IOP Conf. Series: Materials Science and Engineering **366** (2018) 012010 doi:10.1088/1757-899X/366/1/012010

Operation Mode of Danjiangkou Reservoir under Water Diversion Conditions of South-to-North Water Diversion Middle Route Project

Shuo Ouyang[1], Hui Qin[2*], Jun Shao[1], Rui Zhang[3] and Minglong Dai[1]

[1]Bureau of Hydrology, Changjiang Water Resources Commission, Wuhan 430010;
[2] School of Hydropower and Information Engineering, Huazhong University of Science and Technology, Wuhan, 430074, People's Republic of China;
[3]Changjiang Institute of Survey, Planning, Design and Research, Changjiang Water Resources Commission, Wuhan 430010

E-mail (Hui Qin): hqin@hust.edu.cn

Abstract: In order to explore operation scheme of downstream controlling reservoir in water source area for optimized allocation of inter-basin water resources, this paper selected the south-to-north water diversion middle route project in Hanjiang River basin as an instance. The optimized dispatching mode of Danjiangkou Reservoir is built with multiple dispatching objective functions and different dispatching scenarios set, such as maximum water supply during water supply period, minimum discharge, minimum abandoned water and maximum power generation. The simulation results indicate that the model and methods proposed in this paper are feasible and effective.

1. Introduction

For more than half a century, domestic and foreign experts and scholars propose many inter-basin water diversion project planning, decision-making models and methods of management and operation, which could be divided into two categories: firstly, after simplifying complex inter-basin water diversion system through various methods, single mathematical programming model or simulation model is adopted for planning, management and operation decision-making research on inter-basin water diversion projects[1]. Secondly, large-scale system optimized decision model and method are directly adopted. Planning management decision-making research on inter-basin water diversion projects is conducted by setting various large-scale system hierarchical structure models firstly and then applying solution method combined with multiple mathematical programming or simulation techniques (including self-optimization simulation technique) [2]. In recent years, along with continuous development and perfecting of decision-making support system and expert system[3], fuzzy mathematics [4, 5], cooperative game theory [6, 7] and other new theories[8, 9] and methods, people begin to explore application possibility of these theories and methods in planning management decision-making research on inter-basin water diversion project.

However, along with building of inter-basin water diversion projects, the inflow from upstream is obviously reduced, and the hydrological characteristics of river network are vary greatly. Currently, domestic and foreign research mainly focuses on the analysis of impact of inter-basin water diversion on downstream hydrology[10], water quality[11, 12], ecology and salinization[13] of water sources, and less quantitatively focuses on the effect of downstream controlling reservoir of water source in

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inter-basin water diversion. As the inter-basin water diversion with the most work quantities since new China was found, the south-to-north water diversion project (SNWDP) diverts a part of abundant water resources from Yangtze River basin to North China and northwest districts to relieve water resources shortage there [14, 15].

Therefore, in order to explore the operation scheme of controlling reservoir at downstream water source area specific to the optimized allocation of inter-basin water resources, this paper selected the Middle Route Project (MRP) of SNWDP as an instance, set multiple dispatching objective functions and different dispatching scenarios such as maximum water supply during water supply period, minimum discharge, minimum abandoned water and maximum power generation, and built the optimized dispatching mode of Danjiangkou Reservoir. Optimized dispatching of Dangjiangkou Reservoir was simulated by adopting natural runoff of Danjiangkou Reservoir from 1956 to 2010.

The structure of this paper is as follows: Chapter 2 describes the reservoir dispatching model, Chapter 3 discusses the water diversion scheme of MRP, Chapter 4 gives instance analysis, and Chapter 5 makes a summary.

2. Reservoir dispatching model

This paper selected four objective functions, i.e. maximum power generation, minimum abandoned water, maximum water supply during water supply period and minimum discharge, suitable for different scenario stages, and established the controlling reservoir regulation and storage model specific to upstream inter-basin water diversion. The generalized figure (Fig. 1) of the model is as follows:

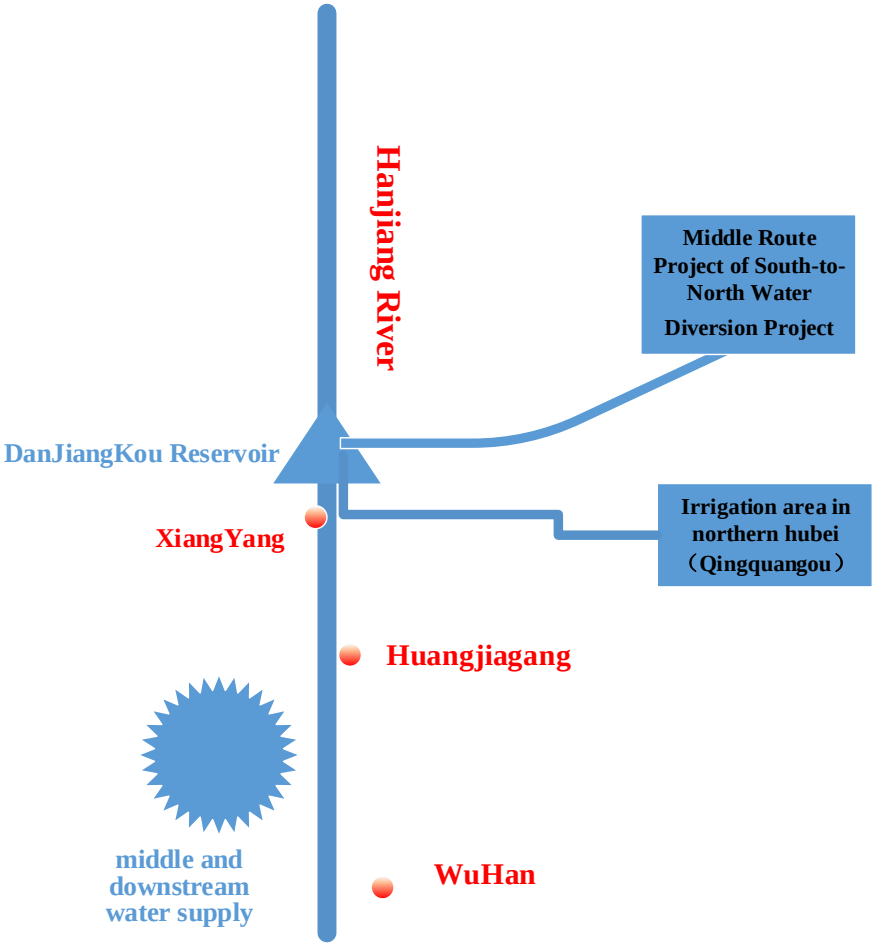


Figure 1 The geographical locations and topological structures of the Middle Route Project of South-to-North Water Diversion Project and Danjiangkou hydraulic complex project

2.1 Objective functions

(1) Minimum abandoned water (Obj1)

$$\min W_d = \min\{\sum_{t=1}^{T} Q_{t,d} \cdot \Delta t\} \tag{1}$$

Where, $Q_{t,d}$ represents abandoned water flow of reservoir during period t, and W_d represents abandoned water volume.

(2) Maximum water supply during water supply period (Obj2)

$$\max W_S = \max\{\sum_{t=1}^{T_S} Q_t \cdot \Delta t\} \tag{2}$$

Where, W_S represents water supply during water supply period, Q_t represents discharge of reservoir during period t, and T_S represents water supply dispatching period.

(3) Minimum discharge (Obj3)

$$\max Q_{f\min} = \max\{\min(Q_{t,f}, t \subset T)\} \tag{3}$$

(4) Maximum power generation (Obj4)

$$\max P = \max\{\sum_{t=1}^{T} N_t \cdot \Delta t\} \tag{4}$$

Where, N_t represents output of reservoir during period t.

2.2 Constraint conditions

Constraint conditions of the above-mentioned model are as follows:

(1) Upper and lower constraint of reservoir capacity (water level):

$$Z_{t,\min} \le Z_t \le Z_{t,\max} \tag{5}$$

Where, $Z_{t,\min}$, $Z_{t,\max}$ and Z_t respectively represent allowable minimum water level, maximum water level and water level in current period of reservoir during period t.

(2) Reservoir water balance constraint:

$$V_t = V_{t-1} + (I_t - Q_t - S_t)\Delta t \tag{6}$$

Where, V_t, I_t and Q_t respectively represent reservoir capacity, reservoir inflow and reservoir outflow during period t of dispatching; and S_t represents water diversion flow of upstream inter-basin water diversion project.

(3) Reservoir discharge capacity constraint

$$Q_{\min} \le Q_{out,t} \le Q_{\max} \tag{7}$$

Where, $Q_{out,t}$ represents discharge of reservoir during period t of dispatching, and $Q_{\max}$ and $Q_{\min}$ respectively represents maximum and minimum discharge capacity.

(4) Reservoir outflow constraint:

$$\left|Q_{out,t} - Q_{out,t-1}\right| \le \Delta Q \tag{8}$$

Where, $Q_{out,t}$ represents reservoir outflow during period t of dispatching, and ΔQ represents maximum amplitude of daily discharge corresponding to the reservoir.

(5) Flood control dispatching rules requirements and basin flood control standards for each reservoir of cascade reservoirs are conformed to.

3. Water division scheme for MRP

MRP diverts water from Danjiangkou Reservoir in Hanjiang River, a tributary of Yangtze River, channelizes and delivers water along plains of Funiu Mountain and Taihang Mountains to the end point, Beijing. Water supply range of MRP mainly includes more than 20 large and medium-sized middle and west cities in Tang-Bai River Plain and Huang-Huai-Hai Plain. MRP can relieve water resources crisis in Beijing, Tianjin and North China and increase water supply for living and industry of Beijing, Tianjin and cities of Henan, Hebei along the route and promote economic development in central China region.

Main monitoring cross-sections of main canal of MRP includes Taocha, Diao River, Fangcheng Caodun River, north bank of Yellow River, north bank of Zhang River, Gangtou Tunnel, north Juma River, Wangqingtuo (Hebei-Tianjin border). The key indicators are as shown in Table 1.

Table 1 Design flow and design level of main monitoring cross-sections

Name of monitoring cross-section	Location	Flow indicator(m^3/s)		Water level indicator
		Design flow	Increased flow	Design level (m)
Taocha	Behind Taocha sluice	350	420	147.38
Diao River	Diao River flume inlet regulating sluice	350	420	146.80
Fangcheng Caodun River	Caodun River inlet regulating sluice	330	400	136.04
North bank of Yellow River	Yellow River-crossing outlet regulating sluice	265	320	111.93
North bank of Zhang River	Zhang River outlet regulating sluice	235	265	91.87
Gangtou Tunnel	Gangtou Tunnel inlet regulating sluice	125	150	65.99
North Juma River	North Juma River underground canal inlet regulating sluice	50	60	60.73
Wangqingtuo (Hebei-Tianjin border)	Wangqingtuo junction chamber inlet sluice	50	60	5.11

4. Instance analysis

4.1 Dispatching operation mode of Danjiangkou Reservoir

After Danjiangkou dam is heightened, the main task of comprehensive utilization is flood control, water supply (including irrigation), power generation, navigation, etc. Because *Danjiangkou Reservoir Dispatching Regulation* has not been complied, this paper proposed the *Flood Control and Water Supply Schemes for Danjiangkou Reservoir* according to the *Water Dispatching Scheme for Middle Route Project Phase I of South-to-North Water Diversion Project* and *Water Allocation Scheme in Hanjiang River Basin* reviewed and approved by the State Council in 2014, under the conditions of meeting water demand by Hangjiang River middle and downstream, following inflow and water levels of Danjiangkou Reservoir and combined with water diversion quantity required by areas receiving water, and conducted partition dispatching according to water levels of Danjiangkou Reservoir. The operating water level of Danjiangkou Reservoir: normal pool level is 170 m; limited water level in flood season is 160 m in Summer (from June 21 to August 20), and is 163.5 m in Autumn (from September 1 to September 30); dead water level is 150 m; and limiting drawdown water level is 145 m.

The specific operation and dispatching schemes of Danjiangkou Reservoir:

(1) Flood control dispatching

The reservoir water level is gradually reduced from May 1, and reduced to 160 m on June 20. From June 21 to August 20, 160 m is controlled as initial dispatch stage of flood control (similar to 145 m operation mode of Three Gorges Reservoir), 160 m water is transited to 163.5 m from August 21 to September 1. 163.5 m is controlled as initial dispatch stage of flood control from September 1 to

September 30, and the reservoir can gradually store water to normal pool level 170 m from October 1 to October 10. During flood period from June 20 to October 10, discharge of reservoir shall be not more than 21,000 m^3/s so as to ensure flood control safety at downstream area.

(2) Water supply dispatching

Water supply objects of Danjiangkou Reservoir include: i) Cities and irrigating areas located in middle and lower Hanjiang River (let-down discharge of reservoir); ii) water diversion of Qingquangou; iii) water diversion for MRP (diversion of Taocha canal head). Where: the designed diversion discharge volume is 350 m^3/s and the increased water volume is 420 m^3/s for Taocha canal head diversion; and the designed water diversion volume of Qingquangou is 100 m^3/s. According to the dispatching principles and dispatching graph regulations, the water is supplied to the water-receiving areas of MRP Phase I in guaranteeing the diversion requirements of the middle and downstream of Han River and Qingquangou.

The dispatching lines include: i) normal pool level line (NPLline); ii) flood control dispatching line (FCline); iii) reduced water supply line 1 (RWSline1); iv) reduced water supply line 2 (RWSline2); v) limited water supply line (LWSline); vi) limiting drawdown water level (LDWline). The six water supply dispatching lines divide the Danjiangkou Reservoir dispatching chart into 5 zones. The water level of the six dispatching lines at the beginning of the month is shown in Table 2.

Table 2 Water level for six dispatching lines of Dangjiangkou Reservoir **Unit: m**

S/N	Line	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1	NPLline	170	170	170	170	170	170	170	170	170	170	170	170
2	FCline	170	164	160	160	163.5	163.5	170	170	170	170	170	170
3	RWSline1	156	156	156	159	161.4	163.5	168	168	168	168	165	160.5
4	RWSline2	155	155	155	155	156	161	163	163	163	161	158	155
5	LWSline	148	148	150	152	152	152	152	152	152	152	152	151
6	LDWline	145	145	145	145	145	145	145	145	145	145	145	145

4.2 Comparison analysis of dispatching results

Based on the above proposed Danjiangkou Reservoir dispatching scheme, 1956-2010 historical runoff data of ten-day natural storage runoff were selected. The DP algorithm and reservoir dispatching model designed in Chapter 2 were applied. Three dispatching cases were set, i.e. initial 157 m (case 1), without consideration of water diversion of phase 1 of MRP after the Danjiangkou dam was heightened (case 2), and in consideration of water diversion of phase 1 of MRP (case 3), to develop the optimized dispatching scheme with different objective functions. The comparison analysis of water resources allocation efficiency in the basin was carried out. See Table 3 for the simulated dispatching results of three cases.

Table 3 water supply dispatching results of Danjiangkou Reservoir in three cases

Case	Object	FSR (%)	MFR (%)	MGE ($\times10^8$kWh)	*MAW* ($\times10^8m^3$)	MSW ($\times10^8m^3$)	MWD ($\times10^8m^3$)	
							TC	QQG
Case 1	Obj4	89	99.83	51.05	49.20	**382.30**	0	3.46
	Obj1	15	97.36	54.27	41.18	**382.28**	0	3.48
Case 2	Obj2	11	96.23	45.92	82.83	**382.56**	0	3.20
	Obj3	15	97.37	42.76	126.40	**382.28**	0	3.48
	Obj1	11	96.54	41.97	22.59	**289.49**	92.81	3.46
Case 3	Obj2	0	94.39	39.11	58.20	**317.91**	64.75	3.10
	Obj3	11	96.52	34.23	72.61	**282.20**	100.11	3.45

The above table shows that in case 1 fill storage ratio (FSR) is 89%, mean annual full ratio (MFR) is 99.83%, mean annual quantity of water supply for downstream (MSW) is 38.23 billion m^3, mean annual abandoned water (MAW) is 4.92 billion m^3, and mean annual generated energy (MGE)is 5.105 billion kWh; in case 2 the abandoned water is minimum, the water supply capacity is the largest, and the minimum discharge is the highest. In the three optimized dispatching schemes, FSR is 15%, 11%

and 15% respectively, MFR is 97.36%, 96.23% and 97.37% respectively, MSW is 38.228, 38.256 and 38.228 billion m^3 respectively, MAW is 4.118, 8.283 and 12.64 billion m^3 respectively, and MGE is 5.427, 4.592 and 4.276 billion kWh respectively. In case 3, the abandoned water is minimum, the water supply capacity is the largest, and the minimum discharge is the highest. In the three optimized dispatching schemes, FSR is 11%, 0 and 11% respectively, MFR is 96.54%, 94.39% and 96.52% respectively, MSW is 28.949, 31.791 and 28.220 billion m^3 respectively, MAW is 2.259, 5.820 and 7.261 billion m^3 respectively, and MGE is 4.197, 3.911 and 3.423 billion kWh respectively. Compared to case 1 and case 2, case 3 reduces FSR by 78-89% and 4-11% respectively, MFR by 3.3-5.5% and 0.853-1.84% respectively, MSW by 6.4-10 billion m^3, and MGE by 0.9-1.7 and 0.6-1.3 billion kWh respectively.

On the other hand, MWD effectively alleviates the problem of water shortage in the north, and MAW is reduced by 0.9-2.7 and 1.8-5.4 billion m^3, which improves the utilization of water resources in the basin.

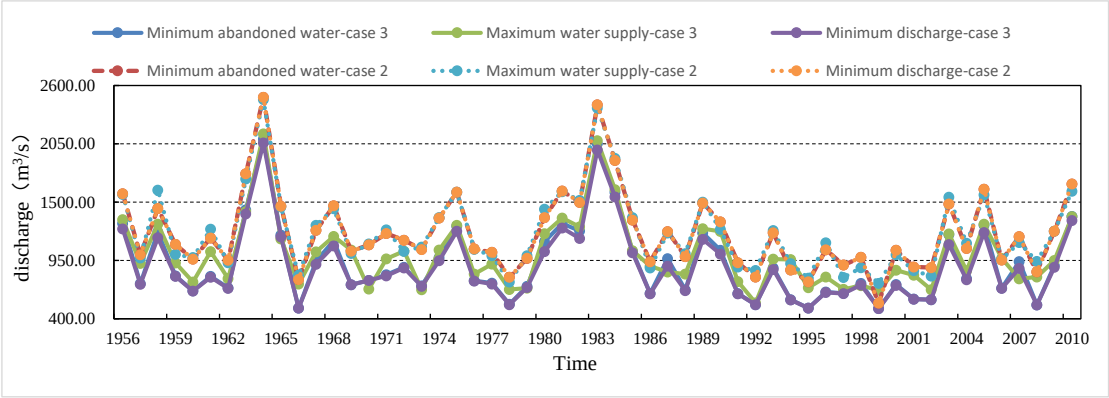


Figure 2 Discharge process of Danjiangkou Reservoir

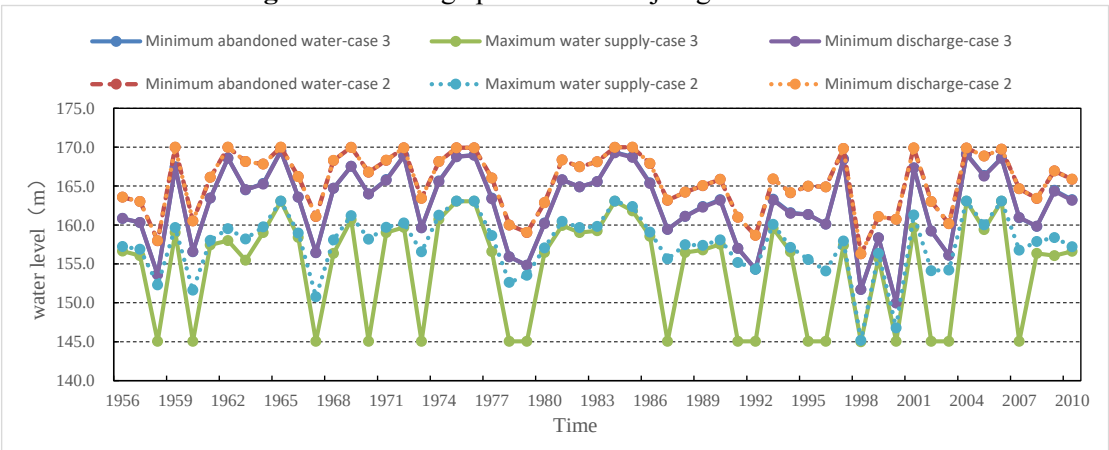


Figure 3 Water level process of Danjiangkou Reservoir

As can be seen from Table 3, Fig. 2 and Fig.3, due to the serious problem of water shortage, phase 1 of MRP has the large water diversion, which has a significant impact on the overall efficiency of water supply, water storage and power generation. In consideration of phase 1 of MRP water diversion conditions, MGE and FSR are less affected in the minor task, reduced by about 4% and 5% respectively.

5. Conclusion

In order to explore the downstream controlling reservoir operation scheme specific to optimal allocation of inter-basin water resources, MRP was selected as an instance to propose the Danjiangkou

Reservoir flood control and water supply scheme. This paper studies the operation mode of downstream controlling reservoir specific to optimal allocation of inter-basin water resources, and quantitatively analyzes the relationship and law of function between inter-basin water diversion, controlling water conservancy project at water source and the downstream reach of water source, which provides theoretical and data support for the development of rational operation scheme of downstream controlling water conservancy project at inter-basin water diversion water source.

Acknowledgments
This work was financially Supported by Hubei Provincial Natural Science Foundation of China (Grant No. 2016CFB391), supported by the Youth Funds of National Natural Science of China (Project No. 51609007), and supported by the National Key R&D Program of China (Item Nos. 2016YFC0402201). Special thanks are given to the anonymous reviewers and editors for their constructive comments.

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