

Decomposition–coordination model of reservoir group and flood storage basin for real-time flood control operation

Benyou Jia, Ping'an Zhong, Xinyu Wan, Bin Xu and Juan Chen

ABSTRACT

The research of joint optimization operation of complex flood control systems is still in the process of development. This paper introduces a decomposition–coordination model for solving the multi-objective optimization problem for real-time flood control operation in reservoir group and flood storage basin. The multi-objective programming is established for maximum safety of the reservoir group and minimum losses of flood storage basin, according to the real-time flood control requirements. Then, a third-order hierarchical optimization decomposition–coordination model is proposed for solving the multi-objective programming problem, based on the decomposition–coordination principle of large scale system theory. It takes advantage of an objective coordination method and model coordination method to accomplish global optimization and combines progressive optimality algorithm to solve the subsystem local optimization. Finally, the model is applied for simulating the storm flood in July 2007 in the middle reaches of the Huaihe River Basin in China. Results show that the proposed decomposition–coordination model can efficiently calculate the reservoir group optima release strategy and flood storage basin diversion process, and meet the safety discharge at the downstream control section.

Key words | decomposition–coordination model, flood control operation, flood storage basin, large scale system theory, multi-objective optimization, reservoir group

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INTRODUCTION

In China, flood disasters cause massive economic losses and casualties, and have a higher ranking in impact than other natural disasters. Reservoirs are the most effective water storage facilities to control floods. As well, flood storage basins, such as low-lying farming areas and large lakes, have been exploited as temporary and auxiliary water storage projects when extreme floods are beyond the water storage capacity of reservoirs. As a result, the critical question arises of how to scientifically and rationally use various engineering facilities to control floods?

Many mathematical models and calculation methods have been applied to solve the problem. Windsor (1973) first initiated a linear programming (LP) model for application in reservoir flood control operation. Yakowitz (1982)

formulated a dynamic programming (DP) model for application in water resources. Unver & Mays (1990) used a nonlinear programming (NLP) model for real-time hourly flood control problems in flood-prone areas, with the model taking the minimum total flood damage as its objective function. Karbowski *et al.* (2005) developed a hybrid analytic/rule-based approach for real-time flood control operation of a single reservoir. Wei & Hsu (2008) used a balanced water level index method to determine the highest release priority in reservoirs, and the method was applied in estimating real-time release in two parallel reservoirs during floods. Zhong *et al.* (2010) presented an excess-water distribution model for real-time flood control operation in a reservoir group; a dynamic adjustment index was proposed

in the model to determine the release priority, and the objective function was to minimize the maximum discharge at a downstream control section. Moreover, many new theories and methods have been introduced into the reservoir optimization operation which have enriched the research methods of reservoir joint operation, such as genetic algorithm (GA) (e.g., Chang & Chen 1998; Chang 2008), fuzzy method (e.g., Cheng & Chau 2001; Fu 2008), particle swarm optimization (PSO) (e.g., Janga Reddy & Nagesh Kumar 2007), artificial neural network (ANN) (e.g., Chandramouli & Raman 2001; EI-Shafie & EI-Manadely 2011), and other real-time models (e.g., Hsu & Wei 2007; Huang & Hsieh 2010; Richaud *et al.* 2011), and uncertainty (e.g., Brandimarte & Di Baldassarre 2012). However, few studies have focused on the joint operation problem of flood storage basin (e.g., Wang *et al.* 2009; Liu *et al.* 2010), especially for real-time flood control optimal operation.

All these studies have successfully solved the corresponding reservoir operation problem in detail. The method depends on the characteristics of the reservoir system. However, the use of a single method has been limited, even not applicable, as reservoir systems increase. At the same time, the method for joint optimal operation for a complex flood control system is still in the process of development.

The decomposition–coordination method of large scale system theory (e.g., Mesarovic 1970; Singhand & Titli 1978; Li *et al.* 2007) can divide a large scale system into several independent subsystems, for which, the coordinators are installed to form hierarchical structure. The subsystems do local optima under some interference information coming from coordinators, and then send feedback to coordinators. The coordinators are responsible for coordinating based on the objective function to achieve the global optimum. The decomposition–coordination method has two significant advantages: the optimization order among each subsystem is arbitrary and the optimization method in each subsystem can be different; the method can reduce system dimensions and save computing time. Thus, it can be explored to analyze and solve the real-time flood control problem for joint operation in a reservoir group and flood storage basin, which has large scale, multi-objective, multi-constraint, non-linear and dynamic characteristics.

In this paper, a third-order hierarchical optimization decomposition–coordination model is introduced to solve the multi-objective optimization problem for real-time flood control operation in a reservoir group and flood storage basin. We seek here to: (1) describe the flood control problem by establishing multi-objective programming; (2) coordinate for global optima in coordinators using an objective coordination method and model coordination method, and calculate for local optima in subsystems using progressive optimality algorithm (POA) (e.g., Howson & Sancho 1975; Simonovic 1979; Turgeon 1981); and (3) apply the decomposition–coordination model for real-time flood control operation.

METHODOLOGY

In this section, we propose a methodology for solving a certain joint flood control operation problem in reservoir group and flood storage basin.

The method includes three processes, as follows. (1) Multi-objective programming: for the mathematical description of real-time flood control problem. (2) Decomposition–coordination model: according to the feature of spatial structure of the multi-objective programming, a corresponding decomposition and coordination method are adopted to establish a decomposition–coordination model. The model contains hierarchical structure, components and calculation methods. (3) Procedures of real-time operation: the calculation process for running the decomposition–coordination model.

In the following sections, we describe the three parts in detail.

Multi-objective programming

A flood control system is a complex connected system, which generally consists of reservoir group, rivers, flood storage basin, and other engineering components. For flood control, the reservoir group changes outflow through the modulation of inflow to effectively reduce the flow peak and flood volume at downstream control section. Rivers attenuate flood waves through river storage. Flood storage basin is the temporary storage place for overflow flood when the flood cannot be

fully controlled by the reservoir group and rivers. For a flood control system, the joint optimization operation should meet four objectives: (1) ensuring dam safety; (2) meeting terminal water storage for reservoir; (3) guaranteeing safety discharge in rivers; and (4) minimizing flood diversion losses in the flood storage basin. The second objective and the third objective are satisfied by constraints Equations (8) and (13). The first objective and the fourth objective are considered in the objective functions. Thus, the multi-objective programming is described as follows.

Objective functions

For the first objective, a reservoir safety function is defined to indicate the safety degree of the reservoir. The objective function which aims to maximize reservoir group safety is described as follows:

$$\max S_R = \sum_{i=1}^n S_{R,i} \quad (1)$$

$$S_{R,i} = 1 - \frac{V_{R,i}^0 + \sum_{t=1}^T \max\{[Q_{R,i}(t) - q_{R,i}(t)] \cdot \Delta t, 0\}}{V_{R,i}^{\text{design}}} \quad (2)$$

where S_R is the reservoir group safety; $S_{R,i}$ is the i th reservoir safety; n is the number of reservoirs; $V_{R,i}^0$ is the i th reservoir flood control capacity which has been used before operating; $V_{R,i}^{\text{design}}$ is the i th reservoir design flood control capacity; $Q_{R,i}(t)$ and $q_{R,i}(t)$ are inflow and outflow of the i th reservoir; Δt is the time interval; T is the length of operation period.

For the fourth objective, a losses function of flood storage basin is defined to indicate the losses in the flood storage basin. The objective function which aims to minimize the losses in the flood storage basin is described as follows:

$$\min C_D = \sum_{i=1}^m C_{D,i} \quad (3)$$

where C_D is the flood storage basin losses; $C_{D,i}$ is the i th flood storage basin losses; m is the number of flood storage basins.

The flood storage basin loss is defined as a cubic polynomial function of flood storage amount, as described by Equation (4):

$$C_{D,i} = C_i + u1_i \cdot (W_{D,i}) + u2_i \cdot (W_{D,i})^2 + u3_i \cdot (W_{D,i})^3 \quad (4)$$

$$W_{D,i} = V_{D,i}^0 + \sum_{t=1}^T q_{D,i}(t) \cdot \Delta t \quad (5)$$

where $W_{D,i}$ is the flood storage amount of the i th flood storage basin; $V_{D,i}^0$ is the initial flood storage amount of the i th flood storage basin; $q_{D,i}(t)$ is the flood storage process of the i th flood storage basin; C_i , $u1_i$, $u2_i$, $u3_i$ are the coefficients of cubic polynomial.

To integrate the magnitude difference between the two objective functions S_R and C_D , the dimensionless method is used. Meanwhile, the weight method is introduced to change the multi-objective problem into a single-objective problem. Accordingly, the composite objective function of large scale system can be formulated as:

$$\min F = \alpha_R \cdot \left(-\frac{S_R}{n}\right) + \alpha_D \cdot \left(-\frac{C_D}{C_D^{\max}}\right) \quad (6)$$

where C_D^{\max} is the theoretical maximum losses in flood storage basin; α_R and α_D are the weighted coefficient of reservoir group and flood storage basin, meeting the relation: $\alpha_R + \alpha_D = 1$.

In Equation (6), S_R and C_D are unknown variables, the other variables are constants, and the equation satisfies the linear superposition. Obviously, the objectives S_R and C_D are competing with each other, the determination of the weighting coefficients α_R and α_D depends on the decision-makers, thus, we can develop a series of analysis schemes for supporting the decision-makers to make the final decisions.

Constraints

Constraints of reservoir. The lowest and the highest water level constraints:

$$Z_{R,i}^{\min} \leq Z_{R,i}(t) \leq Z_{R,i}^{\max} \quad (7)$$

where $Z_{R,i}(t)$ is the i th reservoir water level at time t ; $Z_{R,i}^{\min}$ and $Z_{R,i}^{\max}$ are the i th reservoir allowable minimum and maximum water level at time t .

The terminal water level constraint:

$$Z_{R,i}(T) = Z_{R,i}^{\text{end}} \tag{8}$$

where $Z_{R,i}(T)$ is the i th reservoir terminal water level; $Z_{R,i}^{\text{end}}$ is the i th reservoir controlling terminal water level.

The minimum outflow and the outflow capacity constraints:

$$q_{R,i}^{\min} \leq q_{R,i}(t) \leq q_{R,i}[Z_{R,i}(t)] \tag{9}$$

where $q_{R,i}(t)$ is the i th reservoir outflow at time t ; $q_{R,i}^{\min}$ is the i th reservoir allowable minimum outflow at time t ; $q_{R,i}[Z_{R,i}(t)]$ is the i th reservoir outflow capacity corresponding to water level $Z_{R,i}(t)$ at time t .

The outflow amplitude constraint:

$$|q_{R,i}(t) - q_{R,i}(t - 1)| \leq \Delta q_{R,i} \tag{10}$$

where $\Delta q_{R,i}$ is the i th reservoir allowable amplitude of outflow.

The water balance constraint:

$$V_{R,i}(t) = V_{R,i}(t - 1) + \left[\frac{Q_{R,i}(t) + Q_{R,i}(t - 1)}{2} - \frac{q_{R,i}(t) + q_{R,i}(t - 1)}{2} \right] \cdot \Delta t \tag{11}$$

where $(t - 1)$ and t are the beginning and the end of time period t ; $Q_{R,i}$ and $q_{R,i}$ are the i th reservoir inflow and outflow; $V_{R,i}$ is the i th reservoir storage status; Δt is the time interval.

Constraints of rivers. River flood routing constraint, Muskingum method:

$$Q_{S,i}(t) = C0_i \cdot Q_{S,i-1}(t) + C1_i \cdot Q_{S,i-1}(t - 1) + C2_i \cdot Q_{S,i}(t - 1) \tag{12}$$

where $C0_i$, $C1_i$, $C2_i$ are the parameters of Muskingum of the i th river segment, meeting the relation: $C0_i + C1_i + C2_i = 1$; $Q_{S,i}$ and $Q_{S,i-1}$ are the discharge of the i th and $(i - 1)$ th cross section.

Safety discharge constraint at control section: after regulation of reservoir group and flood diversion of flood storage basin, the river discharge should be less than the safety discharge at the control section:

$$\sum_{i=1}^n q'_{R,i}(t) - \sum_{i=1}^m q'_{D,i}(t) + Q_V(t) \leq q_A \tag{13}$$

where $q'_{R,i}(t)$ and $q'_{D,i}(t)$ are the response process at control section from the i th reservoir outflow process and the i th flood storage basin diversion, respectively; $Q_V(t)$ is the interval flood process; q_A is safety discharge at control section.

Constraints of flood storage basin. The design inflow capacity constraint:

$$q_{D,i}(t) \leq q_{D,i}^{\text{design}} \tag{14}$$

where $q_{D,i}(t)$ is the calculated diversion of the i th flood storage basin at time t ; $q_{D,i}^{\text{design}}$ is the design diversion of the i th flood storage basin.

The design storage capacity constraint:

$$V_{D,i}(t) \leq V_{D,i}^{\text{design}} \tag{15}$$

where $V_{D,i}(t)$ is the flood storage amount of the i th flood storage basin at time t ; $V_{D,i}^{\text{design}}$ is the design storage capacity of the i th flood storage basin.

The water balance constraint:

$$V_{D,i}(t) = V_{D,i}(t - 1) + \frac{q_{D,i}(t) + q_{D,i}(t - 1)}{2} \cdot \Delta t \tag{16}$$

where $V_{D,i}$ and $q_{D,i}$ are the storage amount and the diversion of the i th flood storage basin; Δt is the time interval.

In addition, all the decision variables are non-negative constraints.

Decomposition–coordination model

The proposed multi-objective programming is difficult for directly calculating by a single method in mathematic. However, the programming issue meets the (two levels) original cubic triangle structure (refers to Mesarovic (1970) and Singhand & Titli (1978)) seen from spatial distribution. Thus, it can be solved by a decomposition and coordination method of large scale system theory. The key step for

applying this method is decoupling (relieve the coupling constraints), then, hierarchical structure and coordination approach are formed. This section includes two parts: (1) third-order hierarchical structure for the decomposition and coordination information after two levels decoupling; (2) components and calculation methods including three coordination models and corresponding coordination methods, two local optimization models, and corresponding calculation methods.

Third-order hierarchical structure

Among all the constraints, Equation (13) covers the joint action of reservoir group and flood storage basin, which is the unique coupling constraint of the two types of flood control projects. By adopting the model coordination method to select total diversion $W_D(t)$ in flood storage basin as coordinating variables to decouple Equation (13), constraint Equation (13) can be decoupled into two subsystem constraints for reservoir group and flood storage basin, as shown in Equations (17) and (18).

$$\sum_{i=1}^n q'_{R,i}(t) + Q_V(t) - q_A \leq W_D(t) \tag{17}$$

$$\sum_{i=1}^m q'_{D,i}(t) = W_D(t) \tag{18}$$

Then, Equations (17) and (18) are further decoupled separately by adopting objective coordination method to introduce Lagrange multiplier vectors $\lambda_R(t)$ and $\lambda_D(t)$ as coordinate variables (as seen in the sections *Reservoir group subsystem coordination model* and *Flood storage basin subsystem coordination model*). Finally, a third-order hierarchical structure is shown in Figure 1.

Components and calculation methods

Large scale system coordination model. The associated variables $W_D(t)$ are constantly adjusted as coordinating variables to achieve global optimum, according to the large scale system objective Equation (6) to establish coordination guidelines. The problem can be seen as an extreme value problem with independent variables $W_D(t)$, which can further be regarded as an unconstrained nonlinear programming problem, namely:

$$\min F = \alpha_R \cdot \left(-\frac{S_R}{n}\right) + \alpha_D \cdot \left(-\frac{C_D}{C_D^{\max}}\right) = F(W_D(t)) \tag{19}$$

Considering the physical meaning of $W_D(t)$, we have $W_D(t) \geq 0$. Gradient method was adopted to establish coordination guidelines:

$$W_D^{k+1}(t) = \max \left[W_D^k(t) + \sigma^k \cdot \frac{dF(W_D^k(t))}{dW_D^k(t)}, 0 \right] \tag{20}$$

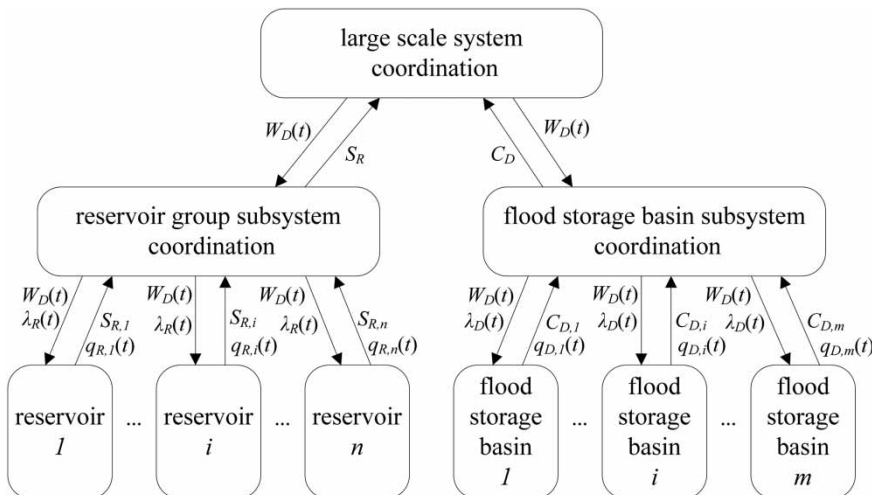


Figure 1 | The third-order hierarchical decomposition–coordination structure.

where k is the number of iterations; σ^k is the k th computation step.

There is no dominant function expression for $F(W_D(t))$, so it cannot be directly derivate with respect to $W_D(t)$. Take Equation (21) for difference calculation:

$$\frac{dF(W_D^k(t))}{dW_D^k(t)} = \frac{F^k - F^{k-1}}{W_D^k(t) - W_D^{k-1}(t)} \tag{21}$$

If iteration in large scale system coordination layer meets the condition $|W_D^{k+1}(t) - W_D^k(t)| \leq \varepsilon$ (where ε is iteration accuracy), the objective function reaches its optimization. If $\nabla W_D(t) = 0$, it means the global optimum can be achieved through the optimal operation of reservoir group without operation of flood storage basin, and may happen with a low discharge flood in basin, or floods occurred in the upper reach of reservoir, or α_R is smaller enough.

Reservoir group subsystem coordination model. The internal constraint in reservoir group subsystem is Equation (17). Based on large scale system objective coordination method, reservoir group subsystem Lagrange function can be described as Equation (22) by introducing Lagrange multiplier vectors $\lambda_R(t)$ and a combination joint constraint Equation (17) with reservoir group objective Equation (1):

$$L_R = \sum_{i=1}^n S_{R,i} + \sum_{t=1}^T \lambda_{R,t} \cdot \left[\sum_{i=1}^n q'_{R,i}(t) + Q_V(t) - q_A - W_D(t) \right] \tag{22}$$

According to the duality principle, the necessary condition of optimal solution is that (partial) derivative must be zero to solve this unconstrained nonlinear optimization problem. Thus, the gradient method was used to establish coordination guidelines:

$$\begin{aligned} \lambda_R^{k+1}(t) &= \lambda_R^k(t) + \sigma_R^k \cdot \frac{\partial L_R^k}{\partial \lambda_R^k(t)} \\ &= \lambda_R^k(t) + \sigma_R^k \cdot \left[\sum_{i=1}^n q'_{R,i}(t) + Q_V(t) - q_A - W_D(t) \right] \end{aligned} \tag{23}$$

Since Equation (17) is an inequality constraint ' \leq ', coordination guidelines can be established as Equation

(24) by satisfying the coordination equation $\lambda_R(t) \geq 0$ according to the duality principle and setting $\lambda_R^{k+1}(t) = 0$ as the time point meeting the constraint.

$$\lambda_R^{k+1}(t) = \max \left\{ \lambda_R^k(t) + \sigma_R^k \cdot \left[\sum_{i=1}^n q'_{R,i}(t) + Q_V(t) - q_A - W_D(t) \right], 0 \right\} \tag{24}$$

where k is the number of iterations; σ_R^k is the k th computation step.

If iteration in the reservoir group subsystem coordination layer meets the condition $|\lambda_R^{k+1}(t) - \lambda_R^k(t)| \leq \varepsilon_R$ (where ε_R is iteration accuracy), it may be concluded that the reservoir group subsystem objective function reaches optimization and the iteration calculation should be stopped.

Flood storage basin subsystem coordination model. Equation (18) is the internal constraint in flood storage basin subsystem. Based on large scale system objective coordination method, flood storage basin subsystem Lagrange function can be described as Equation (25) by introducing Lagrange multiplier vectors $\lambda_D(t)$ and combining joint constraint Equation (18) with flood storage basin objective Equation (3):

$$L_D = \sum_{i=1}^m C_{D,i} + \sum_{t=1}^T \lambda_{D,t} \cdot \left\{ \sum_{i=1}^m q'_{D,i}(t) - W_D(t) \right\} \tag{25}$$

According to the duality principle, the necessary condition of optimal solution is that (partial) derivative must be zero to solve this unconstrained nonlinear optimal problem. Thus, the gradient method was used to establish coordination guidelines:

$$\begin{aligned} \lambda_D^{k+1}(t) &= \lambda_D^k(t) + \sigma_D^k \cdot \frac{\partial L_D^k}{\partial \lambda_D^k(t)} \\ &= \lambda_D^k(t) + \sigma_D^k \cdot \left\{ \sum_{i=1}^m q'_{D,i}(t) - W_D(t) \right\} \end{aligned} \tag{26}$$

where k is the number of iterations; σ_D^k is the k th computation step.

If iteration in flood storage basin subsystem coordination layer meets the condition $|\lambda_D^{k+1}(t) - \lambda_D^k(t)| \leq \varepsilon_D$ (where ε_D is iteration accuracy), it may be concluded that

the flood storage basin subsystem objective function has reached optimization and the iteration calculation should be stopped.

Single reservoir operation. Set $\lambda_R(t)$ and $W_D(t)$ in the reservoir group subsystem coordination layer and Equation (22) can be rewritten into an additive separable form, as Equation (27) shown below.

$$\begin{aligned}
 L_R &= \sum_{i=1}^n S_{R,i} + \sum_{t=1}^T \lambda_R(t) \cdot \left[\sum_{i=1}^n q'_{R,i}(t) + Q_V(t) - q_A - W_D(t) \right] \\
 &= \sum_{i=1}^n \left\{ S_{R,i} + \sum_{t=1}^T \lambda_R(t) \cdot \left[q'_{R,i}(t) + \frac{Q_V(t) - q_A - W_D(t)}{n} \right] \right\} \quad (27)
 \end{aligned}$$

After eliminating constant term, operating objective function for the i th reservoir is shown in Equation (28).

$$\begin{aligned}
 \max F_{R,i} &= S_{R,i} + \sum_{t=1}^T \lambda_R(t) \cdot \left[q'_{R,i}(t) + \frac{Q_V(t) - q_A - W_D(t)}{n} \right] \\
 &= - \frac{\sum_{t=1}^T \max \{ [Q_{R,i}(t) - q_{R,i}(t)] \cdot \Delta t, 0 \}}{V_{R,i}^{\text{design}}} \\
 &\quad + \sum_{t=1}^T \lambda_R(t) \cdot \left[q'_{R,i}(t) + \frac{Q_V(t) - q_A - W_D(t)}{n} \right] \quad (28)
 \end{aligned}$$

The constraints for reservoir operation are Equations (7)–(11). The optimal operation belongs to a multi-stage decision problem, where stage variable is time t , decision variable is the i th reservoir outflow $q_{R,i}(t)$. Considering $q_{R,i}(t)$ and $q'_{R,i}(t)$ can meet Equation (12), namely, $q'_{R,i}(t) = C0_i \cdot q_{R,i}(t) + C1_i \cdot q_{R,i}(t - 1) + C2_i \cdot q'_{R,i}(t - 1)$, the solution for single reservoir optimal problem has backward effectiveness and the POA can be used to solve this problem.

Single flood storage basin operation. Set $\lambda_D(t)$ and $W_D(t)$ in the flood storage basin subsystem coordination layer, and Equation (25) can be rewritten into additive separable form, as Equation (29) shown below:

$$\begin{aligned}
 L_D &= \sum_{i=1}^m C_{D,i} + \sum_{t=1}^T \lambda_D(t) \cdot \left[\sum_{i=1}^m q'_{D,i}(t) - W_D(t) \right] \\
 &= \sum_{i=1}^m \left\{ C_{D,i} + \sum_{t=1}^T \lambda_D(t) \cdot \left[q'_{D,i}(t) - \frac{W_D(t)}{m} \right] \right\} \quad (29)
 \end{aligned}$$

After eliminating constant term, operating objective function for the i th flood storage basin is shown in Equation (30).

$$\begin{aligned}
 \min F_{D,i} &= C_{D,i} + \sum_{t=1}^T \lambda_D(t) \cdot \left[q'_{D,i}(t) - \frac{W_D(t)}{m} \right] \\
 &= u1_i \cdot \left[V_{D,i}^0 + \sum_{t=1}^T q_{D,i}(t) \cdot \Delta t \right] + u2_i \cdot \left[V_{D,i}^0 + \sum_{t=1}^T q_{D,i}(t) \cdot \Delta t \right]^2 \\
 &\quad + u3_i \cdot \left[V_{D,i}^0 + \sum_{t=1}^T q_{D,i}(t) \cdot \Delta t \right]^3 + \sum_{t=1}^T \lambda_D(t) \cdot \left[q'_{D,i}(t) - \frac{W_D(t)}{m} \right] \quad (30)
 \end{aligned}$$

The constraints for flood storage basin operation are Equations (14)–(16). As $q_{D,i}(t)$ and $q'_{D,i}(t)$ meet Equation (12), that is, $q'_{D,i}(t) = C0_i \cdot q_{D,i}(t) + C1_i \cdot q_{D,i}(t - 1) + C2_i \cdot q'_{D,i}(t - 1)$, the solution for single flood storage basin optimal problem has backward effectiveness and POA can be used to solve this problem. In the case study, we can ignore Equation (12), that is, $q'_{D,i}(t) = q_{D,i}(t)$, due to the small distance between flood storage basin and control section. The backward effectiveness problem does not exist at this time, and other methods, such as dynamic programming (DP) method, can be used to solve this problem.

Procedures of real-time operation

In this section, we present the procedures of application of the decomposition–coordination model for real-time operation in a reservoir group and flood storage basin. Figure 2 shows the flowchart of the proposed methodology with a series of repetitive calculation steps in each part. The main steps are described in the following.

- Step 1: Start real-time operation analysis.
- Step 2: Receive and renew the latest hydrological observed information and hydrological forecasting information at current time, including start water level $Z_{R,i}(1)$ at current time in reservoir, reservoir inflow process $Q_{R,i}(t)$, interval flood process $Q_V(t)$, initial water volume $V_{D,i}(1)$ at current time in flood storage basin, and water level at current time at downstream control section.
- Step 3: Input decision control information including weighting coefficients α_R and α_D (by decision-makers), the length of time period T , time interval Δt , flood routing

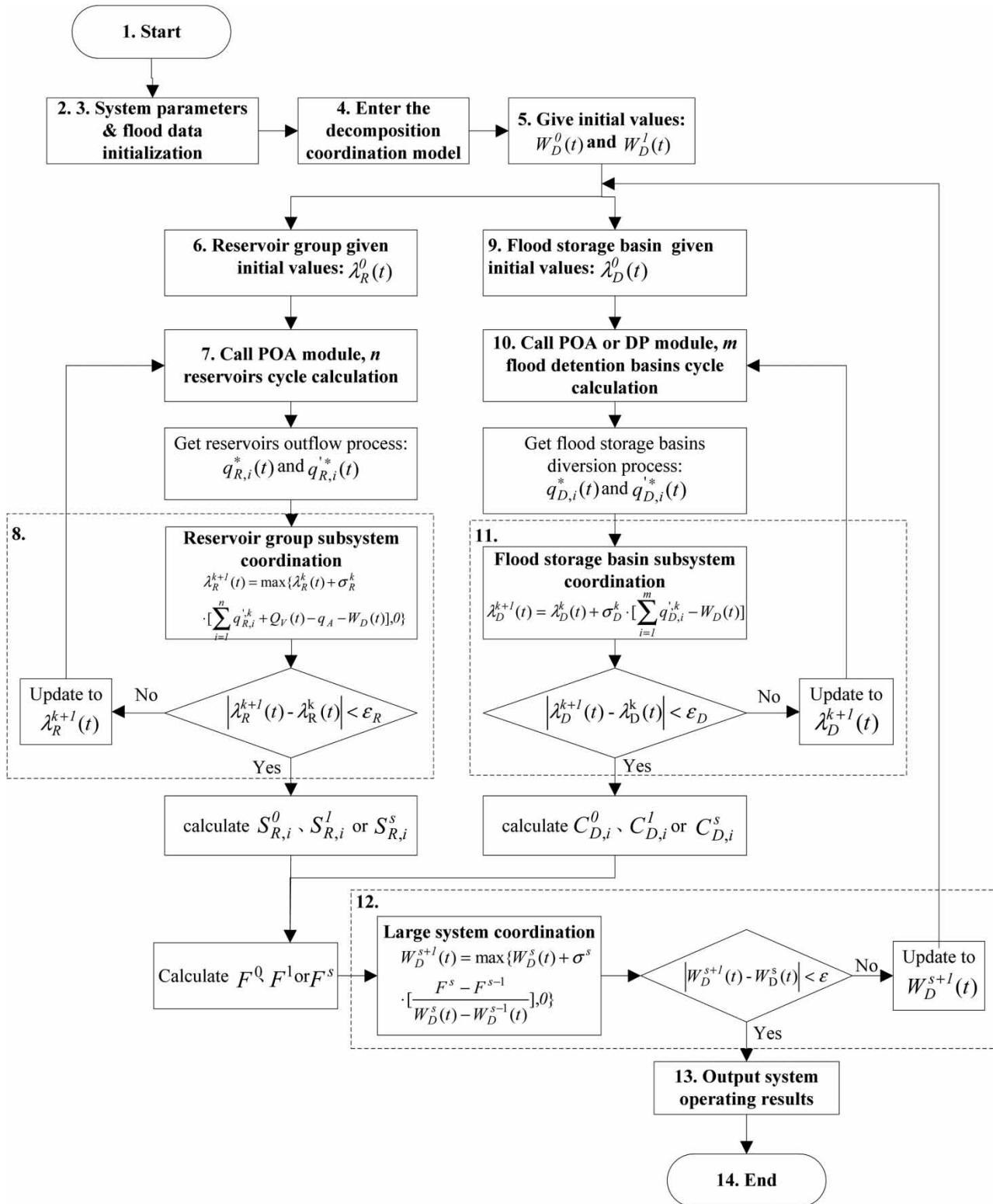


Figure 2 | The large scale system calculation flowchart.

coefficients $C0_i, C1_i, C2_i$, safety discharge q_A at control section, the various control water levels and releases ($Z_{R,i}^{\min}, Z_{R,i}^{\max}, Z_{R,i}^{\text{end}}, q_{R,i}^{\min}, \Delta q_{R,i}$) in reservoir, the design diversion flow $q_{D,i}^{\text{design}}$, the design storage volume $V_{D,i}^{\text{design}}$, and fitting coefficients ($C_i, u1_i, u2_i, u3_i$) in flood storage basin.

Step 4: Apply the decomposition–coordination model for real-time operation in reservoir group and flood storage basin.

Step 5: Given the initial values of $W_D^0(t)$ and $W_D^1(t)$, a recommended approach is described as: (1) calculate the excess flood process in natural state (without reservoir group and flood storage basin operation) at control section, denoted as $WTT(t)$. Thus,

$$WTT(t) = \max \left\{ \sum_{i=1}^n Q'_{R,i}(t) + Q_V(t) - q_A, 0 \right\} \quad t \in [1, T],$$

where $Q'_{R,i}(t)$ is the response process at control section from the i th reservoir inflow $Q_{R,i}(t)$; (2) calculate the initial variables,

$$\begin{cases} W_D^0(t) = \alpha \cdot WTT(t) \\ W_D^1(t) = \beta \cdot WTT(t) \end{cases}$$

where $\alpha, \beta \in (0, 1)$ and $\alpha \neq \beta$.

Step 6: Start joint operation in reservoir group. Given the initial values of $\lambda_R^0(t)$, a recommended approach is

$$\lambda_R^0(t) = \begin{cases} a, & WTT(t) > 0 \\ 0, & WTT(t) = 0 \end{cases}, \text{ where } a > 0.$$

Step 7: Call the POA calculation module to do local optimization, n reservoirs are calculated separately (as seen in the section *Single reservoir operation*).

Step 8: Judge the convergence criteria in reservoir group (as seen in the section *Reservoir group subsystem coordination model*). If the convergence criteria are satisfied, then continue the calculation; otherwise, renew the coordinating information $\lambda_R(t)$, then return to step 7.

Step 9: Start joint operation in flood storage basin. Given the initial values of $\lambda_D^0(t)$, a recommended approach is

$$\lambda_D^0(t) = \begin{cases} b, & WTT(t) > 0 \\ 0, & WTT(t) = 0 \end{cases} \quad \text{where } b > 0.$$

Step 10: Call the POA or DP calculation module to do local optimization, m flood storage basins are calculated

separately (as seen in section *Single flood storage basin operation*).

Step 11: Judge the convergence criteria in flood storage basin (as seen in the section *Flood storage basin subsystem coordination model*). If the convergence criteria are satisfied, then continue the calculation; otherwise, renew the coordinating information $\lambda_D(t)$, then return to step 10.

Step 12: Judge the convergence criteria in large scale system (as seen in the section *Large scale system coordination model*). If the convergence criteria are satisfied, then continue the calculation; otherwise, renew the coordinating information $W_D(t)$, then return to step 6.

Step 13: Output the optimal calculation results including the optimal release process in each reservoir, the optimal diversion process in each flood storage basin, and the final flow synthesis process at downstream control section.

Step 14: End real-time operation analysis.

Notes: The proposed calculation procedures are implemented by the support of computer programming language (Visual Basic 6.0) and database technology (SQL 2008). The initial values of $W_D^0(t)$, $W_D^1(t)$, $\lambda_R^0(t)$, and $\lambda_D^0(t)$ will directly influence the calculation speed and convergence quality, which deserves further study. In this paper, an approach for determining the initial values of the four variables is given for a reference.

STUDY AREA AND DATA

Huaihe River Basin, located between the Yangtze River and Yellow River in China, belongs to a warm temperate semi-humid monsoon climate zone and has continental climate characteristics. Large reservoirs and flood storage basin projects above the Lutaizi station are distributed from upstream to downstream, and can be considered as a complex joint flood control system with reservoirs, rivers, and flood storage basins.

Figure 3 shows the location of the main reservoirs and flood storage basins in the middle reaches of Huaihe River Basin, where Lutaizi is the control section. In the upstream, there are four large reservoirs, Nianyushan, Meishan, Xianhongdian, and Fozilin, and three important flood storage basins near the control section, Qiuji Lake, Jiangtan Lake and Chengdong Lake, and also three main tributaries, the Ying River, Shi-guan River, and Pi River.

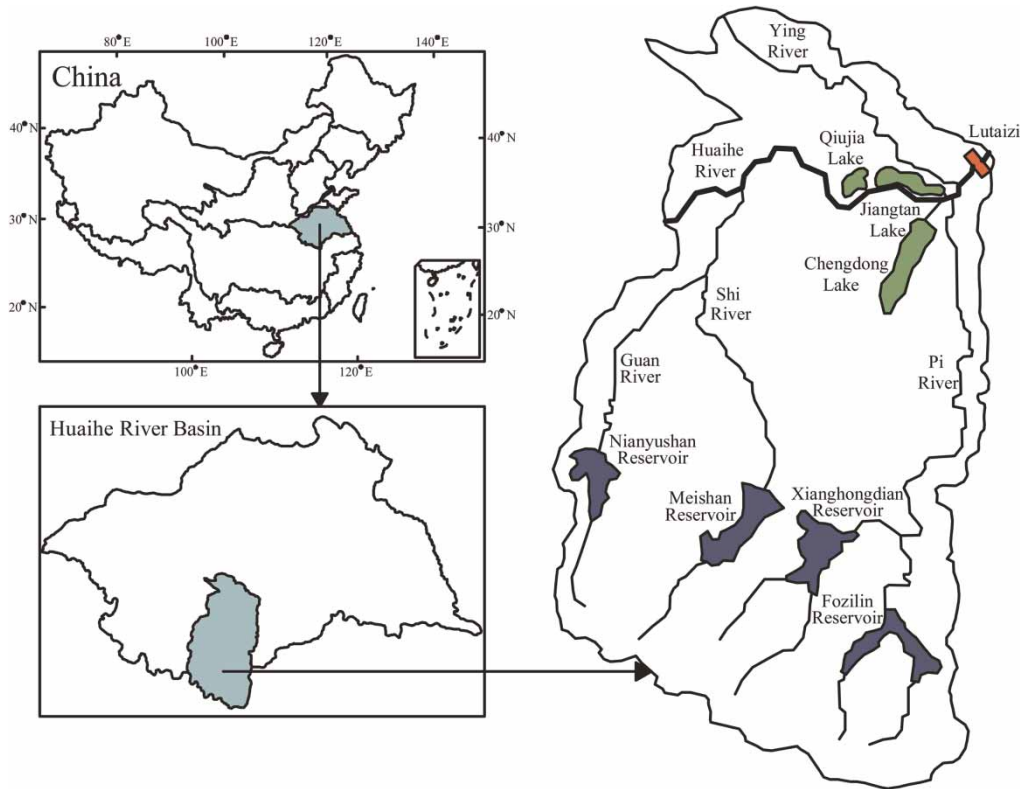


Figure 3 | The main reservoirs and flood storage basins distribution in the middle reaches of Huaihe River Basin.

The flood in July 2007 is used as the case study. The inflow flood process of four reservoirs, interval flood process between reservoirs and Lutaizi, flood process at Lutaizi and each river flood routing parameters are known. The safety discharge at Lutaizi control section is $7,500 \text{ m}^3/\text{s}$, and the time interval is 3 h.

The proposed decomposition–coordination model in the reservoir group and flood storage basin was used for joint flood control. Reservoir group and flood storage basin operating control parameters are shown in Tables 1 and 2. The flood routing is not considered as the three flood storage basins are

close to Lutaizi control section. Downstream flood routing parameters of the four reservoirs are shown in Table 3.

RESULTS AND DISCUSSION

Large scale system joint operation results are shown in Table 4 and Figures 4–7.

Table 4 lists large scale system joint operation results under 20 weight programs, which basically reflect the non-inferior solutions in the two contradictory subsystem

Table 1 | Reservoir operation control parameters

Reservoirs	Start water level $Z_{R,i}(1)/\text{m}$	Terminal water level $Z_{R,i}^{\text{end}}/\text{m}$	Lowest water level $Z_{R,i}^{\text{min}}/\text{m}$	Highest water level $Z_{R,i}^{\text{max}}/\text{m}$	The minimum discharge $q_{R,i}^{\text{min}}/\text{m}^3/\text{s}$	Outflow allowable amplitude $\Delta q_{R,i}/\text{m}^3/\text{s}$
Nianyushan	106.3	106.5	105.8	114.5	60	1,000
Meishan	128.8	129.0	125.3	137.7	100	1,000
Xianghongdian	131.2	131.5	123.0	141.0	100	1,000
Fozilin	117.8	117.8	117.6	125.7	20	1,000

Table 2 | Flood storage basin operation control parameters

Flood storage basins	Initial water volume $V_{D,i}(1)/10^6 \text{ m}^3$	Design storage capacity $V_{D,i}^{\text{design}}/10^6 \text{ m}^3$	Design diversion flow $q_{D,i}^{\text{design}}/\text{m}^3/\text{s}$	Fitting coefficient			
				C_i	$u1_i$	$u2_i$	$u3_i$
Qiuja Lake	86	194	1,200	1.05	-7.3019	16.5970	-5.3486
Jiangtang Lake	324	860	3,400	0.23	-0.3572	0.7553	-0.0577
Chengdong Lake	628	1,590	1,800	1.51	-1.5522	0.4919	-0.0187

Table 3 | River flood routing parameters

Items	$C0_i$	$C1_i$	$C2_i$	Nianyushan to Lutaizi	Meishan to Lutaizi	Xianghongdian to Lutaizi	Fozilin to Lutaizi
Parameters/Reach numbers	0.2	0.6	0.2	18	17	15	15

problems in this large scale system. Large scale system target values are the numerical significance reflected by combining the two contradictory subsystem problems by weighting method, which vary with the weight ratio. In this study, the start water level in each reservoir is real-time status water level, the group reservoir subsystem safety ranges from 2.90 to 3.19. The small variation range indicated inflow water volume is relatively small for each reservoir, each flood storage basin has enough surplus flood storage capacity, and the joint operation can be achieved by simply opening Qiuja Lake to store excess flood. Flood storage basin subsystem loss is located between 0 and 9.26, which indicates that total diversion flood volume is not large.

Figure 4 shows that reservoir group subsystem safety increases with the increase of its own weights, which meets positive correlation. The larger reservoir group weight means the more important reservoir group subsystem safety, thus, the smaller flood control storage needed in the reservoir group, and the larger reservoir group subsystem safety. In this study, when reservoir group weight $\alpha_R \in [0, 0.53]$, only the reservoir group joint operation is needed to control flood and guarantee safety discharge at control section, the corresponding reservoir group subsystem safety is 2.90. When reservoir group weight $\alpha_R \in (0.53, 1]$, we need reservoir group and flood storage basin joint operation to guarantee safety discharge at control section due to the minimum of large scale system objective function. The reservoir group weight 0.53 is a turning

point, reservoir group subsystem safety gradually increases with the increase of reservoir group weights.

Figure 5 demonstrates that flood storage basin subsystem losses decrease with the increase of its own weights, which meets negative correlation. The larger flood storage basin weight means the more important flood storage basin subsystem losses. As a result, the smaller diversion volume needed in flood storage basin, and the smaller flood storage basin subsystem losses. In this study, when flood storage basin weight $\alpha_D \in [0, 0.47]$, we need reservoir group and flood storage basin joint operation to guarantee safety discharge at control section, flood storage basin subsystem losses gradually decrease with the increase of flood storage basin weights. Meanwhile, flood storage basin weight 0.47 is a turning point, there is a jumping phenomenon at turning point in Figure 5, which resulted from initial water volume in flood storage basin as shown in Equation (5), that is, flood storage basin losses are determined by both initial water volume and diversion volume, and can also be corresponding to the constant of once diversion losses. When flood storage basin weight $\alpha_D \in (0.47, 1]$, flood control task can be done independently by reservoir group without the use of flood storage basins. Thus, flood storage basin subsystem loss is 0 at this time.

Figure 6 presents the non-inferior solutions between reservoir group subsystem safety and flood storage basin subsystem losses in this large scale system. In this study, when reservoir group weight is less than 0.53, namely

Table 4 | The large scale system joint operation results

Program number	Weight distribution	Reservoir safety				Reservoir group subsystem safety	Flood storage basin losses			Flood storage basin subsystem losses	Total diversion/ 10 ⁶ m ³	Large scale system target value
		Nianyushan	Meishan	Xianghongdian	Fozilin		Qiuja Lake	Jiangtan Lake	Chengdong Lake			
1	0,1	0.76	0.67	0.56	0.91	2.90	0	0	0	0	0	0
2	0.1,0.9	0.76	0.67	0.56	0.91	2.90	0	0	0	0	0	-0.0725
3	0.2,0.8	0.76	0.67	0.56	0.91	2.90	0	0	0	0	0	-0.1450
4	0.3,0.7	0.76	0.67	0.56	0.91	2.90	0	0	0	0	0	-0.2175
5	0.4,0.6	0.76	0.67	0.56	0.91	2.90	0	0	0	0	0	-0.2900
6	0.5,0.5	0.76	0.67	0.56	0.91	2.90	0	0	0	0	0	-0.3625
7	0.51,0.49	0.760	0.670	0.560	0.910	2.900	0	0	0	0	0	-0.3698
8	0.52,0.48	0.760	0.670	0.560	0.910	2.900	0	0	0	0	0	-0.3770
9	0.53,0.47	0.762	0.672	0.562	0.912	2.908	3.65	0	0	3.65	0.11	-0.3527
10	0.54,0.46	0.764	0.674	0.564	0.914	2.916	3.81	0	0	3.81	1.78	-0.3604
11	0.55,0.45	0.766	0.676	0.566	0.915	2.923	3.97	0	0	3.97	3.47	-0.3680
12	0.56,0.44	0.768	0.678	0.567	0.917	2.930	4.13	0	0	4.13	5.15	-0.3757
13	0.57,0.43	0.770	0.680	0.569	0.919	2.938	4.29	0	0	4.29	6.80	-0.3836
14	0.58,0.42	0.771	0.682	0.571	0.921	2.945	4.45	0	0	4.45	8.42	-0.3915
15	0.59,0.41	0.773	0.684	0.573	0.923	2.953	4.61	0	0	4.61	10.08	-0.3997
16	0.6,0.4	0.77	0.69	0.58	0.92	2.96	4.77	0	0	4.77	11.68	-0.4078
17	0.7,0.3	0.78	0.71	0.59	0.94	3.02	5.89	0	0	5.89	23.06	-0.4949
18	0.8,0.2	0.80	0.72	0.61	0.95	3.08	7.02	0	0	7.02	34.83	-0.5893
19	0.9,0.1	0.82	0.73	0.62	0.97	3.14	8.14	0	0	8.14	47.35	-0.6910
20	1,0	0.84	0.74	0.63	0.98	3.19	9.26	0	0	9.26	62.06	-0.7975

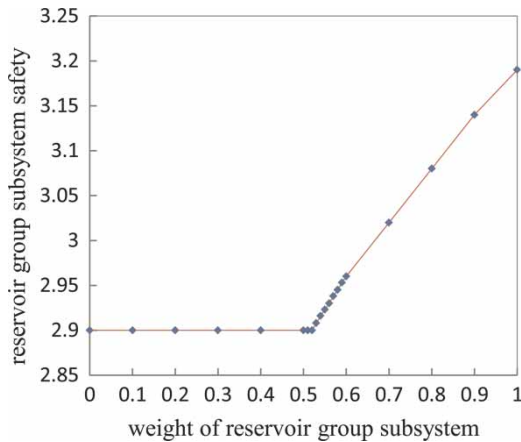


Figure 4 | Relation between reservoir group subsystem safety and its own weight.

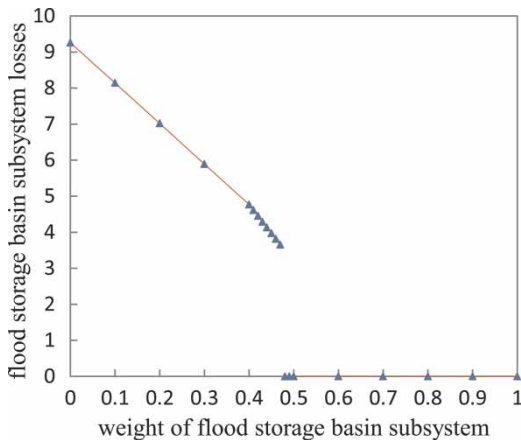


Figure 5 | Relation between flood storage basin subsystem losses and its own weight.

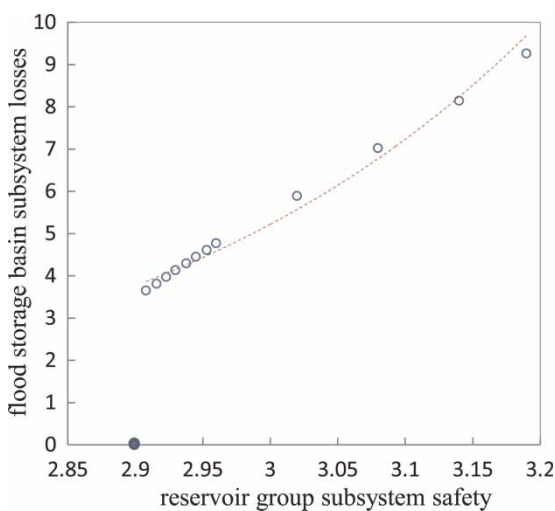


Figure 6 | Relation between reservoir group subsystem safety and flood storage basin subsystem losses in different weights.

flood storage basin weight is greater than 0.47, the relationship between the two subsystem problems is a point, as shown with the solid point in Figure 6; when reservoir group weight is greater than 0.53, namely flood storage basin weight is less than 0.47, the relationship between the two subsystem problems is a positive correlation, constituting the non-inferior solution space, as shown with the hollow points and dotted line in Figure 6. In real-time operation, based on the actual flood situation, expertise and other factors, decision-makers choose appropriate weight ratio under a certain decision preference for joint control flood to gain system flood control benefit. This model has a better decision adaptability than a single-objective optimization model.

Figure 7 demonstrates that the safety discharge at Lutaizi control section can be guaranteed by undertaking the excess flood process through four reservoirs to effectively reduce flood peak and Qiuja Lake to store excess flood in the condition of large scale system global optimum. Results show that the third-order hierarchical decomposition–coordination model is effective.

CONCLUSIONS

A third-order hierarchical decomposition–coordination model for joint flood control of reservoir group and flood storage basin was proposed in this paper and the optimal calculation method and coordination method based on large scale system theory was suggested. The model was applied for real-time flood control operation in the middle reaches of Huaihe River and it has the following characteristics:

- The model decomposes the complex flood control system into several subsystems in accordance with spatial distribution. It has a clear hierarchical structure and independent solution method, which can effectively reduce the large scale system dimension, to a certain extent, and avoid the ‘dimensions disaster’ problem.
- The model is flexible. Large scale system theory guarantees different optimal orders and different optimal methods among different subsystems which are

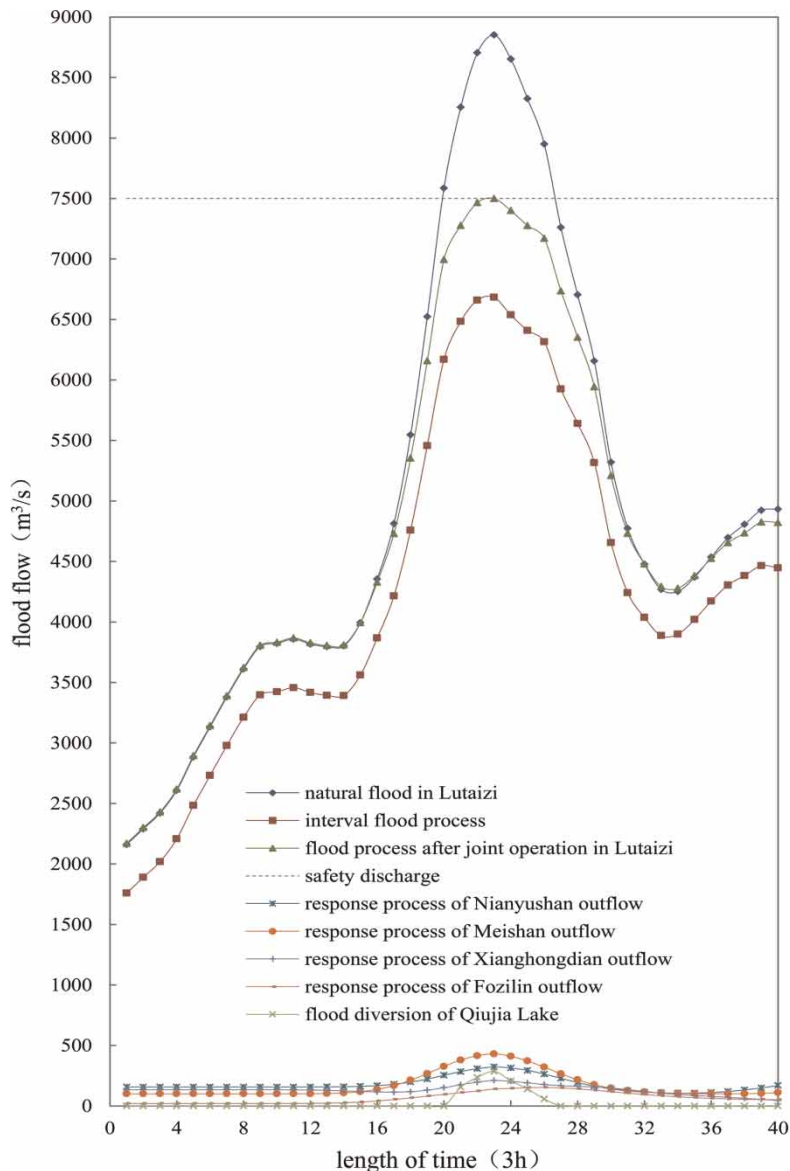


Figure 7 | Flood control joint operation results of program 16.

decomposed from complex large scale system. The specific form of model and solution method for reservoir, flood routing, and flood storage basin can be chosen flexibly, which is convenient for subsystem independent optimal calculation and similar flood control system application.

- The model has some versatility and maneuverability. Considering the requirements of real-time flood control operation, the model supports decision-making of

human–computer interactions and maximizes the benefits in flood control and disaster mitigation through the rolling flood control operation.

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