salinization of the lake during the period 2004–2026 is calculated, as shown in Fig. 8. From the results of simulation, the following conclusions can be drawn:

(a) Reduction in the inflow volume of the lake cannot be explained as the unique reason for the increase in water salinity, and the water salinity possibly decreases under some special conditions (such as Scenario 4);
(b) Reduction in the outflow volume of the lake is disadvantageous for the water circulation of the lake and can increase the water salinity (such as scenarios 2 and 3); and

(c) The water level of the lake is not the only factor that affects water salinization, since water level and water salinity are not always positively correlated. The change in water salinity of the lake is affected by many factors and is the result of their combined effect. These conclusions are consistent with those drawn from qualitative analyses in the section on qualitative analysis, which demonstrates that the complicated coupling model, i.e. the WQQE model, is applicable to simulate the salinization of Bosten Lake, and the control of salinization of the lake should be based on this model.

SALINIZATION CONTROL OF BOSTEN LAKE

The above analysis demonstrates that the salinization of Bosten Lake is a complicated process that is influenced by water and salt circulations as well as by human activities. The water salinity of the lake is closely related to the salt circulation. Thus, the salt circulation itself should be considered as a dominant factor in controlling the salinization of lakes. The water circulation, ecosystems and social and economic development should also be considered, since they are closely associated with the salt circulation of the lake. These factors form theoretical bases for investigating a reasonable management procedure for limiting the salinization of the lake.

Optimal control models

In order to quantitatively express the sustainable development of society–economy–ecosystem, the model was developed by Xia *et al*. (2001b). The principles of the model are explained below:

(a) The degree of environmental quality can be derived by fuzzy mathematics as *LI*, $LI \in [0,1]$. It is a comprehensive index used to measure the environmental quality.
(b) Similarly, the degree of social and economic development level can be expressed as *EG*, $EG \in [0,1]$. It reflects the basic information of the speed and quality of regional social development and economic growth.
(c) A comprehensive index of sustainable development (*DD*) is a combination of the *EG* index and the *LI* index, and can be expressed as:

$$DD = EG^{\beta_1} \cdot LI^{\beta_2} \tag{4}$$

where β_1 and β_2 are the exponential weights of the given social and economic development level (*EG*) and the environmental quality (*LI*), respectively. Since $EG \in [0,1]$ and $LI \in [0,1]$, so $DD \in [0,1]$.
(d) An optimal model is developed to regulate and manage environmental systems in a sustainable way. The objective function is to find the highest value *DD*, i.e. max(*DD*). The constraints should include at least the minimum requirement of social and economic development level, EG_0, the minimum requirement of environmental quality, LI_0, restriction of the interaction between eco-environmental system and socio-economic system, and other restrictions. The interaction between the eco-environmental system and the social-economic system is modelled by coupling the eco-environmental system and the social-economic

system and is expressed as *SubMod*(*EE* –*SE*). The optimized model is given by:

$$\left.\begin{array}{l}\text{Objective function: } \max(DD)\\ \text{Subject to: } EG \geq EG_0\\ LI \geq LI_0\\ SubMod(EE - SE)\\ \text{Other restrictions}\end{array}\right\} \quad (5)$$

Based on the above principles and the WQQE model, an optimal control model (OCM) of the lake salinization can be developed, which is explained below in detail.

Objective equation The comprehensive index of the social, economic and eco-system development (*DD*) in the study area is the highest, and is a typical objective function as analysed above, so the objective function of the model can be expressed as

$$\max(DD) \quad (6)$$

Constraints

According to the control objectives of the OCM model, the lake must be maintained as a freshwater lake, and the integrity of the complex system composed of the water resources system, ecosystem and social-economic system should be ensured.

Simulation of water and salt circulation In the OCM model, the salt and water circulations should be quantitatively expressed. The WQQE model can be used to express the salt and water circulation, and can also be regarded as a restricting equation, which is embedded into the OCM model.

Control of salt concentration of the lake The main objective of controlling salinization is to ensure that the lake is a freshwater lake in any given year. The salinity of standard freshwater is usually lower than 1.0 g L^{-1}. Therefore, to ensure the water salinity of the lake is lower than 1.0 g L^{-1} in a given year, a monthly scale is used in the OCM model:

$$C_s \leq 1.0, \quad Year \geq Y_0 \quad (7)$$

where C_s is the average monthly water salinity of the lake; *Year* is the serial number of year during the period in calculation; and Y_0 is the given year.

Interactions between water, salt, population, industry and agriculture Water is essential for both biotic and abiotic systems. It is an important natural resource and the substantial basis for national or regional economic and social development (e.g. agricultural and industrial production). The relationships between water resources and population, industry, agriculture respectively are given by:

$$\left.\begin{aligned} W_{\mathrm{Ind}} &= X_{\mathrm{Ind}}\alpha_{\mathrm{Ind}} \\ W_{\mathrm{Irrig}} &= X_{\mathrm{Irrig}}\alpha_{\mathrm{Irrig}} \\ W_{\mathrm{Urban}} &= 0.365X_{\mathrm{Urban}}\alpha_{\mathrm{Urban}} \\ W_{\mathrm{Rural}} &= 0.365X_{\mathrm{Rural}}\alpha_{\mathrm{Rural}} \end{aligned}\right\} \tag{8}$$

where, X_{Ind}, X_{Irrig}, X_{Urban} and X_{Rural} are the industrial output value, effective area under irrigation, urban population and rural population respectively; α_{Ind}, α_{Irrig}, α_{Urban} and α_{Rural} are the volume of consumed water resources of industrial output value per 1.0×10^4 yuan, ratio of agricultural irrigation, *per capita* water consumption in urban areas and *per capita* water consumption in rural areas, respectively; W_{Ind}, W_{Irrig}, W_{Urban} and W_{Rural} are the water consumptions of industry, agriculture, urban and rural livelihoods, respectively. Equation (8) expresses the relationships between the industrial water consumption and industrial output value, agricultural water consumption and effective area under irrigation, and water consumption for general life and population.

The drained water volumes and salt quantities from industrial and agricultural production, urban and rural livelihoods, and ecosystems are quantified by:

$$\sum W_{\mathrm{drainage}} = W_{\mathrm{Ind}}\mu_{\mathrm{Ind}} + W_{\mathrm{Irrig}}\mu_{\mathrm{Irrig}} + W_{\mathrm{Urban}}\mu_{\mathrm{Urban}} + W_{\mathrm{Rural}}\mu_{\mathrm{Rural}} + W_{\mathrm{En}}\mu_{\mathrm{En}} \tag{9}$$

where μ_{Ind} and μ_{Irrig} are the drainage coefficients of industrial wastewater and agricultural irrigation water, respectively; μ_{Urban} and μ_{Rural} are the drainage coefficients of urban domestic sewage and rural domestic sewage, respectively; μ_{En} is the drainage coefficient of water consumption for the environment; W_{En} is the water consumption for the environment; and $\Sigma W_{\mathrm{drainage}}$ is the total volume of drained wastewater. The equation expresses the volumes of drained industrial wastewater, agricultural irrigation water, urban domestic sewage, rural domestic sewage and recycled environment water, respectively.

$$\begin{aligned} \sum W_C = {} & W_{\mathrm{Ind}}\mu_{\mathrm{Ind}}C_{\mathrm{Ind}} + W_{\mathrm{Irrig}}\mu_{\mathrm{Irrig}}C_{\mathrm{Irrig}} + W_{\mathrm{Urban}}\mu_{\mathrm{Urban}}C_{\mathrm{Urban}} \\ & + W_{\mathrm{Rural}}\mu_{\mathrm{Rural}}C_{\mathrm{Rural}} + W_{\mathrm{En}}\mu_{\mathrm{En}}C_{\mathrm{En}} \end{aligned} \tag{10}$$

where C_{Ind}, C_{Irrig}, C_{Urban}, C_{Rural} and C_{En} are the average values of salinity of drained industrial wastewater, agricultural irrigation water, urban domestic sewage, rural domestic sewage, and recycled environment water; and ΣW_C is the total quantity of drained salts. The equation expresses the quantities of drained salts from industry, agriculture, urban livelihood, rural livelihood and environment. The parameters of C_{Ind}, C_{Irrig}, C_{Urban}, C_{Rural} and C_{En} can be derived from the historical statistical data or the temporal series models.

Control of water consumption for ecosystems In order to satisfy the environmental water consumption demands in the basin and its peripheral regions, the discharge of the river is generally controlled to maintain a certain minimum value:

$$Q_m \geq Q_s \tag{11}$$

where Q_s is the minimum value of discharge of the river, and Q_m is the value of annual runoff volume at the control section.

Socio-economic development and environmental quality It is assumed that EG_0 and LI_0 are the minimum level of social development and economic growth and the minimum objective of environmental quality, respectively. The constraints on social and economic development and environmental quality are separately expressed as:

$$\left.\begin{aligned} EG &\geq EG_0 \\ LI &\geq LI_0 \end{aligned}\right\} \tag{12}$$

The above nonlinear optimal control model (OCM) is used to find out the measures for controlling salinization of Bosten Lake. In the model, the salinization process can be quantitatively explained, and the complexities and interactions of many social, economic and environmental factors can also be quantitatively described.

Control measures and discussion

The OCM model can be used to investigate optimal management measures for controlling the salinization of the lake. The model has considered three aspects, i.e. the socio-economic development, planning of resources utilization, and planning of environmental conservation. The control variables of the OCM model include: (a) water consumption including the diverted water volume of the Kaidu River Irrigated Area, exploited groundwater volume in the Kaidu River basin, and the volume of water discharged from Bosten Lake to the Kongque River; (b) control of social and economic development including the macroscale control of industrial and agricultural development; (c) control of ecosystems including the area of artificially bred *Phragmites communis*, the water level of the lake, and the water allocation ratio of the East stream to West stream at Bolangsumu Water Allocation Station. The results calculated using the OCM model are presented in Table 4, which includes the social and economic development scale, planning of resources utilization, and planning of environmental conservation. The further discussions of the results are summarized as follows:

1. The volume of diverted irrigation water in the upper reaches of the Kaidu River (including the irrigated areas on the east and west streams) is too high, and the annual volume of diverted irrigation water is currently $1.025\,16 \times 10^9$ m^3. Thus, the inflow to Bosten Lake is reduced and its salt quantity is increased. This leads to the reduction in outflow of the lake, hindering its water and salt circulation, expediting its salinization, and finally restricting the local social and economic development. Therefore, it is an important aspect of both the local social and economic development and the salinization control to reduce the annual volume of irrigation water to a range between 5.8 and 8.5×10^8 m^3 in the upper reaches.
2. The volume of exploited groundwater is very low in the basin, and groundwater is exploited only in some urban areas. Thus, once the groundwater level is increased, land salinization becomes more severe, and the salt quantity drained from farmlands into the lake is increased. According to the calculated results, it is planned to maintain an annual exploited groundwater volume of about 5.0×10^8 m^3 by 2020.

3. The annual volume of outflow from the lake should be controlled at between 1.3 and 1.8×10^9 m^3 to ensure the water consumption in the lower reaches (i.e. the Kongque River Irrigated Area) and the water circulation of the lake and satisfy the water consumption required for local social and economic development.
4. In the basin, the industrial foundation is unsubstantial, and agriculture is dominant. In order to develop the local economy and reduce water consumption, the economic structure should be regulated, in order to gradually increase the industrial scale and reduce the rate of agricultural development.
5. Bosten Lake was well-known for its high yield of *Phragmites communis* in the early 1960s. However, the yield, reserves and quality of *Phragmites communis* are reduced due to the local economic development and the irrational exploitation and utilization of water resources in the Bosten Lake basin, and the environment in the basin has degenerated. Therefore, the growth of *Phragmites communis* in the lake should be improved, and it is an effective way to enlarge the area of artificially bred *Phragmites communis*.
6. The water level of the lake is an important factor affecting salinization of the lake. If the water level is high, the water area of the lake will be expanded, and the evaporation from water surface of the lake will be high, particularly as evaporation is the main cause of water loss in arid areas. If the water level of the lake is low, water and salt circulation will be reduced. Therefore, the water level of Bosten Lake should be controlled at a range of 1 045.0–1 047.5 m a.m.s.l.
7. The Kaidu River is bifurcated at Bolangsumu Water Allocation Station into the East and West streams, which respectively flow into the Big Lake area and Small Lake areas. The functions of these two lake areas are different: the Big Lake area is mainly used to control the discharge of the Kongque River, and *Phragmites communis* grows mainly in the Small Lake area. Therefore, it is very important to rationally allocate the volumes of stream water flowing into these two lake areas. As analysed above, the allocation proportions of the East and West streams at Bolangsumu Water Allocation Station should be controlled in a ratio ranging from 66:34 to 68:32 (see Table 4). Based on the above analyses, the factors affecting salinization of the lake include mainly the inflow, outflow and water level of the lake and the salt quantity drained from farmlands into the lake. Salinization of the lake is the joint effect of these factors.

CONCLUSIONS

In this paper, the WQQE model that can simultaneously describe the systems of water quantity–water quality–ecology is developed to represent the physical process of the salinization of Bosten Lake in western China. On the basis of the WQQE model, an optimal control model (OCM) is also developed and used to investigate the best strategy for controlling the salinization of the lake in the future. The results demonstrated that the developed models can be used to reasonably simulate the physical process of salinization of the lake and to provide meaningful information on how to control the salinization of the lake.

From the models, the following insights are gained regarding the salinization of the lake: (a) the salinization of the lake is a very complex phenomenon depending on

Table 4 Salinization control measures in Bosten Lake basin.

Control variables	Unit	Control value
Water use:		
Irrigation water from the Kaidu River	10^8 m^3 year^{-1}	In 2005: 9.3 to 8.5 In the specified future (about 2020): 5.8
Groundwater exploitation in Kaidu River basin	10^8 m^3 year^{-1}	In 2005: 3 In the specified future (about 2020): 5
Flow into Kongque River from Bosten Lake	10^8 m^3 year^{-1}	13 to 18
Socio-economic control:		
Industry		Increase rate per year before 2020: 1.3%
Agriculture		Decrease rate per year before 2020: 1.1%
Ecosystem control:		
Artificial raising reed area	10^4 ha	0.25
Water level of the Big Lake	m	Adjustment level: 1045.0 to 1047.5 Average level: 1046.0
The proportion of East Stream to West Stream at Bolangsumu Water Allocation Station		66:34 to 68:32

many factors involving the social, economic and ecological systems; and (b) the salinization of the lake is governed by many factors, such as the inflow, outflow and water level of the lake and the quantity of salt carried by irrigation water into the lake. Based on the simulation study, the possible management strategies for controlling the salinization of the lake in the future are summarized in Table 4, which provides specific procedures on how to operate the lake under certain conditions to limit the salinization of the lake.

Although the models are developed to help resolve the salinization problems in Bosten Lake, the methodology and framework developed in this study may potentially be applied in modelling and controlling salinization of other lakes in arid areas, given that the process is similar in principle. Further studies are required to verify this, which are beyond the scope of the present work.

Acknowledgements The research was supported by The Opening Study Foundation of the State Key Laboratory of Water Resources and Hydropower Engineering Science (2003B007 and 2005B016), and Chinese Henan Outstanding Youth Foundation (0512002500), and "The Oasis Scholar Project" of Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The local governments in the Bosten Lake Basin also provided assistance for the study. Useful advice of Dr Sheng Yue (USA), Prof. Jun Xia (China), Dr Lihua Xiong (China) and Dr Bing Chen (Canada) is gratefully acknowledged.

REFERENCES

Alcocer, J., Escobar, E. & Lugo, A. (2000) Water use (and abuse) and its effects on the crater-lakes of Valle de Santiago, Mexico. *Lakes & Reservoirs: Res. Manage.* **5**(3), 145–149.

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

Feng, Q. & Cheng G. D. (1998) Current situation, problems and rational utilization of water resources in arid north-western China. *J. Arid Environ*. **40**, 373–382.

Migahid, M. M. (2003) Effect of salinity shock on some desert species native to the northern part of Egypt. *J. Arid Environ*. **53**(2), 155–167.

Moharana, P. C. & Kar, A. (2002) Watershed simulation in a sandy terrain of the Thar desert using GIS. *J. Arid Environ*. **51**(4), 489–500.

Pala, A. (2003) Runoff modelling of rural catchments in Turkey. *J. Arid Environ*. **54(**3), 505–512.

Williams, W. D. (1999) Salinisation: A major threat to water resources in the arid and semi-arid regions of the world. *Lakes & Reservoirs: Res. Manage*. **4**(3–4), 85–91.

Xia, J., Chen, Z., Huang, G. H. & Rong, X. (2001a) An integrated hydro-ecological modelling approach applied to the Lake Bosten basin in China. *Water Int*. **26**(1), 105–118.

Xia, J., Zuo, Q. T. & Pang, J. W. (2001b) Enlightenment on sustainable management of water resources from past practices in the Bosten Lake basin, Xinjiang, China. In: *Regional Management of Water Resources* (ed. by A. H. Schumann, M. C. Acreman, R. Davis, M. A. Marino, D. Rosbjerg & X. Jun) (Proc. Sixth IAHS Scientific Assembly, Maastricht, July 2001), 41–48. IAHS Publ. 268. IAHS Press, Wallingford, UK.

Xia, J., Zuo, Q. T. & Shao, M. Ch. (2003) *Sustainable Management of Water Resources in Lake Bosten*. Chinese Science Press, Beijing, China (in Chinese).

Zou, X. Y., Li, S. & Zhang, Ch. L. (2002) Desertification and control plan in the Tibet Autonomous Region of China. *J. Arid Environ.* **51**(2), 183–198.

Zuo, Q. T. & Chen, X. (2003) *Water Planning and Management Meeting Sustainable Development*. China Hydropower Press, Beijing, China (in Chinese).

Zuo, Q. T. & Xia, J. (2002) Study on the modelling method of land water quantity and quality and ecology coupling system. *J. Water Conservancy* **1**, 61–65 (in Chinese).

Received 25 July 2005; accepted 31 December 2005