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Sharing Water: Multi-Purpose of Reservoirs and Innovations

Dynamic coordination and control technology of the operating water level during flood season and its application in Xiluodu-Xiangjiaba - Three Gorges cascade reservoirs

Technologie de contrôle et de coordination dynamique du niveau d'eau pendant la saison des crues et son application sur les réservoirs en cascade de Xiluodu-Xiangjiaba et des Trois Gorges

Song Zhang[1*], *Ting* Hu[1], *Man* Zhou[1], *Xing'e* Hu[1]

[1]Operation and Administration Center for River Basin Hydro Complex, China Three Gorges Corporation, The Three Gorges Dam District, China

Abstract. To satisfy the increasing multi-objective scheduling requirements in flood season of the Xiluodu-Xiangjiaba - Three Gorges multi-function cascade reservoir system located in the lower reaches of Jinsha River and the upper reaches of Yangze River, and simultaneously solve the key technical problems of the resource utilization of floods by joint optimal scheduling of cascade reservoirs. This paper explorers and presents a scientific solution of joint dynamic control of the reservoirs' operating water level during flood season that suitable for the flood resources comprehensive utilization of the large-scale cascade reservoirs in the Yangtze River Basin. Specifically, the solution is composed of a dynamic control mode for the operating water level of the cascade reservoir during the main flood season (ie, forecast and pre-impounding, grade regulating, and staged discharge control), a phased release theory of the flood control capacity at the end of flood season and a risk analysis model for the decision of the cascade reservoir scheduling. These new technical solutions were successfully applied to the 2016-2019 scheduling practices of the Xiluodu-Xiangjiaba - Three Gorges cascade reservoir system, the world's largest multi-function multi-reservoir system that operation and management by the China Three Gorges Corporation (CTG). The comprehensive benefits of the cascade reservoir in flood control, power generation, shipping, ecology, and the water supply during reservoir impounding and falling periods have been significantly improved, including greatly reducing downstream flood

* Corresponding author: zhang_song2@ctg.com.cn

pressure, increasing power generation and water supply, improving navigation condition, promoting fish reproduction. Meanwhile, it also verifies that these new technologies are scientific, practical, universal and have a broad application prospect.

Résumé. Pour satisfaire les exigences croissantes de programmation multi-objectifs pendant la saison des crues du système de réservoirs en cascade multifonction Xiluodu-Xiangjiaba - Trois Gorges situé dans le cours inférieur du fleuve Jinsha et le cours supérieur du fleuve Yangze, et pour résoudre simultanément les principaux problèmes techniques de l'utilisation des ressources des crues par une programmation optimale conjointe des réservoirs en cascade, cet article explore et présente une solution de contrôle dynamique du niveau des réservoirs pendant la saison des crues qui permet la mobilisation complète des ressources des crues à l'échelle globale des réservoirs en cascade dans le bassin du fleuve Yangtze. Plus précisément, la solution est composée d'un mode de contrôle dynamique du niveau d'eau des réservoirs en cascade pendant la saison des crues, d'un modèle de libération progressive de la capacité de contrôle des crues à la fin de la saison des crues et d'un modèle d'analyse des risques pour la décision de la programmation des réservoirs en cascade. Ces nouvelles solutions techniques ont été appliquées avec succès aux pratiques 2016-2019 du système des réservoirs en cascade Xiluodu-Xiangjiaba - Trois Gorges, le plus grand système multi-réservoirs multifonctionnel au monde exploité et géré par la China Three Gorges Corporation (CTG). Les avantages des réservoirs en cascade dans le contrôle des crues, la production d'électricité, la navigation, l'écologie et l'approvisionnement en eau pendant les périodes de retenue et de chute du réservoir ont été considérablement améliorés, notamment en réduisant considérablement la pression des crues en aval, en augmentant la production d'électricité et l'approvisionnement en eau, en améliorant les conditions de navigation, en favorisant la reproduction des poissons. Parallèlement, cet article vérifie également que ces nouvelles technologies sont scientifiques, pratiques, universelles et ont une large perspective d'application.

1 Introduction

The Xiluodu-Xiangjiaba - Three Gorges-Gezhouba cascade hydropower stations, developed by China Three Gorges Corporation and put into operation on the main stream of Yangtze River, is the largest watershed cascade hydropower system around the world. Among the system, Xiangjiaba and Xiluodu, located at the lower reaches of Jinsha River, are the key power generation spot of the West-East Electricity Transmission Project in China and they have been put into operation since 2012 and 2013, respectively. The Three Gorges Project (TGP) is the backbone controlling project for harnessing and developing the Yangtze River. The TGP entered into the cofferdam power generation period after its first generating unit was put into operation in 2003 and has began the experimental storage period of 175m since 2008. The Gezhouba hydropower station that 38km downstream away of the TGP has been constructed and put into operation since 1981. It has become the shipping and counter regulating reservoir for the TGP. Over the past few decades, after the construction and operation of a large number of controlling hydropower stations with large reservoir capacity and good regulation performance in the main and tributaries of the Yangtze River, the unified dispatching pattern of large-scale hydropower stations in the upper and middle reaches of the Yangtze River has started to form. In recent years, by means of exploitation research and practical applications of the unified optimized dispatching for the giant cascade hydropower stations, China Three Gorges Corporation has fully conducted the initial comprehensive organization and implementation of the Xiluodu-Xiangjiaba - Three Gorges-Gezhouba cascade hydropower stations for combined flood control, impounding, waning and ecological dispatching in 2017. However, from the layer of technology, the unified dispatching of these four hydropower stations are merely the simple combination for the subsystem optimization of the Xiluodu-Xiangjiaba and the Three Gorges-Gezhouba cascade hydropower systems. The dispatching calculation method for each single hydropower station from upstream to downstream was still used within the subsystems, which can never be called as the true “unified optimization dispatching”. The purpose of this research is to solve the above problem and answer the question of how to deal with the relationship of flood control, power generation, shipping and water resources utilization in the joint multiobjective dispatching, continue to progress and further enhance the general economic operation level of cascade hydropower system.

2 Overview of the Cascade Hydropower System

The Jinsha River Hydropower Base ranks the first place at the “Planning of Thirteen Hydropower Bases in China”, which is the largest hydropower base in China, as well as the main force of the West-East Electricity Transmission Project. Wudongde, Baihetan, Xiluodu and Xiangjiaba are the four world-class giant cascade hydropower stations planned at the lower reaches of Jinsha River. The total installed capacity of the four stations is 4.21 million kW, which is the equivalent of two of the TGP, and its designed annual power generation is about 184.3 billion kW·h. The Xiluodu and Xiangjiaba hydropower stations are the latter two level cascade hydropower stations, have been constructed and put into operation separately in 2012 and 2013. The Xiluodu hydropower station locates at the main stream of Jinsha River flows through Leibo County of Sichuan Province and Yongshan County of Yunnan Province. The upper part connects the flow from the Baihetan and the latter part is with the Xiangjiaba. The main purpose of the hydropower station is to generate power and control flood. In addition, there are comprehensive utilization benefits such as sediment blocking, improving navigation conditions in reservoir area and lower reaches. The Xiangjiaba hydropower station is the lowest one of the cascade hydropower stations development on the main stream of Jinsha River. The left bank of the dam locates in Yibin County of Sichuan Province and the right bank Shuifu County of Yunnan Province. The upper part of the dam is 156.6km away from the Xiluodu river course and the latter part 33km away from Yibin City. Also, it is 700km away from Yichang. The hydropower station mainly generates electricity, improves shipping conditions, takes flood control and irrigation into account, and has the function of reverse regulation of Xiluodu hydropower station. The TGP locates in Sandouping, Yichang, Hubei Province and about 44km far away from the Yichang station on the lower reach. It is the essential key project of harnessing and developing the Yangtze River and also is of comprehensive benefits such as flood control, power generation, shipping and water resources utilization. The Gezhouba hydropower station locates at the lower reach about 38km away from the Three Gorges, whose dispatching mission is to reverse-regulate the unsteady flow process discharged from the daily regulation of the TGP to give full play to the power generation benefits under the conditions of ensuring the safety and unimpeded navigation. The geographical location of the study cascade hydropower stations is shown as Fig. 1. The designed characteristic parameters of each hydropower station are listed in Table 1.

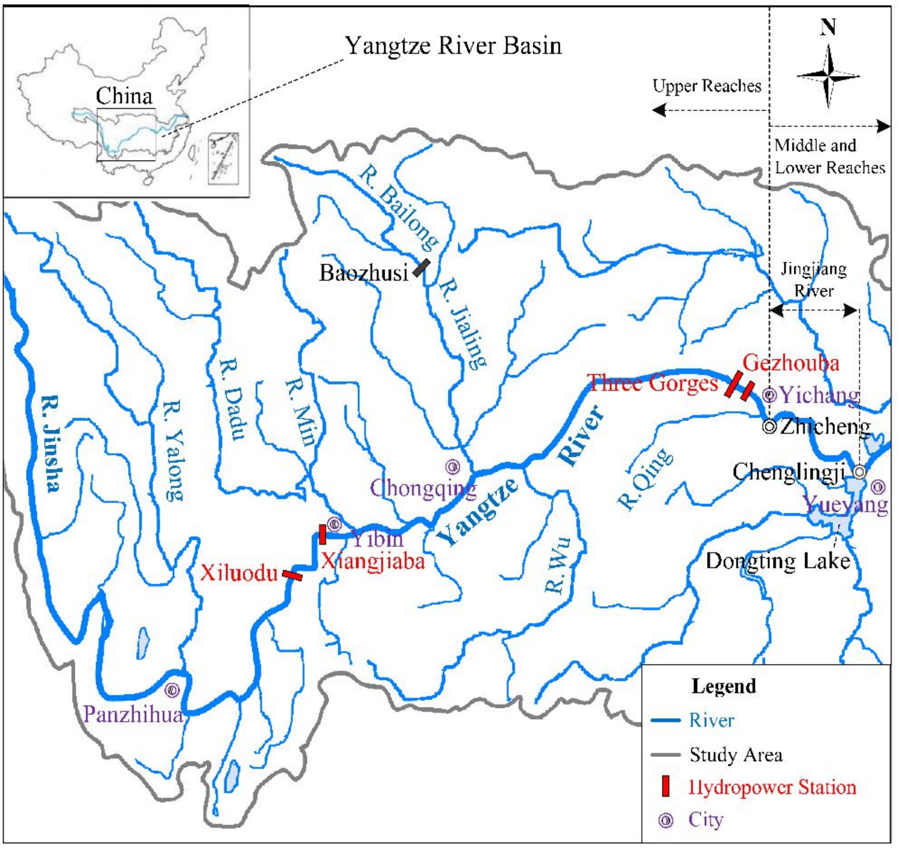

Fig. 1. Sketch map of the Location of each hydropower station.

Table 1. Designed characteristic parameters of the cascade system.

	Xiluodu	Xiangjiaba	Three Gorges	Gezhouba	Cascade system
check flood level/m	609.67	381.86	180.4	67	
design flood level/m	604.23	380	175	66	
flood control level/m	560	370	145	/	
normal pool level/m	600	380	175	66	
dead water level/m	540	370	/	63	
flood control capacity/10^8m^3	46.51	9.03	221.5	/	277.04
regulated storage capacity/10^8m^3	64.62	9.03	165	/	238.65
regulation performance	incomplete year	season	season	Day	
installed capacity/MW	13860	6400	22500	2735	45495
guaranteed output/MW	3395	2009	4990	768	11162
mean annual energy production /(10^8kW·h)	571.2	307.47	882	157	1917.67

3 Optimization Model

3.1 Objective Function

For the Xiluodu-Xiangjiaba-Three Gorges-Gezhouba cascade hydropower stations, the optimized objective function is to maximize the total power generation or the total power benefit of the system during the dispatching period, written as Eq. (1), Eq. (2):

$$\mathrm{Max}\,E=\sum_{t=1}^{T}\sum_{i=1}^{M}P_{i,t} \tag{1}$$

$$\mathrm{Max}\,B=\sum_{t=1}^{T}\sum_{i=1}^{M}c_{i,t}\times P_{i,t} \tag{2}$$

$$P_{i,t}=N_{i,t}\times\Delta t \tag{3}$$

$$N_{i,t}=K_{i,t}\times Q_{i,t}^{gen}\times H_{i,t}^{net} \tag{4}$$

where *E*, *B* = the total power generation and the total power benefit of the cascade hydropower system during the dispatching period, respectively, kW·h and billion yuan. *T* = the number of dispatching periods. *M* = the number of the hydropower stations (*M*=4). $P_{i,t}$ = the power generation of the station *i* in period *t*, kW·h. $N_{i,t}$ = the output of the station *i* in period *t*, kW. $K_{i,t}$ = the output coefficient of station *i* in period *t*. $Q_{i,t}^{gen}$ = the power discharge of the station *i* in period *t*, m^3/s. $H_{i,t}^{net}$ = the average net water head of the station *i* in period *t*, m. Δt = the hours in time unit. $c_{i,t}$ = the average power price in the grid, yuan/kW·h.

3.2 Constraint Conditions

The combined power generation calculation of the cascade hydropower stations includes runoff regulation calculation and hydraulic energy calculation.

(1) Water balance equation

$$V_{i,t}=V_{i,t-1}+\left(I_{i,t}-Q_{i,t}\right)\Delta t \tag{5}$$

where $V_{i,t-1}$ and $V_{i,t}$ = the reservoir capacity of the hydropower station i at the beginning of time period t and t+1, 108m3. and = are the inflow and outflow of the station i in period t, m3/s。

(2) Flow relation equation

$$I_{i,t}=\sum_{j\in\Omega_i}Q_{j,t-\tau(j)}+q_{i,t} \tag{6}$$

where $q_{i,t}$ = the interval inflow of station *i* in period *t*, m^3/s. Ω_i = the set of all direct upstream connective hydropower stations of the station *i*. $\tau(j)$ = the number of water flow propagation time periods from upstream hydropower station *j* to downstream hydropower station *i*.

(3) Discharge equation of spill flow

$$Q_{i,t} = Q_{i,t}^{gen} + Q_{i,t}^{spl} \tag{7}$$

where $Q_{i,t}^{spl}$ = the spill water flow of the station *i* in period *t*, m^3/s.

(4) Hydraulic equation

$$Z_{i,t}^{down} = \begin{cases} Z_1^{down}\left(Q_{i,t}\right) \\ Z_2^{down}\left(Q_{i,t}, Z_{i+1,t}\right) \end{cases} \tag{8}$$

where $Z_{i+1,t}$ = the water level of the hydropower station *i*+1. $Z_{i,t}^{down}$ = the tailwater level of the hydropower station *i*, m.

(5) Reservoir water level constrain

$$Z_{i,t}^{\min} \le Z_{i,t} \le Z_{i,t}^{\max} \tag{9}$$

$$| Z_{i,t} - Z_{i,t-1} | \le \Delta Z_{i,t} \tag{10}$$

where $Z_{i,t}^{\min}$ and $Z_{i,t}^{\max}$ = the minimum and maximum reservoir water level, m. $\Delta Z_{i,t}$ = the permissible daily variation of water level, m.

(6) Output constrain

$$N_{i,t}^{\min} \le N_{i,t} \le N_{i,t}^{\max} \tag{11}$$

where $N_{i,t}^{\min}$ and $N_{i,t}^{\max}$ = the minimum and maximum output of the hydropower station *i*, kW.

(7) Outflow constrain

$$Q_{i,t}^{\min} \le Q_{i,t} \le Q_{i,t}^{\max} \tag{12}$$

where $Q_{i,t}^{\min}$ and $Q_{i,t}^{\max}$ = the minimum and maximum outflow of the hydropower station *i* in period *t*.

(8) Reservoir water level boundary constraint

$$Z_{i,0} = Z_i^{begin}, Z_{i,T} = Z_i^{end} \tag{13}$$

where Z_i^{begin} and Z_i^{end} = the beginning water level and the target water level, m.

(9) Water head calculation formula

$$H_{i,t} = \left(Z_{i,t-1} + Z_{i,t}\right)/2 - Z_{i,t}^{down} \tag{14}$$

$$H_{i,t}^{net} = H_{i,t} - H_{i,t}^{loss} \tag{15}$$

(10) Comprehensive output coefficient calculation formula

$$K_{i,t} = f\left(H_{i,t}, Q_{i,t}^{gen}\right) \text{ 或 } f\left(H_{i,t}^{net}, Q_{i,t}^{gen}\right) \tag{16}$$

3.3 Solving Algorithm

An improved LSSDC-DDDP method was used to solve the model (see Fig. 2 and Fig. 3): (1) Large system decomposition coordination (LSSDC) method, using decomposition and coordination mechanism to decompose the optimization problem of cascade reservoir large system into a series of simple sub-optimization problems, so as to achieve the reduction and decoupling of complex problems. (2) Through the feasible domain decomposition mechanism of decision variables, discrete differential dynamic programming (DDDP) divides the huge solution space of the subsystem into many subspaces, realizing the change of computational complexity from exponential growth to linear growth.

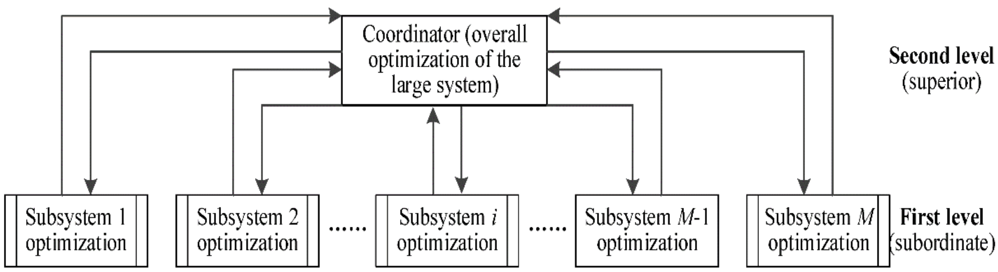

Fig. 2. Decomposition and Coordination Diagram of Large Scale Systems.

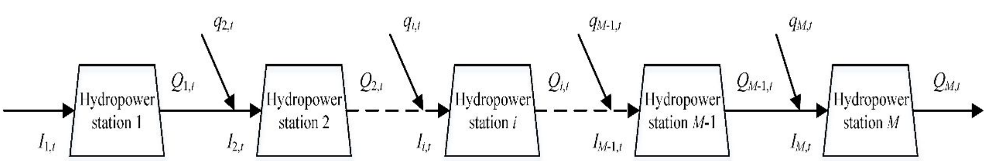

Fig. 3. Schematic Diagram of Cascade Reservoir Group System.

3.4 Constraint Handling

In most applications of the DDDP, the penalty function method has been the most popular approach in handling inequality and equality constraints. In this approach, a penalty term that is proportional to the constraint violation of a solution is added to the objective function to form the penalized function.

4 Model Application

4.1 Calculating Time Intervals

The dispatching time length for the optimization models is one year, calculating unit of which is about 10 days and 36 periods of time in general.

4.2 Inflow Setting

The inflow of the optimized dispatching model adopts the actual inflow data from 2015 to 2017 of cascade hydropower stations (basically includes the dispatching influence from reservoirs put into operation in the upper reaches of Yangtze River), see Table 2.

Table 2. The Actual Inflow of Xiluodu Hydropower Station and the Three Gorges from 2015 to 2017 (Unit: m3/s).

Month	Xiluodu			Three Gorges		
	2015	**2016**	**2017**	**2015**	**2016**	**2017**
1	2110	2390	2330	5780	6420	5310
2	1970	2040	2550	5350	5990	5670
3	2300	2270	2210	6330	7500	6850
4	2190	1860	2020	8860	10200	9550
5	2010	2330	2330	8850	13300	11800
6	*3470*	*5310*	*4650*	*16700*	*21000*	*18300*
7	*4900*	*8720*	*8500*	*19900*	*26800*	*21200*
8	*6180*	*6660*	*7990*	*17200*	*19000*	*19400*
9	*10800*	*8420*	*8240*	*23500*	*14500*	*22500*
10	5640	5790	5940	15900	13600	22200
11	2970	3860	3610	8400	10200	10100
12	1890	2290	2370	6570	6270	6870
Average annual flow	3870	4330	4400	11950	12900	13310
Year(10^8m^3)	**1224**	**1372**	**1391**	**3777**	**4086**	**4214**
Jun.-Sep.(10^8m^3)	664	767	773	2035	2149	2144
Frequency of year	**80%**	**53%**	**49%**	**91%**	**79%**	**68%**

4.3 Starting Water Level

Under different working conditions calculation of the optimized dispatching for cascade hydropower stations (control strategy of inflow plus water level of ten days), the starting dispatching water level of each reservoir at the beginning of the year is Table 3.

Table 3. Settings for the Inflow and the Starting Dispatching Water Level at the Beginning of the Year under Different Conditions.

Objective Function	Inflow	Starting Water Level
maxE or maxB	2015-2017	actual water level at the early of the year

4.4 Water Level Controling and the Minimum Outflow

Considering some uncontrollable factors such as the power grid regulation during the waning period, the flood control in flood season and the like, the upper limit of control water level of cascade hydropower stations in non-flood season is taken as the average water level from 2015 to 2017, and the upper limit is allowed to float in flood season according to the limit water level of flood season. Daily changing level for each hydropower station during the year are shown in Table 4. Average electricity charges for the Xiluodu, Xiangjiaba, the Three Gorges and Gezhouba hydropower station are separately 0.31, 0.3, 0.25 and 0.22 yuan/kW·h. The minimum draining flow of Xiluodu and Xiangjiaba is controlled within 1600m3/s. The minimum draining flow of the Three Gorges during the rainless period is 6000m3/s, and that during the storage period are 10000m3/s and 8000m3/s respectively during September and October.

Table 4. Constraints of the Daily Changing Level within each Cascade Hydropower Station during the Year (Unit: m).

<table>
<tr><th>Dispatching Period</th><th>Xiluodu</th><th>Xiangjiaba</th><th>Three Gorges</th><th>Gezhouba</th></tr>
<tr><td>Storage Period</td><td>Daily Rising Level under 3m
Daily Falling Level under 2m</td><td rowspan="2">Daily Changing Level within 4m</td><td>Daily Rising Level under 3m</td><td rowspan="2">The Maximum Daily Changing Level is 3m</td></tr>
<tr><td>Waning Period</td><td>Daily Changing Level within 2m</td><td>Daily Falling Level under 0.6m</td></tr>
</table>

5 Results Analysis and Conclusion

5.1 Optimized Power Generation

In order to analyze difference between calculation results of models for the maximizing power generation MaxE and the maximizing power generation benefit MaxB, two types of models have been adopted to conduct the optimized dispatching calculation of cascade hydropower station combined generation concerning the actual inflow in 2017, the optimized dispatching process of these two models could be referred to Fig. 4. From Fig. 4, we can see that calculation results to these two models are completely the same. The reason is that as for the Xiluodu-Xiangjiaba-the Three Gorges-Gezhouba cascade hydropower station, the price of electricity on the grid in power production decreases in turn from top to bottom and "the generation efficiency" also decreases accordingly that the unit price benefit and generation efficiency of power station are of the same significance and in the same order so that the optimal decision-making process of the two optimization models under the current electricity price situation is basically equivalent.

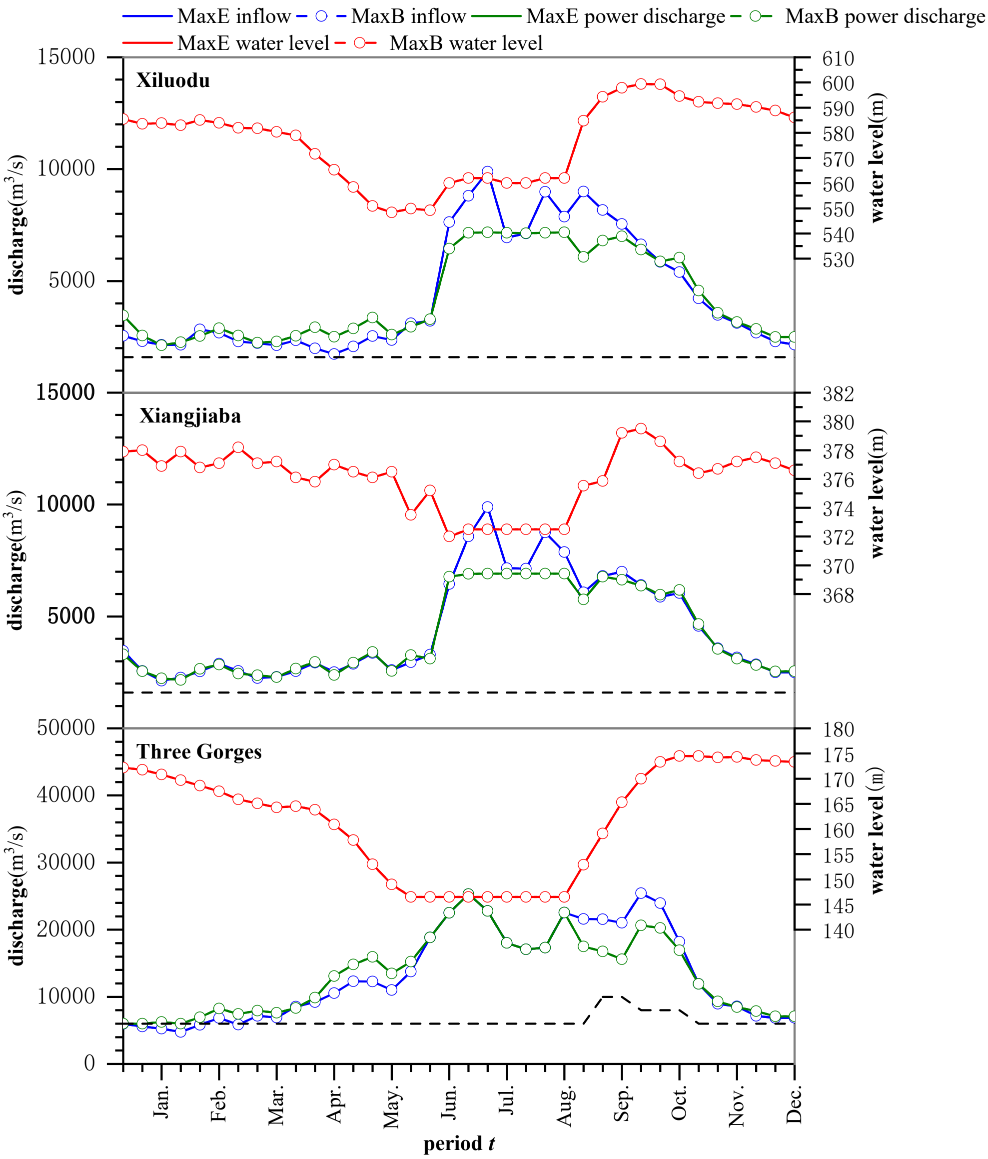

Fig. 4. Comparison of the Optimized Dispatching Processes of MaxE and MaxB Models in 2017.

Furthermore, as for the actual inflow during 2015 to 2017 and calculate the optimized dispatching calculation of cascade hydropower stations according to the MaxE model, statistical results of the optimized generation capacity of the cascade hydropower station and each hydropower station are listed in Table 5, from Table 5 we can see:

(1) With the full installation of Xiluodu and Xiangjiaba cascade hydropower station was completed in 2014, the optimized power generation of cascade hydropower station during 2015 to 2017 is more than the actual power generation on average. In terms of scheduling process diagram, the actual scheduling process is basically consistent with the model optimization process.

(2) The optimized power generation of the Three Gorges is lower than the actual power generation on average. The main reason of which is that the ten days water level control scheme is adopted in the calculation is conservative. In flood season, the operating water

level is controlled within the allowable range of flood limit water level. In actual years, medium and small floods are dispatched, and flood resources are utilized to varying degrees.

Table 5. Statistical Results for the Optimized Power Generation from the MaxE (MaxB) Model in Different Years (Unit: 100 million kW·h).

year	optimized generation power								actual annual output	
	Xiluodu	Xiang jiaba	Three Gorges	Gezho uba	cascade system				cascade system	Three Gorges
					year	flood season	impounding periods	drought season		
2015	574	311	863	171	1919	638	419	862	1909	870
2016	631	344	931	174	2080	730	359	991	2061	935
2017	651	353	966	183	2153	736	461	956	2109	976

5.2 Conclusion

(1) As for the Xiluodu-Xiangjiaba-the Three Gorges-Gezhouba cascade hydropower station, due to the price of power generation tends to be decreasing from upstream hydropower stations to downstream hydropower stations, the "power generation efficiency" tends to be falling and generation efficiency of power station are of the same significance and in the same order so that the optimal decision-making process of the two optimization models under the current electricity price situation is basically equivalent.

(2) Adopt the established optimized dispatching model, 1 billion kW·h, 1.9 billion kW·h and 4.4 billion kW·h have been able to be augmented separately in 2015, 2016 and 2017.

(3) In the optimized model application research, the calculation unit is ten days. While the flood season dispatching setting of the cascade hydropower station includes the control of water level, there are much more uncertainty within the flood season inflow process, flood control situation upstream and downstream of the cascade hydropower station and flood control scheduling strategies. For a further step, flood dispatching data in actual flood season of recent years is needed to draw up unified regulations for flood season to calculate the combined power generation of cascade reservoirs in typical annual flood season and optimize the augmented dispatching power generation.

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