Analysis of Trends and Changes in the Water Environment of an Inland River Basin in an Arid Area

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ABSTRACT: Lake Bosten is the largest inland freshwater lake in China and plays a key role in the local arid-area ecosystem. This study focuses on the dynamics of water salinity of Lake Bosten in the past 55 years (1955–2009) and intends to quantify the associations between the water salinity and the magnitudes of water level, inflow, outflow, total wastewater drainage into the lake, including industrial and residential wastewater. Correlation analysis reveals that the water salinity has strong associations with those six factors ($R = -0.810$, –0.510, –0.844, 0.903, 0.855, and 0.685, respectively). We predict that water level, inflow and water salinity of Lake Bosten will decline in 2010–2019. This study recommends a reduction in salt input to the Bosten River by reducing industrial wastewater discharge along the river and the development of clean production technology. *Water Environ. Res.*, **86,** 104 (2014).

KEYWORDS: lake salinity, trend, industrial wastewater, Lake Bosten, arid inland river.

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Introduction

The arid area in northwestern China is characterized by inland rivers passing through mountains and river basins. Mountains provide water for river development and plain oasis formation, because oasis development as well as the water requirement for production and living in an oasis, is mainly reliant on the mountain water. Water comes out of the mountains and, after use in the mountains and oases, runs into terminal lakes or disappears into deserts. Lake Bosten is the largest inland freshwater body located in Qarasahr basin (86°20′∼87°26′E, 41°44′∼42°14′N), south of Tianshan Mountains. Lake Bosten is the terminus of Kaidu River and the headwater of Konqi River. It is the essential water source for agriculture and industry in Bayingolin Prefecture of Xinjiang. It is important for drought relief, flood and regulation, because 6.5–8.5 billion m^3 in the Lake Bosten reservoir volume can effectively regulate the flood in Konqi River, provide water in irrigation and ecology, and the great water evaporation greatly increases the humidity in the Basin, which has significant ecological functions. In the last 50 years, Lake Bosten has supported rapid, large-scale economic development in the area. This development has lead to increasing environmental deterioration. The water body has been an increase in salinity, influx of wastewater, organic pollution and eutrophication. The large variation in the lake's water level affects reed production, fisheries and wetland biodiversity, which further influences agriculture and industrial development in the downstream Konqi River, Ku'erle City and Lopnur County.

There have been many studies in the last decade on the water environment of Lake Bosten, including environmental change and its affect on the environment, such as air temperature, precipitation, the relative air humidity, for example, as well as changes in runoff into Kaidu River (Cheng and Li, 1997; Li and Yuan, 2002; Wang et al., 2005; Reyihanguli, 2006; Cheng, 1987; Mischke and Wunnemann, 2006; Huang et al., 2009; Mischke et al., 2010). Studies have also been conducted to evaluate water volume, salinity, and evaporation in Lake Bosten (Zhao et al., 2007). These studies have shown that the development of human society has led to the discharge of a large volume of agricultural and industrial wastewater into Lake Bosten, resulting in its rapid change into a slightly salt lake (Zhou et al., 2001). Studies of Bosten sediment have revealed its climate and water level history (Wunnemann et al., 2006; Xiao et al., 2010; Xiao et al., 2009). Here, we report a systematic investigation on the cause of water environment changes in the Lake Bosten area based on records of water level, surface inflow, and water quality covering the last 55 years. We also attempted to predict water level, inflow and water quality for the upcoming decade. Based on these analyses, we propose an industrial wastewater management approach. These analyses are necessary for sustainable development, integrated management of the lake ecosystem, and to provide evidence-based decision-making support.

Methodology

Study Area. Lake Bosten is 55 km long from east to west, and 20 km wide from south to north, on average. When the lake water level is at 1048.75 m altitude, its water surface is 1002.4 km^2, with a volume of 8.8 billion m^3. Its average depth is 8.8 m, and has a maxiumum depth of 17m. The lake is composed of a main part and a chain of smaller, reed filled shallow waters. Its contributing rivers include Huangshui and Qingshui and the perennial Kaidu River. The entire watershed covers 22 000 km^2. Kaidu River is 513 km long originating from the snowy middle

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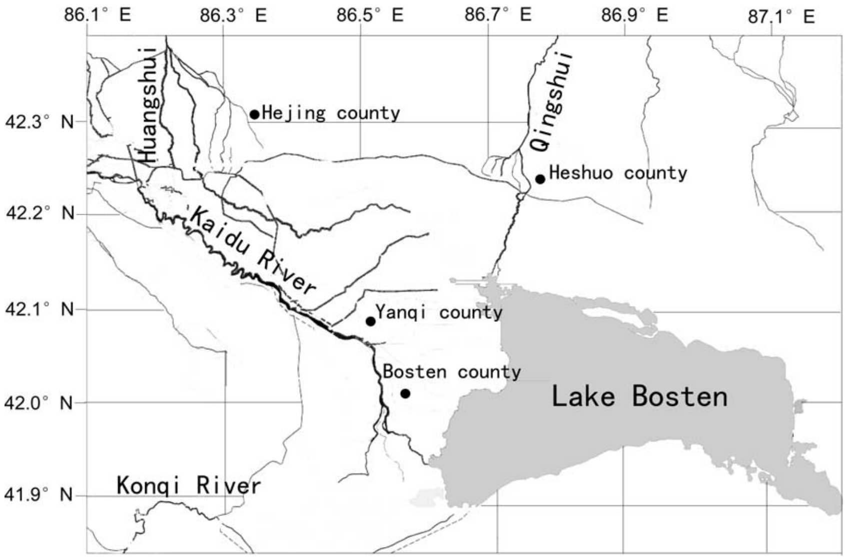

Figure 1—Map of Lake Bosten, Xinjiang

range of Tianshan Mountains. It carries 3.412 billion m^3 water to Lake Bosten per year. Lake Bosten discharges to Konqi River (Figure 1).Recent economic and social development in the watershed has influenced the lake ecosystem and water quality. The agricultural drainage system in Yanqi Basin discharges 200 million tons of agricultural wastewater and 400,000 tons of salt into Lake Bosten. Due to the continuing reduction in freshwater inflow, the Lake's salinity has increased from 0.39 g/L in 1958 to 1.87 g/L in 1986, remaining stable at 1.30 g/L since 2000.

Lake Bosten is located in central Asia where there is plenty of light and heat, but little precipitation. The basin area has an average multiannual temperature of 8.3°C, and an average precipitation of 68.2 mm. Annual evaporation is 1800 to 2000 mm.

Data Source. Data were collected from Xinjiang Hydrological Statistical Almanac, Xinjiang Water Resources Statistic Compilation, Xinjiang Statistical Almanac, Almanac of the Production and Construction Corps of Xinjiang. Data for Bosten watershed hydrology, weather, inflow and water quality were provided by Tarim Watershed Authority, Bayingolin Water Resources Bureau. The data covered the years 1955 to 2009.

Prediction Method.

(1) Cyclic superposition model

Assuming water quality change has a trend in addition to cyclic changes, then the trend can be predicted using a periodic superposition model. The expected value for $T+\tau$ is

$$\mu_{T+\tau} = a_T + b_\tau + \sigma_{T+\tau} \qquad (1)$$

Where, α_T is the average level in time T, b_τ is the slope within the period, $\sigma_{T+\tau}$ is the increment within $T+\tau$.

Using past data, a prediction model can be constructed in two steps.

First, obtain estimates $\hat{a}_T$, $\hat{b}_\tau$ and $d_{T+\tau}(\tau = 1, 2, \cdots, M)$ for a_T, b_τ, and $b_{T+\tau}$, respectively using historical data, and predict future time.

Second, update the model using data from the remaining incomplete cycle, and make a prediction. In such a way, a complete model of T for future time τ:

$$\hat{x}_T(\tau) = \hat{a}_T + \hat{a}_{T\tau} + d_{T+\tau} \qquad (\tau = 1, 2, \ldots M). \qquad (2)$$

Since the calculation is very tedious, we used DPS software to perform superposition calculation, and prediction, and prediction as was done by Tang and Feng (2002).

(2) Box-Jenkins (ARIMA) model

Time series analysis ARIMA model is also called Box-Jenkins methods. They include auto-regressive (AR) method, moving average (MA) method, and autoregressive moving average (ARMA) method.

ARMA model depends on not only past observed data, but also the random error entered in the system, such that

$$X_t = \varphi_1 X_{t-1} + \varphi_2 X_{t-2} + \cdots + \varphi_p X_{t-p} + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} \cdots - \theta_q a_{t-q} \qquad (3)$$

where, the first part is the autoregression part; p: the autoregression order number, $\varphi_1,\ldots, \varphi_p$: the autoregression coefficient; the lower part is the moving average part; q: the

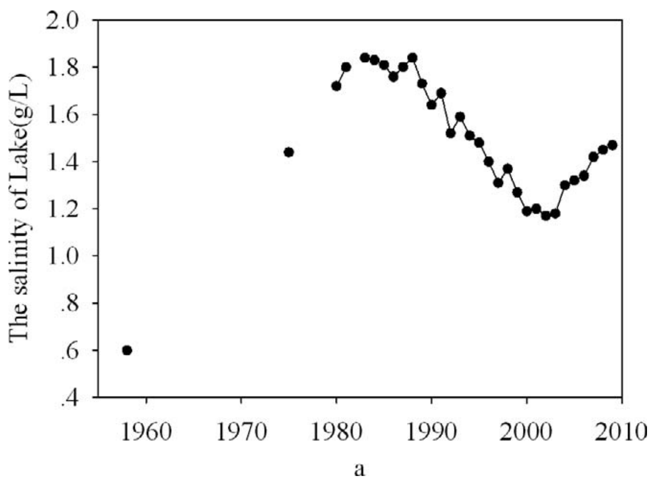

Figure 2—Salinity in Lake Bosten

Table 1—Limit values for surface water environment quality standards.

Serial orders	tems		Classification				
			I	II	III	IV	V
1	pH				6–9		
2	Dissolved oxygen	≥	Saturation was 90% or 7.5	6	5	3	2
3	Permanganate index	≤	2	4	6	10	15
4	Chemical oxygen demand(COD)	≤	15	15	20	30	40
5	Five day biochemical oxygen demand(BOD_5)	≤	3	3	4	6	10
6	Ammonia nitrogen(NH_3-N)	≤	0.15	0.5	1.0	1.5	2.0
7	Total phosphorus(P)	≤	0.01	0.025	0.05	0.1	0.2
8	Total nitrogen(N)	≤	0.2	0.5	1.0	1.5	2.0
9	Copper	≤	0.01	1.0	1.0	1.0	1.0
10	Zinc	≤	0.05	1.0	1.0	2.0	2.0
11	Fluoride(F)	≤	1.0	1.0	1.0	1.5	1.5
12	Selenium	≤	0.01	0.01	0.01	0.02	0.02
13	Arsenic	≤	0.05	0.05	0.05	0.1	0.1
14	Mercury	≤	0.00005	0.00005	0.0001	0.001	0.001
15	Cadmium	≤	0.001	0.005	0.005	0.005	0.01
16	Chromium	≤	0.01	0.05	0.05	0.05	0.1
17	Lead	≤	0.01	0.01	0.05	0.05	0.1
18	Cyanide	≤	0.005	0.05	0.02	0.2	0.2
19	Volatile phenol	≤	0.002	0.002	0.005	0.01	0.1
20	Oil	≤	0.05	0.05	0.05	0.5	1.0
21	Anionic surface active agent	≤	0.2	0.2	0.2	0.3	0.3
22	Sulfide	≤	0.05	0.1	0.2	0.5	1.0
23	Fecal coliform	≤	200	2000	10000	20000	40000

moving average order number; $\theta_{1,}\ldots,\theta_q$: the moving average coefficient; X_t: the observed values of water level or inflow of Lake Bosten at t time.

When modeling with ARMA, time series analysis must satisfy be stationary. Non-stationary time series may be filtered and tested with differencing method. After stationarity is met, an ARMA model can be constructed. After estimates have been obtained, a reverse transformation allows the estimate to fit the unfiltered data. Models established by an entire filter, test and reverse transformation process are called ARMA model, also ARIMA model. If the original data were transformed by d rounds of differencing, the differencing data are noted as ARIMA(p, d,q). This investigation used the ARIMA method to forecast Lake Bosten water level and volume over the next decade.

Results

Water Environment of Lake Bosten in the Past 55 Years. Figure 2 shows the salinity of Lake Bosten over the last 55 years. Salinity of Lake Bosten showed a rapid increase from the 1960s, followed by a gradual decrease in the 1990s, before increasing again after 2002. From 1960 to the 1980s, salinity rose to a high of 1.87 g/L in 1986. Since the 1990s, water salinity has declined. In 2003, lake salinity was 1.17 g/L, the lowest since 1972. After that, salinity increased and was accompanied by eutrophication.

Water body eutrophication refers to the increased influx of nutrients nitrogen and phosphorus, which lead to oxygen exhaustion due to algae proliferation (Jin et al., 2005). From 1992 to 2009, lake water pollution proceeded from the third degree to the fourth degree (Table 1 and Table 2). Eutrophication also increased (Bayingolin Prefecture Environment State Communique, 1999-2009). During 1999 and 2000, lake pollution was the third degree. The main pollutants were nitrogen, sulfur, and permanganate salt, pH, total hardness, chlorides and total phosphorus. Eutrophication level was low. Since 2001, water quality deteriorated. The major pollutants include sulfate salt, permanganate salt (index), pH, total hardness, and chloride. Total nitrogen in Lake Bosten was category V. Permanganate salt index and total phosphorus were category III, and chlorophyll A was category II. During 2002 –2004, permanganate index and total nitrogen were category III, and other indices were category I. Water quality was category III. During 2005–2009, Lake Bosten water quality was category IV, a moderately pollution category. During 2005–2007, the pollutant chemical oxygen demand was category IV. Permanganate index and total nitrogen were category III. Total phosphorus and ammonium nitrogen were category II. All other indices were category I. During 2008–2009, pollutant oxygen demand was category IV, total phosphorus and total nitrogen were category III. Permanganate index, dissolved oxygen and E. coli were category II. All other indices were category I. During 2002–2009, Lake Bosten total nitrogen and total phosphorus indices were changed from either category III to both category III, suggesting increased eutrophication. In 2009, Lake Bosten composite nutritional index was 38, a moderate eutrophication state. Water pollution of Lake Bosten is characterized by salt contamination, local organic contamination and eutrophication. The drainage of high salinity

Table 2—Water quality and eutrophication from the period of 1999–2009 in Lake Bosten.

Characteristics	1999–2000	2001–2004	2005–2009
Water quality	III	III	IV
Eutrophication level	low	deteriorated	moderate eutrophication state

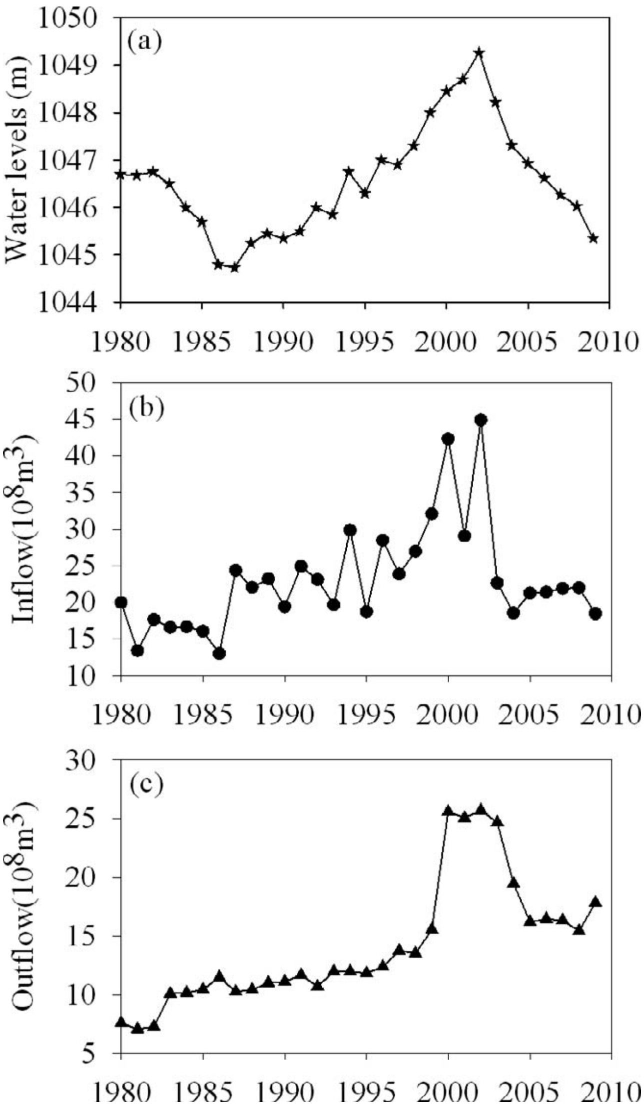

Figure 3—Water levels, inflow and outflow in Lake Bosten

farmland wastewater, industrial and mining wastewater are the primary factors leading to water eutrophication (Ma and Zhang, 2007).

Causes of Water Environmental Change. The change from freshwater lake to salt lake was the combined action of many factors, including weather-caused inflow variation and draining of wastewater from surrounding area.

Inflow and Water Level. Lake Bosten water quality was inversely correlated with inflow and water level (Figure 3); salinity showed an increase-decrease-increase trend, showing the opposite trend to water level. In other words, salinity decreases when water level increases. Water levels in the past 55 years were characterized by 3 stages. From 1955 to 1987, water level declined gradually. The average water level was 1047.2 m altitude. From 1988 to 2002, water levels showed an increasing trend, with an average of 1046.8 m altitude. Between 2003 and 2009, water levels displayed a rapid reduction, with an average water level of 1046.6 m altitude. During the 55 years, water level showed a gradual recession by 66 cm. If evaporation was the same during the last 55 years, reduction in water level implies reduction in water volume. Inflow of water includes river runoffs, precipitation, agriculture drain and ground water. During the 23 years before 2002, inflow to Lake Bosten was 2.374 billion m^3 per year. From 2003 to 2009, inflow to Lake Bosten was 2.088 billion m^3 per year, which was down 0.286 billion m^3 from the previous years. Lake Bosten discharges to Konqi River. A small amount of water leaks through underground channels. Figure 3 clearly shows that outflow from Lake Bosten had two turning points: 2000 and 2004. During the 20-year period before 2000, outflow increased overall to a yearly outflow of 1.101 billion m^3. During the 4-year period from 2000 to 2003, outflow increased to 2.526 billion m^3 per year. Starting from 2004, the outflow clearly decreased to 1.695 billion m^3 per year. The decrease in inflow since 2003 has led to the recession of water level and outflow, though the reduction in outflow was delayed by one year. Water salinity increases along with the reduction in inflow, water level and outflow. The correlation coefficients between salinity and water level, inflow, outflow were –0.810, –0.510 and –0.844, respectively. These data indicate that water level, inflow and outflow were the major factors affecting salinity.

Lake Bosten is an inflow-outflow lake. Inflow determines its water exchange strength. Large amounts of mountain freshwater inflow diluted lake salinity. Outflow brings out a large quantity of salt. The inflow and outflow together replenish and clear the lake. Therefore, an increase in inflow (in other words, to increase Kaidu River runoff) is one of the effective ways to ameliorate the deterioration of the Lake Bosten water body.

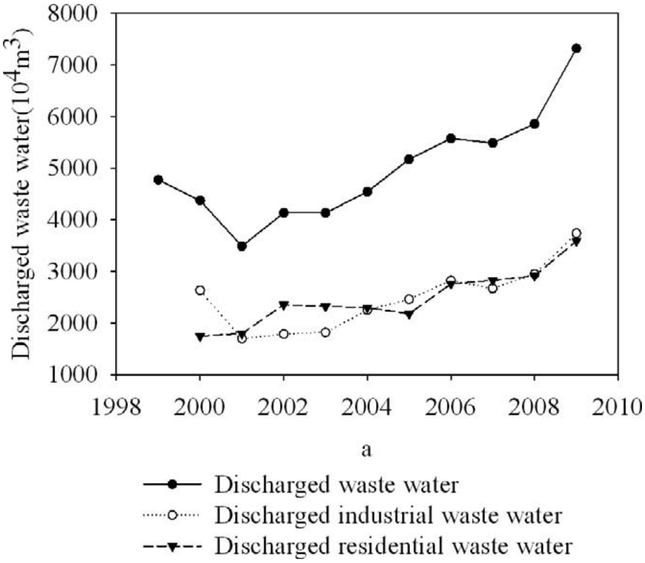

Figure 4—Waste water in Lake Bosten, 1999 to 2009

Lake Water Quality and Surrounding Wastewater Discharge. Figure 4 shows wastewater discharge to Lake Bosten watershed during the period from 1999 to 2009. Wastewater that was discharged to Lake Bosten between 1999 and 2001 displayed a trend of reduction. In 2001, it was 3.488 million *t*. Starting from 2002, wastewater increased yearly. In 2009, the Lake Bosten watershed received 7.323 million t of wastewater, which was 2.09–fold of that in 2001. The discharge of industrial wastewater to Lake Bosten exhibited a decreasing at first followed by an increase trend. In 2001, discharged industrial wastewater was

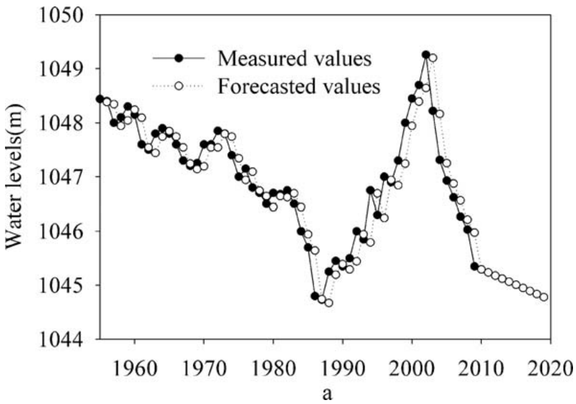

Figure 5—Measured and forecast water levels in Lake Bosten

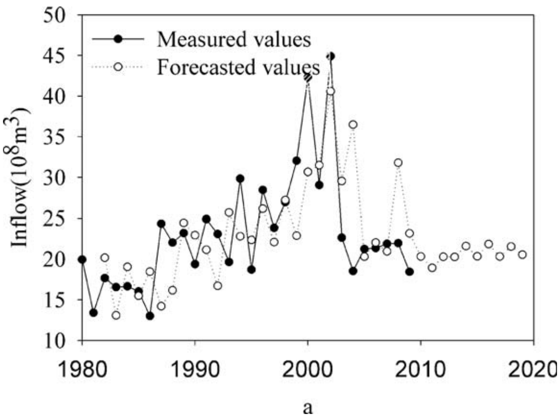

Figure 6—Measured and forecast water quantity in Lake Bosten

1.695 million *t*. In 2009, the discharge topped at 3.736 million *t*, which was 2.2-fold of that in 2001. Discharge of residential wastewater also displayed an increasing trend, though to a lesser extent. Compared with that in 2000, discharge of residential wastewater in 2009 was increased by 1.843 million *t*. Records indicated that industries discharge the major part of wastewater to the lake. The wastewater ultimately reaches the lake by runoff or underground, leading to the deterioration of lake water quality. After 2003, salinity of the lake water exhibited a rising trend (Figure 2), which may be related to the total volume of wastewater discharge. Regression analysis revealed that Lake Bosten salinity was positively correlated with total wastewater discharge and industrial wastewater discharge, with coefficients 0.903, 0.855. It was also positively correlated with residential wastewater discharge, with a correlation coefficient 0.685. These data suggest industrial wastewater was the primary source of lake salt and salinity. Thus reduction in industrial wastewater discharge is fundamentally important to eliminate lake water quality deterioration.

Water Environment Forecast for Lake Bosten. Modeling with ARIMA method requires stationarity of the hydrological time series. A stationarity test was done with DF method. The primary hypothesis was that the time series has a root of unity and alternative was that time series does not have a root of unit but is stationary. By differencing once or multiple times, the root of unity *P* values for water level and inflow were obtained, being 0.049 and 0.029 ($P<0.05$). Salinity *P* values were 0.424 ($P>0.05$). Thus, water level and inflow after differencing become stationary, but water quality did not. Water level and inflow were forecast using ARIMA method, but not salinity.

Water Level and Inflow Forecasts for Lake Bosten. The ARIMA model was distinguished with the sample autocorrelation function and the typical correlation coefficient square estimate value methods, and estimated with the least square method. After estimation, the ARIMA model was diagnosed with the information criterion. Based on these processes, water level and inflow in Lake Bosten were forecast with the ARIMA model.

An optimized model was used to estimate model parameters and test for statistical significance of residual white noise. Results indicated that parameters for water level, inflow and white noise met the requirement. The ARIMA models were ARIMA (0,1,0) and ARIMA (4,2,0).

The forecasting model was fitted with data for water levels and inflow (Figures 5 and 6) and results indicated that the error terms were 2.88 and 2.97. The difference between fitted values and actual values were very small, suggesting a satisfactory fit. Fitting test was to examine the confidence of the model. The focus of the present study was not to fit historical data only, but to predict future water level and inflow so that future water source sustainable management decisions may be made on a sound scientific basis. We used the ARIMA model to predict water level and inflow for the next decade (Table 3, Figure 5, 6). The predictions were that water level will continue to decrease, about 6 cm annually; but inflow will be stable during 2010–2019, being 2.061 million m^3, yet below the inflow during 2005–2008.

Salinity Forecast for Lake Bosten. Salinity trend was predicted for the next 10 years using a superposition model. Important parameters were:

Cycle average smooth, α=0.903
Slope within a cycle, β=0.010
Increment smooth, γ=0.010
Period average A=1.126, slope B= –0.037
Then a prediction model was constructed:

$$X(\tau) = 1.41743567 + -0.03187326{*}\tau + d_{t+\tau} \quad (4)$$

Where, $X(\tau)$ is the predicted value; τ is the period; $d_{t+\tau}$ is the cycle increment.

Fitting of the model with historic records had an error term of 0.042, which is very small (Figure 7), indicating a satisfactory modeling. A forecast for the next 10 years was made for salinity of Lake Bosten (Table 4). It was predicted that salinity of Lake Bosten will decline. A dramatic reduction will occur in 2014 until 2019, down to 1.07 g/L. The average salinity during 2014 to

Table 3—Forecasted values of water level and inflow in the recent ten years in Lake Bosten.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Water level/m	1045.29	1045.24	1045.18	1045.12	1045.06	1045.01	1044.95	1044.89	1044.84	1044.78
Inflow/10^8m^3	20.33	18.95	20.29	20.27	21.61	20.35	21.85	20.33	21.55	20.56

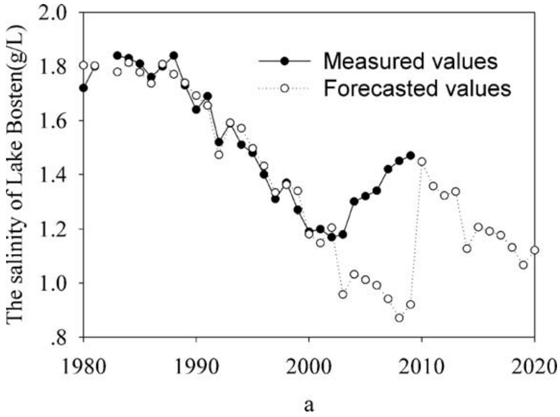

Figure 7—Measured and forecast salinity in Lake Bosten

2019 will be 1.15 g/L. Compared with 2010, this is a reduction of 0.30 g/L. The result will provide a scientific basis for water quality management of the lake in the future.

Discussion

Since the 1950s, changes in the Lake Bosten water environment were closely watched by domestic and international scholars. Studies have shown that water level in Lake Bosten displayed a continuing reduction during 1958 to 1987 (Gao and Yao, 2005). Since 1988, it rose continuously (Wang et al., 2003). The reason for recess is the increased agricultural use of water, leading to the reduced inflow. The rise in water level was due to the increased runoff of Kaidu River and the construction and use of a water-saving irrigation system. We have also systematically examined variations in water level and inflow during the period 2003 to 2009. Results indicated that water level and inflow displayed a continuing recession. Compared with that during 2000 to 2003, inflow between 2003 and 2009 decreased by 286 million m^3. According to the forecast using the ARIMA model, water level will continue to decrease by 6 cm per year for the next 10 years due to decreased inflow. Runoff into the Kaidu River will also decline due to reduced precipitation in the mountains. Records show that the range of precipitation decrease in Kaidu watershed was 42% to 70.5% during October of 2006 to April of 2007 (http://www.xinhuanet.com /chinanews /2007-06/29/content_ 10436935.htm). The total inflow was 1.397 billion m^3, a reduction of 11%. Thus, lower precipitation in the watershed leads to smaller runoff into the Kaidu River, and less inflow to Lake Bosten. This may be the cause of Lake Bosten low water level and inflow.

Due to the influence of weather and human activity, Lake Bosten water level and inflow fluctuated widely between 1955 and 2010, which also resulted in large fluctuations in salinity. Studies have shown that water salinity in Lake Bosten went through good-moderate-bad-moderate changes during the 46 years between 1955 and 2000 (Li and Yuan, 2002). The current study confirmed that report. In addition, the current study has also revealed the rise of salinity after 2000. The cause of salinity change during that period was no longer the result of high salinity agricultural discharge. It is due to the changes of climate in the mountains on one hand, and the increasing residential and industrial wastewater discharge on the other hand. As a result of the inflow reduction, water salinity has increased. Previously, studies have predicted a reduction in water level in the next decade in this paper. Theoretically, salinity should increase. However, the current study predicted the opposite. This may result from improved inflow quality. Despite the reduction of inflow and water level, the reduction in salt inflow results in a reduction in lake water salinity. This illustrated that the recent engineering projects including the installation of the east pumping station, channel leaking prevention, water saving agriculture and utilization of ground water, improvement of the drainage system, and the recovery and protection of wetlands were beneficial to the water environment of Lake Bosten (Chen et al., 2005).

Studies have demonstrated that the elevation of Lake Bosten water salinity was closely related to reductions in inflow and outflow, and increased industrial and residential wastewater discharge. Efforts were made to increase the inflow of freshwater through ecological and engineering approaches. The local government and Tarim Watershed Authority have initiated projects to foster grass and forestland, conserve water resources, and prevent soil erosion in the upstream. In the middle reach of Kaidu River, efforts are being made to utilize ground water, to reduce surface water usage, to reduce leaking, to control ground water level and to increase freshwater inflow. These measures are all implemented from the perspective of waste reduction and inflow increase, but not from the prospect of inflow generation and increasing runoff to Kaidu. We recommend a reduction in salt input and salinity by reducing industrial wastewater discharge. Management of industrial wastewater cannot go back to the old route; it cannot focus on terminal discharge only. Industries must consider comprehensively economic development and water recycling processes, setup regulations for factories and industry wide waste discharge. Industrial wastewater management requires the development of clean production technology. Finally, for terminal management, advanced technology and equipment must be used. Efficiency of pollutant removal must be improved. Only if runoff to the Kaidu River and inflow to Lake Bosten are increased, and wastewater discharge is reduced, will lake clean up be possible, fulfilling the goal of rapidly reducing lake water salinity.

Conclusions

Water level and inflow of Lake Bosten displayed a continuing recession from 2003 to 2009. Compared with the period 2000 to 2003, inflow between 2003 and 2009 decreased by 286 million m^3. It is forecast with the ARIMA model that water level of the Lake Bosten watershed will continue to reduce by 6 cm per year over the next decade as a result of reduced precipitation in the mountains. The current study shows that salinity in Lake Bosten

Table 4—Forecasted values of the salinity in the recent ten years in Lake Bosten

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
The salinity (g/L)	1.45	1.36	1.32	1.34	1.13	1.21	1.19	1.18	1.13	1.07

rose after 2000. The cause of the salinity change during that period was not due to high salinity agricultural discharges, but rather to changes of climate in the mountains on one hand, and increasing residential and industrial wastewater discharges on the other hand. We recommend a reduction in salt input and salinity by reducing industrial wastewater discharges in the watershed of Lake Bosten. Industries must consider comprehensively economic development and water recycle processes, setup regulations for factory and industry wide waste discharge. Industrial wastewater management requires the development of clean production technology.

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