Uncertainty of the water resources allocation system by the Danjiangkou reservoir

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Abstract The Danjiangkou reservoir is planned to be the water source for a water diversion project from south to north China, with 14.5 billion m^3 of water transferred to the north in 2030. The water quantity to be diverted is not only associated with the reservoir capacity, but also with many other factors. In this study, inflow and reservoir release were selected as two major factors. A stochastic runoff simulation model was applied to analyse the uncertainty of the reservoir inflow. Different scenarios of water demand from the downstream area were developed. Monte Carlo based simulations and probability theory were used to assess the uncertainty and risk of water shortage.

Key words probability; reservoir; risk; uncertainty; water supply

INTRODUCTION

The middle route for the south–north water diversion project is one of the largest water resources transfer projects in China. This project is aimed at solving the serious water shortage problem in about 20 cities and 100 counties in the northern part of China. The Danjiangkou reservoir, which is located on the Han River, will function as the water source for the project. In total 14.5 billion m^3 of water will be transferred to the north from this reservoir in 2030. The Danjiangkou reservoir is a large-scale reservoir, with functions of flood control, water supply, hydropower generation and navigation. The current total capacity of the reservoir is about 17.5 billion m^3. To retain more water, the dam of the reservoir will be heightened. After the completion of the project the total reservoir capacity will increase to 29.1 billion m^3 (CISPDR, 2006).

The Han River is the largest tributary to the Changjiang River. It originates from the Qinling Mountains, flows through Shanxi and Hubei Provinces, and enters into the Changjiang in Wuhan City. The total river length is about 1577 km, with a basin area of 159 000 km^2. The river above the Danjiangkou reservoir is about 925 km long, with a contributing area of 95 200 km^2. The annual mean runoff at the dam site is about 40.9 billion m^3, accounting for 70% of the total runoff from the whole basin (HB, 1986).

Precipitation is temporally and spatially variable within the Han basin. The annual mean precipitation over the whole basin is about 884 mm, with 800~2000 mm in the upper basin, 700~900 mm in the middle basin, and 900~1200 mm in the lower basin. The precipitation amount from May to October occupies about 70~80% of the annual value, of which the precipitation amount from July to September accounts for about 40~60% (HB, 1986).

The downstream area of the Danjiangkou reservoir is situated in Hubei Province, involving 28 counties and cities. The area is densely populated with high economic growth and abundant nature resources. The total industry production is nearly 46% of the annual value of the whole province, while the GDP is about 36% (HPSB, 2000).

METHODS AND CONSIDERATIONS

The sources of uncertainty in the Danjiangkou reservoir water allocation system originate from two main factors: uncertainty in runoff and uncertainty in future water demand.

Uncertainty of reservoir inflow

Runoff simulation model Considering the stochastic character of runoff, the one-step auto-regression Thomas-Fiering model (Goel, 2001) was used to simulate monthly runoff. In total, 1000 years of monthly runoff have been simulated based on a 42-year-long (1956–2000) monthly data series. The principle of the Thomas-Fiering model is based on correlation analysis of neighbouring monthly runoff values in the historical data series. Assuming a linear regressive function for each month, the simulation algorithm becomes:

$$Q_{i,j} = \overline{Q}_j + b_j(Q_{i,j-1} - \overline{Q}_{j-1}) + Z_{i,j}S_j(1 - r_j^2)^{0.5} \quad (1)$$

where $Q_{i,j}$ is the runoff of month j in the year i (i represents year, $i = 1, 2, \ldots, n$, and j represents month, $j = 1, 2, \ldots, 12$; when $j = 12$, $j + 1 = 1$, $i = i + 1$); $\overline{Q}_j$, $\overline{Q}_{j-1}$ are the mean runoff volumes of months j and j^{-1}, respectively; $Z_{i,j}$ is a random number, which follows the standard normal distribution and is produced by Monte Carlo techniques; S_j is the standard deviation of runoff in month j; r_j is the correlation coefficient of runoff in month j and month j–1; b_j is the regression coefficient of month j.

Effect of climate change on annual mean runoff The current projection of future climate change is associated with considerable uncertainties, and remains a challenge to scientists. Currently the impacts of climate change on water resources have been generally studied in three ways: (i) simply assuming the temperature and rainfall change scenarios in future; (ii) using statistical methods to build the correlative relationship between temperature, rainfall and runoff based on historical meteorological and hydrological records; (iii) climate change predictions based on GCM models (Shi, 2005).

The latest report of the national assessment of climate change in China announced that the mean annual temperature in China will rise 1.5~2.8°C by 2030, and 2.3~3.3°C by 2050 (Ding *et al.*, 2006). In 1999, the Institute of Atmospheric Physics, Chinese Academy of Science, used seven GCM models to predict climate change based on the assumption that CO_2 concentration doubled in 2030. The average outcome of the seven models indicated that the mean annual temperature in the Han basin in 2030 will increase about 0.9°C, and the rainfall will increase 1.6% (IAP, 1999).

In this study, considering the uncertainty of climate change prediction and the fact of global warming, different climate change scenarios, which were developed based on

the combination of methods (i) and (ii), have been considered for analysis of the impacts on runoff, see Table 1.

The assessment of runoff response to climate change in the Han basin was made by Chen (1999) and Zhu (2005), who applied a monthly water balance model (MWBM, Chen, 1999) and the SWAT model (Zhu, 2005) to investigate the runoff change due to changes in temperature and precipitation. To analyse the uncertainty in runoff stemming from the application of different hydrological models, eight different scenarios of runoff regime change obtained from the outcomes of the MWBM and SWAT models (see Table 1) were set as the reservoir inflow change scenarios.

Table1 Runoff percentage changes based on different climate change scenarios.

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8
Temperature	0	+1°C	+1°C	+1°C	+1°C	+2°C	+2°C	+0.9°C
Precipitation	0	–10%	–10%	+10%	+10%	0	0	1.6%
Runoff	0	–24.7%	–15.3%	+15.1%	+11.0%	–9.7%	–2.0%	–2.7%
Model used		MWBM	SWAT	MWBM	SWAT	MWBM	SWAT	MWBM

Note: S1, Scenario 1; S2, Scenario 2; S3, Scenario 3; S4, Scenario 4; S5, Scenario 5; S6, Scenario 6; S7, Scenario 7; S8, Scenario 8. The sign "+" indicates a relative increase, while the sign "–" indicates a relative decrease.

Uncertainty in water demand

Reservoir release The monthly water release of the Danjiangkou reservoir in 2030 is not only associated with social economic development of the downstream area, but also with many other factors such as: future precipitation in each region, the construction of water works, water demand from the river ecological system, the request of navigation in the main stream, etc. (CWRPB, 2001; CISPDR, 2006). To analyse the uncertainty of reservoir release, precipitation and water works construction downstream were taken as the two main factors. It was assumed that the planned water transfer project from Changjiang to the lower Han River will be completed in 2030 (CISPDR, 2006). How the change in precipitation will affect the water demand from agriculture needs to be carefully considered. The effect of increasing temperature on evaporation is ignored.

Other water users Some farmland and small towns also withdraw water from the Danjiangkou reservoir, and their water requirements should be met before the water diversion. It is assumed that the area of irrigation supplied by the reservoir will not be extended in 2030 (CISPDR, 2006) and that water demand from small towns will grow slightly.

Dynamic reservoir operation model

Objective function

$$\min\left\{\left[\left(q_{1dt}-EQ_{at}\right)^2+....+\left(q_{ndt}-EQ_{at}\right)^2\right]/n\right\} \tag{2}$$

where q_{1dt} and q_{ndt} are the water amounts diverted in month 1 and month n, respectively, and:

$$EQ_{at} = (q_{1dt} + q_{2dt} + ... + q_{ndt}) / n, \quad n \leq 12$$

Restriction conditions

(a) **Restriction of water level**

$$Z_d \leq Z_t \leq Z_m(t) \tag{3}$$

where Z_t is the reservoir water level at time t, $Z_m(t)$ is the high water level allowed at time t, and Z_d is the lowest water level of the reservoir.

Capacity of water release and water demand from the downstream area:

$$q_{td} \leq q_t \leq q(Z_t) \tag{4}$$

where q_t is the water release at time t, $q(Z_t)$ is the reservoir release capacity at water level Z_t at time t, q_{td} is the water demand from the downstream area at time t.

(b) **Restriction of reservoir outflow**

$$|(q_t + q_{dt} + q_{ut}) - (q_{t-1} + q_{dt-1} + q_{ut-1})| \leq \Delta q_m \tag{5}$$

where q_{dt} is the amount of water diverted at time t, q_{ut} is the water use of other users at time t, Δq_m is the allowed reservoir outflow during a unit time period (from t–1 to t).

(c) **Water balance**

$$V_t = V_{t-1} + (Q_t - q_t - q_{dt} - q_{ut} - q_{et})\Delta T_t \tag{6}$$

where V_t, V_{t-1} are the reservoir volumes at time t and t–1, respectively, Q_t is the reservoir inflow at time t, and q_{et} is the water loss of the reservoir at time t, including evaporation and leaching.

Method of risk analysis

Assume that Y is the annual amount of water which can be used for diversion, and X is the water shortage for diversion, $X_i = |Y_i - 14\ 500\ 000\ 000|$ (where the last number is the amount of water in m^3 that should be transferred to the north in 2030 by planning). Assume that $f(x)$ is the probability density function of water shortage, and β is the water shortage in a certain range, then the probability of $X \geq \beta$ could be expressed as follows:

$$P_f(X \geq \beta) = \int_{\beta}^{+\infty} f(x)dx \tag{7}$$

For the purpose of risk analysis, the water shortage is expressed as n_i with units 10^6 m^3, where n_i (= 1, 2, 3, .., 1450) is representing the possible water shortage levels in intervals of 10^6 m^3 from low to high. Assuming that the number of years is M and the number of years with water shortage in level i is expressed by m_i, then the frequency of Y is:

$$p(X = i) = m_i / M \tag{8}$$

The size of the sample is 1000, which can be considered large enough in comparison with the life of the reservoir (e.g. 50 years), thus the frequency of Y in level n can be taken as the probability (Wei, 2002). The risk of water shortage X higher than level n can be defined as:

$$P_n = \sum_{i \geq n} p(i) \tag{9}$$

RESULTS AND DISCUSSION

Average annual water diversion amount

(1) Regarding average annual water amount diverted from the Danjiangkou reservoir, the rank list of climate change scenarios in decreasing order is S4, S5, S1, S7, S8, S6, S3 and S2. In comparison with S1 (no change on temperature and rainfall), the average annual water diversion amount of S2 is less than 35.1%, since the reservoir inflow is reduced by 25% and the 10% precipitation reduction causes an increase in water demand and reservoir release. The average annual water diversion amount of S3 is reduced by 21.6%. However, the average annual water diversion amounts of S4 and S5 raises by 16.2% and 12.6%, respectively, due to more precipitation, more runoff and less water demand from the downstream area as well as from other water users which withdraw water from the reservoir (in comparison with S1, the water demand for other water users of S4 and S4 is reduced by 8.7%).
Although S6 and S7 indicate no climate-induced change in precipitation, the increase of temperature causes a reduction in runoff and, subsequently, in the average annual water diversion amount. In comparison with S1, the average annual water diversion amount of S6 and S7 is reduced by 11.5% and 2.2%, respectively. The outcome (reservoir inflow and release, water diversion amount) of S8 is very close to that of S7 (see Fig. 1(a)).

(2) A comparison of the outcomes produced by two different hydrological models (SWAT, MWBM) indicates that the SWAT-based result shows more water for diversion than the MWBM-based result under the same climate change conditions (S2 and S3, S3 and S5, S6 and S7). The main reason for the difference is that the runoff change in MWBM is more sensitive to change of temperature and precipitation (which might come from the data used for the model parameter calibration) than in SWAT (see Table 1) (Singh, 2002). Zhu (2005) used the 5-year-data (1981–1985) for the SWAT parameter calibration, while Chen (1999)

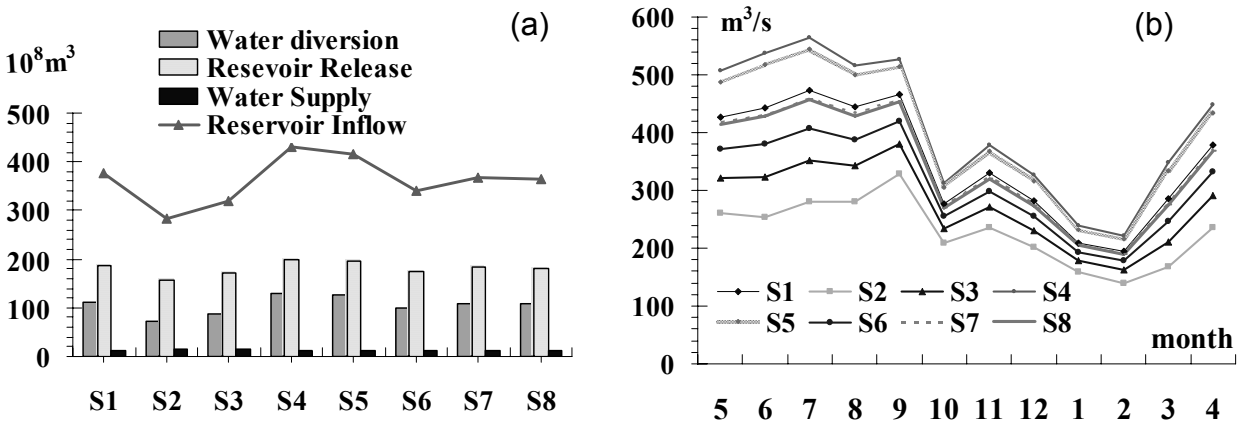

Fig. 1 Comparison of the water diversion amounts under eight scenarios: (a) average annual water diversion amount and reservoir release; (b) monthly average water diversion amount.

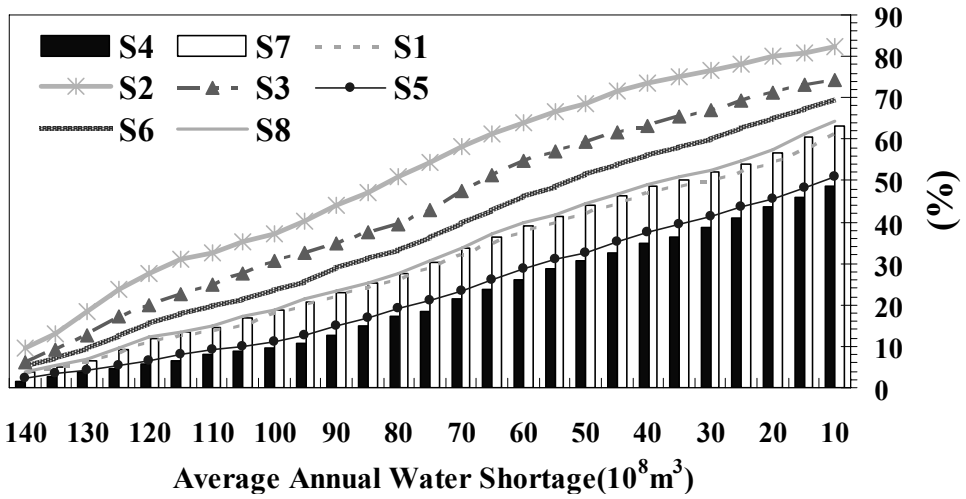

Fig. 2 Risk of water shortage for each scenario at different levels.

used 1966–1989 hydrological data for the MWBM parameter calibration. Zhu (2005) found that the simulation results of runoff was much smaller in dry seasons and larger in wet seasons than the observed runoff values, which means that uncertainty in parameter calibration causes uncertainty in runoff simulation. Figure 1(b) shows the results of monthly average water diversion amount to the north in 2030 under each scenario.

Risk analysis of water shortage for diversion

It can be seen that the risk of water shortage is changing with the climate. The S2 scenario of climate change will cause a very high risk of water shortage in 2030, and S4 is the lowest one. The rank of risk of water shortage for different climate change scenarios from high to low is as follows: S2, S3, S6, S8, S7, S1, S5 and S4, and this

rank also applies to each level *n*. In addition, it should be mentioned that the more the runoff is reduced, the higher the risk of water shortage. Moreover, with the same change in temperature and precipitation, the MWBM-based results indicate a higher risk than the SWAT-based results (see S2 and S3, S4 and S 5, S6 and S7). Therefore, it can be concluded that the assessed risk of water shortage in the Danjiangkou reservoir, as a response to climate change, is highly related to the hydrological model structure. The results are summarized in Fig. 2.

CONCLUSIONS

The response of runoff to climate change has been investigated using different rainfall–runoff models. Comparison of the MWBM and SWAT models shows that the former is much more sensitive to climate change. It is found that the outcome (reservoir inflow and release, water diversion) based on MWBM is more reliable than that based on SWAT.

The Danjiangkou reservoir water allocation system is much more sensitive to change in precipitation than to change in temperature. Runoff reduction due to climate change will be the main risk factor for water shortage and for water diversion in 2030.

The risk of water transfer failure will be very high in 2030. Even without consideration of climate change, the probability of water shortage will be as high as 64.2%. The results of this study indicate that climate change may have a serious impact on the future reservoir operation.

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