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Author(s):
Li, Ning; Kinzelbach, Wolfgang; Li, WenPeng; Dong, XinGuang

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Box model and 1D longitudinal model of flow and transport in Bosten Lake, China

Ning Li [a,b,*], Wolfgang Kinzelbach [a], WenPeng Li [c], XinGuang Dong [d]

[a] Institute of Environmental Engineering, ETHZ, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland
[b] China Institute of Geo-Environmental Monitoring, Beijing, China
[c] Institute of Hydrogeology and Engineering Geology Techniques, China Geological Survey, Hebei, China
[d] Xinjiang Department of Water Resources, Xinjiang, China

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SUMMARY

Bosten Lake in the southeast of Yanqi Catchment, China, supports the downstream agricultural and natural environments. Over the last few decades the intensive agricultural activities in Yanqi Catchment resulted in decreased lake levels and deteriorated lake water quality. A two-box model is constructed to understand the evolution of lake level and salinity between 1958 and 2008. The two-box model of the lake indicates that the evaporation does have the same trend as the observed lake area and the annual average evaporation agrees with the value obtained from the Penman–Monteith approach. To achieve a correct salt balance, the ratio of outflow concentration and average lake concentration has to be around 0.7. This is due to the incomplete mixing of the lake caused by short-circuiting between tributary inflow and the main outflow via the pump stations abstracting water from the lake. This short-circuiting is investigated in more detail by a 1D numerical flow and transport model of the lake calibrated with observations of lake level and lake concentrations. The distributed model reproduces the correct time-varying outflow concentration. It is used for the assessment of two basic management options: increasing river discharge (by water saving irrigation, reduction of phreatic evaporation or reduction of agricultural area) and diverting saline drainage water to the desert.

Increasing river discharge to the lake by 20% reduces the east basin salt concentration by 0.55 kg/m^3, while capturing all the drainage water and discharging it to depressions instead of the lake reduces the east basin salt concentration by 0.63 kg/m^3. A combination of increasing river inflow and decreasing drainage salt flux is sufficient to bring future lake TDS below the required 1 kg/m^3, to keep a lake level that sustains the lake ecosystem, and to supply more water for downstream development and ecosystem rehabilitation.

1. Introduction

With economic development and population increase, the conflicting interests between different sectors of water users concerning water quantity and quality become acute, especially in arid and semi-arid areas. In the Heihe River Catchment in China, 80% of the available surface water had been diverted for irrigation, which led to the drying up of more than 30 tributaries and terminal lakes (Wang and Cheng, 1999). In other arid or semi-arid basins of China the intensive use of upstream river water resources for irrigation or industrial development has also led to significant reduction of downstream river flow or shrinking of lakes (Chen et al., 1999; Zhang et al., 2012).

Most irrigated land in arid and semi-arid regions suffers from different degrees of soil salinization (Abrol et al., 1988). Drainage water from irrigated land carries higher salinity leading to the gradual degradation of downstream rivers' and lakes' water quality (Li, 2009; Feng et al., 2000; Dong et al., 2006). Increased salinity in lakes damages the lakes' ecosystem and reduces biodiversity (Hart et al., 2003; Cyrus et al., 2010; Lawrie and Stretch, 2011a,b).

Lakes are natural storage reservoirs of river flows and provide habitats for diverse species. For conservative water quality constituents, lakes approach an average concentration determined by the concentration of the inflows on a time scale related to the lake residence time. A lake downstream of an agricultural area acts as an integrator of the activities upstream. Lakes and reservoirs have also been used for artificial ecological water releases to the

* Corresponding author at: Institute of Environmental Engineering, ETHZ, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland. Tel.: +41 44 633 4004.
E-mail address: ning.li@ifu.baug.ethz.ch (N. Li).

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downstream. In China several ecological water release projects or water allocation schemes have been carried out to restore an ecosystem or improve lake quality. Examples are the Heihe River Catchment, the Tarim River Catchment, and Baiyangdian Lake (Fang et al., 2007; Ye et al., 2009; Cui et al., 2010). For these and similar projects understanding hydrological and environmental conditions of the lake is the basis for rational water management in the whole basin.

Many tools for the analysis of lake water problems and for decision support in lake management are available. They range from lumped box models to sophisticated 3D models. For water resources management considerable insight can be gained from both box models and distributed models. Box models can be used to estimate unknown terms in the water and solute mass balance equations if all other balance terms are known. The spatially discretized numerical models help to further understand the spatial variations of all terms. Water balance box models have for example been applied to assess the effect of reduced inflow on lake water budget and lake salinity due to climate change (Crowe, 1993; Rimmer et al., 2011), to explore the inflow and outflow contributions to lake water balance (Kummu et al., 2014), to explore the dynamics of the lake level (Chebud and Melesse, 2009), to evaluate the effect of different management scenarios on lake level (Setegn et al., 2011), to study the long-term changes in lake salinity (Rimmer, 2003; Rimmer et al., 2006), to investigate the impact of inflow changes on lake salinity (Lawrie and Stretch, 2011a,b), and to estimate groundwater seepage from lakes (Zhou et al., 2013). Distributed numerical models were applied to lakes to explore the distribution of salt concentration (Rogers and Dreiss, 1995), to investigate water circulation (Rueda and Schladow, 2003), and to predict long term water quality variations (Suh et al., 2004) among other applications.

Bosten Lake is one of the two biggest centres of fishery industries in Xinjiang province (Dong et al., 2007). Bosten Lake also plays an important role for agricultural development and environmental restoration in the downstream river basin as well as for the local economic development. Over the last five decades Bosten Lake suffered from environmental problems due to the intensive agricultural activities in the upstream basin. Before 1958 Bosten Lake was a freshwater lake with a concentration of total dissolved solids (TDS) of 0.6 kg/m^3. But it has become more saline since, with TDS concentrations above 1.8 kg/m^3. The lake level has dropped because river discharge to the lake has been reduced by increased consumptive water use of upstream agriculture. In 1983, a dam was built to restore the lake level. This dam divided Bosten Lake into two basins: a small west basin and a bigger east basin. The decreased water quantity and the diminished water quality of the lake outflow affect the downstream agricultural development and the riverine environment. Since 2000, the Chinese government has invested 11 billion CNY to convey Bosten Lake water to the downstream via pump stations to revitalize the degraded ecosystem of *populus euphratica* forests. From 2000 to 2008 the total amount of water released was about $2.56 * 10^9$ m^3 (Nie, 2007). Because of the environmental and development issues, it is important to understand the hydrological conditions of the lake and to identify a strategy to manage water resources sustainably.

Previous studies of Bosten Lake analysed the salt balance of the lake over decades (Zhao et al., 2005; Zuo et al., 2006; Dong et al., 2006; Zhong and Dong, 2008). In these studies, salt content is measured as TDS and is assumed to be conservative. This assumption is a good approximation considering that the major ions in the lake water (Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-) are far below saturation levels and no precipitation occurs (Xiao et al., 2014). These studies assume complete mixing in each of the two basins of Bosten Lake and set the concentration discharged from each basin to the averaged basin concentration. The assumption of complete mixing is unjustified and will be corrected in this paper. Distributed flow and transport models were not applied to Bosten Lake and this paper is the first study to apply a 1D longitudinal model to Bosten Lake.

This paper analyses the water and salt balances of Bosten Lake from 1958 to 2008 using box models and then uses a distributed model to examine the spatial distribution of TDS concentration. The goal of the modelling effort is to find solutions to the sustainable management of Bosten Lake water resources. Using the box and distributed models gives new insights compared to previous studies of Bosten Lake. The box model for salt content uses coefficients to parameterize the deviation from the assumption of complete mixing. The results demonstrate that the concentration discharged from the east basin is lower than the average basin concentration. This implies that when analysing the lake's salt balance it is inappropriate to assume that the east basin is completely mixed as was done in previous studies. The distributed model shows that higher TDS concentrations occur in the southeast part of the east basin.

The hydrology of the lake is introduced first, followed by a description of the box model, a description of the distributed model, and the formulation of management scenarios. Then the results of both modelling approaches are presented. Finally some conclusions relevant for a sustainable management of the lake are drawn.

2. Study area

Bosten Lake is located in the southeast of Yanqi Catchment in Xinjiang, an arid and semi-arid region in China. It fills a depression caused by faulting and has the bathymetry shown in Fig. 1. In 2008, the lake level was 1046.19 masl with a lake area of 991 km^2 and a lake volume of $6.5 * 10^9$ m^3. The average depth of the lake is 8 m and the maximum depth is 18 m. The lake is the terminal discharge point of the whole basin. All rivers of Yanqi Catchment—Kaidu River, Qingshui River, Huangshui River—flow from their headwaters to Bosten Lake (Fig. 1). The outflow of the lake supports the downstream agricultural and natural environments via the Kongque River. The average precipitation and pan evaporation between 1975 and 2006 were 86 ± 39 mm/year and 2200 ± 325 mm/year respectively. 65% of rainfall and 70% of evaporation happen between May and August. As precipitation is very low, it is neglected in the rest of this paper. Pump stations were built in 1983 to control the outflow from the east basin to Kongque River (Fig. 1). The east basin is therefore no longer a natural lake but is operated as a reservoir.

The data regarding the water and salt sources/sinks (river inflows, drainage discharge, lake outflows, salt mass inflows and outflows) as well as water levels and TDS concentrations for the two basins used in the following analysis, have been collected for the period from 1958 to 2008 by Xinjiang Agricultural University (Table 1). The river inflows to the lake were measured 3 times each month, averaged to estimate the monthly inflows and summed up to lead to the annual inflows used below. All drainage discharges were measured once per month at drain outlets around the lake and summed up to calculate the annual drainage discharge to the lake. Once a month outflows from the west basin and discharge of the pump stations via channel to Kongque River were measured. Integrating their sum over the year yields the annual discharge to Kongque River. Annual mean concentrations in different rivers and drain outlets are averaged values from one-monthly or two-monthly monitoring data. The annual water inflows multiplied by the corresponding TDS concentrations yield the annual salt mass inflows to the lake. The yearly averaged lake levels were calculated from monthly measurements. The east basin volume is interpolated from the documented relation between lake level

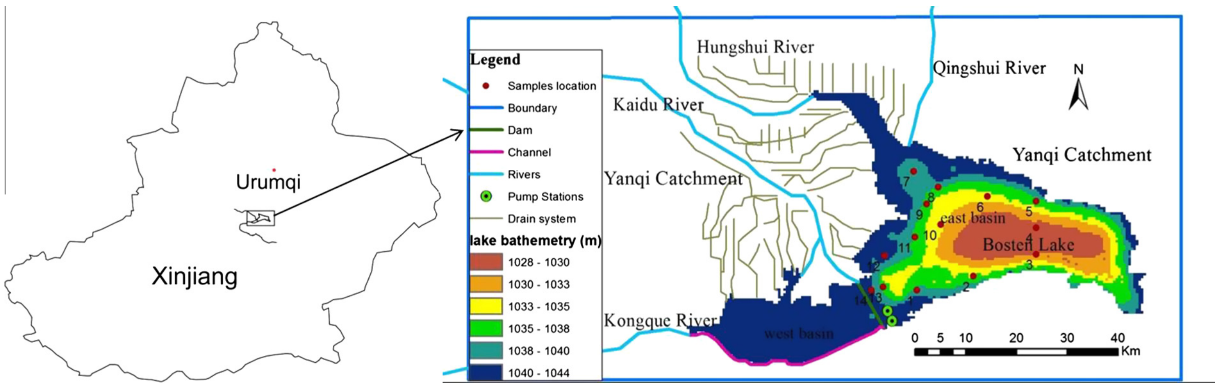

Fig. 1. Bosten Lake and its main river inflows and outflows.

Table 1
Annual means and standard deviations of lake data from 1958 to 2008.

Characteristic	Units	East basin	West basin
Water inflows			
River inflows	10^6 m^3	1526.6 ± 655.1	922.7 ± 328.7
Drainage discharge to lake	10^6 m^3	163.4 ± 25.4	31.9 ± 4.4
Water outflows			
Discharge to Kongque River	10^6 m^3	903 ± 230.9[a]	747.1 ± 422.7
Salt mass inflows			
Salt mass from rivers	10^6 kg	440.8 ± 189.5	267.5 ± 97.8
Salt mass from drains	10^6 kg	397.4 ± 67.7	77.8 ± 12.7
Observations			
Lake level	m	1047.1 ± 0.9	1047.2 ± 0.55
Lake volume	10^9 m^3	7.4 ± 0.9	–
Lake TDS concentration	kg/m^3	1.54 ± 0.24[b]	–

[a] Refers to the pumping rate from the east basin between 1983 and 2008.
[b] Refers to the TDS concentrations observed in 1974 and between 1980 to 2008.

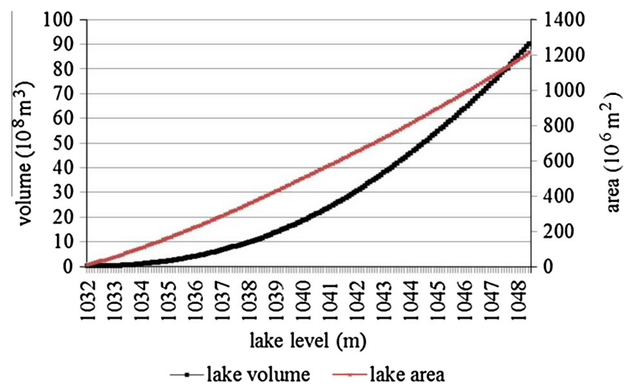

Fig. 2. Lake volume and area versus lake level in the east basin.

and lake volume. The recorded profile data of lake area and lake volume versus lake level have been collected by Xinjiang Agricultural University (Fig. 2). The profiles are given as piecewise linear curves. With the water level, the east basin surface area and volume are varying according to these profiles. The annual TDS concentration in the east basin is taken as the average of TDS concentrations measured at 14 sites at a depth of 0.5 m below the water surface and at irregular intervals around 6 or 7 times every year (Fig. 1). We have no access to single measurements from the 14 sites. Only the average values of the 14 sites over the year are available and used in the study. Besides the data related to the lake, the annual average values of TDS concentrations in Kongque River (0.73 ± 0.2 kg/m^3) are also required for the box model. They are calculated from the average values of measurements taken at irregular intervals over the year.

3. Methodology

3.1. Box model

A box model or multi-box model simulates the average state of a system through mass balancing by neglecting or only crudely considering the heterogeneities in the system. For Bosten Lake the average groundwater inflow to the lake and the seepage from the lake are estimated to be about 50 million m^3/year and about 60 million m^3/year respectively over the period 1982–1985 (Pei, 1988). These values of groundwater inflow and seepage are much lower than the surface flows into and out of the lake. Thus in the box model analysis, which uses two boxes, the water exchange between groundwater and lake is neglected.

Bosten Lake is treated as one box before 1983 and as a two box system after dam construction in 1983. There is limited water exchange between the east and west basins after 1983 through two gates on both ends of the dam. According to previous investigations, the exchange rate between the two lakes is small, but the exact value is unknown (personal communication). Thus, in this study the water flux exchanged between the two basins after 1983 is neglected for reasons of simplicity. Since the inflow to and outflow from the basins have been measured, the evaporation from both the west and east basins can be calculated through the water balance equations.

3.1.1. Water balance model

The water balance of Bosten Lake is determined using a simple box model, and is expressed in discrete time steps as follows. The time discretization is a central difference scheme shown in Fig. 3. The box in the figure is treated as a basic unit to calculate the water balance.

$$\frac{Q_{lakein,t-\Delta t} + Q_{lakein,t}}{2} - \frac{Q_{lakeout,t} + Q_{lakeout,t+\Delta t}}{2} - Q_{eva,t} = \frac{V_{lake,t+\Delta t} - V_{lake,t-\Delta t}}{2\Delta t} \quad (1)$$

Q_{lakein} is the total water inflow to the lake (m^3/year), $Q_{lakeout}$ is the total water outflow from the lake (m^3/year), Q_{eva} is the lake evaporation (m^3/year), V_{lake} is the lake volume (m^3), and Δt is the time step of 1 year.

Before 1983, the whole lake is simulated as one box. In Eq. (1) Q_{lakein} refers to surface water inflow from Kaidu River, Qingshui River, Huangshui River, and drainage discharge from the drain system while $Q_{lakeout}$ is the outflow from the west basin to Kongque River.

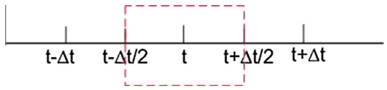

Fig. 3. Time discretization in the stepwise water balance computation.

After 1983, the whole lake is simulated as a two-box model. For the east basin, Q_{lakein} in Eq. (1) includes the eastern branch of Kaidu River, Huangshui River, Qingshui River and most of the irrigation drainage from the agricultural area. $Q_{lakeout}$ is the pump stations' discharge. Q_{eva} is the east basin evaporation. V_{lake} is the east basin volume. For the west basin, Q_{lakein} in Eq. (1) is the river inflow from the western branch of Kaidu River and some drainage water from the drain system. Q_{eva} is the evaporation of the west basin and V_{lake} is its volume.

The east basin volume is interpolated from the profile data of lake volume versus lake level. The west basin volume is computed by multiplying its area with the average water depth which is calculated using the average lake level minus the average lake bottom of the west basin. The west basin area is interpolated from a linear function fitting the relation between the west basin level and the west basin area obtained through remote sensing images of 5 years by Steiner (2010).

3.1.2. Salt mass balance model

The balancing procedure is now applied to the lake TDS, using the mass balance equations in discrete time steps as follows:

$$\sum_i C^i_{lakein,t} q^i_{lakein,t} - \sum_i C^i_{lakeout,t} q^i_{lakeout,t} = \frac{C_{lake,t} V_{lake,t} - C_{lake,t-\Delta t} V_{lake,t-\Delta t}}{\Delta t} \quad (2)$$

C^i_{lakein} is the TDS concentration of inflow source i (kg/m^3), q^i_{lakein} is the water inflow rate of source i (m^3/year), $C^i_{lakeout}$ is the TDS concentration of outflow sink i (kg/m^3), $q^i_{lakeout}$ is the water outflow rate of sink i (m^3/year), C_{lake} is the average TDS concentration in the lake (kg/m^3). It is assumed that TDS is a conservative solute (Xiao et al., 2014).

Before 1983 C^i_{lakein} are the TDS concentrations in Kaidu River, Qingshui River, Huangshui River and the drain system. $C^i_{lakeout}$ is the TDS concentration at the outflow of the west basin.

After 1983, for the east basin, C^i_{lakein} are the respective TDS concentrations in the eastern branch of Kaidu River, Qingshui River, Huangshui River and the eastern drain system. $C^i_{lakeout}$ is the TDS concentration at the pump stations in the east basin. In this case $C_{lake,t}$ is the average TDS concentration in the east basin, i.e. $C_{ebasin,t}$ (kg/m^3). For the west basin C^i_{lakein} are the TDS concentrations in the western branch of Kaidu River and the western drain system respectively. In this case $C_{lake,t}$ is the average TDS concentration in the west basin, i.e. $C_{wbasin,t}$ (kg/m^3).

The TDS concentration in Kongque River is a mixture of the outflow of the west basin and the flow from the pump stations in the east basin, which is expressed as follows.

$$C_{Kongque,t} = \frac{C_{wbasinout,t} q_{wbasinout,t} + C_{ebasinout,t} q_{ebasinout,t}}{q_{wbasinout,t} + q_{ebasinout,t}} \quad (3)$$

$C_{Kongque,t}$ is the TDS concentration in Kongque River in the year t (kg/m^3). $C_{wbasinout,t}$ is the TDS at the discharge point of the west basin in the year t (kg/m^3). $q_{wbasinout,t}$ is the discharge from the west basin to Kongque River in the year t (m^3/year). $C_{ebasinout,t}$ is the TDS at the pump stations in the east basin in the year t (kg/m^3). $q_{ebasinout,t}$ is the discharge rate at the pump stations in the year t (m^3/year).

Three parameters ($\alpha, \beta, \gamma \in (0, 1]$) are introduced to express the ratios of concentrations at different locations. The basin mixing parameter α is the ratio of the average TDS concentration in the west basin and the average TDS concentration in the east basin before 1983 ($C_{wbasin,t} = \alpha C_{ebasin,t}$). The west basin mixing parameter β is the ratio of the TDS concentration at the outflow of the west basin and the average TDS concentration in the west basin ($C_{wbasinout,t} = \beta C_{wbasin,t}$). The east basin mixing parameter γ represents the ratio of the TDS concentration at the pump stations and the average TDS concentration in the east basin after 1983 ($C_{ebasinout,t} = \gamma C_{ebasin,t}$). Based on Eqs. (2) and (3) the parameters ($\alpha, \beta, \gamma \in [0, 1]$) are calibrated to minimize the residuals between the observed and computed TDS concentrations in the east basin and Kongque River using the Root Mean Squared Error (RMSE) criterion,

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{2}\sum_t^{T_N}\left(C_t^{cal,j} - c_t^{obs,j}\right)^2}{2T_N}} \quad (4)$$

$C_t^{cal,j}$ are the calculated TDS concentrations in the east basin ($j = 1$) or in the Kongque River ($j = 2$) in year t (kg/m^3) respectively. $c_t^{obs,j}$ are the observed concentrations in the east basin ($j = 1$) or in the Kongque River ($j = 2$) in year t (kg/m^3). T_N is the number of time steps (years).

The concentration in the lake in 1958 is unknown due to a lack of records and is assumed to be 0.6 kg/m^3 according to estimates quoted in some previous studies of Bosten Lake (Zuo et al., 2004; Wang et al., 2004, 2005).

3.2. Distributed model

Because of inadequate availability of observations such as distributions of lake levels and lake TDS, 2D or 3D numerical lake models cannot be calibrated and are not feasible at the moment. In the future, more observation stations could provide vertically and horizontally distributed data concerning the effects of thermal stratification and wind forcing on the distribution of TDS concentration, which are not considered in this study. For Bosten lake, average water level and TDS concentration were used to calibrate and validate the 1D model; along-basin water velocities and along-basin TDS concentrations were not used for calibration and validation, because the 1D model considered here only considers the main flow pattern in the lake. The annual main river inflows to the lake amount to over 20% of the lake volume while the annual evaporation flux is also over 20% of the lake volume. These two items have a very large effect on the general lake circulation pattern. The prevailing winds in the area are south-western and north-western with low average wind speeds of around 3.5 m/s. The wind forces may influence vertical mixing and the local lake water circulation, but not the general pattern. For lake water movement, only the general lake circulation is considered in this case study. For transport simulation, actually the mixing effects of wind forcing are incorporated in an averaged way in our approach via the dispersion coefficient of the 1D model. The justification for representing the lake by a 1D numerical model is that concentration differences are most pronounced in the longitudinal direction of the east basin. There is a discharge flux to Kongque River towards the west and also an evaporation driven flow towards the far eastern end of the lake. As will be shown later, the outflow by evaporation in Fig. 5 is of the same order of magnitude as the outflow to Kongque River. These main flux directions are captured in the conceptual 1D model (Fig. 4). All other spatial flow details apart from the main directions are neglected. Five vertical TDS profiles in the north, west, south and southeast of the lake were obtained in June in 1984. Three samples were taken in each

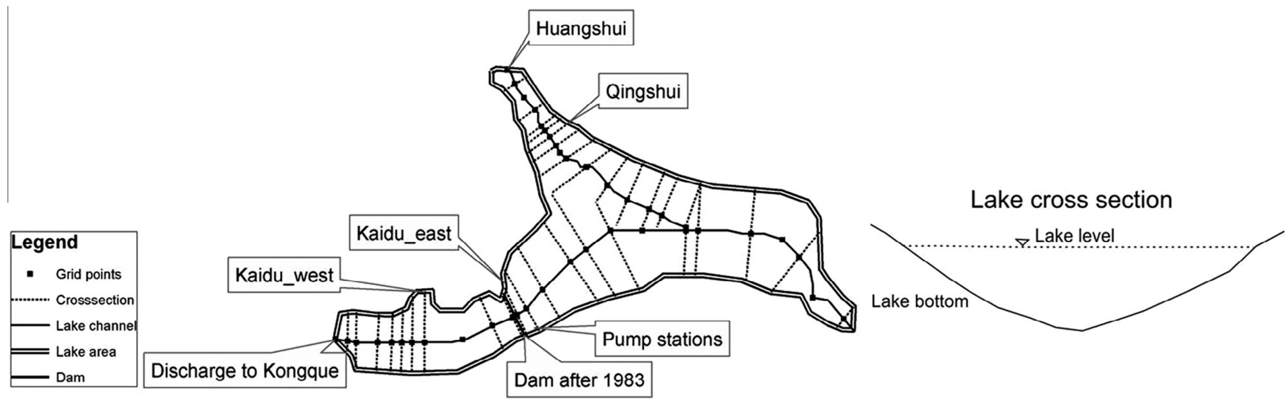

Fig. 4. Sketch map of conceptual model.

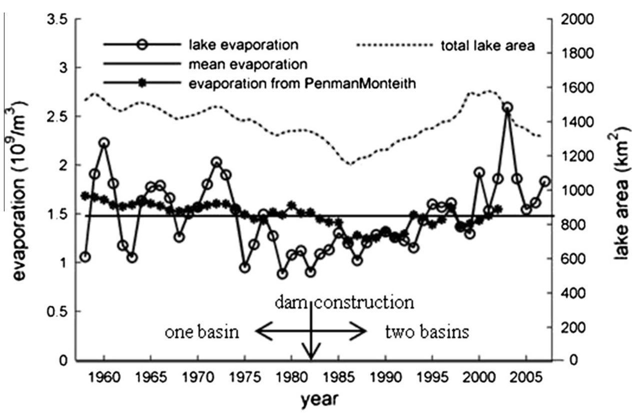

Fig. 5. Evaporation from Bosten Lake.

profile at 0.5 m below the water surface, half the water depth and 0.5 m above the lake bottom (Cheng, 1993). The results showed that the vertical distribution of lake TDS varies, but the maximum vertical difference observed was only around 0.04 kg/m^3 and thus small against the average value. Besides, Bosten Lake is a shallow lake and its vertical thermal stratification is not obvious. Hu et al. (2005) pointed out that there is almost no vertical thermal stratification observable in the shallow lakes of the arid areas of Central Asia. So the vertically averaged modelling of Bosten Lake is justified. The distributed model is constructed using MIKE11 which is a 1D simulation model for rivers and lakes (DHI, 2011a,b). It has been successfully applied to model water flow and water quality in rivers and lakes (Hansen et al., 2009; Doulgeris et al., 2012; Ahmed, 2010, 2014). Both annual and monthly variations of lake level will be examined in the 1D model.

3.2.1. Governing equations

The hydrodynamic module (HD) of MIKE 11 uses an implicit, finite difference scheme to solve the Saint Venant equations. The equations are derived from mass conservation and momentum conservation, with Manning's equation as closure. They read as follows

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q \quad \text{(Mass conservation)} \tag{5}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\frac{\partial h}{\partial x}=g(S_0-S_f) \quad \text{(Momentum conservation)} \tag{6}$$

$$S_f=\frac{n^2Q^2}{R^{\frac{4}{3}}A^2} \quad \text{(Manning's equation)} \tag{7}$$

A is the cross-sectional area of the channels (m^2), t is the time (s), x is the longitudinal distance along the channels (m), q represents the sources/sinks per unit channel length (m^2/s), Q is the flow rate (m^3/s), h is the water depth (m), S_0 is the slope of the channel bottom (–), S_f is the friction slope (–), n is the Manning roughness coefficient and R is the hydraulic radius (m).

The one-dimensional advection–dispersion model (AD) of the channels used to compute the concentration distribution is written as follows, according to the mass conservation equation.

$$\frac{\partial AC}{\partial t}+\frac{\partial QC}{\partial x}-\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right)=C_{in}q_{in}-Cq_{out} \tag{8}$$

C is the lake TDS concentration (kg/m^3), D is the dispersion coefficient (m^2/s), A is the cross-sectional area of the channels (m^2), C_{in} is the source concentration and q_{in}/q_{out} is the lateral inflow/lateral outflow per unit channel length (m^2/s).

3.2.2. Model set up

The two lakes are conceptualized as 1D channels with wide cross-sections (Fig. 4). The thinner black lines are the channels in MIKE11. They are discretized into 40 grid-cells with an average length of 4000 m. There are 35 cross sections (dark dash lines in Fig. 4) obtained from the recorded lake bottom elevation. The bathymetry input to the model accurately reproduced the lake water volume for different water levels. The inflows to the lake from the rivers, the discharge to Kongque River and the pumping rate from the east basin are introduced as specified flow boundary conditions. The drainages of the east and west basins are added to the hydrodynamic model as point sources. The concentrations of the inflow and the point sources are specified concentration boundaries. The dam between east basin and west basin is simulated as a controlling structure with zero discharge between the two basins after 1983. The eastern end of the lake is simulated as a closed boundary condition, where a zero flux across the boundary is applied in both the HD and AD models. The evaporation from the lake is introduced as a sink q in Eq. (5) and adds up to the value obtained from the box model. Its monthly distribution over the year follows the pattern of monthly changes of the observed pan evaporation (Xinjiang Agricultural University). The evaporation of a cell is computed according to its lake surface area. The lake area is positively correlated to the lake level because the cross-sections of the lakes follow a bowl shape (Fig. 4). In the transport equation q_{in} is non-zero and refers to the drainage discharge while the q_{out} term is disregarded as evaporation does not carry salt. Manning's n of the west basin is larger than that of the east basin, reflecting the increased bed friction due to weed growth in the west basin. The values of Manning's n are calibrated in the numerical flow model using yearly and monthly lake level data. The dispersion coefficient is calibrated in the solute transport model using yearly lake TDS data. The 1D numerical model simulates the time interval from 1958 to 2008. The time step of the flow model is 4 min, the one for the advection–dispersion model is half of that to ensure consistency between the staggered grid (H and Q points) of the hydrodynamic simulation and the normal grid of the transport simulation (DHI, 2011b).

3.2.3. Model validation

For the validation of the numerical model, computed lake levels from 1958 to 2008, and lake TDS concentrations in 1974 and between 1983 and 2008 are compared to their observed values. This comparison is analysed using Nash–Sutcliffe efficiency coefficients (Nash and Sutcliffe, 1970).

$$E = 1 - \frac{\sum_{t=1}^{T}(O^t - M^t)^2}{\sum_{t=1}^{T}(O^t - \overline{O})^2} \tag{9}$$

E is the Nash–Sutcliffe efficiency coefficient, T represents the number of time steps, O^t is the observed value at time t, $\overline{O}$ is the average observed value over time T, M^t is the modelled value at time t.

3.3. Scenario formulation

Water resources management in Bosten Lake has to cope with challenges arising from water quantity and quality. The lake level should be in the secure range between 1045.5 masl and 1048 masl to protect the water environment of Bosten Lake itself (according to communication with the local experts). The lake TDS concentration should be lower than 1 kg/m^3 (threshold between fresh water and brackish water) (http://glossary.ametsoc.org/wiki/Freshwater). The discharge from the lakes to Kongque River should be as large as possible to sustain the downstream requirements of agriculture and the riverine forest environment. In order to explore the factors influencing the lake water quantity and water quality, four different scenarios are simulated with the numerical 1D flow and transport model. Computed results for 2008 serve as initial conditions for the different scenarios simulated over 50 years each. The amount of water that can be diverted from the lake to the downstream is determined by setting the lake level at the outflow to a safe value of 1046 masl. The model then automatically yields the flow rate, which can be abstracted by the pump stations under the condition of keeping that outflow level constant. After 50 years a steady state is reached in all scenarios. They are defined in the following:

Scenario 0 (S0): This basic scenario takes the average values for lake sources and sinks from the time interval 1983 to 2008 i.e. after the dam construction for extrapolation to 2050. This implicitly assumes that the effects of climate change remain negligible over that period.

Scenario 1 (S1): This scenario is based on S0 and increases the discharge of rivers to the lake by 20% by diverting less irrigation water. To reduce the diversion, several options are available: They include

– plastic mulching on the cultivated area to reduce evapotranspiration and decrease the irrigation demand;
– water saving irrigation technology such as drip irrigation;
– decrease of cultivated area to decrease the total water demand;
– irrigating with groundwater to reduce unproductive phreatic evaporation by lowering the groundwater table and
– improving the efficiency of irrigation channels by renovating the irrigation channel system.

All these methods can be combined. Climate change supposedly will increase river inflows. According to Chen et al. (2008), the maximum of the annual river runoff could increase by 38% of its current value. Given the uncertainty of this projection we disregard it and only postulate a 20% increase in discharge to the lake, which can realistically be reached by the options mentioned.

Scenario 2 (S2): This scenario is based on S0 but produces no drainage to the lake by transferring 100% of the highly saline drainage water to depressions in the desert.

Scenario 3 (S3): This scenario combines a reduction of river water diversion and a partial transfer of saline drainage to the desert, increasing the river inflow by 20% and decreasing the drainage salt flux by 30%.

4. Results

4.1. Evaporation and lake concentration from box model

Fig. 5 shows that the annual lake evaporation calculated from the water balance equation shows large changes from year to year. This may be due to inaccuracies in the calculation of the volumes of the two basins and other uncertainties in the input data. But in the long run, the evaporation does have the same trend as the observed lake area: first it decreases till 1987, then increases till 2004, and thereafter it decreases again. The computed annual average evaporation for the whole lake is around $1.5 * 10^9$ m^3/year, which is practically equal to the value obtained from the Penman–Monteith approach (Steiner, 2010).

The salt mass balance equation leads to the calibrated parameters ($\alpha = 0.9, \beta = 0.8, \gamma = 0.7$) yielding the minimum RMSE of 0.167 kg/m^3 between simulated and observed TDS concentrations in Kongque River and the east basin. In both cases simulated TDS concentrations are still higher or lower than observed values in some years (Fig. 6), but the model results overall fit the observations well. It will be shown later that the errors are mainly due to the variation of the east basin mixing parameter γ with time.

The modelled TDS concentrations in the east basin, at the pump stations, in the west basin and at the discharge point of the west basin are shown in Fig. 7. The TDS concentration in the east basin is higher than that in the west basin and the difference between the two concentrations increases after 1983. This is caused by the dam constructed in 1983, which prevents mixing between the two lakes. It leads to a slight increase in the east basin concentration and a slight decrease in the west basin concentration after 1983. The concentration at the pump stations in the east basin is lower than the average concentration of the east basin because the pump stations are close to the fresh river water discharge of

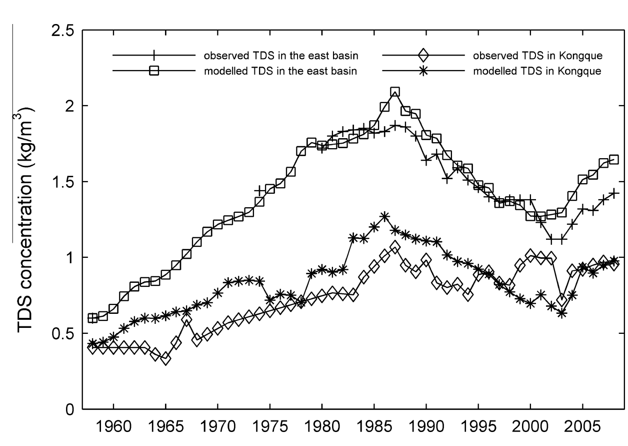

Fig. 6. Modelled and observed TDS concentrations for the east basin and for Kongque River.

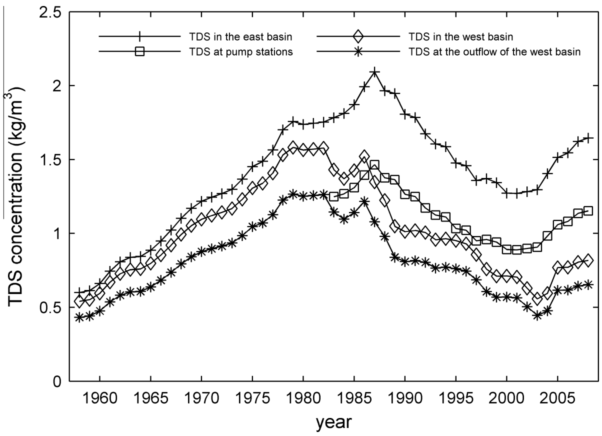

Fig. 7. Modelled TDS concentrations from salt mass balance model.

the eastern branch of Kaidu River and preferentially draw water from there. The concentration at the discharge point of the west basin is lower than the average concentration in the west basin. This is also caused by dilution through fresh river discharge, this time from the west branch of Kaidu River. This difference decreases after 1983 because the dam interrupts the direct hydrological connection between the east and west basins.

4.2. Distributed model results

After model calibration, Manning's n values for the west and east basins are 0.125 and 0.04 respectively, which are in the range given for beds with low biomass by De Doncker et al. (2009). The calibrated dispersion coefficients for the west and east basins are both 7 m^2/s, which is near the lower bound of the range between 0.1 and 100 m^2/s given by Shen et al. (2010) based on measurements for seven rivers. The comparison between simulated and observed values of lake levels and TDS is shown in Fig. 8. The lake level in the east basin recovers after 1987 because of the increased river runoff and the dam construction controlling the water discharge from the east basin. After 2000, much more water is pumped to Tarim River to revitalize the riverine forest in the downstream, so the east basin level starts to decrease again. The average TDS concentration in the east basin is obtained by dividing its total salt mass by its total volume. The modelled TDS concentration in the east basin follows the dynamics of the observed lake concentration. The Nash–Sutcliffe efficiency coefficients are given in Table 2. An efficiency coefficient of 1 means perfect fit between observations and simulations. A negative value indicates that the modelled value is worse than the mean value of the observation. All of the efficiency coefficients indicate a good fit to the observations. Compared to the efficiency coefficients of the east basin water level, the lower values for the yearly and monthly west basin water levels are caused by the bigger deviation between observations and calculations at the beginning of the time period. If the first 10 years are excluded, the efficiency coefficients of the yearly and monthly west basin water levels for the last 40 years improve to 0.77 and 0.56 respectively. The relatively low coefficient of the monthly west basin water level is also caused by sudden water level jumps observed in some months, which are in contrast to the smoother curve obtained in the calculation.

4.3. Scenario analysis

The results of the numerical flow and transport model under the four scenarios S0, S1, S2 and S3 are shown in Fig. 9 and Table 3. Scenario S0 implies that the east basin TDS concentration

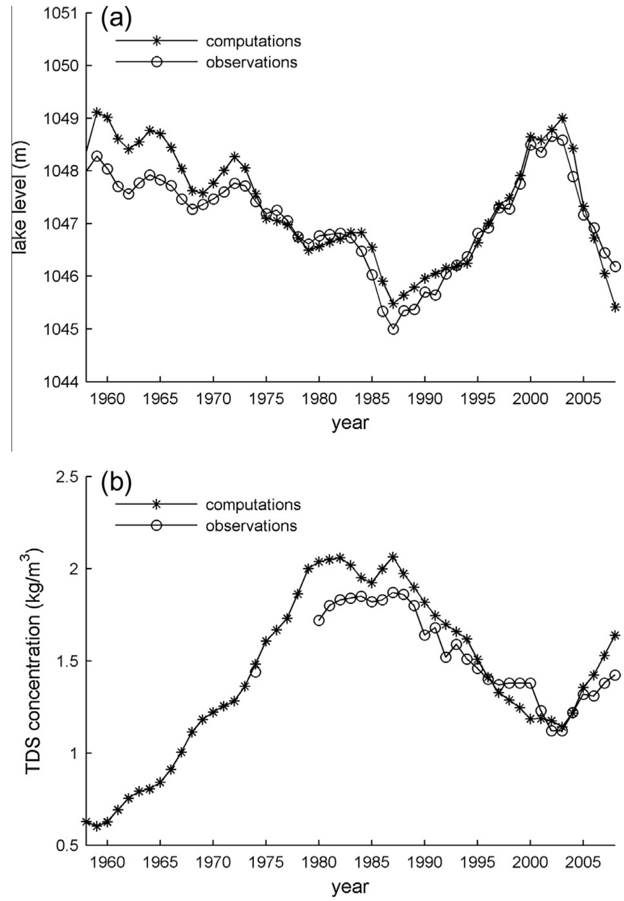

Fig. 8. Computed and observed yearly values in the east basin from 1958 to 2008. (a) Lake level. (b) Lake TDS concentration.

Table 2
Nash–Sutcliffe efficiency coefficients for different modelled outputs.

Items	Efficiency coefficients
Yearly water level in the east basin	0.75
Monthly water level in the east basin	0.73
Yearly water level in the west basin	0.44
Monthly water level in the west basin	0.34
Lake TDS in the east basin	0.64

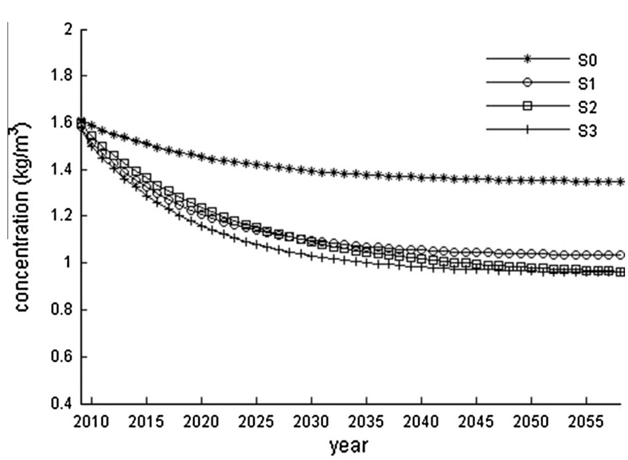

Fig. 9. East basin TDS concentrations from 2009 to 2058 in different scenarios.

Table 3
Results in 2050 for different scenarios.

Scenarios	Level in the east basin (m)	Discharge to Kongque (m^3/s)	TDS in the east basin(kg/m^3)	Average TDS in the whole lake (kg/m^3)
S0	1046	48.18	1.35	1.24
S1	1046	65.54	1.03	0.97
S2	1046	43.65	0.97	0.9
S3	1046	64.04	0.96	0.9

is decreasing over the 50 year period and levels off at around 1.4 kg/m^3. This value is still higher than the required 1 kg/m^3 (Fig. 9). For the other scenarios, the discharge to Kongque River will rise with the increase of the river inflow (S1) and decrease with the decrease of the drainage discharge (S2) (Table 3). The lake TDS concentration is decreasing in both cases (S1 and S2) (Fig. 9). Even though the east basin will become a fresh water lake with lake TDS lower than 1 kg/m^3 under scenario S2, it would be an economic challenge to transfer 100% of the highly saline drainage water away from the lake. Hence, a combination of scenarios is necessary to meet also economic constraints. The results from scenario S3 show that the lake discharge to Kongque River is significantly increased in comparison with scenario S0 while at the same time the lake TDS concentration is lower than 1 kg/m^3 (Table 3). Fig. 9 demonstrates that the lake TDS concentrations under scenarios S2 and S3 reach almost the same final value, but scenario S3 reaches steady state faster (within 30 years) than scenario S2. The combined scenario S3 achieves the sustainability goals for the lake with respect to both quantity and quality. In S3, the water release from the lake to the downstream can be increased by 16 m^3/s benefitting the downstream agricultural development and ecological needs. The average TDS concentrations of the whole lake obtained under the different scenarios are lower than the corresponding concentrations in the east basin because of the lower concentration of the west basin water (Table 3).

5. Discussion

5.1. Spatial concentration distribution obtained from the numerical model

Even though the box model is only a rough approximation of reality, it did help to better understand the hydrological condition of the lake. A ratio of 0.7 between the TDS concentration at the pump stations and the east basin is obtained from the simple mass balance equation. The 1D numerical model calculates this ratio explicitly and shows that it varies in time (Fig. 10). The average ratio over the period from 1983 to 2008 is around 0.75 which is slightly higher than the value from the box model. The east basin mixing parameter of less than 1 implies that the assumption of complete mixing in the east basin is not appropriate. Using the constant mixing ratio of the box model of 0.7 already reduces the error in computing the outflow concentration considerably.

If instead of a constant value we use the time-varying parameter γ obtained from the numerical model in the box model, the observed and computed TDS values of the east basin become almost identical (Fig. 11). The RMSE of TDS concentration in that case is around 0.07 kg/m^3 which is much lower than the value of 0.13 kg/m^3 calculated using a constant γ of 0.7 in the box model. This shows that the main error in the box model is the imperfect incorporation of incomplete mixing. The east basin mixing parameter γ is not constant in time but depends on the yearly varying hydrological conditions. The box model method (Eqs. (2) and (3)) applied in this specific case can be viewed as a way to determine

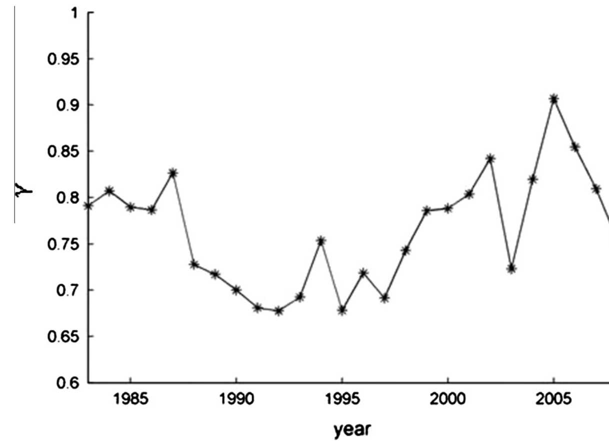

Fig. 10. Parameter γ (the TDS concentration at the pump stations over average concentration of the east basin) from 1983 to 2008.

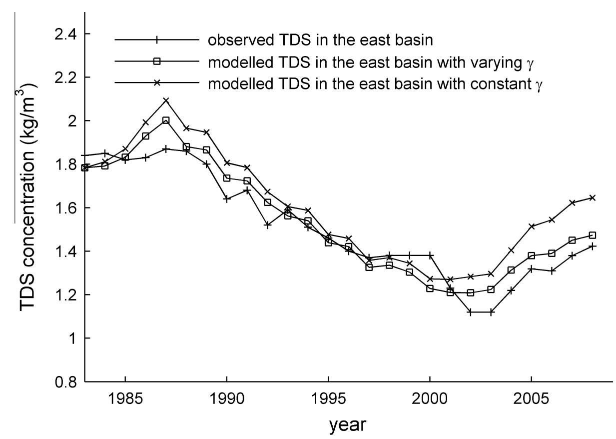

Fig. 11. Modelled TDS concentration from the box model using the time-varying paramter γ from Fig. 10.

the degree of mixing in lakes and reservoirs. It is an alternative to other methods such as the system identification method used by Rimmer et al. (2006) to verify the complete mixing in Lake Kinneret. The estimation of the mixing parameter γ performed for the east basin could be applied to other lakes and reservoirs as long as the inputs required in Eqs. (2) and (3) are available for the corresponding study areas. The value of γ depends on the concentration and flow rate of the inflow and outflow, as well as the lake volume (Eqs. (2) and (3)). The mixing parameter γ could also be used to estimate a residence time that accounts for short-circuiting. The residence time can be calculated as follows:

$$T_{resi,true} = \frac{1}{\gamma} T_{resi,completemix} \tag{10}$$

$$T_{resi,completemix} = \frac{C_{lake} V_{lake}}{C_{lake} Q_{lakeout}} \tag{11}$$

where $T_{resi,true}$ is the residence time accounting for short-circuiting. $T_{resi,completemix}$ is the residence time assuming complete mixing. In this case study, the ratio γ is around 0.7, so the residence time is 1.43 times higher than the value obtained from the complete mixing assumption made by researchers in the past.

Fig. 12 shows the TDS concentrations at cross-sections close to the 14 sampled locations which are mainly distributed in the western and central parts of the east basin (14 red dots in Fig. 1). It is obvious that the TDS concentrations at the cross-sections are

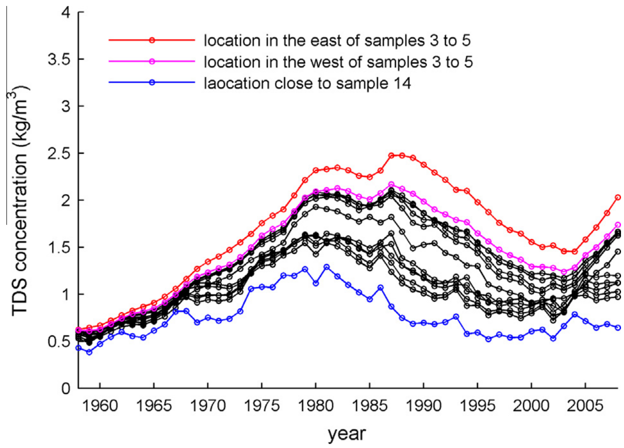

Fig. 12. Simulated TDS values in 14 sampling points of the east basin from 1958 to 2008.

inhomogeneously distributed in the east basin. The locations close to Kaidu River have lower concentrations (blue line in Fig. 12) and those close to the southeast corner have higher concentrations (purple and red lines in Fig. 12). The reasons are obvious: The proximity of the outflow in the west and the river inflow induces a short-circuit between the two (Fig. 1). While the outflow in the west removes salt from the east basin, the evaporation driven outflow towards the east accumulates salt in the east basin. These two processes result in a fast water exchange in the western part and low mixing in the eastern part of the lake. With the outflow of $1.6 * 10^9$ m^3/year in the west and the lake evaporation of $1.5 * 10^9$ m^3/year towards the east being practically of the same size, a strong concentration gradient from east to west develops.

5.2. Implications for water resources management

The results from the scenario analysis indicate that the available lake water discharge to Kongque River is directly affected by the river discharge to the lake. This is consistent with conclusions from previous studies (Zuo et al., 2004; Zhong and Dong, 2008). Reducing the river diversion for irrigation in Yanqi Catchment should be a key decision in future water resources management. Decision makers should realize that the present constraint on the lake level and the demand to increase the discharge to Kongque River contradict each other. More lake discharge to support the downstream agricultural development and riverine ecology may require a lake level below the secure range. The scenario analysis shows that increasing river discharge to the lake will provide more outflows to support downstream agricultural development. This would be a trivial statement if the lake level and thus the lake area were constant in different scenarios. In reality more inflow means larger lake area and more evaporation.

The east basin TDS concentration can be reduced to 1 kg/m^3 by increasing river discharge and decreasing the drainage discharge to the lake. 20% increase in river discharge to the lake decreases the east basin TDS by 0.55 kg/m^3 in 50 years. Reducing the drainage discharge to the lake to zero decreases the east basin TDS by 0.63 kg/m^3. At the same time 8% of inflow to the lake will be lost. The desired concentration decrease is reached with this relatively small loss because the concentration of the drain discharge is much higher than that of the river. Capturing drainage water seems more efficient than any other measure with respect to the water quality goal. Technically the drainage could be diverted into the desert to be evaporated. The combined measure composed of elements of the two scenarios seems more desirable. It diverts more water to support downstream development, keeps a reasonable lake level to sustain the lake's own environment and also improves the east basin TDS concentration to a value lower than 1 kg/m^3. The values of meteorological and hydrological parameters in the scenario analysis are based on their historical time series and only one realization consisting of the averaged historical values is used. This is unlike other studies such as the one by Rimmer et al. (2011) who consider a number of time series of inflows, precipitation, evaporation and so on. Therefore lake concentration and lake discharge under different scenarios cannot be shown here with their probability distributions. But the one realization scenario analysis quantifies the average effect of different management scenarios on the lake level and lake TDS concentration, which provides sufficient evidence to the decision makers to choose among options.

This study also suggests that decision makers should be cautious in choosing a water resources strategy on the basis of lake TDS concentration. Bosten Lake has been a two basin system since 1983, so the two basins should be considered separately. The average TDS concentration for Bosten Lake is lower than that of the east basin due to the lower concentration in the west basin. It may be easier to manage the quality constraint for the whole lake's TDS (Li, 2009), but it provides misleading information on the east basin TDS concentration.

6. Conclusion

The paper uses a two box model and a distributed numerical model of the two basin system to analyse the flow and salt transport in Bosten Lake. It also suggests a viable solution for overall water resources management in the region. Both the box model and the numerical model are based on the time series of observations between 1958 and 2008. The box and numerical models show clearly that the average TDS concentration of the lake is not the same as the concentration flowing out of the lake. It is inappropriate to treat Bosten Lake as a completely mixed box with respect to TDS. This conclusion is important for the application of box models in other studies where lakes are not completely mixed due to short circuiting between inflow and outflow.

All values of lake levels and lake TDS concentrations computed with the hydrodynamic model and the advection–dispersion model show a very good agreement with the observations, with only small deviations between the calculations and observations remaining. They can be explained among other things by imperfect sampling. The numerical model is an excellent tool to understand the spatial distribution of hydrological variables.

This 1D model is an important step in the process of building a distributed coupled numerical model of the whole Yanqi Catchment required in the more detailed planning of concrete management measures and their spatial distribution in the basin.

The scenario analysis shows the lake concentration dynamics with respect to river inflow and drainage concentration. If agricultural management achieves a flow increase by a reduction of the unproductive evaporation and a decrease of the drainage salt flux by evaporating some drainage water in depressions instead of discharging it into the lake, the goal of 1 kg/m^3 can be reached within a 30 year period.

Parameter uncertainty and predictive uncertainty for different management scenarios considering an ensemble of climate realizations were not discussed here. They are the subject of a subsequent paper which examines the probability distribution of outcomes due to different strategies.

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