# Research on the jointly optimal water-supply operation of a multi-reservoir system in Jinchang City of Shiyang River basin, China

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**Abstract** There are three reservoirs providing water for Jinchang City in Shiyang River basin, China. To resolve water scarcity problems, a mathematical model of jointly optimal operation of a multi-reservoir is established, which is based on the minimum amount of water shortage as the aim function. Processes of optimal operation of three reservoirs are calculated according to in–out discharge data from 1990 to 2007 using the Genetic Algorithm method. The result indicates that the total amount of water supply reaches 633 $hm^3$ in Jinchang City through the operation system, the ratio of water shortage decreases from 28.1% to 16.1%. In addition, an ANN model is proposed for optimal operation. Comparing with the Genetic Algorithm method, the ANN model is better, with a smaller simulation error (<8%). The pattern of jointly optimal operation of a multi-reservoir can provide a basis for the optimal allocation of water resources in Jinchang City.

**Key words** reservoirs operation; genetic algorithm; artificial neural network; water supply

## INTRODUCTION

Multi-reservoir operation is put forward during the construction of hydropower stations. Mases first introduced the concept of optimal operation of a single reservoir (Su Tongfen, 2010). The objectives of multi-reservoir operation are widely related to engineering hydrology, water forecasting, regional social and economic development and water demands of each department. It has complexity and uncertainty. With the development of system engineering theory and computer technologies, methods such as linear programming and dynamic rules have been gradually used in multi-reservoir operation (Foufoula & Kitanidis, 1988; Chen Ningzhen, 1993; Liu Linpu, 2004; Wang Li, 2006; Wang Meiliang, 2006). Especially artificial neural networks (ANN) and Genetic Algorithm methods have been effective tools to resolve jointly multi-reservoir operation problems (Wei Liutao *et al.*, 1994; Hu Tiesong *et al.*, 1995; Neelakantan & Pundarikanthan, 2000; Wang Bailu *et al.*, 2002; Liu Pan *et al.*, 2006).

### Case study site description

With the development of population and social economy, water demand quantity has gradually increased in recent years, which leads to a more and more sharp contradiction between water supply and water demand in the upper, middle and lower river reaches (Hong Guobin, 2003; Pang Pengsha & Dong Renjie, 2004). Shiyang River basin is located in an arid area in northwestern China. The sustainable development of industry and agriculture, and improvement of water conservancy engineering, water utilization and consumption have quickly increased in the upstream, while water quantity has decreased year after year. The mass consumption and apparent deterioration of water resources make available freshwater resources decrease increasingly. Water shortage has become an important issue affecting food safety, human health and natural ecosystem balance (Beekman, 1998; Zhu Yongmao *et al.*, 2001). Human activities, such as reservoir building and irrigation diversion, can not only change the migration paths of natural water, but can also effect the space–time distribution of water quantity and quality. Human activities can coordinate water resources allocation between upstream and downstream and become effective ways for resolving water shortage problems.

Jinchang City is located in the eastern Hexi Corridor and northern Qilian Mountain; its coordinate is 37°47′10″–39°00′30″N, 101°04′35″–102°43′40″E, and its area is 9600 $km^2$. It is an important industry city based on non-ferrous metal smelting and chemical products production in Shiyang River basin. Though there are three reservoirs as main water supply sources, water shortage and allocation problems are severe and urgently need to be solved. The predicted total water demand is 620.4 $hm^3$, water supply is 528.3 $hm^3$, water shortage is 92.1 $hm^3$, and water shortage ratio is 17.4% in 2020 (Zhu Gaofeng *et al.*, 2004; Liu Jiali, 2004; Liang Wenshou, 2005; Cai Shengju, 2008). Jointly optimal operation of multi-reservoir can play an important role in reasonable water resources allocation, alleviation of contradiction between water demand and supply, and progress of economic and social development. Figure 1 shows the geographical position and water supply process of three reservoirs in Jinchang City.

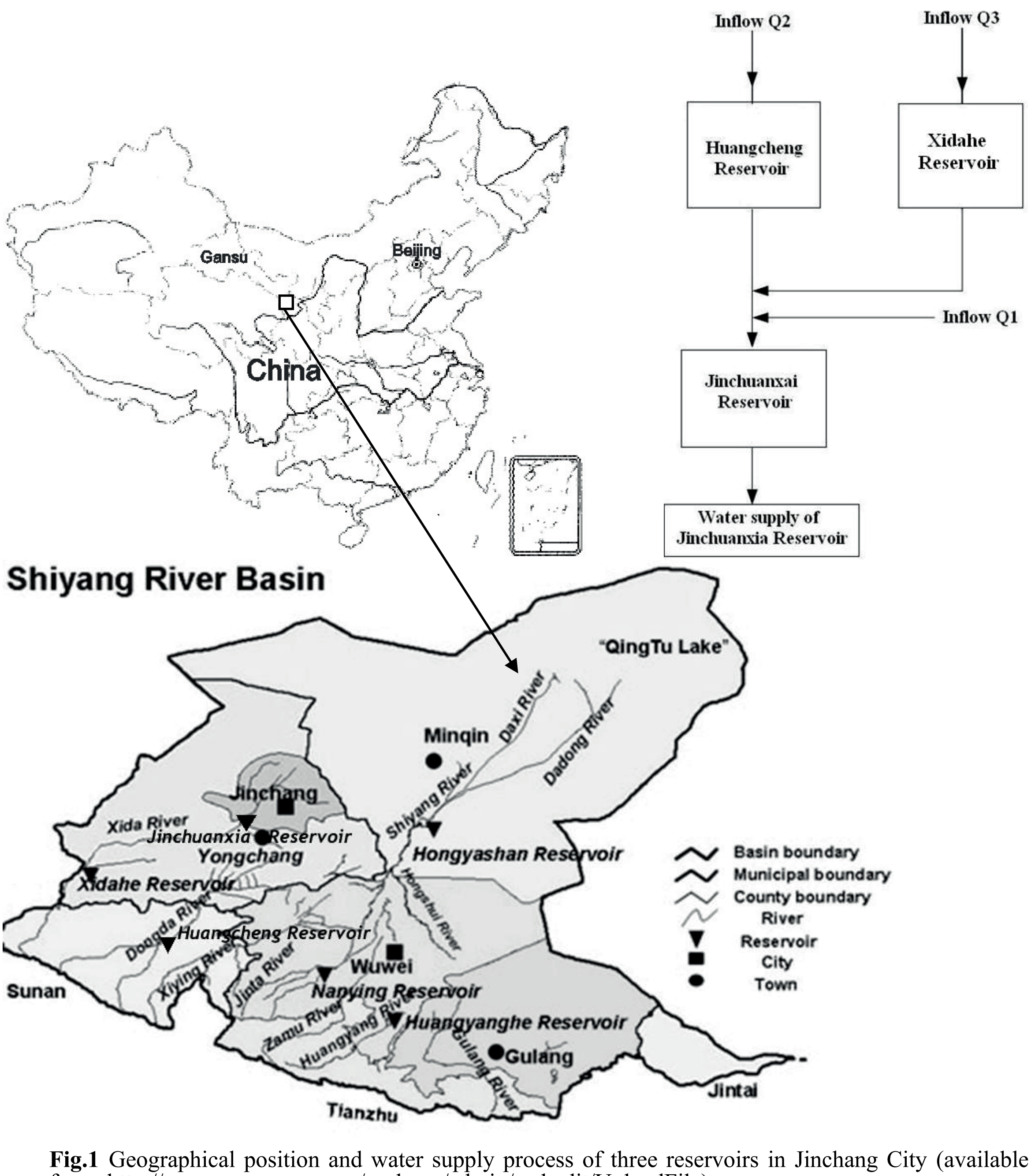


**Fig.1** Geographical position and water supply process of three reservoirs in Jinchang City (available from: http://www.gsmwr.com.cn/wrdmap/admin/webedit/UploadFile).

### Current situation of reservoirs for water supply

At present, the water supply source of Jinchang City is mainly surface water from Huangcheng Reservoir , Xidahe Reservoir and Jinchuanxia Reservoir (see Fig. 1). Regulation of annual runoff from the reservoirs could meet the water demand of every department. The parameters of each reservoir are shown as Table 1.

**Table 1** The basic characteristics of reservoir parameters.

| Parameter | Huangcheng Reservoir | Xidahe Reservoir | Jinchuanxia Reservoir |
|---|---|---|---|
| River | Dongdahe River | Xidahe River | Jinchuan River |
| Controlled basin area /km$^2$ | 1030 | 788 | 2053 |
| Built time | December 1985 | October 1974 | October 1965 |
| Total storage capacity/hm$^3$ | 80 | 54.3 | 65 |
| Beneficial capacity/hm$^3$ | 64 | 51.3 | 60.5 |
| Dead capacity/hm$^3$ | 8 | 3 | 6 |
| Main water supply objects | Jinchuanxia Reservoir, Dongdahe irrigated area | Jinchuanxia Reservoir, Xidahe irrigated area | Jinchang City, Jinchuan irrigated area |

## ESTABLISHMENT OF THE MODEL OF JOINTLY OPTIMAL OPERATION OF MULTI-RESERVOIR SYSTEM

### Objective function

The joint operation of three reservoirs mainly means to recognise the maximum quantity of water supply to the downstream of Jinchang City based on ensuring the water demand of basic agricultural irrigation, industry production, domestic and ecological system upstream. This can meet the needs of economic and social development, and improve the urban water supply security. Therefore, the object of jointly optimal operation system is the minimum quantity of annual total water shortage. The objective function is shown below (Zhou Ming & Sun Shudong, 1999):

$$\min G = \min \sum_{m=1}^{M} Q\left(\left[\min\left(0, R_t^m - T_t^m\right)\right]^2\right) \tag{1}$$

$$R_t^m = V_t^m + Q_t^m - V_{t+1}^m - L_t^m \tag{2}$$

where $M$ is the number of reservoirs, $m = 1, 2, \ldots, M$ ($M = 3$). $R_t^m$ is the available outflow of No. $m$ reservoir during the No. $t$ period. It is affected by initial storage capacity ($V_t^m$), inflow ($Q_t^m$), storage capacity of next period ($V_{t+1}^m$), loss of evaporation and leakage ($L_t^m$). $T_t^m$ is the water requirement of the No. $m$ reservoir in downstream during the No. $t$ period. $t$ is the total number of time periods in a year (1, 2… 12).

Objective function means to the optimal minimum, with the equation shown as below (Wang Bailu *et al.*, 2002):

$$F(X) = \begin{cases} T_{\max} - f(x), & if \quad f(x) \le T_{\max} \\ 0, & if \quad f(x) \ge T_{\max} \end{cases} \tag{3}$$

The maximum of water requirement ($T_{\max}$) is determined by water requirement in the planning year. $f(x) = f(V_t, V_{t+1}, Q, T, L)$. It is a defined function relating to initial/last storage capacity, inflow, time $t$ and loss of a reservoir in a certain period.

### Constraint conditions

The constraint condition of the reservoir water balance is (Zhang Shuanghu, 2004):

$$V_j(k,t+1) = V_j(k,t) + 3600 \times (QR_j(k,t) - QS_j(k,t)) \times \Delta t \tag{4}$$

where $j$ is serial number of each reservoir, $j$ = 1,2,3. $j$ = 1 represents Jinchuanxia Reservoir. $j$ = 2 represents Xidahe Reservoir, $j$ = 3 represents Huangcheng Reservoir . $V_j(k,t+1)$ and $V_j(k,t)$ are storage capacities of No. $j$ reservoir in No. ($t$+1) and No. $t$ period in No. $k$ year. $QR_j(k,t)$ is inflow of No. $j$ reservoir in No. $k$ period. $QS_j(k,t)$ is outflow of No. $j$ reservoir in No. $k$ period. $\Delta t$ is the time length in the caculating time period.

Constraint condition of reservoir storage capacity (Wang Bailu *et al.*, 2002):

$$V_j^{\min}(k,t) \le V_j(k,t) \le V_j^{\max}(k,t) \tag{5}$$

where, $V_j^{min}(k,t)$ is the minimum capacity of No. $j$ reservoir in No. $t$ period. $V_j^{max}(k,t)$ is the maximum capacity in No. $t$ period (less than flood regulating storage).

Constraint condition of outflow of Jinchuanxia Reservoir (Ma Dehai & Ma Leping, 2010):

$$\sum_t^T QC_1(k,t) \le \sum_t^T \alpha_{21} QC_2(k,t) + \sum_t^T \alpha_{31} QC_3(k,t) + \sum_t^T \alpha_{11} QR(k,t) \tag{6}$$

where $t$ is total time periods ($t$ = 1,2,3,…,12), $T$ = 12. $QC_1(k,t)$, $QC_2(k,t)$ and $QC_3(k,t)$ are presented as the outflow of Jinchuanxia Reservoir, Xidahe Reservoir and Huangcheng Reservoir, respectively, in No. $t$ period in No. $k$ year. $QR(k,t)$ is the spring inflow of Jinchuanxia Reservoir in No. $t$ period in No. $k$ year. $\alpha_{21} + \alpha_{31} + \alpha_{11} = 1$.

Constraint condition of inflow of Jinchuanxia Reservoir:

$$\sum_t^T Q_1R(k,t) \le \sum_t^T Q_2C(k,t) + \sum_t^T Q_3C(k,t) - \sum_t^T Q_2G(k,t) - \sum_t^T Q_3G(k,t) \tag{7}$$

where $Q_1R(k,t)$ is monthly average inflow of Jinchuanxia Reservoir. $Q_2C(k,t)$ and $Q_3C(k,t)$ are monthly average outflow of Xidahe Reservoir and Huangcheng Reservoir . $Q_2G(k,t)$ and $Q_3G(k,t)$ are monthly average requirement flow of Xidahe and Dongdahe irrigated area, respectively.

Constraint condition of water consumption (Ma Dehai & Ma Leping, 2010):

$$\sum_t^T Q_1C(k,t) = a\sum_t^T N(k,t) + b\sum_t^T G(k,t) + c\sum_t^T S(k,t) \tag{8}$$

where $a$, $b$, $c$ are monthly allocation percents of agricultural and industrial and domestic water use in Jinchang City respectively; $a+b+c$ = 1. $N(k,t)$, $G(k,t)$, $S(k,t)$ are monthly water consumption of agriculture and industry and living, respectively.

Constraint condition of water requirement (Ma Dehai & Ma Leping, 2010):

$$\sum_t^T R_t^m = \sum_t^T RG_t^m + \sum_t^T RN_t^m + \sum_t^T RS_t^m - \sum_t^T TD_t^m \tag{9}$$

where $R_t^m$ is water requirement of No. $m$ reservoir. $RG_t^m$ is industrial water requirement of No. $m$ reservoir. $RN_t^m$ is irrigated and ecological water requirement of No. $m$ reservoir. $RS_t^m$ is domestic water requirement of No. $m$ reservoir. $TD_t^m$ is groundwater requirement repeated to surface water.

**Optimal operation functions**

The optimal operation of multi-reservoirs is affected by the initial storage capacity and inflow of reservoirs. The relating function is shown as below:

$$u_t = f_t(V_t, Q_t^2, Q_t^3) \tag{10}$$

where $u_t$ is decision function of outflow in No. $t$ period. $V_t$ is the storage capacity or water level in No. $t$ period. $Q_t^2$ is the outflow of Xidahe Reservoir in No. $t$ period. $Q_t^3$ is the outflow of Huangcheng Reservoir in No. $t$ period.

Making an approximated linear process of the function above to get a linear equation gives:

$$u_t = a_t x_t + b_t y_t + c_t \tag{11}$$

where $a_t$, $b_t$ and $c_t$ are under determined parameters of the No. $t$ period's function; ($t$ = 1, 2…12). The residual square should be the minimum.

$$\min_{a_t, b_t, c_t} \sum_{i=1}^{n} \left[u_t^i - (a_t x_t^i + b_t y_t^i + c_t)\right]^T \left[u_t^i - (a_t x_t^i + b_t y_t^i + c_t)\right] \tag{12}$$

$$\alpha = (a_t, b_t, c_t)^T, \beta = \begin{pmatrix} x_t^1 & y_t^1 & 1 \\ & \cdots & \\ x_t^i & y_t^i & 1 \\ & \cdots & \\ x_t^n & y_t^n & 1 \end{pmatrix}, Y = \begin{pmatrix} u_t^1 \\ \cdots \\ u_t^i \\ \cdots \\ u_t^n \end{pmatrix} \tag{13}$$

$Y = \beta\alpha$. By matrix operating to get $\alpha = (\beta^T\beta)^{-1}\beta^T Y$.

The optimal state tends to stabilise during long time calculation. When the calculated time period is longer and flow quantities of each period are independent of each other, the decision value can be calculated, i.e. $\overline{u_t} = a_t \overline{x_t} + b_t \overline{y_t} + c_t$, to get the following:

$$u_t - \overline{u_t} = a_t(x_t - \overline{x_t}) + b_t(y_t - \overline{y_t}) \tag{14}$$

where $\overline{u_t}$, $\overline{x_t}$, $\overline{y_t}$ is average optimal operation quantity, average outflow quantity, and irrigation flow quantity, respectively.

## SOLUTION OF MULTI-RESERVOIR OPTIMAL OPERATION FUNCTIONS

For these functions above, the genetic algorithm method is first used to resolve the optimal operation project of reservoirs, then compared to the artificial neural network method (ANN).

### Genetic algorithm method

As an optimal method, a genetic algorithm can simulate the biological evolution process on a computer based on natural selection and inheritance mechanism (Wang Bailu *et al.*, 2002). This method can repeatedly modify the population related to solution of the problem. First, new individuals are produced continually. Secondly, based on the theory of survival of the fittest, the optimal system resolution project is obtained by not taking individuals with the largest adaptation degree into crossover and mutation operation.

### Genetic algorithm application in optimal operation of multi-reservoir

Genetic algorithm calculation in the optimal operation of multi-reservoir is mainly realized in MATLAB software.

### Parameter constraints

The three reservoirs are annual-operating reservoirs. A month is taken as the calculating period and marked as $S_1$, $S_2$, $S_3$… $S_{12}$. The specific constraint conditions are shown in Table 2.

Agricultural irrigation period of Huangcheng Reservoir is mainly from May to October. The irrigation period of Xidahe Reservoir is mainly from April to July and in October. The irrigation period of Jinchuanxia Reservoir is mainly from April to May and in October.

### Process and result of multi-reservoir operation

Based on the series of runoff data of Dongdahe River and Xidahe River, using the frequency analysis method provided the following results: typical wet year ($P$ = 10%) is 2003–2004, typical average year ($P$ = 50%) is 1997–1998, typical dry year ($P$ = 90%) is 2001–2002.

**Table 2** Constraint conditions of reservoir inflow and outflow (unit: $hm^3$).

| Constraints | | Periods $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $S_7$ | $S_8$ | $S_9$ | $S_{10}$ | $S_{11}$ | $S_{12}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Huangcheng Reservoir | Lower | 10 | 6 | 6 | 6 | 32 | 32 | 32 | 32 | 32 | 32 | 15 | 10 |
| | Upper | 15 | 10 | 10 | 10 | 48 | 48 | 48 | 48 | 48 | 48 | 25 | 15 |
| Xidahe Reservoir | Lower | 0 | 0 | 4 | 4 | 20 | 20 | 20 | 5 | 5 | 20 | 5 | 0 |
| | Upper | 0 | 0 | 10 | 10 | 31 | 31 | 31 | 16 | 16 | 31 | 16 | 0 |
| Jinchuanxia Reservoir | Lower | 8 | 8 | 8 | 8 | 20 | 20 | 10.5 | 10.5 | 10.5 | 10.5 | 20 | 8 |
| | Upper | 11 | 11 | 11 | 11 | 30 | 30 | 13 | 13 | 13 | 13 | 30 | 11 |
| Water requirement in Jinchang City | Lower | 8 | 8 | 8 | 8 | 20 | 20 | 10.5 | 10.5 | 10.5 | 10.5 | 20 | 8 |
| | Upper | 11 | 11 | 11 | 11 | 30 | 30 | 13 | 13 | 13 | 13 | 30 | 11 |

**Table 3** Results of jointly operation of multi-reservoir in wet year of Jinchang City.

| Month | Outflow ($hm^3$) Huangcheng Reservoir | | Xidahe Reservoir | | Jinchuanxia Reservoir | |
|---|---|---|---|---|---|---|
| | After operation | Before operation | After operation | Before operation | After operation | Before operation |
| January | 15.00 | 9.07 | 0.00 | 0.00 | 10.12 | 7.85 |
| February | 10.00 | 5.43 | 0.00 | 0.00 | 8.54 | 7.21 |
| March | 10.00 | 4.42 | 11.20 | 0.47 | 8.54 | 7.95 |
| April | 10.00 | 10.53 | 11.20 | 0.47 | 8.54 | 8.42 |
| May | 37.63 | 37.98 | 28.76 | 23.29 | 18.80 | 21.37 |
| June | 37.63 | 40.67 | 28.89 | 31.30 | 18.80 | 24.34 |
| July | 37.63 | 41.34 | 28.76 | 27.35 | 18.80 | 16.53 |
| August | 37.63 | 51.46 | 17.92 | 15.43 | 18.80 | 12.99 |
| September | 37.63 | 49.49 | 17.92 | 24.72 | 18.80 | 22.37 |
| October | 37.63 | 31.24 | 28.76 | 30.05 | 18.80 | 8.44 |
| November | 25.00 | 18.07 | 17.92 | 15.02 | 12.28 | 27.84 |
| December | 15.00 | 15.05 | 0.00 | 0.00 | 11.62 | 9.78 |

**(a) Process and result of multi-reservoir operation in wet year** It is assumed that the crossover number is 100, the crossover process tends to stabilise after more than 20 generations. The results of tending a stable iterative procedure may be obtained by crossover/mutation process and tentative genetic algorithm calculation. In a wet year, the total optimal water supply is 654 $hm^3$. A multi-reservoir operation result in a wet year is shown in Table 3.

After optimal operation of three reservoirs, the water needs of Jinchang City are met by realizing a balance between water utilization in a city and irrigated area. In irrigation seasons, the water supply to Jinchang City is decreased. In non-irrigation seasons, water supply increases. For Hungcheng Reservoir, water adjustments of increasing outflow from January to March play an ensuring role in the water supply from Jinchuanxia Reservoir to Jinchang City. For Xidahe Reservoir, considering the inflow increases with rainfall during September and October to meet downstream needs, so by diverting water to Jinchuanxia Reservoir during March to April and storing water in the peak period of water utilization can achieve the effect of water regulation during dry and wet seasons. For Jinchuanxia Reservoir, this operation meets the increasing water supply needs in Jinchang City.

**(b) Process and result of multi-reservoir operation in the average year** It is assumed that the crossover number is 100, the crossover process tends to stability after more than 25 generations. In an average year, the total optimal water supply is 633 $hm^3$. Multi-reservoir operation results in an average year are shown in Table 4.

After operation, it is shown that the outflow of Xidahe Reservoir is 0 from December to February, which is mainly because of freezing in winter. The outflows of Huangcheng Reservoir and Jinchuanxia Reservoir increase from May to November because of less water utilization in Xidahe irrigated area in spring and autumn. Water utilization in the summer irrigation period is relatively bigger, which is in accordance with actual data. So the crop structure should be adjusted to increase the yield of crops and decrease the quantity of agricultural water utilization. The optimal operation of Xidahe Reservoir is mainly obtained by decreasing water diversions in June and increasing outflow from March to April. The outflow of Jinchuanxia Reservoir in most months is increased, while it obviously decreases in November and increases in October. The operation ensures the increasing water supply of Jinchang City.

**(c) Process and results of multi-reservoir operation in dry year** It is assumed that the crossover number is 100, the crossover process tends to stabilise after more than 25 generations. The total water supply can reach up to 548 $hm^3$, which can meet the basic needs of industrial and agricultural and domestic water utilization. The multi-reservoir operation result in dry years is shown in Table 5.

**Table 4** Results of jointly operation of multi-reservoir in average year of Jinchang City.

| Month | Outflow ($hm^3$) | | | | | |
|---|---|---|---|---|---|---|
| | Huangcheng Reservoir | | Xidahe Reservoir | | Jinchuanxia Reservoir | |
| | After operation | Before operation | After operation | Before operation | After operation | Before operation |
| January | 15.00 | 10.91 | 0.00 | 0.00 | 9.69 | 7.73 |
| February | 10.00 | 8.53 | 0.00 | 0.00 | 9.25 | 7.53 |
| March | 10.00 | 6.07 | 11.94 | 0.94 | 9.35 | 9.15 |
| April | 10.00 | 9.83 | 11.94 | 3.84 | 9.35 | 8.66 |
| May | 34.51 | 36.47 | 24.50 | 17.90 | 23.17 | 21.62 |
| June | 34.51 | 37.99 | 24.50 | 29.45 | 23.17 | 20.35 |
| July | 34.51 | 47.35 | 24.50 | 25.08 | 23.17 | 15.67 |
| August | 34.51 | 33.60 | 14.40 | 11.73 | 23.14 | 11.59 |
| September | 34.51 | 34.87 | 14.40 | 10.30 | 23.14 | 9.65 |
| October | 34.51 | 32.57 | 24.50 | 25.95 | 23.17 | 8.84 |
| November | 25.00 | 20.80 | 14.38 | 12.87 | 16.60 | 25.00 |
| December | 15.00 | 13.58 | 0.00 | 0.03 | 9.69 | 12.36 |

**Table 5** Results of jointly operation of multi-reservoir in dry year of Jinchang City.

| Month | Outflow ($hm^3$) | | | | | |
|---|---|---|---|---|---|---|
| | Huangcheng Reservoir | | Xidahe Reservoir | | Jinchuanxia Reservoir | |
| | After operation | Before operation | After operation | Before operation | After operation | Before operation |
| January | 15.00 | 13.39 | 0.00 | 0.00 | 8.94 | 8.27 |
| February | 15.00 | 11.88 | 0.00 | 0.00 | 8.94 | 7.45 |
| March | 15.00 | 4.82 | 0.97 | 0.72 | 8.94 | 8.68 |
| April | 15.00 | 1.84 | 0.97 | 0.69 | 13.51 | 8.74 |
| May | 24.21 | 28.79 | 20.00 | 19.54 | 23.44 | 19.61 |
| June | 24.21 | 21.90 | 20.00 | 24.08 | 23.43 | 16.63 |
| July | 24.19 | 46.31 | 20.00 | 20.84 | 23.41 | 12.43 |
| August | 24.18 | 21.43 | 0.97 | 3.01 | 22.12 | 10.08 |
| September | 24.19 | 14.98 | 0.97 | 0.81 | 22.12 | 8.45 |
| October | 24.19 | 23.38 | 20.00 | 28.60 | 23.42 | 7.85 |
| November | 24.18 | 29.58 | 10.00 | 10.74 | 22.73 | 19.73 |
| December | 15.00 | 8.79 | 0.00 | 0.00 | 8.94 | 11.85 |

After optimal operation, the water supply of Huangcheng Reservoir is decreased in July, but increased from January to April. Analysis indicates that this phenomenon is likely to be related to flood discharge in selected serial years, as the agricultural water supply and demand is basically balanced in the irrigation period from May to July in other years. At the same time, the need of water supply of the Dongdahe irrigated area can be met by controlling the population value in the genetic algorithm. The optimal operation of Xidahe Reservoir is mainly realized by decreasing the outflow in June and October, and increasing the outflow in May, while the same as original data in other months. The outflow of Jinchuanxia Reservoir in most months is increased after reservoirs operation in upstream. The operation ensures the increasing water supply in Jinchang City.

**(d) Result analysis of multi-reservoir operation in serial years** The jointly operation in serial years is constrained according to the data from 1990 to 2007. The storage capacity at the end of December of each year is equal to the capacity in early January of the following year. Using the method above the jointly operation process of three reservoirs during 18 years was obtained. It is assumed that the crossover number is 100, generation length is 20 and crossover percentage is 0.8. The part of optimal operation results is shown in Table 6.

**Table 6** The optimal operation results in serial years in Jinchang City ($hm^3$).

| Year | Outflow ($hm^3$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Huangcheng Reservoir | | | | Xidahe Reservoir | | | | Jinchuanxia Reservoir | | | |
| | Month | | | | Month | | | | Month | | | |
| | May | June | July | Aug. | May | June | July | Aug. | May | June | July | Aug. |
| 1990 | 39.62 | 39.63 | 39.61 | 39.62 | 20.34 | 25.32 | 35.32 | 16.00 | 20.00 | 20.00 | 15.50 | 12.90 |
| 1991 | 35.00 | 35.00 | 45.00 | 13.03 | 10.00 | 20.00 | 30.00 | 10.00 | 20.00 | 20.00 | 15.50 | 9.73 |
| 1992 | 26.00 | 20.00 | 30.00 | 18.86 | 13.09 | 21.79 | 13.09 | 13.08 | 20.00 | 20.00 | 15.50 | 9.01 |
| 1993 | 35.03 | 35.03 | 38.71 | 35.01 | 28.64 | 30.59 | 28.64 | 16.00 | 20.00 | 20.00 | 15.50 | 11.61 |
| 1994 | 29.90 | 26.56 | 33.89 | 26.54 | 14.11 | 22.24 | 14.11 | 14.11 | 20.00 | 20.00 | 15.50 | 10.43 |
| 1995 | 35.36 | 27.53 | 34.26 | 27.53 | 17.23 | 23.82 | 17.22 | 16.00 | 20.00 | 20.00 | 15.50 | 11.83 |
| 1996 | 32.22 | 30.64 | 36.22 | 30.64 | 15.60 | 22.92 | 15.62 | 15.60 | 20.00 | 20.00 | 15.50 | 12.42 |
| 1997 | 29.40 | 25.69 | 33.40 | 25.70 | 17.10 | 23.75 | 17.11 | 16.00 | 20.00 | 20.00 | 15.50 | 10.88 |
| 1998 | 28.73 | 24.45 | 32.72 | 24.46 | 17.63 | 24.05 | 17.63 | 16.00 | 20.00 | 20.00 | 15.50 | 11.65 |
| 1999 | 27.89 | 22.78 | 31.89 | 22.78 | 10.95 | 20.89 | 10.95 | 10.94 | 20.00 | 20.00 | 15.50 | 10.67 |
| 2000 | 30.66 | 27.91 | 34.66 | 27.91 | 13.15 | 21.83 | 13.17 | 13.18 | 20.00 | 20.00 | 15.50 | 10.47 |
| 2001 | 26.04 | 20.04 | 30.04 | 18.97 | 10.00 | 20.00 | 8.99 | 10.00 | 20.00 | 20.00 | 15.50 | 9.00 |
| 2002 | 28.80 | 24.59 | 32.80 | 24.61 | 10.00 | 20.00 | 9.16 | 10.00 | 20.00 | 20.00 | 15.50 | 9.74 |
| 2003 | 45.00 | 45.00 | 49.21 | 49.21 | 31.07 | 32.15 | 31.05 | 16.00 | 20.00 | 20.00 | 15.50 | 13.53 |
| 2004 | 31.69 | 29.70 | 35.69 | 29.71 | 24.65 | 28.06 | 24.63 | 16.00 | 20.00 | 20.00 | 15.50 | 12.52 |
| 2005 | 32.28 | 30.76 | 36.28 | 30.76 | 15.36 | 22.79 | 15.32 | 15.36 | 20.00 | 20.00 | 15.50 | 12.85 |
| 2006 | 36.94 | 36.93 | 39.88 | 36.95 | 27.20 | 29.69 | 27.22 | 16.00 | 20.00 | 20.00 | 15.50 | 12.83 |
| 2007 | 32.06 | 30.38 | 36.06 | 30.35 | 19.01 | 24.84 | 18.99 | 16.00 | 20.00 | 20.00 | 15.50 | 11.18 |

According to constraints and analysis on the histogram of the optimal operation of multi-reservoir in Jinchang City during 18 years, the constraining water supply quantities in spring/summer and autumn/winter irrigation seasons are met. At the same time, the outflow in the wet years obviously increases, e.g. the operation data obviously increases in 2003. This phenomenon is in accordance with original data in total. In the non-irrigation seasons, water consumption is relatively less and the outflow is relatively low, which are in agreement with reality. Changing trends of each year are constant. There are two peak values, in spring/summer and autumn/winter irrigation periods, and the peak values of each reservoir do not coincide with data after optimal operation, so the overall arrangement is realized on the time scale. This makes the utilization of limited water resources to improve and to realize the optimal allocation of water resources in Jinchang City.

During the solution processes of long serial optimal operation, the tentative calculations are very unstable in the crossover and mutation processes. It tends to be stable at the 29th generation.

Long serial water operation projects are consistent with actual values. These projects are according with regulation characteristics of reservoirs and practical reality.

## MULTI-RESERVOIR OPERATION FUNCTIONS BASED ON ANN

There are many decision variables that appear in linear and nonlinear relationships affecting the operation of reservoirs. As a parallel computing model, the Artificial Neural network (ANN) can consider multi-reservoir function elements and undertake complicated nonlinear operation (Ma Xixia & Xia Longxing, 2005).

### BP Neural Network

Back propagation (BP) algorithm is one of the most important learning algorithms in the ANN model. The BP network is composed of an input layer, an output layer and one or more hidden layers (Chang Jianxia *et al.,* 2001; Ma Xixia & Xia Longxing, 2005). There are several neurons in every layer, which are connected with each other according to individual weighting. The learning process of BP mainly includes forward propagation and back-propagation. In the former process, input information is spread from input layer node to hidden layer node, after action function the information is spread from hidden layer node to output layer node (Ma Xixia & Xia Longxing, 2005). The output result can be obtained at last. If the desired output cannot be obtained in the output layer, then turning to back-propagation. The error signal along the original connection path is returned. It is done to modify the weight and threshold values to make the error signal smaller. After repeated calculation, the training process finishes when the error is less than the permissible error. The recessive nonlinear relationship between dependent variables and independent variables are reflected by weight and threshold values. In order to speed up the convergence rate, normalized processes on original data are made and the data ranges from 0 to 1. In this paper, the improved BP neural network model was used in the research of the joint operation of multi-reservoir in Jinchang City (Miao Yiping & Ji Changming, 2003).

### Operation functions of multi-reservoir

Taking inflow, initial storage capacity, storage capacity and evaporation and leakage losses at the end of different periods of each reservoir as input variables, the irrigation flow of Dongdahe and Xidahe irrigated areas also as input variables, outflow of Jinchuanxia Reservoir as output variable, each month as a calculating period and constructing a topological structure with 12 network layers. The numbers of hidden layer nodes are obtained from training by self-adaptive methods. By training samples composed of long serial calculated results of optimal operation of multi-reservoir, the hidden nonlinear relationship of Jinchuanxia Reservoir outflow with the inflow, storage capacities and irrigation flow of three reservoirs is established, which is the multi-reservoir operation function.

The 15 years' samples (from January 1990 to December 2004) are selected from eighteen-year long serial optimal operation data sets (1990–2007) of three reservoirs in order to carry on network training. Then the known samples from January 2005 to December 2007 are chosen to make inspection. The initial rate is 0.9 and permissible error accuracy is 0.002. The global error and training numbers of Jinchuanxia Reservoir network training are shown as Table 7. Inspection results are shown as Table 8.

Table 8 shows that the calculated error is relatively small (relative error less than 8%) by using the BP network model. The established multi-reservoir operation function model based on ANN can reflect the optimal outflow of Jinchuanxia Reservoir. A comparison between simulation and actual values is shown in Fig. 2.

## COMPARATIVE ANALYSES ON BP NETWORK AND GENETIC ALGORITHM

After multi-reservoir optimal operation by using a genetic algorithm, the water supply in Jinchang City is increased to 633 $hm^3$ and that of Jinchuanxia Reservoir reaches up to 202.89 $hm^3$. The ratio

**Table 7** Global error and training numbers of Jinchuanxia Reservoir network training.

| Network | $R_1$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ | $R_6$ |
|---|---|---|---|---|---|---|
| Month | January | February | March | April | May | June |
| Training number | 1500 | 2200 | 2358 | 2280 | 2275 | 3282 |
| Training rate | 0.06 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 |
| Global error (%) | 1.00 | 1.00 | 4.00 | 1.60 | 1.40 | 4.50 |
| Network | $R_7$ | $R_8$ | $R_9$ | $R_{10}$ | $R_{11}$ | $R_{12}$ |
| Month | July | August | September | October | November | December |
| Training number | 2200 | 2800 | 3860 | 3962 | 2000 | 1800 |
| Training rate | 0.06 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 |
| Global error (%) | 1.40 | 2.20 | 4.00 | 1.00 | 1.00 | 5.40 |

**Table 8** Inspection results of BP operation function model of Jinchuanxia Reservoir.

| Period | BP model | Outflow ($hm^3$) | | Relative error (%) | Period | BP model | Outflow($hm^3$) | | Relative error (%) |
|---|---|---|---|---|---|---|---|---|---|
| | | Actual value | Simulation value | | | | Actual value | Simulation value | |
| 2005.01 | $R_1$ | 8.52 | 8.60 | 0.84 | 2006.07 | $R_7$ | 16.23 | 16.24 | 0.08 |
| 2005.02 | $R_2$ | 8.27 | 8.27 | 0.02 | 2006.08 | $R_8$ | 17.65 | 17.29 | 2.04 |
| 2005.03 | $R_3$ | 8.68 | 8.62 | 0.69 | 2006.09 | $R_9$ | 10.01 | 9.24 | 7.66 |
| 2005.04 | $R_4$ | 10.60 | 10.23 | 3.49 | 2006.10 | $R_{10}$ | 7.85 | 7.86 | 0.09 |
| 2005.05 | $R_5$ | 23.89 | 23.57 | 1.36 | 2006.11 | $R_{11}$ | 25.69 | 25.81 | 0.48 |
| 2005.06 | $R_6$ | 24.73 | 23.62 | 4.48 | 2006.12 | $R_{12}$ | 11.54 | 11.47 | 0.57 |
| 2005.07 | $R_7$ | 15.64 | 15.43 | 1.33 | 2007.01 | $R_1$ | 7.82 | 7.77 | 0.62 |
| 2005.08 | $R_8$ | 12.00 | 12.26 | 2.20 | 2007.02 | $R_2$ | 6.89 | 6.85 | 0.64 |
| 2005.09 | $R_9$ | 10.37 | 9.95 | 4.03 | 2007.03 | $R_3$ | 7.20 | 7.26 | 0.89 |
| 2005.10 | $R_{10}$ | 8.38 | 8.36 | 0.25 | 2007.04 | $R_4$ | 7.75 | 7.86 | 1.44 |
| 2005.11 | $R_{11}$ | 30.02 | 29.72 | 1.00 | 2007.05 | $R_5$ | 23.25 | 23.09 | 0.67 |
| 2005.12 | $R_{12}$ | 9.56 | 10.08 | 5.44 | 2007.06 | $R_6$ | 24.60 | 23.94 | 2.67 |
| 2006.01 | $R_1$ | 8.06 | 7.94 | 1.46 | 2007.07 | $R_7$ | 15.40 | 16.12 | 4.69 |
| 2006.02 | $R_2$ | 7.09 | 7.12 | 0.37 | 2007.08 | $R_8$ | 13.07 | 12.88 | 1.45 |
| 2006.03 | $R_3$ | 8.49 | 8.46 | 0.38 | 2007.09 | $R_9$ | 8.63 | 8.96 | 3.80 |
| 2006.04 | $R_4$ | 9.75 | 9.97 | 2.25 | 2007.10 | $R_{10}$ | 8.62 | 8.63 | 0.16 |
| 2006.05 | $R_5$ | 23.68 | 23.66 | 0.09 | 2007.11 | $R_{11}$ | 24.49 | 24.45 | 0.16 |
| 2006.06 | $R_6$ | 24.47 | 24.25 | 0.88 | 2007.12 | $R_{12}$ | 12.21 | 12.18 | 0.28 |

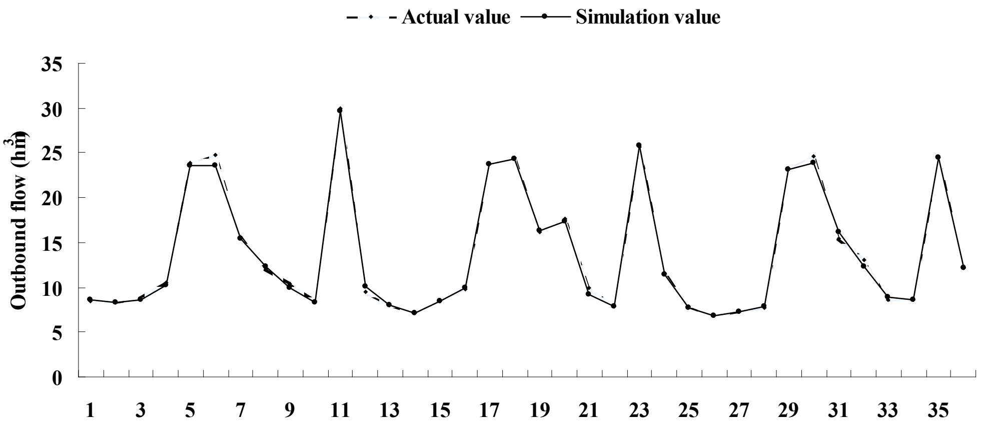


**Fig. 2** Fitting curve between simulation and actual values of outflow of Jinchuanxia Reservoir from 2005 to 2007.

of water shortage also decreases from 28.1% to 16.1%. By using the operation function from the BP neural network algorithm, water supply in 2007 is 160 $hm^3$, which is a little different from the original value (159.93 $hm^3$). The results of optimal operation of each reservoir show that the genetic algorithm is better than the BP neural network method.

The establishment of optimal operation function by the BP neural network method mainly comes from the learning of samples. It cannot make more scientific optimal allocation on annual inflow according to the specific changes of industrial and domestic water demand. Genetic algorithm can take constraints on industrial and domestic water demand in order to realize optimal operation. In this point, genetic algorithm is better than BP neural network method.

Relative error between simulation results by BP neural network method and actual samples is <8%. However, the error of genetic algorithm is larger. The fitting of samples by BP neural network method is obviously better than that of genetic algorithm.

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## REFERENCES

Beekman, G. B. (1998) Water conservation, recycling and reuse. *Water Resour. Develop.* 14(3), 353–364.

Cai Shengju (2008) Shiyang River basin water resources disposition research. MSc Thesis, Lanzhou University, Lanzhou, Gansu, China.

Chang Jianxia, Huang Qiang & Wang Yimin (2001) The method for solution to operation rules of water supply multi-reservoirs based on improved BP network in Xi'an. *J. Xi'an Univ. Technol.*17(2), 169–173.

Chen Ningzhen (1993) Function and Operation of Reservoirs. *M.China WaterPower Press.*

Foufoula, E. & Kitanidis, P. K. (1988) Gradient dynamic programming for stochastic optimal control of multi-dimensional water resources systems. *Water Resour. Res.* 24(8), 1345–1359.

Hong Guobin (2003) Preliminary study of water resources situation and sustainable development in China. *Hubei Water Power* 52, 8–9.

Hu Tiesong, Yuan Peng & Ding Jing (1995) Application of artificial neural network to hydrology and water resources. *Adv. Water Sci.* 6(1), 76–78.

Liang Wenshou (2005) Water-saving potential and measures for industry and residents in Jinchang City. MSc Thesis, Lanzhou University, Lanzhou, Gansu, China.

Liu Jiali (2004) Present evaluation of water resources and trend analysis of water supply and demand in Gansu Province. MSc Thesis, Xi'an University of Technology, Xi'an, Shaanxi, China.

Liu Linpu (2004) Comprehensive review research of multi-reservoir optimal operation technology. *Shanxi Hydromechanics* 4, 91–92, 94.

Liu Pan, Guo Shenglian, Li Wei, *et al*. (2006) A review of application of genetic algorithm to reservoir operation. *Adv. Sci. Technol. Water Resour.* 26(4), 78–83.

Ma Dehai & Ma Leping (2010) Study and application of optimized allocation of water resources based on water demands of irrigation area and useful operation of reservoir. *Water Resources and Hydropower Engineering* 41(9), 1–4.

Ma Xixia & Xia Longxing (2005) Artificial neural network model of dispatching function in Zhaopingtai reservoir. *Hydroelectric Energy* 6, 20–21.

Miao Yiping & Ji Changming (2003) Improving neural network algorithm for establishing reservoir operation function. *J. Wuhan Univ. Hydraulic and Electric Engng* 36(1), 42–44, 58.

Neelakantan, T. R. & Pundarikanthan, N. V. (2000) Neural network-based simulation optimal model for reservoir operation. *J. Water Resour. Plan. Manage.* 126(2), 57–64.

Pang Pengsha & Dong Renjie (2004) Research on the situation and strategy of water resources in China. *Water Conservancy Sci. Technol. Econ.* 10(5), 267–268.

Su Tongfen (2010) A modified immune particle swarm algorithm and research on cascaded reservoir optimal scheduling. MSc Thesis, Taiyuan University of Technology, Taiyuan, Shanxi, China.

Wang Bailu, Cheng Chuntian, Liu Jun, *et al*. (2002) Application of genetic algorithm and increment dynamic planning algorithm in optimal operation of reservoir. *Water Resource & Hydropower of Northeast China* 20(9), 1–4.

Wang Li (2006) Study on multi-objective optimal of Sanmenxia reservoir dispatching. MSc Thesis, Hohai University, Nanjing, Jiangsu, China.

Wang Meiliang (2006) On economic scheduling scheme of Dong Shen water supply project. MSc Thesis, Hohai University, Nanjing, Jiangsu, China

Wei Liutao, Liang Niansheng & Yu Jinjiang (1994) Application of artificial intelligence in stochastic dispatching of multi-reservoir system. *Journal of Huzhong University of Technology*, 25–29.

Zhang Shuanghu (2004) Research on united dispatching of reservoir system in Yeerqiang Basin. MSc Thesis, Xi'an University of Technology, Xi'an, Shaanxi, China.

Zhou Ming & Sun Shudong (1999) Genetic algorithms: theory and applications. *M. National Defence Industry Press, Beijing, China.*

Zhu Gaofeng, Ma Jinzhu, Su Yonghong, *et al*. (2004) Studies on water resources feature and the water demand and supply balance of Jinchang. *J. Arid Land Resources & Environment* 18(8), 154–157.

Zhu Yongmao, Su Hua & Liu Wei (2001) Current situation and further of water resources in China: strategy of water resources management for the 21st century. *Water Resour. Production* 4, 13–15.