Study on flood control projects joint flood control operation of The Daqing river basin

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Abstract. Baiyangdian Lake is an important pivotal project in the Daqing River Basin. The research on the joint flood control operation of water projects in the Daqing River Basin seems particularly important as higher requirements have been set for the flood control in the basin based on the construction of the Xiong'an New Area. In this paper, a joint flood control operation model was set up and solved with the joint flood control operation objective of minimizing the highest water level of Baiyangdian Lake. A study on the joint flood control operation under different flood conditions was carried out under the premise of ensuring the safety of reservoir projects. The optimal operation can ensure that the Wen'anwa flood storage and detention area will not be opened in the event of a hundred-year flood, reduce the highest water level of Baiyangdian Lake to a certain extent, effectively alleviate the pressure on the flood control of dikes and Baiyangdian Lake and provide support for guaranteeing the flood control safety of the Xiong'an New Area.

1. Introduction
The Daqing River is a larger river system in the Haihe River Basin, originating from the eastern foot of the Taihang Mountains and divided into north and south branches upstream of Dongdian. The upper reaches of Baiyangdian Lake are mainly located in the Daqing River mountainous area where there are 6 large reservoirs, including Hengshanling, Koutou, Wangkuai, Xidayang, Longmen and Angezhuang. Except for the Angezhuang Reservoir located in the north branch of Daqing River, the other 5 are located in the upper reaches of Baiyangdian Lake in the southern branch. This study focuses on the southern branch of Daqing River with more reservoirs which is the Zhaowang River system composed of Zhulong River, the tributaries of which are Cihe River and Shahe River, etc., Tanghe River, Qingshui River, Fuhe River, Baohe River and Pinghe River, etc. All these rivers flow into Baiyangdian Lake.

The flood control operation of the Daqing River Basin directly concerns the safety of Beijing, Tianjin and Hebei Province. In particular, new requirements have been set for the flood control of the Haihe River Basin, especially the Daqing River Basin, during the construction of the Xiong’an New Area. Its operation methods and conditions have undergone great changes in comparison with those in the design stage of flood control projects. A complete flood control strategy is essential to the safety of flood control in the basin. The single reservoir operation rules formulated in the design and planning stage of reservoir projects in the Daqing River Basin can hardly meet the flood control needs after changes of the current
situation. It is necessary to further improve and optimize the operation rules and methods [1]. The reservoir group and Baiyangdian Lake have formed a flood control engineering system [2]. Flood control projects in the basin are interconnected both hydraulically and hydrologically when a flood comes in the flood season. It is difficult to find an optimal operation method of the flood control engineering system by only adjusting or optimizing the operation method of a single flood control project [3]. To improve the overall flood control capacity of the river basin, it is necessary to comprehensively consider the conditions of related engineering facilities such as dikes, flood retention areas and flood diversion and storage areas, and minimize the impact and loss of floods in the river basin and improve its overall flood control capacity under the premise of ensuring the safety of water conservancy facilities so as to achieve the purpose of minimizing disaster losses in the river basin [4].

2. Joint flood control operation model and solution

2.1. Joint flood control operation model of the flood control engineering system.

Aiming at the joint flood control operation of the flood control engineering system in the Daqing River Basin, this paper first analyzed the requirement for the joint flood control of the system and established a joint flood control operation model. The flood control safety of the North Xin'an Dike is mainly protected in the upper reaches of Baiyangdian Lake. That is, the lower the water level of the main area of Baiyangdian Lake in the flood season is, the better things will be [5]. How to keep the water level of Baiyangdian Lake within a safe range through the joint operation of upstream reservoirs has become the focus of research on flood control in the upper reaches of the Daqing River.

With the flood control engineering system in the basin or the same river as the object, this study first recognized the current storage conditions and flood control capacity of the system and drew up a flood regulation plan for the control section corresponding to the object of protection based on the predicted flood magnitude (peak, amount and frequency) in the event of a flood in the basin, finally realizing the joint operation of the flood control engineering system. In the process of model building, consideration was given to the arrival time of the flood; the outflow of flood control projects was subjected to flood routing based on the existing Muskingum routing model of the studied basin and the Muskingum method, and the inflow of downstream flood control projects in the area was superimposed [6].

The mathematical model for the joint optimal flood control operation of the flood control engineering system includes an objective function and constraints. The pros and cons of the joint optimal flood control operation of the flood control engineering system were measured with the criterion of the lowest corresponding control section of Baiyangdian Lake. A corresponding joint flood control operation model was set up with consideration given to constraints such as local inflow, channel discharge constraint, maximum level limit, level variation constraint and discharge capacity [7-8]. The joint flood control operation of flood control projects in the Daqing River Basin concerns optimization. The operation rules of Baiyangdian Lake are judged based on the water level change of Shifangyuan, not only guaranteeing the safety of surrounding dikes, but also reducing the maximum discharge flow and to a certain extent alleviating the downstream flood control pressure. Generally, the mathematical model mainly involves the following formulas when the flood control capacity is limited or given [9-10]:

\[
\min \left( \max_{[h_{0},h_{f}]} Z_{\text{Baiyangdian Lake}}(t) \right)
\]

(1)

In the implementation process, the operation period was discretized to facilitate calculation:

\[
M = \frac{t_{f} - t_{0}}{\Delta t}
\]

(2)

The objective function of formula 1 can be written as:
\[
\begin{align*}
\text{Min} \left( \max \left( Z_{\text{Baiyangdian Lake}} (1), Z_{\text{Baiyangdian Lake}} (2), \ldots, Z_{\text{Baiyangdian Lake}} (M) \right) \right)
\end{align*}
\]

Corresponding constraints in the joint flood control operation model of the flood control engineering system mainly include:

\[
\begin{align*}
\sum_{j=1}^{M} \left( \frac{Q_{j,i} + Q_{j+1,i}}{2} - \frac{q_{j,i} + q_{j+1,i}}{2} \right) \Delta t = \Delta V_j \\
q_{j,i} \leq Q_{j,i} \\
q_{j,i} \leq f_i(Z_{j,i}) \\
Q_{j,i} + Q_{j+1,i} - \frac{q_{j,i} + q_{j+1,i}}{2} = \frac{\Delta V_{j,i}}{\Delta t} \\
Q_{j+1,i} = c_0 \cdot Q_{j+1,i} + c_1 \cdot Q'_{j,i} + c_2 \cdot Q_{j,i+1} \\
Q'_{j,i} = q_{j,i} + \Delta Q_{j+1,i} \\
Z_i = f_2(V_j) \\
Z_{j,i} < Z_{\text{Setting}}; \ \ \Delta Z_{j,i} < \Delta Z_{\text{Setting}} \\
i = 1, 2, \ldots, m; \ \ j = 1, 2, \ldots, M
\end{align*}
\]

Where, \( Q_{j,i} \) is the inflow of the flood control project \( i \) in the period \( j \);
\( q_{j,i} \) is the outflow of the flood control project \( i \) in the period \( j \);
\( \Delta Q_{j,i} \) is the flow of the section between the flood control project \( i \) and the control section in the period \( j \) (which has been subjected to inverse routing to the outflow \( i \));
\( Q_{j,i} \) is the outflow of the \( i \)-level reservoir in the period \( j \) (including the flow from the flood control project to the downstream section);
\( Z_{j,i} \) is the water level of the \( i \)-level flood control project in the period \( j \);
\( Z_{j,i} \) and \( Z_{\text{Set}} \) are the water level and the set water level of the \( i \)-level reservoir in the period \( j \) (high flood control level or design flood level);
\( \Delta Z_{j,i} \) and \( \Delta Z_{\text{Set}} \) are the amplitude of variation of the water level and the set water level of the \( i \)-level reservoir in the period \( j \) respectively;
\( f_i(Z_{j,i}) \) is the discharge capacity function of the \( i \)-level reservoir in the period \( j \);
\( f_2(V_j) \) is the capacity curve function of the \( i \)-level reservoir.
\( c_0, c_1, c_2 \) are Muskingum routing coefficients.

2.2. Flood control operation model solution.
The joint flood control operation of flood control projects is very complicated, containing a variety of linear and nonlinear constraints. Solving with conventional optimization algorithms usually has disadvantages such as large amount of calculation and poor solution accuracy. Among intelligent optimization algorithms, the particle swarm optimization algorithm (PSO algorithm) is a new algorithm more effective for the solution of optimal joint operation with simple design and programming, small amount of calculation and fast convergence [11]. An intelligent algorithm is selected as the solution...
method, and the deterministic sampling method and optimization strategy applicable to the algorithm are adopted to generate the best new reservoir group in the basin with better peak clipping effects and the minimum highest water level of the control section corresponding to the object of protection. This cycle continues until the solution meets the optimization criterion or a satisfactory solution is obtained. Aiming at the objective function of joint optimal operation, that is, pursuing the goal of minimizing the water level of the object of protection, the characteristics of each module are reflected through the change of constraints. However, this does not prevent the adoption of a unified algorithm because the basic definitions of variables, objective functions and main constraints are still consistent. 

$i$ represents a reservoir. We assume that there are $n$ reservoirs numbered as $i = 1, 2, ..., n$ and divide the operation cycle into $M$ periods. $j$ represents a period variable and $j = 1, 2, ..., M$.

Solving the problem of optimal flood control operation of reservoir groups with PSO mainly includes the generation of an initial group, that is, the formation of corresponding decision variables (individuals) of the initial flood control operation plan, the calculation of the objective function value of the group and the realization of the optimized operator. The design process of the solution with the PSO algorithm is as follows:

2.2.1. Generation of an initial group. In PSO, the actual value of decision variables is directly used as a code composed of the outflow vectors of project control projects in each period, the length of which is equal to the number of decision variables.

$$Q = (q_1, q_2, \ldots, q_i, \ldots, q_M)$$  \hspace{1cm} (5)

Where $q_i = (q_{i1}, q_{i2}, \ldots, q_{in})^T$  \hspace{1cm} $q_j = (q_{j1}, q_{j2}, \ldots, q_{jn})^T$  \hspace{1cm} $q_M = (q_{1M}, q_{2M}, \ldots, q_{nM})^T$

Several initial solutions are obtained, which are corresponding to several joint operation schemes. Then, the solution strategy of the PSO algorithm is adopted for iterative optimization. The optimal solution of the problem is finally obtained.

In the operation period, the inflow process and the local inflow process of flood control projects are known, and their initial water levels are known. The initial water level is the current level in real-time flood control operation. The flood control outflow process of flood control projects in the joint optimal flood control operation has certain constraints when discharge facilities involved in the discharge of flood control projects and their discharge capacities are known. Therefore, not all individuals are feasible. For the corresponding optimization model, the flood control outflow of flood control projects in each period is required to meet the flood discharge and flow capacity constraints and the initial flood control capacity constraints of the projects. Therefore, each individual produced in the procedure must be verified for feasibility.

2.2.2. Fitness calculation. The individual fitness set is equal to the corresponding objective function value, and the solution with the smallest objective function value is the optimal solution. In the algorithm, the discharge capacity and artificial flood constraints are automatically satisfied in the coding of the operation plan, while other constraints such as the initial flood control capacity constraints and water balance are considered in the design of the particle swarm operator. The fitness function is:

$$F = \text{Min} \left( \max_{t \in [t_0, t_f]} Z_{	ext{Baiyangdian Lake}} (t) \right)$$  \hspace{1cm} (6)

2.2.3. Design of PSO algorithm. After the initial group is selected and the fitness calculation method is determined, the deterministic sampling method and optimization strategy applicable to the algorithm are adopted. To ensure global convergence, the optimal individual retention strategy is adopted after the mutation operation. That is, the optimal individuals in the group and their fitness values are retained
after mutation in the generation G. This cycle continues until the solution meets the optimization criterion or a satisfactory solution is obtained.

3. Analysis of joint flood control operation

3.1. Boundary conditions.

For the objective function of joint flood control operation of the flood control engineering system in the Daqing River Basin, i.e. the goal of minimizing the water level of Baiyangdian Lake, Hengshanling, Koutou Reservoir, Longmen Reservoir and Angezhuang Reservoir did not participate in the joint operation task of Baiyangdian Lake due to their small capacity and weak flood regulation ability according to the classification of capacity levels of flood control reservoirs. According to the study, Baiyangdian Lake was optimized jointly with Xidayang Reservoir and Wangkuai Reservoir. Other reservoirs were operated according to the design operation rules. In the optimization process, consideration was given to the 500-year flood design of Xidayang and Wangkuai Reservoirs. As the typical flood level is lower than the standard 500-year flood level, the maximum level of the reservoirs cannot be close to the design flood level (corresponding to the storage capacity \( V_{\text{Design}} \)). On the basis of the highest level of reservoirs under rule-based operation (corresponding to the storage capacity \( V_{\text{Rule-based highest}} \)), the main potential operation under rules corresponds to the flood control capacity \( (V_{\text{Potential}} = V_{\text{Design}} - V_{\text{Rule-based highest}}) \) corresponding to the difference between the highest level and the design flood level. In the optimization process, the maximum storage capacity available was set to \( V_{\text{Rule-based highest}} + 1/3 \times V_{\text{Potential}} \) for floods below the level of typical 50-year floods and \( V_{\text{Rule-based highest}} + 1/3 \times V_{\text{Potential}} \) for typical 50-year floods and above, including “638” floods. Figure 1 is a flow chart of solving the problem of joint flood control operation in the Daqing River Basin with the PSO algorithm. Meanwhile, the model should also meet the following assumptions: floods in the basin upstream of Baiyangdian Lake have the same frequency; upstream reservoirs in the basin before the flood are maintained at the flood control level, and the Zaolinzhuang Gate is fully open. In such case, a lower water level can ensure the safety of surrounding dikes and reduce the maximum downstream discharge flow.

Flood control and regulation were carried out according to the Daqing River Flood Control Plan (GH [2007] No. 33) approved by the State Council and the Daqing River Flood Control Operation Plan (GX [2008] No. 11) approved by the State Flood Control and Drought Relief Headquarters, which correspond to the principle of application in Baiyangdian Lake. That is, when the water level of Shifangyuan along Baiyangdian Lake reaches 9m and continues to rise, Zhangshuinian, Diannan New Dike, Simen Dike and North Xin'an Dike shall be opened in sequence and the flood shall be diverted to the surrounding low-lying lakes to ensure the safety of Qianli Dike. At the same time, there is the Wen'anwa flood storage and detention area around Baiyangdian Lake that can be used for flood diversion. The flood is diverted to the area mainly via Xiaoguan. Application rules of Wen'anwa: When the water level of Diliubao along Dongdian reaches 6.5m and continues to rise, threatening the safety of the urban area of Tianjin, while the flood discharge capacity of the channel is fully maintained, 1) Guodi Gate shall be used and the counter dikes on both sides of the gate shall be opened successively for flood diversion to Jiakouwa if the water level of Shifangyuan along Baiyangdian Lake is less than 9m. The flood shall be diverted to Wen'anwa at the breach of Tanli Gedian Dike when the water level of Diliubao along Dongdian is still up to 6.5m and continues to rises after full application of Jiakouwa; 2) The Wangcun flood-diversion sluice and the breach of Tanli Gedian Dike shall be used for flood diversion to Wen'anwa when the water level of Shifangyuan along Baiyangdian Lake is more than 9m. 3) The flood shall be diverted to Wen'anwa at the breach of Xiaoguan if the water level of Shifangyuan along Baiyangdian Lake reaches 9.85m and continues to rise, threatening the safety of Qianli Dike.
3.2. Typical flood calculation results.
The design peak, volume and hygrograph of floods under different design standards were obtained with the actual “638” flood in the Daqing River system as the analysis object. To verify the effectiveness of the joint operation proposed herein, typical “638”, 50-year, 100-year and 200-year flood conditions were regarded as input conditions, and a comparison was made with the designed rule-based operation.

3.2.1. Typical “638” flood. The Wen'anwa flood storage and detention area was opened in both the rule-based operation and the optimal operation under the typical "638" flood conditions. Figure 2 shows the inflow, outflow and water level operation results of Wangkuai Reservoir, Xidayang Reservoir and Baiyangdian Lake.
3.2.2. Typical 50-year flood. The Wen'anwa flood storage and detention area was not used in both the rule-based operation and the optimal operation under typical 50-year flood conditions. Figure 3 shows the inflow, outflow and water level operation results of Wangkuai Reservoir, Xidayang Reservoir and Baiyangdian Lake.

![Figure 3. Operation results of Wangkuai Reservoir, Xidayang Reservoir and Baiyangdian Lake under 50-year flood conditions](image)

3.2.3. Typical 100-year flood. Under typical 100-year flood conditions, the Wen'anwa flood storage and detention area was opened in the rule-based operation but not opened in the optimal operation. Figure 4 shows the inflow, outflow and water level operation results of Wangkuai Reservoir, Xidayang Reservoir and Baiyangdian Lake.
3.2.4. Typical 200-year flood. The Wen'anwa flood storage and detention area was opened in both the rule-based operation and the optimal operation under 200-year flood conditions. Figure 5 shows the inflow, outflow and water level operation results of Wangkuai Reservoir, Xidayang Reservoir and Baiyangdian Lake.
3.3. Analysis of results of joint flood control operation.
A study on optimal joint operation has been carried out for the joint operation of the flood control engineering system in the Daqing River Basin. Table 1 and Table 2 show the comparison of maximum outflow of Wangkuai and Xidayang Reservoirs. Table 3 shows the comparison of the highest water level of Baiyangdian Lake.

Table 1. Maximum outflow of Wangkuai Reservoir

| Flood frequency | The designed rule-based operation (m$^3$/s) | Optimal operation(m$^3$/s) |
|-----------------|--------------------------------------------|----------------------------|
| Typical “638” flood | 6959                                      | 2399                       |
| Typical 10-year flood | 255                                       | 110                        |
| Typical 20-year flood | 2500                                      | 311                        |
| Typical 30-year flood | 2500                                      | 526                        |
| Typical 50-year flood | 2500                                      | 723                        |
| Typical 100-year flood | 4941                                      | 1272                       |
| Typical 200-year flood | 6843                                      | 2112                       |
Table 2. Maximum outflow of Xidayang Reservoir

| Flood frequency       | The designed rule-based operation (m³/s) | Optimal operation (m³/s) |
|-----------------------|-----------------------------------------|--------------------------|
| Typical “638” flood   | 4779                                    | 1358                     |
| Typical 10-year flood | 300                                     | 107                      |
| Typical 20-year flood | 300                                     | 130                      |
| Typical 30-year flood | 390                                     | 415                      |
| Typical 50-year flood | 4045                                    | 826                      |
| Typical 100-year flood| 4143                                    | 1076                     |
| Typical 200-year flood| 5033                                    | 1397                     |

Table 3. Comparison of the highest water level of Baiyangdian Lake

| Flood frequency       | The designed rule-based operation (m) | Optimal operation (m) |
|-----------------------|---------------------------------------|-----------------------|
| Typical “638” flood   | 9.39                                  | 9.20                  |
| Typical 10-year flood | 7.77                                  | 7.52                  |
| Typical 20-year flood | 8.50                                  | 8.25                  |
| Typical 30-year flood | 8.88                                  | 8.59                  |
| Typical 50-year flood | 9.01                                  | 8.97                  |
| Typical 100-year flood| 9.17                                  | 9.01                  |
| Typical 200-year flood| 9.43                                  | 9.21                  |

According to Table 1 and Table 2, Xidayang and Wangkuai Reservoirs have reserved a part of the flood control capacity in the joint optimal operation of the flood control engineering system in Daqing River Basin compared to the rule-based operation of single reservoirs. Their highest water levels were 3-4m lower than the design flood level even under typical "638" and 200-year flood conditions. The outflow of Wangkuai Reservoir under the conditions of floods of all frequencies decreased greatly. That of Xidayang Reservoir only increased slightly under 50-year flood conditions, and decreased greatly under the conditions of floods of other design frequencies. The joint operation has reduced the flood control pressure of downstream rivers and meanwhile created conditions for the reduction of the water level of the downstream Baiyangdian Lake. Meanwhile, in response to 100-year floods, the Wen'anwa flood storage and detention area was opened according to the rules of operation. In the optimal operation, however, the area was not opened and the highest level of Baiyangdian Lake was reduced by 0.17m, showing significant benefits of joint operation. According to Table 3, the highest water level of Baiyangdian Lake has also been reduced to varying degrees, indicating significant results of joint operation. The reason is that part of the flood control capacity of Xidayang and Wangkuai Reservoirs was borrowed temporarily to avoid the simultaneous arrival of flood peaks of the six reservoirs to Baiyangdian Lake. Compared with the rule-based operation, it can effectively reduce the flood peaks entering Baiyangdian Lake and achieve the purpose of lowering the water level of Baiyangdian Lake.

4. Conclusion
Oriented at the flood control problem of the Daqing River Basin, this study aimed to minimize the highest water level of Baiyangdian Lake, which can not only ensure the safety of surrounding dikes, but also relieve the pressure of flood control in the lower reaches of Baiyangdian Lake. A joint flood control operation model for the Daqing River Basin was established and solved with an intelligent optimization algorithm, realizing the joint optimal operation of the flood control engineering system in the Daqing River Basin. The joint operation has, on the one hand, reduced the flood control pressure of downstream...
rivers and dikes, and on the other hand, created conditions for the reduction of the water level of the downstream Baiyangdian Lake. Part of the flood control capacity of Xidayang and Wangkuai Reservoirs was borrowed temporarily to avoid the simultaneous arrival of flood peaks of the six reservoirs to Baiyangdian Lake. Compared with the rule-based operation, it can effectively reduce the flood peaks entering Baiyangdian Lake and achieve the purpose of lowering the water level of Baiyangdian Lake.

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