STUDY ON THE JOINT OPERATION SCHEME OF NIERJI AND FENMAN RESERVOIRS IN SONGHUA RIVER BASIN

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ABSTRACT

Nierji and Fengman reservoirs are the control projects on the mainstream of the Nenjiang river and the second Songhua river in Songhua river basin respectively. The joint use of the two reservoirs is very important for the allocation of water resources of Songhua river in the reach above Harbin. In this study, Nierji and Fengman annual inflow series are selected to analyze the encounter probability of drought period and high-water period of the two reservoirs. The results show that the asynchronous frequency of drought period and high-water period of the two reservoirs are obviously higher than the synchronous frequency. It makes for developing the joint operation scheme of the reservoirs. By using the simulation-optimization method, the reservoir Optimal joint operation model of Songhua river above Harbin reach is constructed, and the reservoir operation rules are extracted intelligently. The results show that: The scheduling scheme based on the simulation-optimization method can give full play to the complementary effect of the two reservoirs. On the premise of basically meeting the basic ecological water demand of the river, and the water demand for livelihood and industrial purpose along both sides of the river in 2030, compared with the conventional dispatching mode, this dispatching scheme can increase the water supply by 395 million m^3. For the more, it can reduce the damage depth when water demand beyond the guaranteed rate.

Songhua river basin is the area where China's major grain-producing and old industrial base are located. Water resources are important factor that restricting economic and social development in the river basin. At present, the water consumption of various industries in the basin above the reach of Harbin has increased rapidly, and the contradiction in water use has been gradually highlighted. Nierji and Fengman reservoirs have a total storage capacity of 18.987 billion m^3, and a beneficial capacity of 14.583 billion m^3, account for 57.6% of the total storage capacity and 62.14% of the beneficial capacity of the all reservoirs in the basin above Harbin reach respectively.

In this study, the Songhua river basin of above Harbin reach was taken as the study area. The feasibility of the joint operation of the two reservoirs was studied by analyzing the encounter probability of the two reservoirs's high-water period and low-water period. Based on three prerequisites, the joint operation scheme of the two reservoirs was worked out respectively. The first prerequisite is the water flow in the river should meet the needs of ecological and shipping purposes. Second, the conventional operation method and the simulation-optimization method can be used in the scheme. Finally, the supply and demand of water resources should be in a balance.

1. THE STUDY ARES OVERVIEW

1.1 Type area

The study areas covers three regions. First is Nenjiang river basin region, the second region is the Second Songhua river basin and the third region is the mainstream section of a river within Sanchahe and Harbin in the Songhua river.

The Nenjiang river originated in the Southern slope of Yilihuli mountain, Great Xing'an Range. The river is the northern source of the Second Songhua river, and it flows from north to south through several places which are Heihe city, Da Xinganling district, Nenjiang county, Nehe city, Fuyu county, Qiqihaer city, and Daqing city. After the Nenjiang river joins the Second Songhua river at the confluence around Sanchahe in Zhaoyuan County, it finally flows into the mainstream of Songhua river. The length of the Nenjiang river is 1370 km, with a drainage area of 298,500 km^2. The Second Songhua river is located in the range of the east Longitude124 ° 30 ′ ~ 128 ° 45 ′ and the north latitude 40 ° 45 ′ ~ 45 ° 30 ′, with a drainage area of 73,400 km^2 and watercourse of 958 km. It flows through 26 cities/counties, such as Antu, Dunhua, Jilin, Changchun and Fuyu, etc. in Jilin province. The Second Songhua river flows into the Songhua river at Sanchahe. The river reaches form Sanchahe to Harbin is the upstream reach of the Songhua river. The length of the upstream watercourse is 240 km. Here the terrain is relatively flat, and the river slope is gentle. The landscapes along both sides of the watercourse are very similar, and there are wide alluvial land, grassland, and wetland in Songnen plain.

The population above river reach of Harbin in the Songhua river basin is 39.19 billion, and from which 21.18 billion are urban. The FDP of this region is 1970 billion. The proportion of the primary industry, secondary industry, and the tertiary industry is 13%, 51%, and 36% respectively. The actual irrigation area of farmland is 37.52 million mu (2.5 million hectares), of which the irrigation area of the paddy field is 17.5457 million mu (1.17 million hectares).

2. GENERAL SITUATION OF THE TWO RESERVOIRS

Nierji reservoir is located in the middle reach of the Nenjiang river, where a transition zone that the Nenjiang river flows from mountain area into the vast Songnen Plain. The catchment area above the reservoir is 66,400 km^2, which accounts for 22.25% of the drainage area of Nenjiang river. This is a large key project for flood control, water supply for livelihood and industrial and agricultural purposes, and with functions of power generation, improving shipping conditions downstream of the river and the water ecological environment. The average annual runoff at the dam site is 10.478 billion m^3, which accounts for 47.39% of the total average annual runoff in Nenjiang river basin.

Fengman reservoir is located in Fengman gorge, Jilin province, where the Second Songhua river mainstream flows through from. The drainage area above the dam site is 42500 km^2, which is 57.9% of the total drainage area of the Second Songhua river. This is a large key project mainly for power generation, and with functions of flood control, water supplying for urban people livelihood and agricultural purpose, and environment needs. The average flow at the dam site is 13.534 billion m^3, which is 82.89% of the total average annual runoff in the Second Songhua river.

3. CALCULATING METHOD

3.1 The analyzing method of wetness-dryness encountering

In this study, two-dimensional joint distribution models of Copula function was used to analyze the wetness-dryness encountering of the two reservoirs. At present, four kinds of Archimedean Copula Functions are often used in hydrology to analysis wetness-dryness encountering. Those functions are shown in the Table 1. where τ is the Kendall coefficient, which reflects the nonlinear correlation between two-dimensional variables. When τ is known, the parameter θ can be derived by the relationship between the τ and θ. The τ can be calculated by the following formula:

$$\tau = \frac{1}{c_n^2} \sum_{i<j} sgn\left[(x_i - x_j)(y_i - y_j)\right]$$

where

$$sgn\left[(x_i - x_j)(y_i - y_j)\right] = \begin{cases} 1, f\ (x_i - x_j)(y_i - y_j) > 0 \\ 0, f\ (x_i - x_j)(y_i - y_j) = 0 \\ -1, f\ (x_i - x_j)(y_i - y_j) < 0 \end{cases}$$

Table 1 : Four copula functions are commonly used in hydrology.

Copula functions	$c_\theta(u,v)$	parameter value	Relationship between τ and θ
Clayton	$(u^{-\theta} + v^{-\theta} - 1)^{-1/\theta}$	$\theta > 0$	$\tau = \frac{\theta}{\theta + 2}$
Gumbel-Hougaard	$\exp[-((-\ln u)^\theta + (-\ln v)^\theta)^{1/\theta}]$	$\theta \geq 0$	$\tau = 1 - \frac{1}{\theta}$
Frank	$-\frac{1}{\theta}\ln[\frac{(e^{-\theta u} - 1)(e^{-\theta v} - 1)}{(e^{-\theta u} - 1)}]$	$\theta > 0$	$\tau = 1 - \frac{4}{\theta}\left[-\frac{1}{\theta}\int_\theta^0 \frac{t}{\exp(t) - 1} dt - 1\right]$

Ali-Mikhail-Haq	$uv/[1-\theta(1-u)(1-v)]$	$-1 \leq \theta > 1$	$\tau = \left(1-\frac{2}{3\theta}\right)-\frac{2}{3}\left(1-\frac{1}{\theta}\right)^2 \ln(1-\theta)$

3.2 Reservoir dispatching methods

3.2.1 *The conventional operation method*

The water resource balance calculation for establishing a conventional operation method is based on the water balance of reservoirs, watercourses or areas. The water resources calculation includes the water supply and demand balance in a calculation unite and in the process of water supply and discharge. The system generalization includes determination of calculation units, selection of important water conservancy projects, setting off main nodes or sections, identification of available water sources, classification of water users along the river, etc. The analysis of water supply and demand is based on the four-level water resources division, taking zonal and large reservoirs as a calculation unit. The large reservoir is considered as single nodes in water resources regulation calculation. The reservoir is operated according to the existing regulation diagram, and the water consumption inside and outside the river and the power generation of the reservoir is calculated as a whole. If the water demand cannot be met, the guide curve and drainage volume of the reservoir regulation diagram could be manually modified according to the water consumers' demand in the downstream..

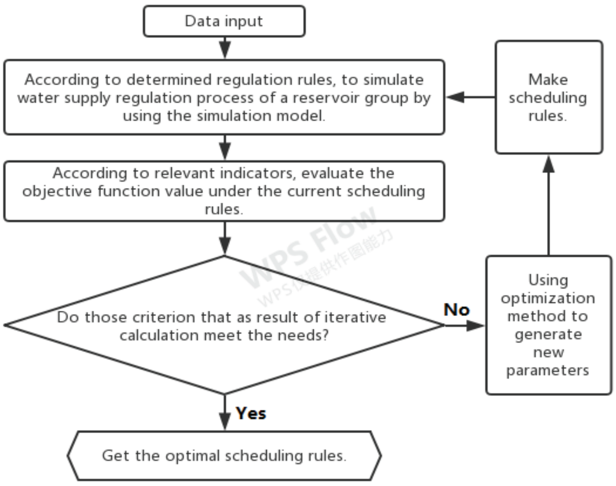


Figure 1 : The Simulation -- optimization framework for determining the joint operation rules of a reservoir group

3.2.2 *The simulation-optimization method*

The simulation-optimization method has the advantages of simulation and optimization. The optimal solution can be found by the intelligent computer evolutionary algorithm. This method helps to reduce the amount of manual calculation, and it conduces to find an optimal solution or approximate optimal solution. The simulation-optimization method is particularly suitable for solving the complex problem of reservoir group joint operation. The optimal scheduling steps of simulation-optimization mode for reservoir group regulation are shown in Figure 1.

(1) In a feasible domain, a set of scheduling rules is selected randomly as the initial scheduling rules;

(2) According to the initial scheduling rules, the joint operation process of reservoir group is simulated, and the relevant evaluation indexes are calculated;

(3) Convert the relevant evaluation index from step (2) into the fitness value of the heuristic algorithm.

(4) Depend on the fitness value that corresponds to different scheduling rules, new scheduling rules can be generated by the heuristic algorithm. Take the newly generated scheduling rules to step (2) for reprocessing, a set of satisfactory scheduling rules can be generated.

The simulation-optimization method takes the basic operating rule curves of the regulation diagram as a decision variable, the feasible solution can be evaluated by the result of the reservoir simulation operation. Afterward the position of the scheduling line can be adjusted by the intelligent algorithm until a satisfactory regulation diagram is obtained. Although it is difficult to guarantee that the solution obtained is optima in strict terms. In general, the regulation diagram is acceptable for the decision-maker.

4. ANALYSIS ON RUNOFF ENCOUNTERING

By using the Clayton copula function, the joint distribution model is established. Through the natural runoff process of two reservoirs, the parameters τ and θ in the model can be calculated. The value of τ and θ were τ= 0.104 and θ= 0.233. The fitting effect of the two-dimensional theoretical distribution and the empirical distribution of Clayton copula is shown in Figure 2. The correlation coefficient of the two functions is 0.983. That means that the Clayton copulas can fit the annual runoff joint distribution of the two stations very well.

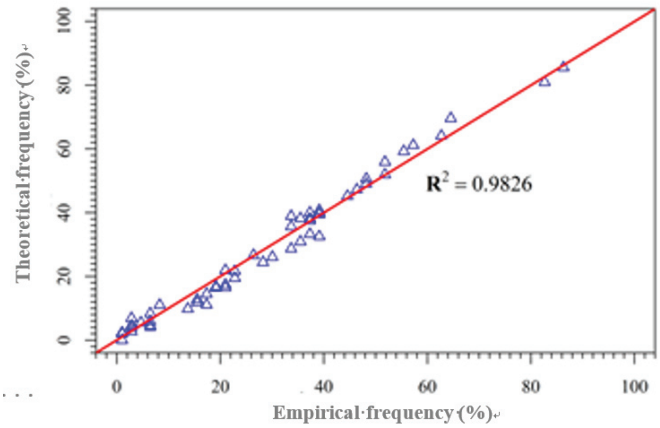


Figure 2 : Fitting effect chart of the two-dimensional joint distribution function of annual runoff of the two reservoirs.

Based on the above two-dimensional joint distribution model, the runoffs encountering high flow and low flow of the two reservoirs was studied. Let x (the Nierji reservoir) and Y (the Fengman reservoir) be two runoff events, and x_{pf}, y_{pf} and x_{pk}, y_{pk} with flow frequency of 37.5% and 62.5% respectively, then there are 9 types of runoff encountering between X and y.

high- high flow type: $p_1 = p(X \geq x_{pf}, Y \geq y_{pf})$;

high- normal flow type: $p_2 = p(X \geq x_{pf}, y_{pf} \leq Y \leq y_{pk})$;

high -low flow type : $p_3 = p(X \geq x_{pf}, y \leq y_{pk})$;

normal-high flow type : $p_4 = p(x_{pf} \leq X \leq x_{pk}, Y \geq y_{pf},)$;

normal-normal flow type : $p_5 = p(x_{pf} \leq Y \leq x_{pk}, y_{pf} \leq Y \leq y_{pk})$;

normal-low flow type $p_6 = p(x_{pf} \leq Y \leq x_{pk}, Y \leq y_{pk})$;

low- high flow type : $p_7 = p(X \leq x_{pk}, Y \geq y_{pf})$;

low-normal flow type : $p_8 = p(X \leq x_{pk}, y_{pf} \leq Y \leq y_{pk})$;

low-low flow type : $p_9 = p(X \leq x_{pk}, Y \leq y_{pk})$;

The above nine types can be divided into two types: high and low flows synchronous and high and low flows asynchronous. Among them, there are three types of high and low flows synchronous and six types of high and low flows asynchronous. The annual runoff encountering probability at the Nierji and Fengman hydrologic stations are shown in Table 2.

Table 2 : The annual runoff encountering probability at the Nierji and Fengman hydrology stations.

Time	high and low flows synchronous %				high and low flows asynchronous %						
	HH	NN	LL	Total	HN	HL	NH	NL	LH	LN	Total
Whole year	16.89	6.42	15.92	39.22	8.81	11.81	8.81	9.78	11.81	9.78	60.78

*H = high flow, L = Low flow and N = normal flow in the paper.

When the two reservoirs are in high flow or normal flow, the reservoirs can meet the downstream water demand by using alone. In this case, it is not necessary to carry out joint reservoir operations. The joint use of the reservoir is very necessary under the following situation: HH, HN, NH, NN, the total odds of this case is 40.92%.

When one of the two reservoirs is low flow and the other is not, the water demand along the river channel will increase. It is difficult to ensure the navigation flow of the mainstream of Songhua river above Harbin river reach. Especially in the case of continuous low flow, it is necessary to carry out the joint operation of the two reservoirs. Since both reservoirs are multi-year regulating reservoirs with a strong capacity of water regulation, the two are all qualified for joint operation. The conditions that are suitable for the combined use of the reservoirs and can give full play to its benefits are: high and low water flows, low and high water flows, normal and low water flows, low and normal water flows, and the total odds of these case is 43.16%.

5. THE JOINT OPERATION SCHEME

5.1 Total amount of water resources

The average annual water resources amount of Songhua river basin above Harbin section is 58.71 billion m^3, from which 34.842 billion m^3 is Nenjian rivers resources, the water resources amount of the second Songhua river basin is 18.322 billion m^3 and the water resources amount in the mainstream of the Songhua rive above Harbin section is 5.546 billion m^3.

Table 3 : Average annual water resources amount Unit: 100 million

Region	Provinces and regions	Amount of Surface water	Groundwater storage	amount of unrepeated water resources	Amount of water resources
The Nenjiang river	Heilongjiang	66.38	64.67	41.48	107.86
	Inner Mongolia	204.09	47.43	9.44	213.53
	Jilin	4.07	25.22	22.96	27.03
	Subtotal	274.53	137.33	73.89	348.42
The second Songhua river	Jilin	164.59	50.39	17.36	181.95
	Liaoning	1.25	0.35	0.02	1.27
	Subtotal	165.84	50.74	17.38	183.22
The mainstream of the Songhua river in section between Sanchahe and Harbin	Heilongjiang	27.01	16.31	9.03	36.04
	Jilin	13.21	7.74	6.21	19.42
	Subtotal	40.22	24.05	15.24	55.46
Amount in total		480.59	212.11	106.51	587.10

5.2 Water Requirement

5.2.1 *The water requirement outsides of the river*

The average annual water requirement amount of the Songhua river above Harbin section is 30.047 billion m^3. from which, first is 17.672 billion m^3 the average annual water requirement from the Nenjiang river. Second 8.673 billion m^3 from the second Songhua river and third 3.703 billion m^3 from the mainstream of the Songhua river above Harbin section. The Average annual water requirement amount of the Songhua river is shown in Table 4.

Table 4 : Average annual water requirement of the Songhua river

Region	Provinces and regions	Water for life	Water for industry	Water for paddy field	Water for upland field	Water for sideline production	Water for maintain town environment	Average annual water requirement amount
The Nenjiang river	Inner Mongolia	3.03	4.82	15.75	12.66	3.66	0.16	40.07
	Jilin	1.8	1.88	25.2	11.74	3.25	0.05	43.92
	Heilongjiang	8.72	16.46	44.26	10.66	12.11	0.51	92.72
	subtotal	13.55	23.16	85.21	35.07	19.02	0.71	176.72
The second Songhua river	Jilin	13.47	23.53	40.29	6.58	1.55	0.96	86.37
	Liaoning	0.03	0.02	0.31	0	0	0	0.36
	subtotal	13.5	23.54	40.6	6.58	1.55	0.96	86.73

The mainstream river reach between Sanchahe to Harbin of the Songhua river	Jilin	1.52	0.9	8.74	2.89	0.16	0.08	14.3
	Heilongjiang	4.61	1.66	13.72	1.56	1.02	0.16	22.73
	subtotal	6.13	2.56	22.46	4.45	1.18	0.24	37.03
Songhua river basin (above Harbin section)	Inner Mongolia	3.03	4.82	15.75	12.66	3.66	0.16	40.07
	Jilin	16.79	26.31	74.23	21.22	4.96	1.09	144.59
	Heilongjiang	13.33	18.12	57.98	12.22	13.13	0.67	115.45
	Liaoning	0.03	0.02	0.31	0	0	0	0.36
	Amount in total	33.18	49.27	148.27	46.1	21.75	1.92	300.47

*Unit: 100 million

5.2.2 *The minimum ecological flow demand in the river channel*

In this study, the control sections are selected based on The Songhua river Comprehensive Planning (2012-2030). They are Dalai section, Fuyu section, and Harbin section. In terms of water flow and water Quantity, the guaranteed rate of minimum ecological water demand in the river channel is set at 90%. The low flow period is from November to April, and the high flow period is from May to October. The minimum ecological water flow and quantity requirements are shown in Table 5.

Table 5 : The minimum ecological water flow and quantity requirement at the control sections.

River system	Name of sections	minimum ecological water flow (m^3/s)	minimum ecological water quantity requirement (100 million m^3)	
			water quantity in low flow period	water quantity in high flow period
The Nenjiang river	Dalai	35	11.96	23.93
The second Songhua river	Fuyu	100	15.64	15.9
The mainstream of the Songhua river	Harbin	250	39.1	52.91

5.2.3 *The requirements of flow for shipping purposes*

The general plan for the development of the main channel of the Songhua river is: improving navigation capacity in some sections of the river course by reconstructing the river courses and channelizing the waterway. It is planned to reconstruct 8 sections of the river including Laozhou, Dadingzishan, Hongtai, Tonghe, Yilan, Minzhu and Yuelai. The Planned reconstruction channel mileage is 597 km, and planned navigable flow at Harbin section (from May to October, P = 90%) is 550m^3 / s according to The Songhua river Comprehensive Planning (2012-2030).

5.3 The operation schemes

To meet the water requirement both of the watercourse and along the watercourse. Both water supply dispatch and power generation are targeted to be handled from inside and outside of the river.

To meet the water demand in the watercourse and out the watercourse, based on the water supply, power generation, and water supply objectives of Nierji and Fengman reservoirs, the conventional operation method and the simulation optimization method are need to be used.

5.3.1 *Conventional operation method*

According to the operation analysis with the renewed dispatching guiding diagram of Fengman reservoir (as shown in Figure 3) and the initial dispatching guiding diagram of Nierji reservoir (as shown in Figure 4), the results show that the water demand meets the requirements, but the shipping flow does not fully meet. That is to say, the ecological flow of each section of the Nenjiang river and the mainstream of the Songhua river in Harbin meets the requirements, but the guaranteed rate of the water flow for shipping in Harbin section is 81%.

If both reservoirs use the renewed dispatching guiding diagram to regulate water resources (as shown in Figures 4 and 6). The analysis results of water supply and demand show that the water demand in each section of the river meets the requirements, but the shipping flow can not be met fully. In other words, the ecological flow of the Nenjiang river, the second Songhua river and the mainstream of the Songhua river in Harbin section can be satisfied, but the guaranteed rate of the shipping flow in Harbin section is 90%.

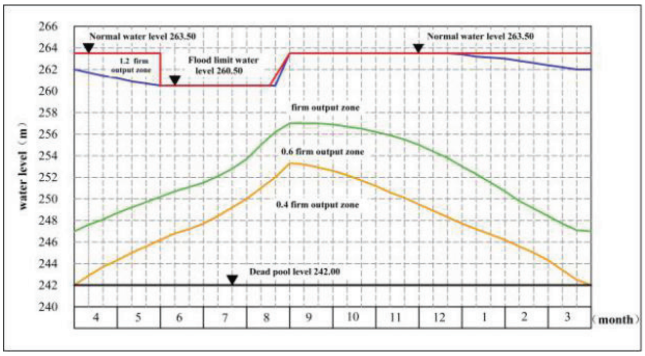


Figure 3 : The renewed dispatching guiding diagram of Fengman reservoir

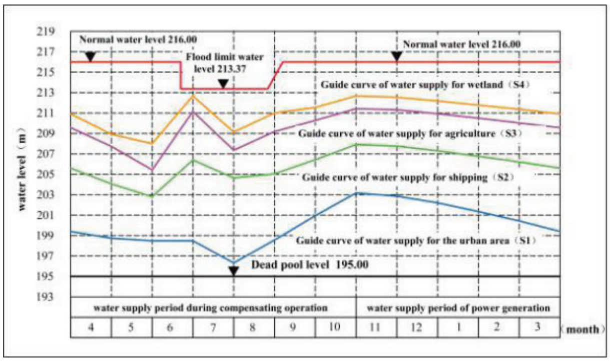


Figure 4 : the initial dispatching guiding diagram of the Nierji reservoir, that developed in the preliminary design stage

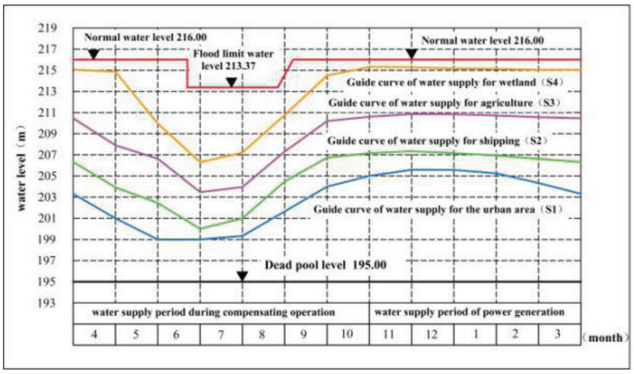


Figure 5 : The renewed dispatching guiding diagram of Nierji reservoir

5.3.2 *The simulation-optimization operation methods*

To seek the best goal of each scheme, four scheduling schemes are proposed by the simulation optimization method, as shown in Table 6.

Table 6 : Four scheduling schemes

Scheduling Schemes	Content of the scheme
Scheme one	The power generation of Fengman and Nierji reservoirs are as much as possible. The water supply inside and outside the river are all met the needs.
Scheme two	The power generation of Fengman reservoir achieves its maximum capacity, and the water supply for power generation of Nierji reservoir is fully satisfied. The ecological and shipping water flow in the watercourse meet the needs, and the water supply outside the watercourse is meet the needs.
Scheme three	The power generation of Nierji reservoir achieves its maximum capacity, and the water supply for power generation of Fengman reservoir is fully satisfied. The ecological and shipping water flow inside the watercourse not meet the needs, and water supply outside the watercourse is meet the needs.
Scheme four	The power generation of both Nierji reservoir and Fengman reservoirs achieve their maximum capacities, but water supply inside and outside the river are not meet the needs.

The four optimal operation schemes of the two reservoirs are shown in Table 7 and Table 8. For the scheme one, the water demand meets the requirements both inside and outside the river. The average annual power generation of Fengman reservoir is about 1763 million KW · h, and the average annual power generation of Nierji reservoir is 564 million KW · H; For the scheme two, the average annual power generation of Fengman reservoir is increased by 17 million KW·h. and the Nierji reservoir reduces power generation by 01 million KW · H. The water demand inside the watercourse is not on the required level. For the scheme three, the average annual power generation of Fengman reservoir is reduced by 4 million KW·h. and the Nierji reservoir increases power generation by 1 million KW·H. The water demand inside the watercourse does not meet the requirement too. For the scheme four, the average annual power generation of Fengman reservoir is increased by 17 million KW·h. and the Nierji reservoir increases power generation by 8 million KW·H. The water demands inside and outside the watercourse both does not meet the requirements.

It can be seen from the calculation results of the four schemes that the increasing power generation at the cost of water supply is not able to meet the demands inside and/or outside however the watercourse is not significant. Therefore, scheme 1 is recommended as the optimal scheduling scheme. The scheme can increase 395 million m^3 of off-channel water supply and reduce the damage depth when water demand beyond the guaranteed rate. The scheduling diagrams of scheme one are generated by the simulation-optimization method. See Fig. 7 and Fig. 8.

Table 7 : Multi-year average operation index of the Fengman reservoir

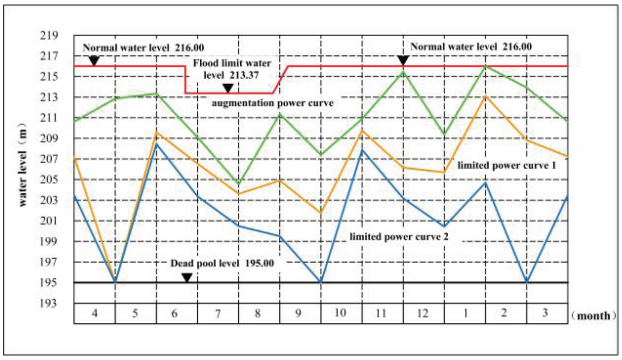
Scheme	Reservoir inflow	Local inflow	Power flow	Surplus water	Discharge flow	Evaporation and infiltration loss	Operating level	Energy output
Scheme one	118.0	43.5	117.1	0	117.1	0.9	257.7	17.63
Scheme two		43.7	117.0	0	117.0	1.0	258.4	17.80
Scheme three		43.9	117.1	0	117.1	0.9	257.5	17.59
Scheme four		42.2	116.9	0	116.9	1.1	261.1	18.33

*Unit 10^8 m^3;m;10^8 KW·h

Table 8 : Multi-year average operation index of the Nierji reservoir

Scheme	Reservoir inflow	Water supply	Local inflow	Power flow	Surplus water	Discharge flow	Evaporation and infiltration loss	Operating level	Energy output
Scheme one	103.0	2.6	35.5	93.3	5.2	98.5	1.9	213.1	5.64
Scheme two		2.6	36.0	93.3	5.2	98.5	1.8	213.0	5.63
Scheme three		2.6	35.0	93.3	5.2	98.5	1.9	213.0	5.65
Scheme four		2.6	34.5	93.2	5.2	98.4	1.9	213.5	5.72

*Unit 10^8 m^3;m;10^8 KW·h



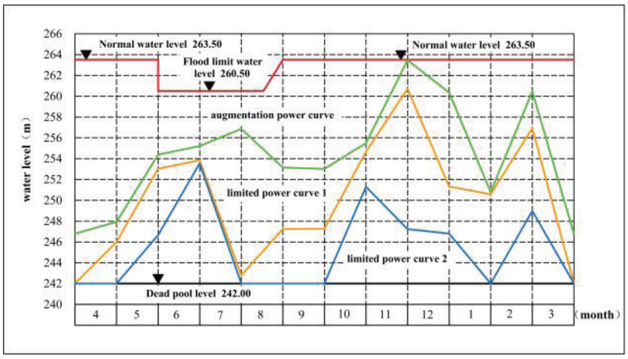


Figure 6 : The optimized scheduling schemes of Fengman reservoir

Figure 7 : The optimized scheduling schemes of Nierji reservoir

6. CONCLUSIONS

The asynchronous frequency of the high flow period and low flow period of the two reservoirs is obviously higher than the synchronous frequency. This suggests that the annual periodic fluctuation of water flow is generally conducive to the joint operation of the reservoirs. When reservoirs joint operation with little significance (in the case of HH, HN, NH, and NN), the occurrence frequency is 40.92%. When reservoirs joint operation with great significance (in the case of HL, LH, NL, and LN), the occurrence frequency is 43.16%. The frequency of adverse to joint scheduling (in the case of the two reservoirs both in low flow) is 15.92%.

(2)The reservoir can not meet the water demand inside and outside the river by using the conventional dispatch scheme. By changing the regulation rules of Fengman reservoir and modulating the regulation rules of Nierji reservoir, the water demand inside and outside the river is able to meet the requirements.

(3)According to the calculation results of the simulation-optimization method, there are limited effects on increasing power generation, at the cost of water demand inside and outside the river the requirements are not met. Therefore, a scheduling scheme both meet the water demand inside and outside the river is recommended in this study. By using the scheduling scheme which is developed from the simulation-optimization method not only meets, the basic ecological, industrial and livelihood water demands outside the river in 2030, but also can increase the water supply by 395 million m^3 and reduce the damage the depth when water demand beyond the guaranteed rate.