

Research on Joint Impoundment Dispatching Model for Cascade Reservoir

Xuemin Wang · Jianzhong Zhou · Shuo Ouyang · Chunlong Li

Received: 31 August 2013 / Accepted: 10 October 2014 /
Published online: 5 November 2014
© Springer Science+Business Media Dordrecht 2014

Abstract As more and more large reservoirs been built, competitive impoundment problem of cascade reservoirs becomes a serious matter in the flood recession. Combining the impounding principle with K value discriminant method, a novel impounding strategy of cascade reservoirs is proposed for determining the impoundment sequence and opportunity of each reservoir in premise of the flood control safety. At the same time, the impounding water level control lines of different frequency runoff are drawn according to the flood routing simulation, and then the Impounding Operation Chart (IOC) is manufactured. On this basis, a model of impoundment dispatching in advance based on the IOC is developed. Then the proposed method can be obviously accelerated by using Self-adaptive Electromagnetism-like Mechanism algorithm (SEM). Compared with the original design of impounding scheme, the result indicates that the optimal scheme can improve the fill storage ratio of cascade reservoirs and ease the contradiction between supply and demand of water resources as well with guaranteeing the safety of flood control in the watershed.

Keywords Competitive impoundment · Impoundment sequence and opportunity · Flood control · Impoundment dispatching

1 Introduction

Impoundment scheduling problem (ISP) in the flood recession is important to improve the reservoir comprehensive benefit. Since more and more reservoirs have been built, it is of more difficulty to fill reservoir storage at the end of the flood season according to the original design, which would lead to the decrease of Fill Storage Ratio (FSR) and power generation efficiency. A new reasonable impounding scheme for reservoirs needs to be set for hydrological environment of various watershed. For example, the total capacity of reservoirs in the upstream of Yangtze River, the built reservoirs and being built reservoirs, is more than 80 billion m^3 , and regulating storage is more 40 billion m^3 . With the Jinsha River cascade and the other large reservoirs in the upper reaches, the difficulty of Impoundment of the Three Gorges Reservoir

X. Wang · J. Zhou (✉) · S. Ouyang · C. Li
School of Hydropower and Information Engineering, Hubei Key Laboratory of Digital Valley Science and Technology, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
e-mail: jz.zhou@hust.edu.cn

(TGR) is increasing. In dry years, the water level of TGR is hard to reach the normal water level in the terminal period according to the original designed impounding scheme, at the same time the power generation efficiency of TGR will decrease by the same discharge because of the lower water level. On the other hand, it will raise the risk of river flood control when reservoir impounds ahead of schedule. Therefore, it is urgently necessary to study on the joint impoundment operation of four reservoirs in the Jinsha River and the TGR for establishing a unified impounding scheduling scheme. The scheme will improve FSR of each reservoir, and eases the contradiction between supply and demand of water resources in the premise of flood safety.

For solving ISP of single reservoir or multi-reservoir, the rainfall-runoff forecasting method (Zhou et al. 2014), flood season segmentation (Liu et al. 2010), dynamic control of flood limited water level (Chen et al. 2013), operation mode of flood control (Yazdi and Neyshabouri 2012), impounding time (Peng et al. 2003) have already been proposed and various success have been achieved. Babel et al. (2005) have presented a interactive integrated water allocation model to optimize allocation of limited water to different user sectors. Li et al. (2006) found that the comprehensive benefit of TGR will be the biggest with impounding water ahead of schedule at the end of flood season. Yun and Singh (2008) proposed multiple duration limited water level and dynamic limited water level for flood control considering the water supply of reservoir. Allowing for inflow forecasting error and uncertainty of the flood hydrograph shape in the operation of TGR, an operation model, which is for dynamic controlling flood limit water level and optimizing impoundment timing, was established by Li et al. (2010). Liu et al. (2011) proposed a multi-objective refill operation model in view of the requirements of flood control, power generation, navigation and FSR, and developed the “simulation-optimization-test” mode to optimize the rule curves for TGR. Mehta and Jain (2009) The developed a policy to minimize the damage due to floods and droughts and to determine optimum releases against demands for domestic supply, irrigation and hydropower generation. The existing research works achieve more fruitfully in determining the single reservoir impoundment sequence, timing and manner, but merely focusing on impoundment strategy and single scale, less concerning practical problems, impoundment scheduling model of CRS and its efficient solution techniques.

This paper combines the impoundment principle (Chen 2010) with K value discriminant method (Wang 1991) and presents a new impoundment strategy to determine impoundment sequence and opportunity of each reservoir in river basin. Simultaneously, the impounding water level control lines of historical typical runoff of different frequency are drawn according to flood routing simulation of each typical runoff, and then Impounding Operation Chart (IOC) is manufactured. On this basis, the paper establishes the Cascade Reservoir Impoundment Dispatching Model (CRIDM). The CRIDM is solved to formulate a reasonable impoundment scheme with Self-adaptive Electromagnetism-like Mechanism algorithm (SEM). Finally, a case study is implemented for solving ISP of the well-known cascade reservoirs (four reservoirs) in lower Jinsha River and the Three Georges Reservoir (JFCR-TGR, the Jinsha Four Cascade Reservoirs and the Three Georges Reservoir) by using the CRIDM and SEM method. The study results reveal that CRIDM can formulate the new impoundment scheduling schemes of JFCR-TGR, which can improve FSR and ease the contradiction between supply and demand of water resources as well with guaranteeing the safety of flood control in the watershed.

This paper is organized as follows. [A New Strategy for Determining Impoundment Sequence and Opportunity of Reservoirs](#) details the new impoundment strategy of CRS, and [Model Formulation of CRIDM](#) formulates the CRIDM. In [Self-Adaptive Electromagnetism-Like Mechanism Algorithm](#) we briefly describe the procedure of SEM. In [Case Study: Joint](#)

Impoundment Dispatching of JFCR-TGR System, the computational results of a practical ISP are presented. **Conclusions** outlines the conclusions of this paper.

2 A New Strategy for Determining Impoundment Sequence and Opportunity of Reservoirs

The K value discriminant method is the current method for identifying the impoundment sequence, the K value is calculated as follows:

$$K_i = \frac{W_i + \sum_i V}{F_i \sum_i H} \quad (1)$$

Where K_i is the K value of the i -th reservoir; W_i is the total income water of the i -th reservoir; $\sum_i H$ is the total water head of the i -th and all downstream reservoirs; $\sum_i V$ is the total water storage of all upper reservoirs of the i -th reservoir; F_i is the surface area of the i -th reservoir.

The discriminant method reflects the energy loss caused per unit of electric energy, and the reservoir should be given priority for impounding water if its K value is greater than those of others. When the reservoirs formulate the impounding sequence in river basin according to the discriminant method completely, the reservoirs will be running to keep it staying at the highest total head as far as possible. In this case, reservoirs can get a higher guarantee output. However, two shortcomings still exist for the discriminant method: first, the method does not consider the geographical position relations and the connection between flood control task and hydraulic power of each reservoir, and cannot alleviate the competitive impoundment of river basin only considering the maximum power of reservoirs at the end of the period; second, the abandoned water is ignored in the method, which will prematurely empty the reservoir with a smaller discriminant coefficient, in this case, the water storage is likely to be discontent at the end of the period. In the opposite, the reservoirs, with a larger discriminant coefficient, will impound too quickly in flood season, which will cause more abandoned water.

To solve the problem above for reasonable impoundment of CRS, this paper establishes the impoundment strategy referencing K value discriminant method and the three impoundment principles proposed by Chen J. in 2010.

- a) In the same river basin, the benefit of a single reservoir submits to CRS, and the total benefit of watershed is most important.
- b) For CRS, the upstream reservoirs impound water before the downstream reservoirs, and reservoirs in a branch impound water prior to reservoirs in the main stream.
- c) To protect the flood safety, the reservoirs, with little flood control capacity or none flood protection assignment, impound water before other reservoirs, and reservoir in a branch impoundment prior to reservoirs in the main stream.

The specific steps, for grading the impoundment rank of reservoirs according to the new impoundment strategy, are as follows: if the reservoirs are located in the upstream or have none flood protection assignment, they impound water before other reservoirs and are of the first rank; then the reservoirs, with little flood control task, are of the second rank; and as for the reservoirs need to impound last, as the key reservoirs to control the river basin and with huge storage capacity for flood protection assignment, they are of the third rank; finally, the K value of CRS has been calculated according to the discriminant method to determine the

impoundment sequence in different class, and the reservoirs, whose K value is greater than those of the others in the same class, should impound water firstly.

3 Model Formulation of CRIDM

ISP is a difficult task considering the complicated constraints and multi purposes, which often conflict with each other. The navigation benefits and the flood safety are damaged when the start time of impoundment is advanced or the power generation is increased; if the impoundment is delayed, the navigation will be improved, conversely, the generation benefit and navigation reliability of downstream will be reduced. To comprehensively consider multiple objectives, a joint impoundment dispatching model for cascade reservoir is presented in this paper to maximize the power generation of CRS in impounding period with guaranteeing the flood safety, navigation, water supply and maximizing FSR. The CRIDM is programmed in JAVA language and expressed as follows.

3.1 Objective Function

In the established model, there are two categories of objective functions, which are maximizing the full storage degree and generation of CRS. F_1 and F_2 are used as the name of the maximum FSR and power generation separately.

1) Maximize the full storage degree.

The full storage degree equals the final reservoir storage divided by the total normal storage capacity of CRS. And the objective function maximizing the full storage degree is shown as follow.

$$\text{Maximize } F_1 = \max \sum_{i=1}^N S_i / \sum_{i=1}^N TS_i \quad i = 1, 2, 3, \dots, N \quad (2)$$

where S_i is the final storage of the i -th reservoir; TS_i is the normal storage capacity of the i -th reservoir; N is the number of CRS. In this paper, full storage degree of the model is translated into the final water level for ensuring maximum storage capacity.

2) Maximize the power generation.

The maximum power generation is composed of the power generation of each reservoir, and it is formulated as:

$$\text{Maximize } F_2 = \max \sum_{t=1}^T \sum_{i=1}^N P_i^j \cdot \Delta t \quad t = 1, 2, 3, \dots, T \quad (3)$$

where P_i^j is the power of the i -th reservoir at the t -th period; Δt is the time interval of a period; T is the number of the period.

3.2 Constraints

In the impoundment model, the operation rule, made by watershed management organization, is necessary to be satisfied. Such as, the reservoirs in the Yangtze River are required to reach full impoundment at the end of flood season. And the constraints of the reservoirs should be considered as well. The constraints of the impoundment model are shown as follows:

1) Water balance equation

In general, evaporation and leakage losses from reservoirs during flood periods are an insignificant portion of the total flow and are therefore not included in the model (Windsor 1973). Thus, for each reservoir in CRS system, the water balance equation (Delgoda et al. 2013) is in common and shown as:

$$S_t^i = S_{t-1}^i + (I_t^i - Q_{out,t}^i) \Delta t; \quad i = 1, 2, \dots, N; t = 2, 3, \dots, T \tag{4}$$

$$Q_{out,t}^i = Q_{div,t}^i + Q_{aband,t}^i + Q_{loss,t}^i; \quad i = 1, 2, \dots, N; t = 2, 3, \dots, T \tag{5}$$

where S_t^i is the i -th reservoir storage capacity at the t -th operational period; I_t^i and $Q_{out,t}^i$ are the i -th reservoir flood inflow and water release volume at the t -th operational period, respectively; $Q_{div,t}^i$, $Q_{aband,t}^i$ and $Q_{loss,t}^i$ are the i -th reservoir water release of power generation, abandoned discharge and loss flow at the t -th period, respectively; the elements of loss flow include the evaporation, water supply, leakage and navigation, and so on, while the evaporation is ignored in this research.

2) Upstream water level upper and lower limit

$$Z_{t,\min}^i \leq Z_t^i \leq Z_{t,\max}^i \tag{6}$$

where $Z_{t,\max}^i$ and $Z_{t,\min}^i$ are the maximum and minimum water level limit of i -th reservoir at the t -th period; Z_t^i is the water level of the i -th reservoir at the t -th period.

3) Water discharge upper and lower limit

The constraint is obtained by combining some other constraints. The ecological requirement, water supply demand, navigation and other constraints are converted into the limit of water discharge for reservoirs. So this constraint can be rewritten as:

$$\min [Q_{t,\max}^i, Q_{e,\max}^i, Q_{n,\max}^i, Q_{\max}(Z_t^i)] \geq Q_{out,t}^i \geq \max [Q_{t,\min}^i, Q_{e,\min}^i, Q_{s,\min}^i, Q_{n,\min}^i] \tag{7}$$

where $Q_{\max}(Z_t^i)$ is the function to search the maximum water discharge capability of the i -th reservoir for the corresponding water level Z_t^i at the t -th period. Where $Q_{t,\max}^i$ and $Q_{t,\min}^i$ are the maximum and minimum limit water release value of i -th reservoir at the t -th operational period, respectively; $Q_{e,\min}^i, Q_{e,\max}^i, Q_{s,\min}^i, Q_{s,\max}^i, Q_{n,\min}^i$ and $Q_{n,\max}^i$ are the minimum and the maximum water release value of i -th reservoir at the t -th period for the ecological requirement, water supply and navigation severally; and then $\min [Q_{t,\max}^i, Q_{e,\max}^i, Q_{n,\max}^i, Q_{\max}(Z_t^i)]$ is the upper limit of water discharge, rather $\max [Q_{t,\min}^i, Q_{e,\min}^i, Q_{s,\min}^i, Q_{n,\min}^i]$ is the lower limit of water discharge got by choosing the maximal value between the $Q_{t,\min}^i, Q_{e,\min}^i, Q_{s,\min}^i$ and $Q_{n,\min}^i$.

4) Generation limits

Restrained by the demand of power grid and the installed capacity of hydropower station, the generation output is kept within boundaries. This constraint can be written as:

$$P_{t,\max}^i \geq P_t^i \geq P_{t,\min}^i \tag{8}$$

where $P_{t,\max}^i$ and $P_{t,\min}^i$ are the maximum and minimum power output limits of i -th reservoir at the t -th period severally; P_t^i is power output of i -th reservoir at the t -th period.

- 5) For the stable operation of cascade reservoirs, the fluctuation range of water level in the scheduling process is limited.

$$|Z_t^i - Z_{t+1}^i| < Z_F^i \tag{9}$$

where Z_t^i and Z_{t+1}^i are the water level of the i -th reservoir at the t -th and $(t+1)$ -th period; Z_F^i is the fluctuation range of water level of i -th reservoir.

3.3 Solving Process of CRIDM

To solve the CRIDM, there are two main procedures, the IOC (Procedure 1) and the scheduling mode (Procedure 2), as shown in Fig. 1. Procedure 1: the IOC is formed by different impounding control lines of various frequency inflows. Firstly, the constraints of impounding period are calculated considering the flood risk of diverse operating water levels (Xiaohua et al. 2010; Zhang et al. 2011); secondly, with the goal of full impoundment at the end of period, the water level process is used to reversely deduce the starting time of impoundment; finally, the impounding water level control lines of typical frequencies are delineated according to the above objective functions with SEM, then the IOC is completed. Procedure 2: by using long series runoff, the associated operations of each year are plotted according to the IOC. The scheduling mode of IOC is to select a reasonable scheduling process line (RSPL) to be followed according to the inflow frequency and the operation strategy of CRS at the current time. The method for selecting RSPL is as follows: when the inflow is

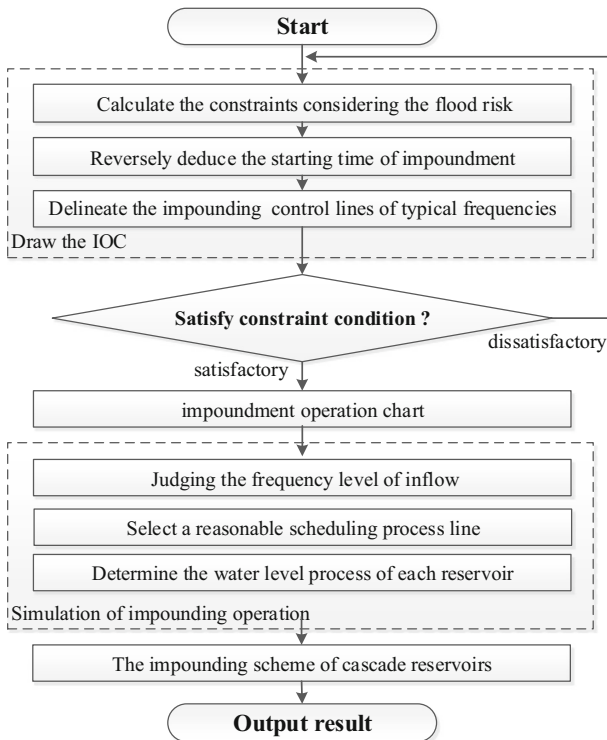


Fig. 1 The flowchart of model solution

small, for the goal of full impoundment, the closest control line which is above the current water level is selected as the RSPL; if the inflow is large, for flood control safety, the closest control line which is under the current water level is selected; sometimes the inflow is not too small or too large for the current water level, the water level is suggested to maintain the same. The specific means for determining the operation water level of a reservoir is shown.

$$Z_{i+1} = \begin{cases} \begin{cases} UZ_{i+1} & IP_i \geq 0.1\% \\ Z_i & IP_i < 0.1\% \end{cases} & ZP(UWL_i) \geq 5\% \\ \begin{cases} UZ_{i+1} & IP_i \geq 1\% \\ Z_i & 0.1\% \leq IP_i < 1\% \\ DZ_{i+1} & IP_i < 0.1\% \end{cases} & 1\% \leq ZP(UWL_i) < 5\% \\ \begin{cases} UZ_{i+1} & IP_i \geq 1\% \\ Z_i & 0.1\% \leq IP_i < 1\% \\ DZ_{i+1} & IP_i < 0.1\% \end{cases} & 0.1\% \leq ZP(UWL_i) < 1\% \\ \begin{cases} UZ_{i+1} & IP_i \geq 1\% \\ Z_i & 0.1\% \leq IP_i < 1\% \\ DZ_{i+1} & IP_i < 0.1\% \end{cases} & 0.01\% \leq ZP(UWL_i) < 0.1\% \\ \begin{cases} Z_i & IP_i \geq 90\% \\ DZ_{i+1} & IP_i < 90\% \end{cases} & Z_i > WL_i(0.01\%) \end{cases} \quad (10)$$

where Z_{i+1} is the water level of the reservoir at the $(i+1)$ -th period; Z_i is the water level of the current period; $WL_i(0.01\%)$ is the water level of the impounding control line of 0.01 % frequency; IP_i is the frequency of the inflow at the current period; UWL_i is the closest control line which is coincident or higher than the current water level of the reservoir; UZ_{i+1} is the $(i+1)$ -th water level of UWL_i ; $ZP(UWL_i)$ is the frequency of UWL_i ; DZ_{i+1} is the $(i+1)$ -th water level of the closest impounding control line which is lower than the current water level.

4 Self-Adaptive Electromagnetism-Like Mechanism Algorithm

Electromagnetism-like Mechanism (EM), proposed by Birbil and Fang in 2003, is a novel optimization algorithm of intelligent methods (Birbil and Fang 2003). EM originates from the electromagnetism theory of physics considering each sample point as a charged particle spread over the solution space (Tsou and Kao 2008). The fundamental procedures of EM include initialization of population *Initialize()*, local search *Local()*, calculation of total force *CalcF()*, and movement of particles *Move()*. the basic strategy of EM is described by Birbil in 2003. The modified operation used in this paper is shown as follows.

4.1 Modification of EM Operators

The procedure of the local search is used to do an optimum search to different local aspects of optimization goals. The original procedure is shown as:

$$X_k^i = \begin{cases} X_k^i + \lambda_1(\delta \max(U_k - L_k)) & \text{if } rnd() > 0.5 \\ X_k^i - \lambda_1(\delta \max(U_k - L_k)) & \text{otherwise} \end{cases} \quad (11)$$

where $rnd()$ and λ_1 are random numbers of the uniform distribution between $[0, 1]$; δ is the step coefficient to determines the step of the local search; k is the index of the dimensionality.

But the local search method used in the fundamental algorithm is simple that it can not fully search the nearby region (Gol Alikhani et al. 2009). In this paper, a self-adaptive mechanism is added to the local search operation for adapting the features of changed hydrological environment. The modification of this step revises the evolution step of EM, as follows:

$$X_k^i = \begin{cases} X_k^i + Div(g) \cdot (\max(U_k - L_k)) & \text{if } rnd() > 0.5 \\ X_k^i - Div(g) \cdot (\max(U_k - L_k)) & \text{otherwise} \end{cases} \quad (12)$$

where $Div(g)$ is the g -th self-adaptive function; g is the index of the generation.

$$Div(g) = \begin{cases} \lambda \cdot \delta \cdot \exp\left(-\alpha \cdot \text{count} \cdot g / MAXG\right) & \text{if } \text{count} > r \\ \lambda \cdot \delta \cdot \exp\left(-g / MAXG\right) & \text{otherwise} \end{cases} \quad (13)$$

where $MAXG$ denotes the total evolution number; α is the self-adaptive parameter; count and r is the number and threshold value of stagnation.

4.2 Calculation Process of SEM

The calculation Process of SEM is modified and described in Table 1.

5 Case Study: Joint Impoundment Dispatching of JFCR-TGR System

5.1 System Description

The JFCR-TGR system is a multidimensional water resource conservancy system involving flood control, irrigation, ecological requirement and water supply demand. Figure 2 shows the geographical location of the JFCR-TGR system, which consists of two major river basins: the lower reaches of the Jinsha River and the Yangtze River.

In lower reaches of the Jinsha River, there are four world-class reservoirs: Wudongde, Baihetan, Xiluodu and Xiangjiaba reservoir. The Three Gorges Reservoir, situated in the middle reach of Yangtze River, is the largest water conservancy project in the world. Main

Table 1 General scheme of SEM

Algorithm SEM ($N, D, MAXG, LSITER, \delta, r$)

N : number of sample points
 $MAXG$: maximum number of iterations
 δ : local search parameter

D : dimensionality of decision variable
 $LSITER$: maximum number of local search iterations
 r : the threshold value of stagnation

1. Initialize (N)
2. $g \leftarrow 1$
3. while ($g < MAXG$) do
4. $Div(g, \delta, r)$
4. Local ($LSITER, Div$)
5. $F \leftarrow CalcF()$
6. Move()
7. $g \leftarrow g + 1$
8. End while



Fig. 2 Map of JFCR-TGR system. **a** Impounding operation chart of Wudongde reservoir. **b** Impounding operation chart of Baihetan reservoir. **c** Impounding operation chart of Xiluodu reservoir. **d** Impounding operation chart of Xiangjiaba reservoir. **e** Impounding operation chart of TGR

parameters of JFCR-TGR are presented in Table 2. In this paper, the inflow of 55 years, from 1956 to 2010, are used to simulate the impounding schemes.

5.2 Impoundment Dispatching Strategy on JFCR-TGR System

To instantiate the CRIDM on the JFCR-TGR system, the new impoundment dispatching strategy is used to discriminate the impoundment timing and sequence of each reservoir in the system. The specific implementation steps are detailed as follows:

- Step 1 we contrast the different features of the JFCR-TGR and it is shown in the Table 3.
- Step 2 we determine the classification of JFCR-TGR according to the result of the Step 1, and the result is shown in the Table 3. The following geographical locations can be seen in Fig. 2. The Wudongde and Baihetan are the upper reservoirs of JFCR-TGR system, which do not take responsibility of river flood control definitely. They are of the first rank in the system. Xiluodu and Xiangjiaba are the middle reservoirs, and the flood control capacity of Xiluodu reservoir is larger than Xiangjiaba reservoir, see in Table 2. Xiluodu reservoir needs to cooperate with Xiangjiaba and TGR for the downstream flood control, and it is of the second rank in the system. Xiangjiaba and TGR have important flood protection assignment. Xiangjiaba reservoir is responsible

Table 2 Main flood characteristics of JFCR-TGR

Reservoir name	Flood control limit level (m)	Normal water level (m)	Gross storage (m ³)	Flood control capacity (m ³)	Minimum discharge (m ³ /s)	Designed discharge capacity (m ³ /s)
Wudongde	962.5	975	74 × 10 ⁸	24.4 × 10 ⁸	1500	36200
Baihetan	790	825	206 × 10 ⁸	73.24 × 10 ⁸	1500	40000
Xiluodu	560	600	126.7 × 10 ⁸	46.5 × 10 ⁸	1800	43700
Xiangjiaba	367	380	51.6 × 10 ⁸	9.03 × 10 ⁸	1300	49800
TGR	145	175	393 × 10 ⁸	221.5 × 10 ⁸	4500	98800

Table 3 Features contrast of JFCR-TGR

Reservoir name	Wudongde	Baihetan	Xiluodu	Xiangjiaba	TGR
Geographic position	Jinsha River				Yangtze River
	Upper reache	Upper reache	Middle reache	Middle reache	Middle reache
Flood protection assignment	None	None	None	Yes	Yes
Flood control capacity (m ³)	24.4×10 ⁸	73.24×10 ⁸	46.5×10 ⁸	9.03×10 ⁸	221.5×10 ⁸
Impoundment rank	1	1	2	3	3

for the flood control of the Chuanjiang Segment. With 22.15 billion m³ of flood control capacity, TGR needs to undertake the flood control safety of the Jingjiang Segment. Therefore, Xiangjiaba and TGR are of the third rank.

Step 3 The K values of each reservoir in each year are calculated based on the K value discriminant. The k value of JFCR-TGR system in September 1997 is detailed in the Table 4.

From the table above, it can be seen that the K value of each reservoir is gradually reduced in operation period because of impounding water. The K value of Xiangjiaba reservoir is the biggest in the period on account of the minimum reservoir area, the lowest downstream water head and the larger natural inflow. In accordance with the calculation formula of discriminant method, K value of the reservoir should be the largest. Because Wudongde and Baihetan reservoirs are located in the upstream with a high downstream water head and small natural inflow, the K values of these two reservoirs are minimums basically. Although the TGR is located in the downstream, due to its large storage (see Table 2), the surface area of the reservoir is much more

Table 4 K value of JFCR-TGR in September (×10⁻⁵)

Day	Wudongde	Baihetan	Xiluodu	Xiangjiaba	TGR	Period	Wudongde	Baihetan	Xiluodu	Xiangjiaba	TGR
1	306	240	581	993	486	16	112	116	265	821	263
2	290	232	541	980	468	17	104	107	257	810	252
3	274	225	505	968	450	18	96	98	250	799	241
4	259	217	473	956	433	19	89	90	243	789	230
5	244	209	444	944	416	20	81	81	236	779	220
6	229	202	417	932	400	21	73	74	230	769	209
7	215	194	393	921	384	22	66	67	224	759	200
8	201	187	372	909	369	23	58	60	218	749	190
9	187	179	351	898	354	24	51	53	212	740	181
10	173	172	332	886	340	25	43	47	207	730	172
11	160	165	315	875	326	26	36	40	201	721	164
12	151	153	306	864	313	27	29	35	196	712	155
13	142	142	297	853	300	28	21	29	191	703	147
14	129	137	280	842	287	29	14	24	186	694	139
15	121	126	272	831	275	30	7	18	181	684	131

than other reservoirs, so that its K value is small. Oppositely, K value of Xiluodu reservoir is larger than TGR due to its smaller surface area.

Step 4 Combined with the IOC and computation results of K values, the order for impounding water is made sure in each rank and the impoundment starting and expiration time of JFCR-TGR system is determined and shown in the Table 5.

5.3 Parameters Settings

The SEM is implemented to solve ISP problems of JFCR-TGR System, and parameters settings of SEM are as follows: the population size $N=50$, the maximum number of generation $MAXG$ is selected as 1,000, the maximum iteration number for local search operation $LSITER$ is set as 10, threshold value of stagnation r is set as 5, the local area parameter $\delta=0.29$ and the self-adaptive parameter α is selected as 0.8955 on the basis of test function simulation and trials of the model.

5.4 Results and Discussion

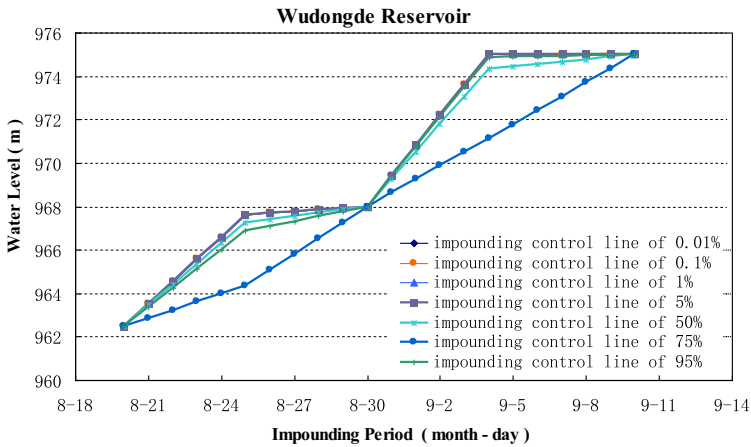
With CRIDM instantiation and SEM initialization in the sections above, the CRIDM is implemented to solve ISP of JFCR-TGR System. Meanwhile, the 95, 75, 50, 5, 1, 0.1 and 0.01 % frequency runoff are adopted as typical inflows for drawing IOCs of JFCR-TGR. The series runoffs, from year 1956 to 2010, are used as the long series inflows of JFCR-TGR to simulate joint impoundment scheduling. To verify the effectiveness of CRIDM, the results of CRIDM are compared with the original impoundment strategy.

Figure 3 displays the IOCs of the JFCR-TGR with seven impounding control lines of the seven typical inflows, while Table 5 details the key indicators values of the impoundment scheduling solutions obtained by CRIDM and the original impoundment strategy. Moreover, for the TGR is the largest and most downstream reservoir, its operation process of two typical years, 1997 and 1999, are shown in Figs. 4 and 5 respectively. Because the whole JFCR-TGR

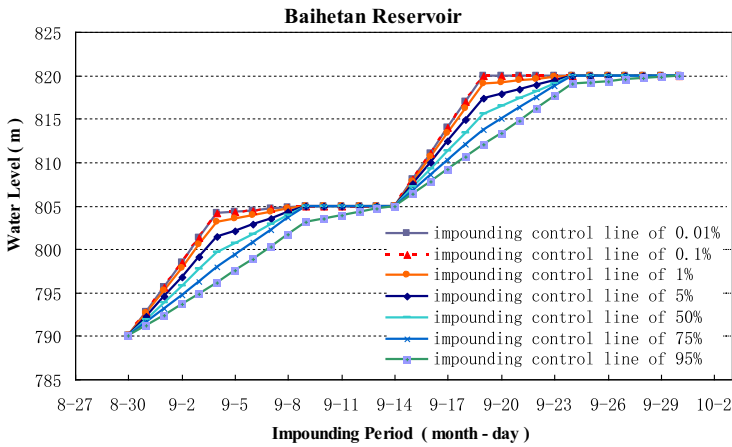
Table 5 Comparison of impounding schemes for JFCR-TGR

Reservoir name	Impoundment scheme	Impoundment starting time	Time expiration	Impoundment time (days)	FSR (%)	APG ($\times 10^8$ kW h)	AAW ($\times 10^8$ m ³)
Wudongde	Optimal scheme	20 Aug.	10 Sept.	22	100	40.44	15.76
	Design scheme	10 Aug.	10 Oct.	61	100	40.43	19.44
Baihetan	Optimal scheme	30 Aug.	30 Sept.	31	100	79.04	12.32
	Design scheme	10 Aug.	10 Oct.	61	100	78.55	17.55
Xiluodu	Optimal scheme	1 Sept.	10 Oct.	40	100	88.53	35.53
	Design scheme	10 Sept.	30 Sept.	20	100	83.75	49.53
Xiangjiaba	Optimal scheme	10 Sept.	30 Sept.	20	100	19.62	13.07
	Design scheme	10 Sept.	20 Sept.	10	100	15.38	4.54
TGR	Optimal scheme	11 Sept.	31 Oct.	50	90.9	133.61	32.58
	Design scheme	1 Oct.	31 Oct.	31	69.1	115.23	30.14
CRS	Optimal scheme	–	–	–	90.9	333.34	121.21
	Design scheme	–	–	–	69.1	361.23	108.82

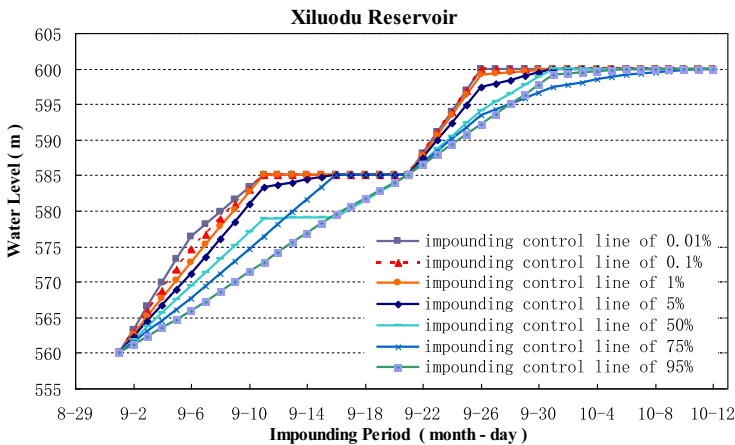
FSR Fill Storage Ratio, APG Annual Power Generation, AAW Annual Abandoned Water



(a) Impounding operation chart of Wudongde reservoir

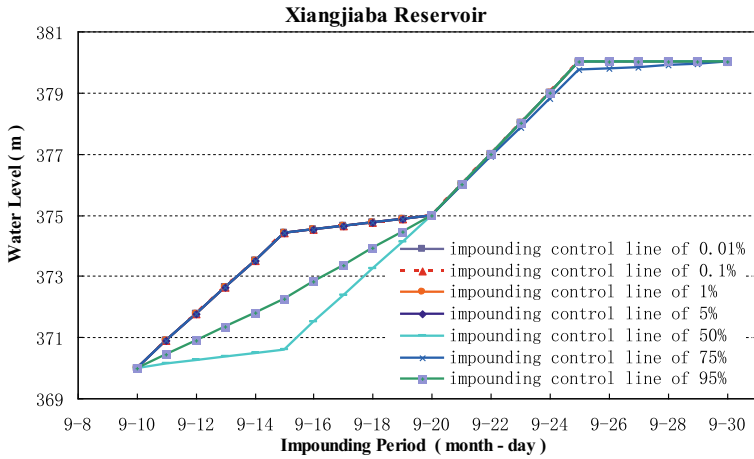


(b) Impounding operation chart of Baihetan reservoir

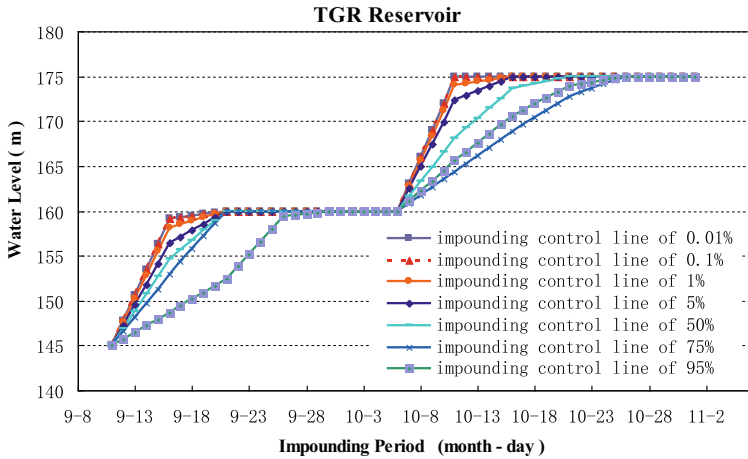


(c) Impounding operation chart of Xiluodu reservoir

Fig. 3 Impounding operation chart of JFCR-TGR



(d) Impounding operation chart of Xiangjiaba reservoir



(e) Impounding operation chart of TGR

Fig. 3 (continued)

is calculated, the inflow of TGR has been optimized by the upstream reservoirs, which makes the inflow of the optimal scheme is different from the design scheme.

From Fig. 3, we can see that the IOCs of TGR, Wudongde, Baihetan, Xiluodu and Xiangjiaba reservoirs, obtained by CRIDM. In rainy years, the original impounding scheme can reduce the flood risk. But in dry years, it can not guarantee full impoundment of the reservoirs by increasing the discharge. And the CRIDM can ensure the flood safety and make the reservoirs fully filled in both rainy and dry years.

Furthermore, Table 5 details the Fill Storage Ratio (FSR), Annual Power Generation (APG) and Annual Abandoned Water (AAW) of reservoirs. In Table 5, the FSRs of Wudongde and Baihetan reservoirs are always 100 % under the original impounding scheme and optimal impounding scheme, while the APG of the optimal impounding scheme is greater than the original impounding scheme, about 0.025 and 0.6 % for the two reservoirs. The AAWs are

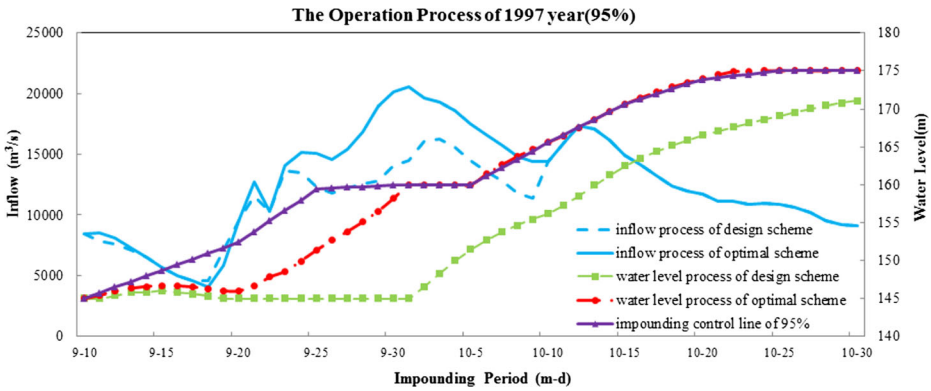


Fig. 4 Impoundment process of TGR in 1997 year

reduced from 1.944 and 1.755 billion m^3 to 1.576 and 1.232 billion m^3 separately. Compared with the original planning, the FSRs of Xiluodu and Xiangjiaba reservoirs are 100 % under the two modes, while the APGs of two reservoirs are increased by 5.7 and 27.6 % because of the high running head and extended impounding period. The FSR and APG of TGR are 90.9 % and 13.361 billion kW h, which are increased by 31.5 and 16 % under the optimal impounding scheme separately. At the same time, AAW is the 3.26 billion m^3 , which is increased by 8.1 %. The reason for the advance is that the designed impounding time of TGR is too late, and the starting water level is too low to reach the normal water level when the upstream reservoirs concentrated to impound simultaneously.

Moreover, from Figs. 4 and 5, the optimal impounding scheme of TGR begins on September 11th, and the control water level is 160 m. Considering the downstream flood safety, navigation and supply demand, TGR is filled after October 20th. The impounding period of original scheme is from October 1st to October 31st, and the final water levels are 171.37 and 175 m, which fails to achieve the normal water level in the dry year 1997.

For JFCR-TGR as a whole, the optimal impoundment scheme improves FSR and APG, reduces AAW without raising the flood control risk. The competitive impoundment problem is mitigated greatly.

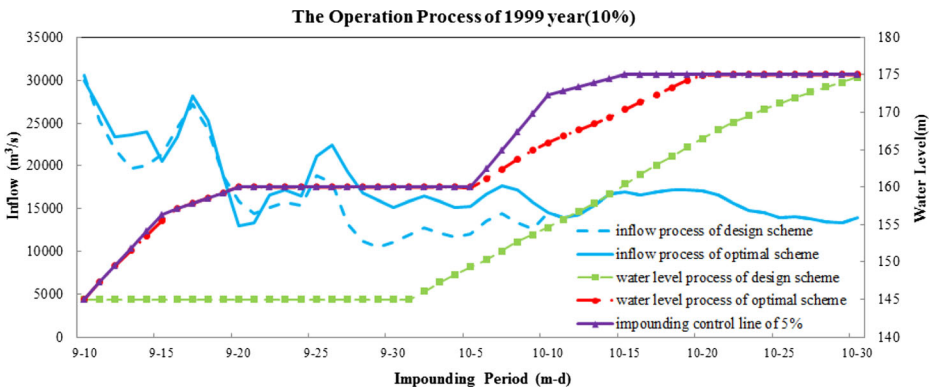


Fig. 5 Impoundment process of TGR in 1999 year

6 Conclusions

Impoundment scheduling problem (ISP) in the flood recession is a research hotspot because of the competitive impoundment in a cascade reservoirs system (CRS). In order to solve the problem above, this article presents a novel impoundment strategy to determine impoundment sequence and opportunity of each reservoir in river basin. Then, the IOC is manufactured by drawing impounding water level control lines according to the simulation of historical typical runoff of different frequency. On this basis, the paper develops CRIDM to optimize the impounding process of CRS. CRIDM is solved to formulate a rational impoundment scheme by Self-adaptive Electromagnetism-like Mechanism algorithm (SEM). The results of a case study, to solve joint ISP of the Cascade Reservoir in Jinsha River (four reservoirs) and Three Georges Reservoir (JFCR-TGR), reveal that the new strategy of impoundment scheduling is reasonable in the flood recession when more and more larger reservoirs are built. This paper provides a new method for the unified impoundment management of the inter-basin reservoirs.

Moreover, we need to illustrate that there are also some blemishes in CRIDM. The runoff lag time, from one reservoir to another, is not considered in this model, while it can change the inflow process of the downstream reservoirs. For future studies, these flaws is going to be considered and CRIDM can be used in a more complex object instance, such as the series-parallel CRS.

Acknowledgments This study is financially supported by the National Natural Science Foundation of China (No. 51109086) and the research funds of University and college PhD discipline of China (No. 20100142110012).

References

- Babel M, Gupta AD, Nayak D (2005) A model for optimal allocation of water to competing demands. *Water Resour Manag* 19:693–712. doi:10.1007/s11269-005-3282-4
- Birbil SI, Fang SC (2003) An electromagnetism-like mechanism for global optimization. *J Glob Optim* 25:263–282. doi:10.1023/a:1022452626305
- Chen J (2010) Discussion on the unified water storage of the reservoirs in Yangtze River basin. *China Water Resour* :10–13 (in Chinese)
- Chen J, Guo S, Li Y, Liu P, Zhou Y (2013) Joint operation and dynamic control of flood limiting water levels for cascade reservoirs. *Water Resour Manag* 27:749–763. doi:10.1007/s11269-012-0213-z
- Delgoda D, Saleem S, Halgamuge M, Malano H (2013) Multiple model predictive flood control in regulated river systems with uncertain inflows. *Water Resour Manag* 27:765–790. doi:10.1007/s11269-012-0214-y
- Gol Alikhani M, Javadian N, Tavakkoli-Moghaddam R (2009) A novel hybrid approach combining electromagnetism-like method with Solis and Wets local search for continuous optimization problems. *J Glob Optim* 44:227–234. doi:10.1007/s10898-008-9320-z
- Li Y, Gan F, Deng J (2006) Preliminary study on impounding water of Three Gorges Project in September. *Shuili Fadian Xuebao/J Hydroelec Eng* 25:61–66
- Li X, Guo S, Liu P, Chen G (2010) Dynamic control of flood limited water level for reservoir operation by considering inflow uncertainty. *J Hydrol* 391:126–134. doi:10.1016/j.jhydrol.2010.07.011
- Liu P, Guo S, Xiong L, Chen L (2010) Flood season segmentation based on the probability change-point analysis technique. *Hydrol Sci J* 55:540–554. doi:10.1080/02626667.2010.481087
- Liu X, Guo S, Liu P, Chen L, Li X (2011) Deriving optimal refill rules for multi-purpose reservoir operation. *Water Resour Manag* 25:431–448. doi:10.1007/s11269-010-9707-8
- Mehta R, Jain SK (2009) Optimal operation of a multi-purpose reservoir using neuro-fuzzy technique. *Water Resour Manag* 23:509–529. doi:10.1007/s11269-008-9286-0
- Peng Y, Li Y-T, Zhang H-W (2003) Study on the impounding time and objective decision of the Three Gorges Project at the end of flood period. *Shuikexue Jinzhan/Adv Water Sci* 14:682–689
- Tsou CS, Kao CH (2008) Multi-objective inventory control using electromagnetism-like meta-heuristic. *Int J Prod Res* 46:3859–3874. doi:10.1080/00207540601182278

- Wang DB (1991) A method of compensated regulation calculation for a group of hydropower stations improved criterion for mula method. *Water Resour Power* 9:130–136 (in Chinese)
- Windsor JS (1973) Optimization model for the operation of flood control systems. *Water Resour Res* 9:1219–1226. doi:[10.1029/WR009i005p01219](https://doi.org/10.1029/WR009i005p01219)
- Xiaohua D, Ji L, Yinghai L, Huijuan B, Xia D (2010) Dynamic application and risk analysis of flood control water level to the Three Gorges Reservoir by utilizing mid-term inflow forecasts. In: *Power and energy engineering conference (APPEEC), 2010 Asia-Pacific*, 28–31 March 2010. pp 1–5. doi:[10.1109/appeec.2010.5449235](https://doi.org/10.1109/appeec.2010.5449235)
- Yazdi J, Neyshabouri S (2012) Optimal design of flood-control multi-reservoir system on a watershed scale. *Nat Hazards* 63:629–646. doi:[10.1007/s11069-012-0169-6](https://doi.org/10.1007/s11069-012-0169-6)
- Yun R, Singh VP (2008) Multiple duration limited water level and dynamic limited water level for flood control, with implications on water supply. *J Hydrol* 354:160–170. doi:[10.1016/j.jhydrol.2008.03.003](https://doi.org/10.1016/j.jhydrol.2008.03.003)
- Zhang YP, Wang GL, Peng Y, Zhou HC (2011) Risk analysis of dynamic control of reservoir limited water level by considering flood forecast error. *Sci China Technol Sci* 54:1888–1893. doi:[10.1007/s11431-011-4392-2](https://doi.org/10.1007/s11431-011-4392-2)
- Zhou J, Ouyang S, Wang X, Ye L, Wang H (2014) Multi-objective parameter calibration and multi-attribute decision-making: an application to conceptual hydrological model calibration. *Water Resour Manag* 28:767–783. doi:[10.1007/s11269-014-0514-5](https://doi.org/10.1007/s11269-014-0514-5)