Simulation of Climate Change Impacts on Streamflow in the Bosten Lake Basin Using an Artificial Neural Network Model

Xi Chen[1]; Jinglu Wu[2]; and Qi Hu[3]

Abstract: Impacts of climate change on water resource in the Bosten Lake basin in the south slope of the Tianshan Mountains in Xinjiang, China, were evaluated using an artificial neural network model. The model was trained using the error backpropagation algorithm and validated for a major catchment that covers 82% of the Bosten Lake basin and has the only available weather and streamflow data. After validating the model it was used to examine the surface hydrology responses to changes of regional temperature and precipitation. Major results showed that because of an additional effect on glacier melt in the upper reach of the basin temperature increase can cause large increases of streamflow. Model results also showed that if the current climate trend continues, the annual streamflow would increase by 38% of its current volume, and the summer and winter streamflow would increase by 71.8 and 11.4% of their respective current volume in the next 50–70 years, highlighting challenges for the basin's water resources management and flood protection.

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Introduction

From the end of the Little Ice Age to the mid-1980s, a warm and dry condition developed and prevailed in northwestern China (Shi et al. 2003). This epoch of warm/dry condition ended in 1987, and has since given way to a warm and increasingly humid condition in western China. A prominent response to this change of regional climate has been the rising water level of the Bosten Lake in the southern slope of the Tianshan Mountain (Fig. 1, the Bosten Lake is the largest lake in inter continental China). This rising water level of 3.5 m between 1987 and 2000 indicates that with increase of both precipitation and temperature the attributes in the water cycle of the region must have changed. Warmer temperatures could have sped snowpack and glacier melt in the mountainous head water areas of the Bosten Lake basin, and the increased annual precipitation may have increased basin vegetation cover and evapotranspiration and partitioned differently the rainwater contribution to streamflow and recharge to the lake. From economic and engineering concerns, these changes have raised the potentials of flooding and the magnitudes of flood damages (Jiang et al. 2002).

To understand the water cycle change and associated potential of flood damages this study applied a neural network model to evaluate the surface hydrology in the Boston Lake basin. Because of very limited surface observations this study was focused on the Kaidu River catchment that consists of 82% of the Bosten Lake basin and has observations from a couple of ground stations. Streamflow and its variations with recent change of regional climate in the Kaidu River catchment were examined using the neural network model. In addition, streamflow changes were estimated assuming that the current warm and wet trend were to

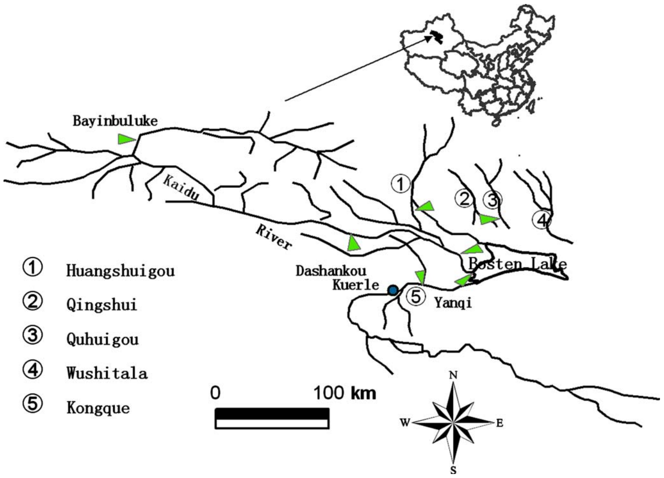

Fig. 1. (Upper panel) Geographical location of Bosten Lake; (lower panel) tributaries in Bosten Lake basin

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[1] Chair Professor, State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai Univ., Nanjing 210098, P.R. China (corresponding author). E-mail: xichen@hhu.edu.cn

[2] Professor, Nanjing Institute of Geography and Limnology, Nanjing 210008, P.R. China. E-mail: w.jinglu@niglas.ac.cn

[3] Associate Professor, Climate and Bio-Atmospheric Sciences Group, School of Natural Resources and Dept. of Geosciences, Univ. of Nebraska-Lincoln, Lincoln, NE 68583-0728. E-mail: qhu2@unl.edu

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continue in the region and compared to changes in a doubled atmospheric carbon dioxide (CO_2) scenario.

Meteorological and Hydrological Characteristics of Study Region

The Bosten Lake basin (Fig. 1) is 2.7×10^4 km^2. Although the lake is fed by several major rivers in the basin, e.g., the Kaidu River, Huangshui Canal, and Qingshui River, only the Kaidu River maintains streamflow year round and serves as a continuous source to the lake. The main stretch of the Kaidu River is 513 km started in the middle of the Tianshan Mountain. Total catchment is 2.2×10^4 km^2, nearly 82% of the Bosten Lake basin. Annual mean flow of the Kaidu River is 3.99×10^9 m^3, serving as one of the primary water sources for the oases in southern Xinjiang.

In the Bosten Lake basin precipitation varies considerably; more precipitation in the west mountainous regions and less in the east Yanqi basin (between Dashankou and Yanqi station, Fig. 1). In the head water areas of the basin are 722 glaciers with total coverage of 445 km^2 (Lanzhou Institute of Glaciology and Geocryology 1987). The mean annual amount of ice-melt water in the past 2 decades is estimated as 5.08×10^8 m^3, contributing to 15.2% of the annual mean runoff of the Kaidu River. Because of the glacier melt contribution, temperature change in the region has a significant influence on the streamflow of the Kaidu River and the Bosten Lake level.

In this study, the Kaidu River catchment upsteam from the Dashankou station (Fig. 1) was the focused area because the small population in the harsh mountainous environment has only slightly perturbed the environmental conditions, thus allowing us to evaluate the natural changes of the stream flow and climate. At the Dashankou station both the streamflow and surface meteorological conditions have been recorded. Besides this station, the only other station in the basin is at Bayinbuluke (Fig. 1). Monthly precipitation, temperature, and surface evaporation recorded at Bayinbuluke were used in this modeling study for the following reasons. (1) The elevation of Bayinbuluke is 2,459 m above the sea level and is 1,331 m at Dashankou. Annual precipitation at the former is 268 mm and is much more than 122 mm at the latter, showing an increase of precipitation with elevation. Annual precipitation variations at the two stations are incoherent, with a correlation coefficient of 0.37. Because of this poor coherence relationship it is inappropriate to use an average of the two stations' precipitation to represent the Kaidu River basin precipitation. (2) Because the elevation at Buyinbuluke is near the averaged elevation of the Kaidu River basin and the elevation is a major factor in precipitation variation across the basin, Bayinbuluke precipitation and temperature have a better representation of the climate condition in the Kaidu River basin.

At Bayinbuluke station, average annual pan evaporation ($\Phi 20-20$ cm in diameter) is 1,113 mm, mean annual temperature is $-4.6°$C, mean annual maximum temperature is $10.8°$C, and minimum temperature is $-19.4°$C. Importantly, there has been a fairly robust relationship between the monthly mean temperature (T) and pan evaporation (E_{pan}) at the station from 1980 to 2001, $E_{\text{pan}}=0.1158T^2+6.6986T+100.01$, $R^2=0.9286$. This relationship allowed us to use temperature to derive evaporation and use it to estimate streamflow response to climate change.

Finally, the contribution of monthly precipitation ($P_t, \ldots, P_{t-n}$), temperature ($T_t, \ldots, T_{t-n}$), and stream discharges ($Q_{t-1}, \ldots, Q_{t-n}$) to Q_t was determined by the correlation test at the significance level of 0.05. Analyses of the streamflow (Q), precipitation (P), and temperature (T) variations for the period 1977–2001 in the Kaidu River basin have indicated that its streamflow lagged the precipitation by 1 month, partially because of the surface runoff processes and influence from ice-melt water. This lag will be used in construction of the artificial network model.

Artificial Neural Network Model

Primarily because of the very limited observations an artificial neural network model was used to evaluate streamflow responses to climate variation. Such a model is a network of interconnected neurons or nodes, $u_1, \ldots, u_n$. Each neuron consists of a number of input arcs (in our case inputs to streamflow, $x_1, \ldots, x_n$) and contributes to streamflow outputs, y. Thus, a neural network model can be written as

$$y = f(u_j) \tag{1}$$

with

$$u_j = \sum w_i x_i - \theta_j \tag{2}$$

In Eq. (2), w_i=weight of x_i and θ_j=critical value. The function f in Eq. (1) is a logistic sigmoid function or a hyperbolic tangent function (Dawson and Wilby 1998, 2001)

$$f(u) = \frac{1}{1+\exp(-u)} \tag{3}$$

Two hidden layers in the neural network are adopted. The number of neurons in the hidden layer was initially set between $2\sqrt{n+m}$ and $2n+1$ according to Hajela and Berke (1991) and Fletcher and Goss (1993), where n and m represent the numbers of input and output neurons, respectively. Then neurons are added or removed on a trial-and-error basis to seek the optimal number of hidden neurons while keeping a stable solution for the model. Details of these processes are given in Flood and Kartam (1994a,b).

Model Training and Validation

To determine an appropriate set of weights in Eq. (2), the model was trained using the error backpropagation algorithm and momentum was used for speeding convergence to an error minimum. Based on the error signal received, connection weights were updated so that the network converged to a stable state that allowed all the training patterns to be encoded. This process was guided by using Nash–Sutcliff efficiency coefficient (NSC), the root mean squared error (RMSE), and mean of the relative absolute error (RAE) between observed and simulated monthly discharge.

To maximize the accuracy and stability of the model for the available data, the data were divided into three subsets: two training periods from 1977 to 1990 and from 1995 to 2001, and a validation period from 1991 to 1994. Additional validation was made using monthly mean values from 1978 to 2001. The first training period included a dry period, 1983–1986, when its average precipitation was 11% lower and its annual mean temperature was $0.58°$C lower than their corresponding average of 1977–2001 (a cool and dry period). In the second training period from 1995 to 2001 the climate was wet and warm—the 1995–2001 average annual precipitation was 31% higher than the average of 1977–2001 and annual mean temperature was $1.35°$C

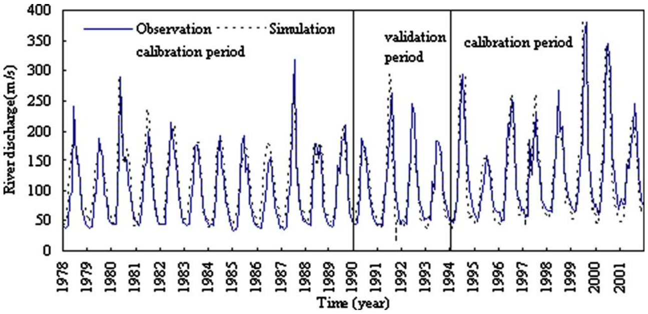

Fig. 2. Model trained and validation results of streamflow

higher than the annual mean value of 1977–2001. These large variations in temperature and precipitation in these very different climate epochs enabled us to train the model more robustly for predictions. In training the model, all input and output data were normalized to an internal representation between 0 and 1 in order for them to receive equal attention in the training process (see Maier and Dandy 2000).

The calculation used MATLAB software. The training goal for error criterion was 0.0001 and initial value of streamflow was randomly generated. With the model inputs of $Q_{t\text{-}1}$, P_t, $P_{t\text{-}1}$, T_t, and $T_{t\text{-}1}$, where the subscripts indicate current time, t, and previous time, t-1 (because of the time lag of streamflow to precipitation), the optimal network topology resulted in one output, two layers, and eight hidden-layer neurons.

Model training results are shown in Fig. 2. The NSC value is 0.91, RMSE is 11.3 $m^3 s^{-1}$, and RAE is 4.51%. In the validation period the NSC value is 0.85, RMSE is 10.5 $m^3 s^{-1}$, and RAE is 6.25%. Annual monthly mean streamflow was calculated in the model with input of monthly total precipitation and mean temperature. The modeled simulations were close to the observation, with a NSC value of 0.97 and absolute error of the monthly mean discharge of 0.8 $m^3 s^{-1}$, merely 0.7% of the monthly mean value. These results show that the artificial neural network model is accurate and reliable to describe the hydrological processes and their effect on streamflow in the Kaidu River.

Impacts of Climate Change on Streamflow

After the neural network model was stabled to describe the Kaidu River streamflow and hydrology, the model was used to further examine the influence of precipitation and temperature change on streamflow in the Kaidu River. Figs. 3 and 4 show the responses of Kaidu River streamflow at the Dashankou station to the basin temperature and precipitation changes, respectively. These results show that with the current precipitation the streamflow would increase by 7–25% of the current value in response to the region's temperature increase of 1–3°C. On the other hand, with the current temperature, the streamflow would increase by 1.4–11% of the current value in response to 5–25% increase of the annual precipitation. The larger response of the streamflow to temperature increase is unique and could be an indication of a significant positive effect of temperature on ice and snow melting, compared to its effect on surface evaporation. This glacier melt effect on surface hydrology is in sync with the result of Shi (2001), who showed that because of the warming the ice melt volume has increased by 25–50% of volume at the beginning of this century in the southwest Tianshan Mountains.

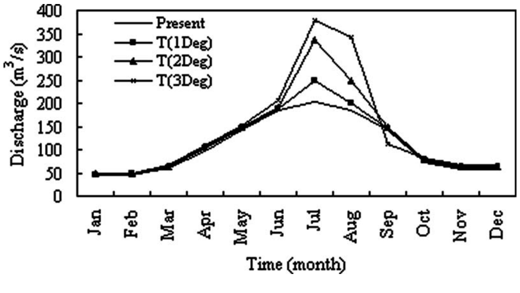

Fig. 3. Modeled streamflow in warmer climate with 1–3°C increase in air temperature

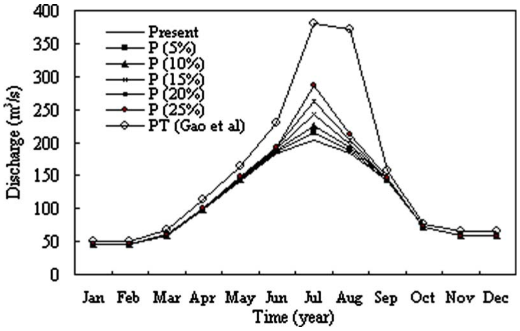

Fig. 4. Modeled streamflow in wet climate with 5–25% increase in precipitation and streamflow corresponding to precipitation projected in Gao et al. (2003)

Responses of the streamflow to the temperature and precipitation change also varied in seasons, with the largest response in summer (June, July, and August), consistent with the large melting effect on the streamflow. For example, the streamflow increased by 11–62% of the current value when summer temperature increased by 1–3°C, compared to the increase of 3–10% for the same temperature increase in winter (December, January, and February). The contrast between the increase of streamflow in summer and winter in response to the 5–25% increase of seasonal precipitation is 2.7–21% and 0.2–0.8%, respectively.

General circulation modeling studies (e.g., Gao et al. 2003), have suggested that the average annual temperature would increase by 2.5–3.0°C in western China, and 2.7°C in the Kaidu River and Bosten Lake region in 50–70 years following the course of doubling the atmospheric CO_2 concentration. In accordance, over the period the seasonal temperature in the region would increase by 3.0, 3.0, 2.7, and 2.0°C in winter, spring, summer, and autumn, respectively. Meanwhile, the annual precipitation would increase by 25%, and the increase of seasonal precipitation would be 47, 36, 9, and 28% in winter, spring, summer, and autumn, respectively. In response to these simultaneous changes in both temperature and precipitation, our model projected the changes in streamflow of the Kaidu River basin by 38.6, 71.8, and 11.4% for annual, summer, and winter, respectively (Fig. 4).

Conclusions

The recent shift to a warmer and wetter climate and rising streamflow and lake levels in western China has raised the need to reexamine and understand the surface hydrology. This understanding can also help address the related question of how the surface hydrology may continue to evolve if the current trend continues. To meet the need an artificial neural network model was developed and used to describe the relationship of the Bosten Lake basin streamflow and the precipitation and temperature. Results from the trained and calibrated model using limited precipitation and temperature observations indicated that the model is able to accurately describe surface runoff and streamflow in the Kaidu River basin, which is a surrogate of the Bosten Lake basin.

Model results showed a stronger response of the streamflow in the Kaidu River to the increase of temperature than to the increase of precipitation at the observed magnitudes. These response differences are especially large in the summer season. These results are consistent with the fact that a large portion of the input to the surface streams and the Bosten Lake is from melting snow and glacier in the mountainous head water areas of the basin. Higher temperature would result in more and faster melting and thus a larger supply to the streamflow.

The model results also suggested that the present situation of stingy water resources in the Bosten Lake basin could be improved if the region's current warming and moistening trends continue. Increasing streamflow could elevate the flood potential, however, particularly during summer because the largest increase in streamflow would occur in July and August, raising new challenges for water resources management and planning for the Bosten Lake basin and western China.

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