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Improved multi-reservoir operation rules of water supply system based on target storage curves

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ABSTRACT

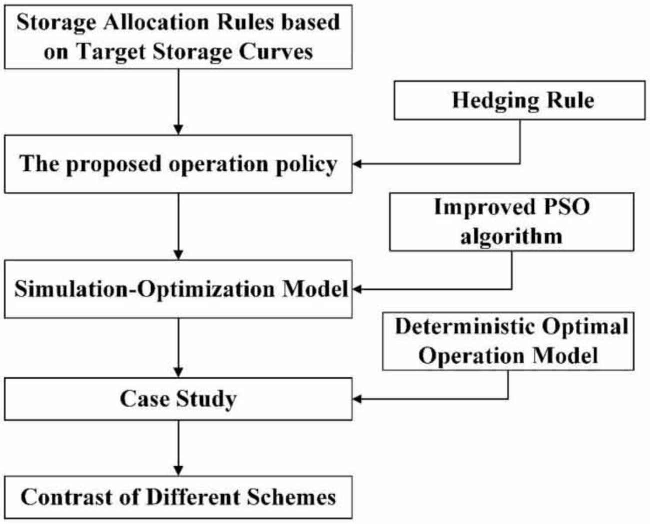
This paper proposes a multi-reservoir operating policy for water supply by combining target storage curves with the hedging rule. The curves are derived to solve the allocation problem of joint demand. There are three steps in the proposed methodology: Firstly, the optimal release schedule using dynamic programming to solve a long-term operation model is established, from which the suitable forms of target storage curves are identified. Secondly, a simulation and optimization model is built to identify the key points of the curves with the hedging rule based on aggregated reservoir using improved particle swarm optimization (IPSO). Finally, synthetic inflow series is used to test and verify the efficiency of the proposed rule. The water-supply multi-reservoir system located in the Liaoning province of China is employed as a case study to verify the effect of the proposed operating policy and the efficiency of target storage curves. The results indicate that the proposed operating policy is suitable to handle the multi-reservoir operation problem, especially for periods of drought. The target storage curves also show improved performance for distribution of system storages.

Key words: hedging rule, improved particle swarm optimization, multi-reservoir operating policy, simulation and optimization model, target storage curves

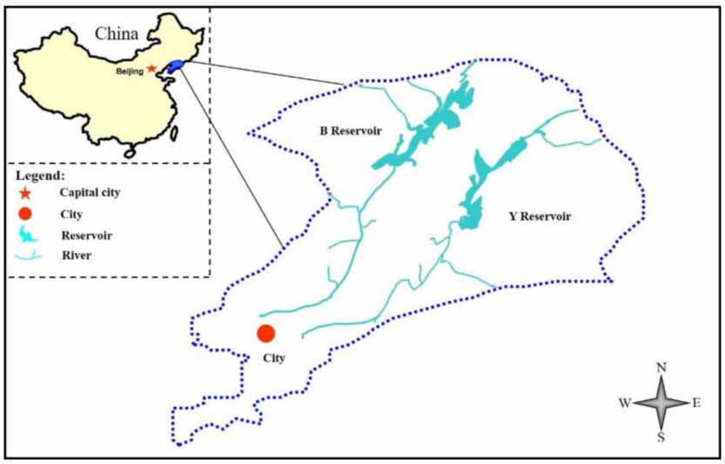
HIGHLIGHTS

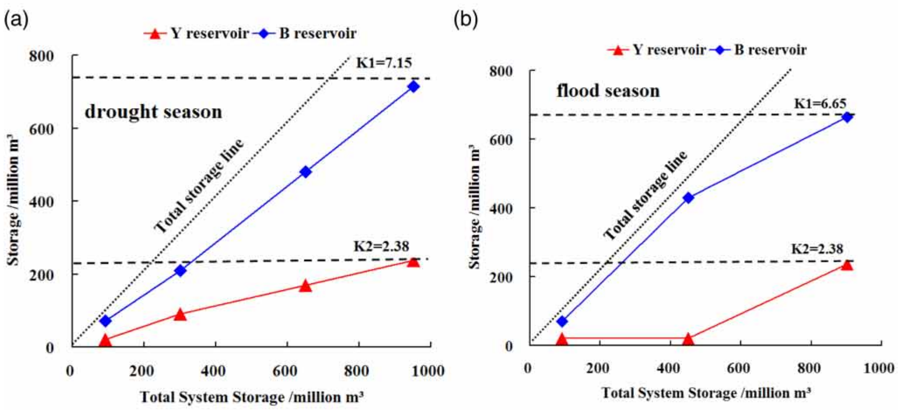
- A multi-reservoir operating policy by combining target storage curves with the hedging rule is proposed.
- The results indicate that the optimized operation solution is suitable to minimize the shortage index and maximize the assurance rate.

GRAPHICAL ABSTRACT



(1) the flowchart of proposed operation rules based on Target Storage Curves





Target storage curves for drought season Target storage curves for flood season.

(2) The application of proposed method in Liaoning province of China.

1. INTRODUCTION

Reservoirs are one of the most efficient methods of integrated water resource development and management (Liu *et al.* 2020; Kumar & Yadav 2022). The operation of a multi-reservoir system can be coordinated to take advantage of reservoirs with different storage capacities along diverse streams. The optimal joint operation rule enables the full use of the system to spatially and temporarily redistribute water resources with the goal of maximizing economic benefits while preventing a severe water shortage (Labadie 2004; Tian *et al.* 2019).

Operating rules are always identified by using either fitting or simulation-based optimization methods (Celeste & Billib 2009). Deterministic optimization techniques, including linear programming (LP), nonlinear programming (NLP) and dynamic programming (DP), can be implemented to produce samples for fitting (Rani & Moreira 2010). Although the fitting method helps identify the forms of the operating rules, this maximum goodness-of-fit criterion for selecting operating rules does not always produce the best operating rules as measured by simulation in actual operation. Simulation-based optimization methods, namely parameterization–simulation–optimization (Koutsoyiannis & Economou 2003), are one of the most important and efficient methods of deriving reservoir operating rules within an implicit stochastic optimization (ISO) framework (Celeste & Billib 2009; Rani & Moreira 2010), which is often applied to deriving the optimal operating rules for the long-term operation. For this method, most aspects of stochastic inflows, including spatial and temporal correlations among unregulated runoff, are implicitly incorporated into modeling by inputting observed or synthetic samples. A method involving optimization, fitting and refinement has been adopted to obtain the optimal refill rules for China's Three Gorges Reservoir (Liu *et al.* 2006).

For water supply systems with parallel reservoirs supplying joint demands, that is, downstream demands that can be satisfied by any one or more of the multiple reservoirs, the space rule and NYC rule are usually used (Oliveira & Loucks 1997). The space rule attempts to equalize the ratio of available space in each of parallel reservoirs at the end of a period to the expected inflow into each reservoir during the reminder of the refill season, while the NYC rule attempts to equalize the probability of filling of each reservoir (Clark 1956). Both the space and the NYC rules attempt to avoid the situation of having some reservoirs spilling while the others remain unfilled (Oliveira & Loucks 1997), but they cannot be applied directly and do not provide clear indications on how to operate the complex system that has several purposes and heavy constraints.

Target storage curves or balancing curves are proposed by Liu (1973) for the management of spatial distribution of reservoir storage volumes within a multiple reservoir system. Stochastic Dynamic Programming (SDP) is a frequently-used fitting method for deriving target storage curves which can be represented by curve estimation of the optimal operation (Perera & Codner 1996). As is mentioned above, the fitting method does not have good performance in actual operation. Oliveira & Loucks (1997) used the optimization method for deriving balancing curves with the assumption of piecewise linear function defined by five coordinates, which is the lack of theoretical analysis based on an optimal release schedule. They can hardly cooperate with the complex system with side demand or constraint of maximum shortage of water supply.

Under these conditions, the amount of total release should be determined as a premise. The hedging rule is the kind of operating rule used for rationing water supply during droughts, which would rather incur a sequence of smaller shortages than one catastrophic shortage (Liu *et al.* 2020). Many studies on the hedging rule have been made by researchers (Yeh 1985; Shih & ReVelle 1994; Srinivasan & Philipose 1996; Lund & Guzman 1999; Tu *et al.* 2003; Guo *et al.* 2004). The aggregation method is an effective approach for transforming a multi-reservoir system into an equivalent reservoir (Brandão 2010), which is applied to simplify multi-reservoir systems by building a virtual reservoir in this study. The aggregated reservoir method has good performance of regarding suitable total releases in water supply systems.

This study was conducted to extend the joint operating policies for multiple reservoir systems that are specified by the hedging rule based on an equivalent reservoir, which define the total combined release as a function of the total storage and time of year, together with target storage curves indicating the ideal distribution of storage levels among the reservoirs. The suitable forms of target storage curves are identified based on the optimal release schedule obtained from a deterministic optimal operation model. A simulation-based optimization model was then established to minimize the shortage index and maximize the assurance rate. The improved particle swarm algorithms (Jiang *et al.* 2007) in combination with the simulation model are employed to optimize the decision variables, which include the key points of hedging curves and target storage curves. Additionally, reservoir simulation may be based on both the observed inflows and synthetic inflows so that the efficiency of the operating rules may be further tested and compared (Koutsoyiannis & Economou 2003). China's water supply system of reservoirs in parallel, which include the B and Y reservoirs, was selected as a case study. In addition, two other schemes, parametric rules and compensation adjustment rules, were also implemented to simulate the operation of the system for comparative purposes.

2. METHODOLOGY AND PROCEDURE

There were five steps used to derive the joint operating rule curves:

1. A deterministic long-term optimal operation model was used to produce the optimal storage of individual reservoir for water supply system by using DP optimization, by analyzing which the suitable forms of target storage curves were identified (Section 2.1).
2. The Hedging rule for multipurpose water supply demands based on the aggregated reservoir was conducted to specify the total amount of release to the joint demands while the desired release for local water demand is connected with specified individual reservoir (Section 2.2).
3. The target storage curves are presented as the mean of these distributions for various total system storages (Section 2.3).
4. Coordinate parameters instead of key points of target storage curves and hedging rule curves are tested through simulation and then refined with simulation-based optimization using improved particle swarm algorithms (Section 2.4).
5. The synthetic inflow series generated from hydrologic simulation were used to test and verify the joint operating rule (Section 2.5).

2.1. Deterministic optimal operation model

2.1.1. Objective function and constraints

Water shortage is a major socioeconomic problem. From the viewpoint of water-resources planning and management, an effective water-shortage index should capture such basic characteristics as its frequency, intensity, and duration. Moreover, a shortage index should serve as an indicator of the social tolerance limits to water shortage. To establish the objective function of the model, we use modified shortage index (MSI) developed by Hsu and Cheng (Hsu 1995) to characterize the extremely uneven distribution of the hydrological conditions. The MSI is modified from the shortage index (SI) developed by the U.S. Army Corps of Engineers (Hydraulic Engineering Center (HEC) 1975). The MSI not only incorporates the basic shortage characteristics, but also emphasizes the consequential socioeconomic impacts of water shortage. The MSI can be expressed as follows:

$$MSI = \frac{100}{T}\sum_{t=1}^{T}\left(\frac{TS_t}{TD_t}\right)^2 \tag{1}$$

$$TS_t = \begin{cases} \left|TD_t - \sum_{i=1}^{N} R_{it}\right| & if \ \sum_{i=1}^{N} R_{it} < TD_t \\ 0 & if \ \sum_{i=1}^{N} R_{it} \geq TD_t \end{cases} \tag{2}$$

where TS_t and TD_t are total shortage and total demand in the tth period; T and N are total number of time periods and number of reservoirs; R_{it} is actual release of reservoir i in tth period. Additionally, a weighting method is used to specify the hierarchy of the MSI for different types of water demand (G is total number). Then the optimization objective can be characterized as,

$$f = \min\left\{\sum_{j=1}^{G} w_j \cdot MSI_j\right\} \tag{3}$$

The following constraints have been applied to the model:

1. The water balance equation.

$$S_{i,t+1} = S_{it} + I_{it} - R_{it} - L_{it} - SP_{it} \tag{4}$$

2. The water storage capacity constraints.

$$S_{it}^{\min} \leq S_{it} \leq S_{it}^{\max} \tag{5}$$

3. The reliability constraint.

$$\frac{\#\left(\sum_{i=1}^{N} R_{it} \geq D_t\right)}{T} \geq P_0 \tag{6}$$

4. The release constraints.

$$R_{it}^{\min} \leq R_{it} \leq R_{it}^{\max} \tag{7}$$

5. The reservoir states at the initial and final time.

$$S_{i1} = S_i^b \;,\; S_{i,T+1} = S_i^e \tag{8}$$

where S_{it} and S_{i+1} are the initial and final water storages of reservoir i at time period t, respectively; I_{it} and R_{it} are the inflow and release of reservoir i during time period t, respectively; $S_{it}^{\min}$ and $S_{it}^{\max}$ are the minimum and maximum allowable water storage for reservoir i during time period t, respectively. #() counts the number of times that the total release is greater than or equal to the systems' joint demand D_t. P_0 is the designed assurance rate. L_{it} is the total loss due to evaporation and leakages; SP_{it} is the reservoir spill; S_i^b and S_i^e are the reservoir storage at the initial and final time period, respectively. $R_{it}^{\min}$ denotes the minimum reservoir release subject to downstream irrigation, water supply, shipping and ecology, and $R_{it}^{\max}$ denotes the maximum reservoir release, which depends upon flood control and sluice release capacity.

2.1.2. Optimization method

As the above deterministic optimization model for reservoirs is a multistage problem, it is easily solved by using the DP algorithm. Equations (3) and (1) can also be combined into a more intuitive objective function as follows:

$$\min \quad \sum_{j=1}^{G} w_j * \sum_{t=1}^{T} \left(\left(\frac{TS_t}{TD_t} \right)^2 + g\left(\sum_{i=1}^{N} R_{it} \right) \right)_j \tag{9}$$

where $g\left(\sum_{i=1}^{N} R_{it}\right)$ is a penalty function defined as follows:

$$g\left(\sum_{i=1}^{N} R_{it}\right) = \begin{cases} k\left(D_t - \sum_{i=1}^{N} R_{it}\right)^{\alpha}, & \sum_{i=1}^{N} R_{it} < D_t \\ 0, \ \sum_{i=1}^{N} R_{it} \geq D_t \end{cases} \tag{10}$$

where k and α are both adjustable positive constants that enable the assurance rate of water supply (Equation (6)) to meet the constraint.

To resolve the curse of dimensionality, modified dynamic programming algorithms such as discrete differential dynamic programming (DDDP), dynamic programming successive approximation (DPSA) and the progressive optimality algorithm (POA) are often used to identify the near-optimal solution (Celeste & Billib 2009).

2.2. Hedging rule based on the aggregation reservoir

For joint water demands that can be satisfied by any individual reservoir, the aggregation reservoir is established to contribute a hedging rule for water supply. Assumption of three planned joint demand $D_{it}(i = 1,2,3)$, different kind of water demand requires different reliability. The order of priority from highest to lowest is D_{1t}, D_{2t}, D_{3t}. The corresponding threshold vectors are set Z_i, where $z_{1t} \leq z_{2t} \leq z_{3t}$ exists all the time. As shown in Figure 1, Z_i divides water space of the aggregation reservoir into four areas. To decide the total amount of joint demand using the hedging rule in a different area can be expressed mathematically as,

$$RJ_t = \begin{cases} D_{1t} + D_{2t} + D_{3t} & ; \ V_t \in zone\ \text{I} \\ D_{1t}*\beta_1 + D_{2t} + D_{3t} & ; \ V_t \in zone\ \text{II} \\ D_{1t}*\beta_1 + D_{2t}*\beta_2 + D_{3t} & ; \ V_t \in zone\ \text{III} \\ D_{1t}*\beta_1 + D_{2t}*\beta_2 + D_{3t}*\beta_3 & ; \ V_t \in zone\ \text{IV} \end{cases} \tag{11}$$

where RJ_t is the total amount of water required to supply joint demand at time period t, while $V_{\max}$ and $V_{\min}$ denote the maximum and minimum storage capacities of the aggregation reservoir respectively. V_t is the initial water storage in the aggregation reservoir at time period t. β_i is the rationing factor for hedging. The value of rationing factors can be obtained either by optimization or according to the experts' knowledge.

2.3. Storage allocation rules based on target storage curves

The real storage S_{it} is generally different from the target storage $\hat{S}_{it}$ because of the physical constraints that were not considered in the determination of $\hat{S}_{it}$. Target storage curves define the spatial distribution of reservoir storage volumes within a multiple reservoir system. They can be expressed mathematically as follows:

$$S_i^* = f(V) \tag{12}$$

$$s.t. \quad V = \sum_{i}^{N} (BS_i + I_i - L_i - SP_i) - R \tag{13}$$

$$\sum_{i=1}^{N} S_i^* = V \tag{14}$$

$$S_i^{\min} \leq S_i^* \leq S_i^{\max} \tag{15}$$

where V and S_i^* are the total system storage and the ideal storages of reservoir i at the end-of-period respectively, while BS_i is the beginning-of-period storage for reservoir i (known). R is the total release from the reservoirs system. Any reference to a time interval is omitted for convenience and other variables are described before.

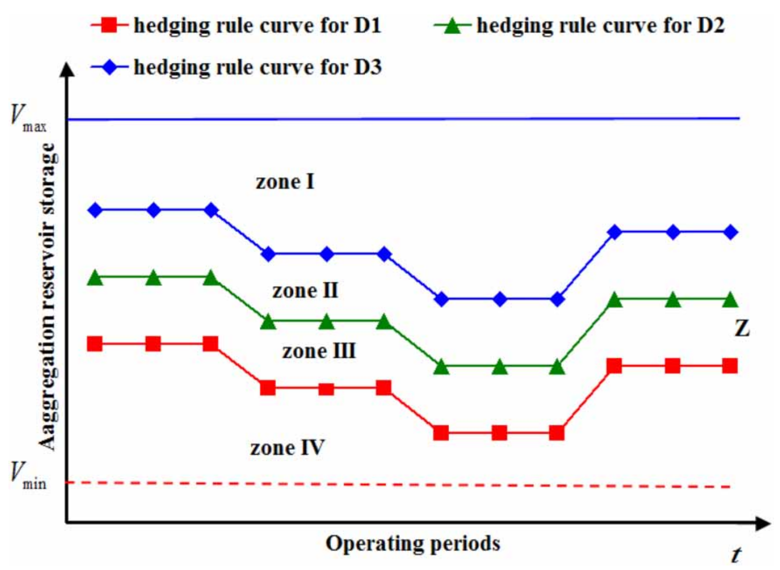


Figure 1 | Schematic of hedging rule based on aggregation reservoir.

The reasonable relationship in Equation (12) is the key problem of research in balancing curves (Lund & Ferreira 1996; Nalbantis & Koutsoyiannis 1997). In this article, the piecewise linear relationship implied in the optimal storage strategy is found while the suitable forms of target storage curves are identified (this relationship will be validated in the case study of the Biliu and Yingnahe reservoir system in Section 4.1). Figure 2 illustrates the concept of target storage curves in an example of a two-storage reservoir system. For a given total system storage V at a given period, the curves specify the storage volumes at reservoirs 1 and 2 as S_1^* and S_2^* respectively, where the sum of S_1^* and S_2^* equals V. Thus the gradient of total storage line equals 1 (45 °line in Figure 2).

The target storage curves are defined for the whole range of total system storage, giving preferred storage volumes of individual storages. The interpretation of target storage curves is important to understand how water is stored in a multi-reservoir system. If the slope of individual reservoir is less than that of total storage, then the excess water should be stored in both reservoirs. The amount of water stored is related to the difference of gradient of the target storage curves. After the G-point in Figure 2, the gradient of Curve 1 is 0 due to reservoir 1 reaching full capacity. Then the change of the total storage is equal to that of reservoir 2. In this paper, the target storage curves for reservoirs in each period are defined by connecting piecewise linear functions having end points A, B, C, D, as shown in Figure 2. If the net total system storage at the end-of-period t lies between points $B(x_B, y_B)$ and $C(x_C, y_C)$, which is determined by the hedging rule in Section 2.2, then the target storage $S_{i,t+1}^*$ of reservoir can be computed through the following equation:

$$S_{i,t+1}^* = x_B + \frac{x_C - x_B}{y_C - y_B}(V_{t+1} - y_B) \tag{16}$$

The remaining storage for reservoir at period t yields the following equation:

$$S_{it}^{lone} = S_{it} + I_{it} - RI_{it} - L_{it} \tag{17}$$

where S_{it} is the initial storage in reservoir i at period t, while I_{it} and L_{it} denote the inflow and loss respectively. RI_{it} is the water supply for individual demand. By comparing the remaining storage and the target storage, storage allocation rule for joint

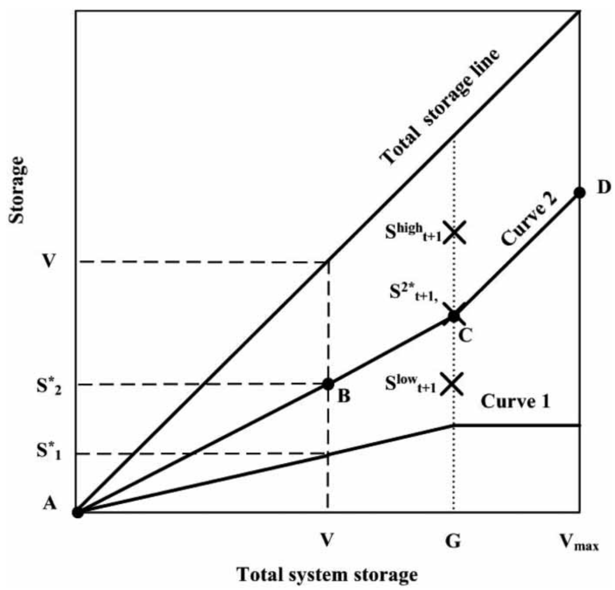


Figure 2 | Schematic of target storage curves.

demand can be defined as follows:

1. If $S_{it}^{lone} > S_{i,t+1}^{*}$ $(i = 1, 2, \cdots, N)$ (S_{t+1}^{high} in Figure 2), all reservoirs should release water to the joint demand until target storages are reached. The final storage for reservoir at period is equal to the target storage. The excess water for joint demand is seen as abandoned system water.
2. If $S_{it}^{lone} < S_{i,t+1}^{*}$ $(i = 1, \cdots, M(M < N))$ ($S_{i,t+1}^{low}$ in Figure 2) and no water is supplied by reservoir, the final storage for reservoir at period is equal to the remaining storage. Water supply task is completed by the remaining reservoirs. The amount of water to be released from the individual reservoir is related to the different locations of the target storage, trying to leave the system as close as possible to the desired storages. The end-of-period storage for reservoir at period can be estimated by

$$S_{j,t+1} = S_{j,t+1}^{*} + \frac{(S_{jt}^{lone} - S_{j,t+1}^{*})(V_{t+1} - \sum_{i=1}^{M} S_{it} - \sum_{j=1}^{N-M} S_{j,t+1}^{*})}{\left(\sum_{j=1}^{N-M} (S_{jt}^{lone} - S_{j,t+1}^{*})\right)} \tag{18}$$

2.4. Simulation–Optimization model

2.4.1. Objective function and constraints

The simulation–optimization model includes system simulation with an application of the proposed joint operating rules and optimization to generate optimal parameters using improved PSO method. The general framework of the model is shown in Figure 3. The top and bottom rule curves $Z_i(i = 1, 2, \cdots, 12)$, $Z_j(j = 13, 14, \cdots, 24)$ based on the aggregation reservoir and the coordinates $(X_{it}^{A}, Y_{it}^{A}) \sim (X_{it}^{D}, Y_{it}^{D})$ of key points in target storage curves are considered as decision variables. Individual hedging rule curves should be included if there is a local water demand that is connected with specified individual reservoir. Equation (3) is chosen as the objective function in the model with the constrains of Equations (4)–(8) and the following additional constraints.

1. The relationship between total amount of water supply for joint demand and that from an individual reservoir:

$$\sum_{i=1}^{N} RJ_{it} = RJ_t \tag{19}$$

2. The target storage constraints:

$$V_{t+1} = \sum_{i=1}^{N} S_{i,t+1} = \sum_{i=1}^{N} S_{i,t+1}^{*} \tag{20}$$

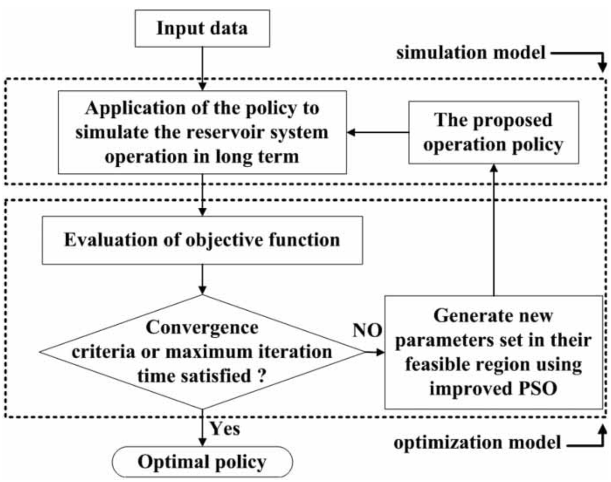


Figure 3 | Framework of simulation–optimization of the joint operation.

3. Hedging rule curves constraints:

$$\begin{cases} \sum_{i}^{N} S_i^{\min} \le Z_{13} \le Z_1 \le \sum_{i}^{N} S_i^{\max} \\ \qquad\quad \vdots \qquad \vdots \\ \sum_{i}^{N} S_i^{\min} \le Z_{24} \le Z_{12} \le \sum_{i}^{N} S_i^{\max} \end{cases} \tag{21}$$

4. The coordinates constraints:

$$\begin{cases} \sum_{i=1}^{N} S_i^{\min} = X_{it}^A \le X_{it}^B \le X_{it}^C \le X_{it}^D = \sum_{i=1}^{N} S_i^{\max} \\ S_i^{\min} = Y_{it}^A \le Y_{it}^B \le Y_{it}^C \le Y_{it}^D = S_i^{\max} \\ X_{it}^A = \sum_{i=1}^{N} Y_{it}^A, \; \cdots, X_{it}^D = \sum_{i=1}^{N} Y_{it}^D \end{cases} \tag{22}$$

5. System spill constraints:

$$\begin{cases} VP_t = \min\left[\left(V_{t+1} - \sum_{i=1}^{N} \min\left(S_i^{\max'}, S_i^{\max}\right)\right) 0\right] \\ S_i^{\max'} = S_{it} + I_{it} - RI_{it} - L_{it} \end{cases} \tag{23}$$

where VP_t is the spill of system at time period t. $S_i^{\max'}$ is the storage limit associated with individual demand. RJ_t is the amount of water supplied to joint demand at time period t determined by rule curves based on the aggregation reservoir. Other variables are described before.

2.4.2. Optimization algorithm

Due to the complexity of modern simulation models in the form of nonlinearity, discontinuity, and discreteness, heuristic search procedures are developed rapidly nowadays. Oliveira & Loucks (1997) presented an approach to optimize operating rules for multi-reservoir systems using genetic algorithms (GA). Long Le Ngo and colleagues (Le Ngo *et al.* 2007) proposed to optimize control strategies for reservoir operation adopting the shuffled complex evolution (SCE) algorithm. Reddy & Kumar (2007) presented a particle swarm optimization (PSO)-based solution to a detailed operational model for short-term reservoir operation for irrigation of multiple crops.

The PSO algorithm was proposed by Kennedy & Eberhart (1995). As a population-based search algorithm, PSO uses the local and global search capabilities to find better quality solutions based on the simulation of the social behavior of birds within a flock. In recent years, PSO has been widely applied to reservoir system operation (Yan *et al.* 2019; Guo *et al.* 2020). The improved particle swarm optimization (IPSO) method (Jiang *et al.* 2007) is taken to solve the optimization problem in this study, which has the strength and ability of broadly and deeply searching for solutions. The procedures are illustrated below:

1. Generate an initial $L \times P$ numbers of particles within feasible region, where L is the number of population and P is the number of particles in each population.
2. Sort the population into one primary group and L-1 subordinate groups.
3. Each group is evolved using standard PSO.
4. Update the velocity and the position of particles in primary group by consideration of the subordinate groups.
5. Mix and exchange the information of each subgroup after a certain number of iterations.
6. Iterate until accuracy requirement is met.

More detailed steps about the algorithm are referred to in Jiang *et al.* (2007). Overall, this study mainly focuses on the reservoir operating rule.

3. CASE STUDY

The reservoir system chosen for the application of the proposed operating policy is B and Y reservoirs in parallel, which are located at the B River basin and the Y River basin respectively in the Liaoning province of China. The B River basin covers an area of 2,848 km^2 with an annual rainfall between 300 and 350 mm, while the Y River basin covers an area of 1,004 km^2 with an annual rainfall between 450 and 500 mm. The layout of the B-Y parallel reservoirs system is illustrated in Figure 4.

Both B and Y River basins are water sources for Dalian city. The agricultural and industrial water demands of Dalian are provided together by the two reservoirs through their joint operation, while each reservoir has its own environmental demand. The reservoir characteristics and main purposes are presented in Table 1. The flood season is concentrated between July and September, during which the inflow makes up a large part of the total annual inflow. The active storage of B reservoir significantly reduces during the flood season. Monthly inflow data for the system are a series of hydrological records spanning 53 years from 1951 to 2003. The average monthly inflow and the annual inflow of each individual reservoir are listed in Table 2 and Figure 5. According to the distribution of runoff, Hydrological year is divided into four operating periods in this study: before flood season (April to June), flood season (July to September), after flood season (October to December) and drought season (January to March). Thus, each of the decision variables for operating curves contains 4 groups of variables instead of 12, which makes the solving process more convenient.

4. RESULTS AND ANALYSIS

4.1. Results of deterministic optimization

A deterministic optimization model for the B and Y parallel reservoirs system was built with the objective function of Equation (9) and constraints from Equations (4)–(8). Due to only two reservoirs in the system, the DP method can be used to acquire the optimal storage strategy (Figure 6). It should be noted that the objective function using the DP method was a maximum value under perfect operation (Table 3), which cannot be operated in practice.

Figure 6(a) is plotted with the storages of individual reservoirs versus the total system storage for each time period based on the optimal storage strategy obtained from the DP algorithms. The results reveal a remarkable piecewise linear relationship

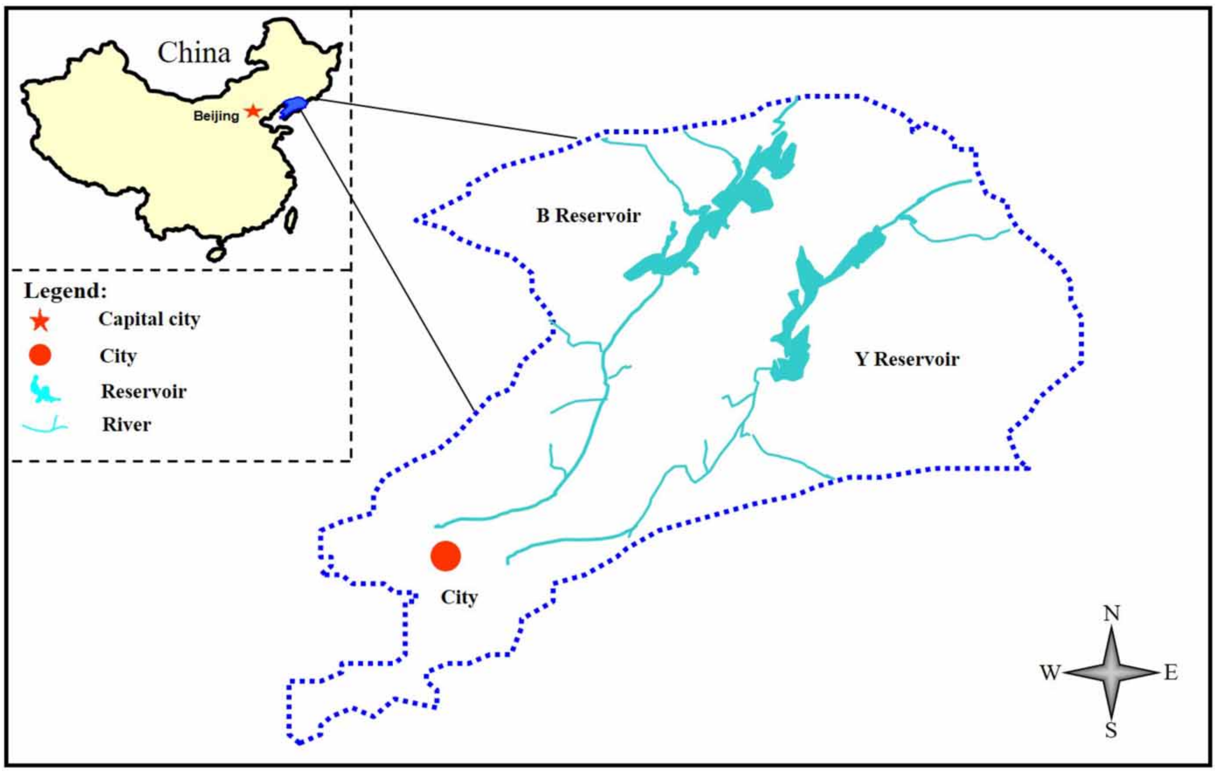


Figure 4 | The location of B and Y reservoir systems.

Table 1 | Reservoir characteristics

Reservoir	Active storage (in million m^3) Drought season	Flood season	Dead storage (million m^3)	Task
B	644.50	594.25	71.00	I, A,EB
Y	217.20	217.20	20.82	I, A,EY

I, Industrial demand; A, Agricultural demand; EB,EY, Environment demand for B and Y reservoir.

Table 2 | Mean value of monthly inflows into the B and Y reservoir system

Reservoir	Time Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
B	3.9	9.9	3.0	12.8	10.3	35.4	243.1	168.6	43.1	11.4	7.0	3.5
Y	4.2	9.9	3.2	13.3	10.7	35.8	247.4	169.3	43.4	11.7	7.2	3.7

Note: Values are presented in million m^3.

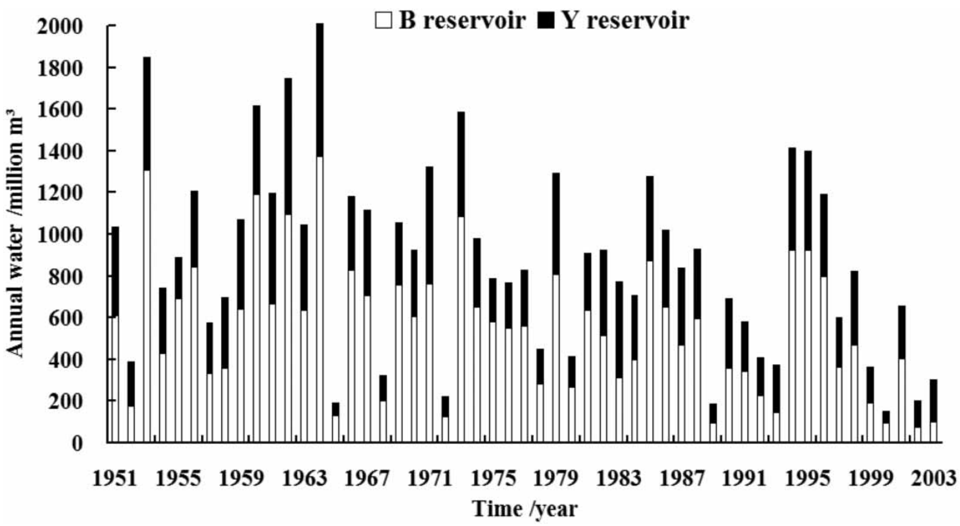


Figure 5 | The annual inflow into each individual reservoir from 1951 to 2003.

between individual storage and the total storage for the aggregated reservoir, which is emphasized by the fitted dashed lines of the points in the drought season as shown in Figure 6(b). Such storage distributions were found for each season. Therefore, the individual ideal or target storage of each reservoir can be described by one piecewise linear curve based on total system storage in this study, by which means the joint demand of water supply tasks can be distributed indirectly.

4.2. Results of the proposed joint operating rule

The storage space of the equivalent reservoir is divided into three zones by the two pieces of the hedging rule curve in Figure 7. The water supply rule in each zone is described in Equation (11) in Section 2.1. In this case, the rationing factors of water supply for agriculture and industry are equal to 0.7 and 0.9, respectively. In Figure 7, the higher is the planning guarantee ratio of the water demand, the lower is the position of the hedging rule curve corresponding to it. For example, when the storage of the equivalent reservoir stays in zone 2, the water supply for agriculture is rationed, but that of industry is not rationed. For the two pieces of the hedging rule curve, there are some characteristics in common. During the flood season between July and September, their positions are very low while both after the flood and in the drought season from October

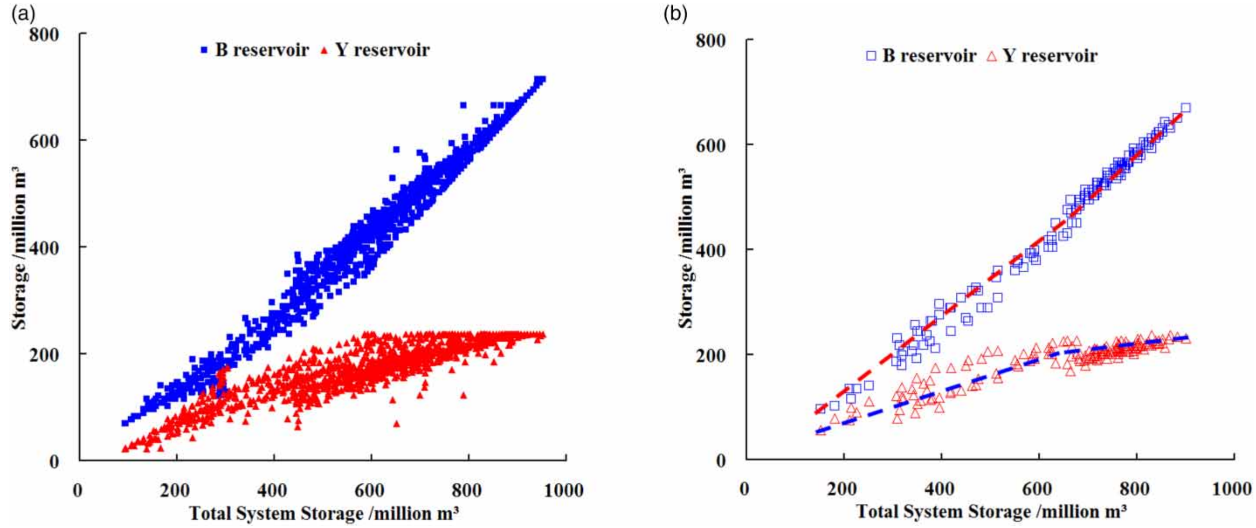


Figure 6 | The optimal storage strategy. (a) The optimal storage strategy based on observed inflow using DP. (b) The relationship between total system storage and individual reservoir storage in the drought season.

Table 3 | Comparison of different schemes with observed inflow

Scheme	Modified shortage index (%) Industrial	Modified shortage index (%) Agricultural	Reliability (%) Industrial	Reliability (%) Agricultural	Annual spillage (million m^3)
DP	1.14	8.89	95.21	90.19	222.22
Compensation regulation	5.60	29.53	90.50	76.56	243.46
Parametric rule	1.93	12.90	93.26	83.17	233.18
Target storage curves	1.61	12.12	94.18	85.61	227.55

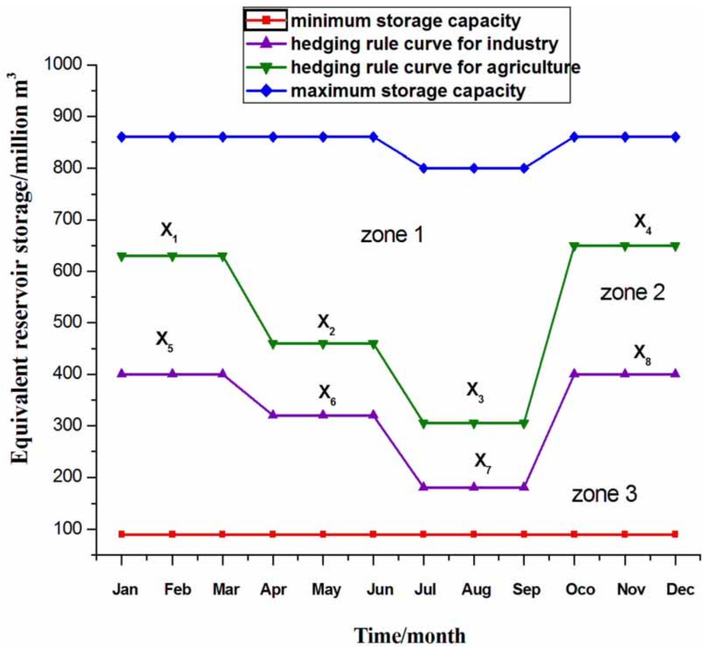


Figure 7 | Derived hedging rule curves for the B and Y reservoir systems.

until March the hedging rule curves are rather high. Hedging rule curves are triggering storage volumes that restrict the water supply if the reservoir storage falls below them. The higher the hedging rule curves, the more frequently water supplies are rationed. During the periods prior to the flood season, the hedging rule curves are kept down, so that the frequency of restricting water supply would be reduced and the storage of the reservoir could be emptied in order to capture the massive inflows during the coming flood season. By contrast, hedging rule curves are lifted up during the after-flood season and drought season, so that the frequency of restricting water supply would be increased and as much water as possible can be kept in the reservoir to prevent the catastrophic shortage in the next drought season.

The target storage curves obtained by the simulation–optimization model are shown in Figure 8(a) and 8(b) for the flood and drought seasons, respectively. K1 and K2 denote the maximum capacities of B and Y reservoirs at the current period, respectively. There are little differences among other three seasons except for the flood season, so the curves of the before-flood season and the after-flood season are not shown in this study, and can be represented by the curves in Figure 8(a) for the drought season.

Some general observations can be made from Figure 8(a). The optimized curves for the drought season and the fitted curves based on the optimal storage strategy in Figure 6(b) share a high degree of similarity. The gradient of target storage curves of the B reservoir is greater than that of the Y reservoir for various total system storages, while both gradients are between 1 and 0, which indicates that both reservoirs should release water to joint demand simultaneously in the drought season and the B reservoir should release more under the same conditions of inflows and independent demands. According to the statistics in the no-flood season, the proportions of water supply task allocation of joint demand for B and Y reservoirs were about 78 and 22%, respectively, while active storages of the B and Y reservoirs reflect a similar relationship.

The research found that various combinations of target storage curves performed equally well during the flood season due to high flow (Oliveira & Loucks 1997). For the flood season the inflows are always greater than the demand. The key problem of optimization is that the spatial distribution of excess water is needed to avoid spills within a multi-reservoir system (Perera & Codner 1996). With minimal total spills in the flood season, the target storage curves are selected as shown in Figure 8(b). It is worth noting that the gradient of the Y reservoir curve is about 0 at the beginning of the refill season, which means that excess water should be stored in the B reservoir due to its larger capacity. After that, filling of these reservoirs is equally gradual until both reservoirs are close to full.

The operating policy could be evaluated only at critical periods, when the inflows are low and/or demands are high (Oliveira & Loucks 1997). A series of prolonged drought periods was chosen to evaluate the performance index of each policy in this study, while many policies performed equally well during high flow periods. With the optimal storage strategy under prolonged drought months using the DP method as a benchmark, three statistical indicators including relative error (*RE*), correlation coefficient (R^2) and efficiency coefficient (*EC*) were employed to estimate the performance of storage

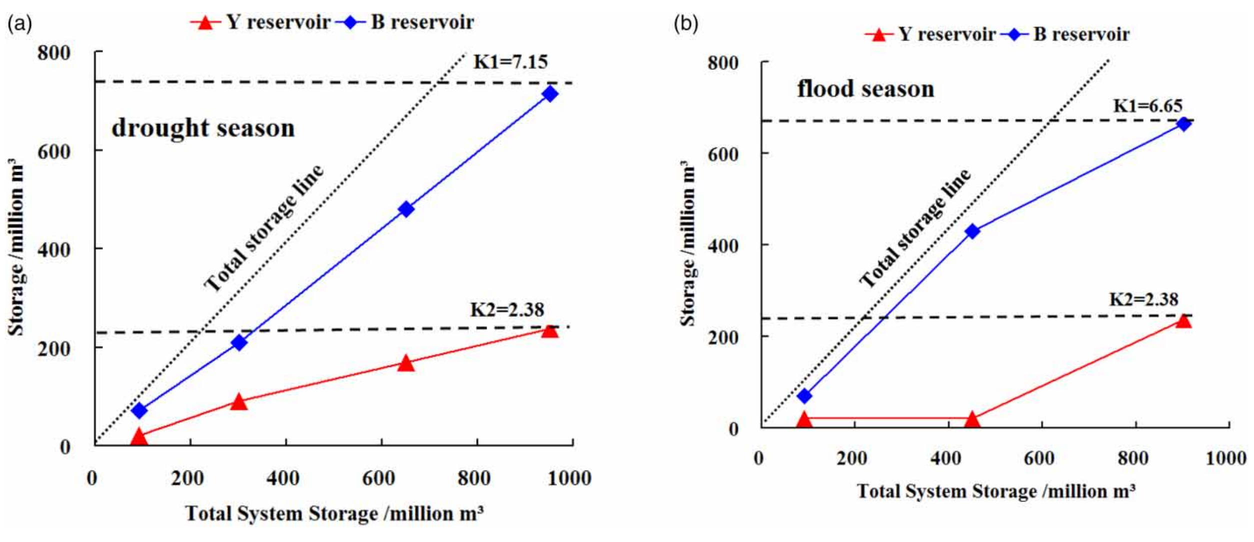


Figure 8 | Target storage curves of B and Y reservoirs. (a) Target storage curves for the drought season. (b) Target storage curves for the flood season.

allocation under target storage curves. They can be expressed mathematically as follows:

$$RE = \frac{\sum_{i=1}^{n}(M_i - O_i)}{\sum_{i=1}^{n} O_i} \tag{24}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(M_i - \overline{M_i})(O_i - \overline{O_i})\right]^2}{\sum_{i=1}^{n}(M_i - \overline{M_i})^2 \sum_{i=1}^{n}(O_i - \overline{O_i})^2} \tag{25}$$

$$EC = 1 - \frac{\sum_{i=1}^{n}(M_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O_i})^2} \tag{26}$$

where M_i is the simulated value. O_i is the optimal value. $\overline{M_i}$ and $\overline{O_i}$ are simulated and optimal mean values respectively. Other variables have been described previously.

As shown in Figure 9, the storage processes of B and Y reservoir under target storage curves (TSC) is close to the optimal storage strategy. The relative error (RE), correlation coefficient (R^2) and efficiency coefficient (EC) between the two storages of B reservoir using the DP and target storage curve methods are 2.05, 0.96, 0.97, respectively, while that of the Y reservoir are 4.28, 0.94, 0.96, respectively. These above indexes indicate the proposed joint operating rule by combining target storage curves with the hedging rule and shows a high degree of agreement with ideal storage procedure under perfect operation. D1, D2 denote the dead storages of B and Y reservoirs, respectively in Figure 9. When the prolonged drought periods end, both storages of each individual reservoir under different methods achieve their respective minimum limits of storage at the same time, which reflects the rationality of the proposed rule in the distribution of the system storage.

For the refill season, which is the flood season from July to September in this study, a good operating policy should avoid the situation of having some reservoirs spilling, while the others remain unfilled (Oliveira & Loucks 1997). Synchronization index of storage rate (SISR) is employed in this study to express the synchronization conditions of B and Y reservoirs for the refill season, which is the ratio of the two reservoirs, storage rate (SR). Space rule considers that the synchronization index should be very close to 1 when the system spill occurs. Figure 10 shows the synchronization index process when both B and Y reservoir spills are in the refill periods. The mean value is 1.01 while the standard deviation is 0.03, which indicates that B and Y reservoirs are always both filling up when system spill occurs.

The above findings demonstrate that the joint operating rule with target storage curves is efficient and reliable for reservoir operation.

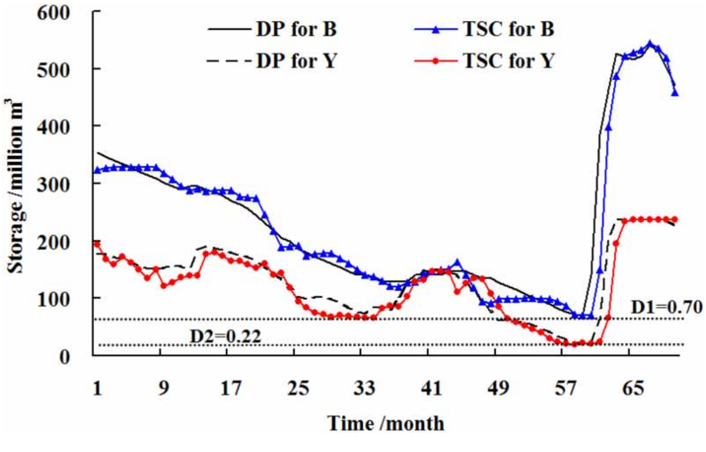


Figure 9 | The comparison of storage of individual reservoird over prolonged drought periods.

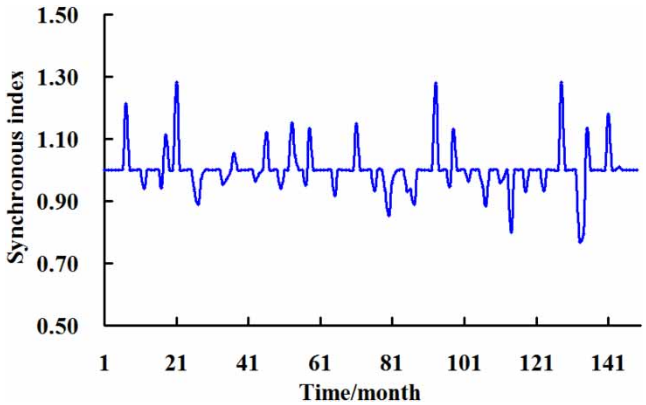


Figure 10 | Synchronous index of storage rates when system spill occurs.

4.3. Contrast of different schemes

In order to analyze the effect of the target storage curves further, different storage allocation rules were employed for comparison, all of which cooperated with hedging rule curves based on the aggregated reservoir with the same optimization objective and constrains. The compensation regulation method is used commonly in the actual operation, while the parametric rule was proposed by Nalbantis & Koutsoyiannis (1997). The results based on observed inflow data are shown in Table 3. Additionally, fifty 53-year-long synthetic monthly inflow series were produced randomly using hydrologic simulation as shown in Section 2.5 to further verify the validity of the method, mean values of which are listed in Table 4.

From Tables 3 and 4, some obvious conclusions can be derived. First, the scheme of target storage curves has lower MSI and higher reliability than that of the compensation regulation and parametric rule with both the generated inflow and the observed inflow, which are the most similar with the optimal results of the DP method. Furthermore, the annual spillage of the schemes presents the same relationships, which can be analyzed to evaluate the effectiveness of the reservoir operating rule because a good operating policy transfers more spills into the water supply for the water-supply system. Second, the indexes of the parametric rule are superior to the ones derived from the compensation regulation method, which indicates that the compensation regulation operating rule is inferior to the other rules in the efficiency of water-resources allocation. As is shown in the tables, the annual spillages are the largest in all schemes. In addition, the reliability of industrial is higher than that of agriculture while the MSI of industry is lower than that of agriculture in all schemes, due to their different priorities, which is shown as the hedging rule curves in Figure 7.

In a parallel multi-reservoir water supply system, excellent operating rules should be able to equalize the probability of spills among reservoirs during the refill season and that of emptying among reservoirs during the drawdown season (Lund & Guzman 1999), which indicates that reservoirs in the system should have a significant positive correlation in SR, which is the ratio of current reservoir storage to full storage. The distribution of SR under different allocation rules is shown in Figure 11. x, y denote the average SR of B and Y reservoirs, respectively, while r is the coefficient of correlation, higher values of which indicate the more reasonable allocation of the system storages. Figure 11 shows that the coefficient of correlation of the target storage curves was almost twice as large as that of the compensation regulation and about one-third larger than that of the parametric rule, which demonstrates that the rule of the target storage curves is more effective than other allocation rules on system storage allocation.

Table 4 | Comparison of different schemes with synthetic inflow

Scheme	Modified shortage index (%) Industrial	Modified shortage index (%) Agricultural	Reliability (%) Industrial	Reliability (%) Agricultural	Annual spillage (million m^3)
DP	3.22	15.60	92.34	80.19	231.36
Compensation regulation	35.21	95.46	88.96	72.35	269.25
Parametric rule	5.26	35.41	90.12	75.12	250.17
Target storage curves	4.32	26.92	90.21	75.33	245.30

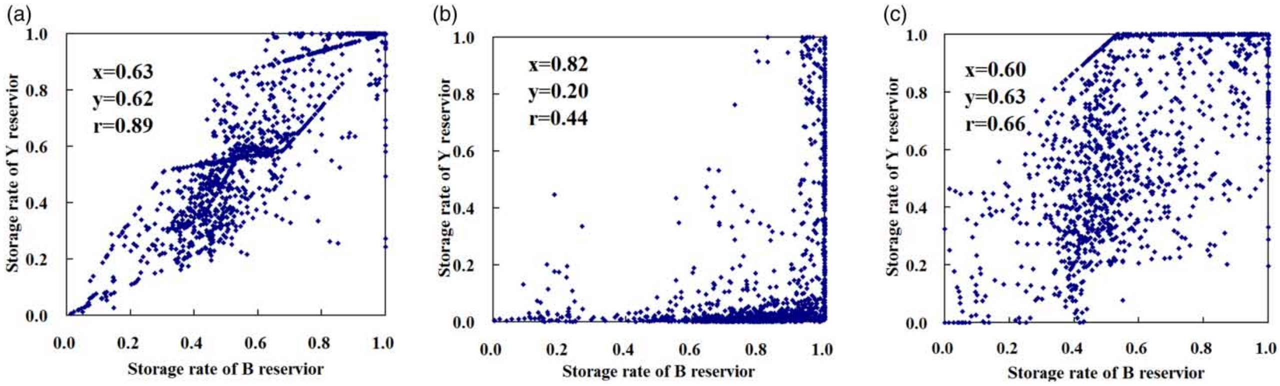


Figure 11 | Distribution of storage rates under different storage allocation rules. (a) Target storage curves. (b) Compensation regulation. (c) Parametric rule.

It is worth noting that the SR of the Y reservoir is always less than 0.1 when that of the B reservoir is less than 0.9 in Figure 11(b). This is because in all situation and periods, compensation regulation rules make the reservoirs with small capacity in the system, which is the Y reservoir in this study, release storage first to joint demand until reaching the minimum limit, which does not make full use of the compensation effect of different inflows and results in a large amount of spills in reservoir B (as described in Tables 3 and 4).

Additionally, the distribution of the system storages using the compensation regulation rule is shown in Figure 12. Through the fitting method, the target storage curves corresponding to the compensation regulation rule are obtained as shown in Figure 12, where the dashed line and the solid line indicate flood season curves and no flood season curves, respectively. According to the description of target storage curves in Section 2.3, the special curve can describe the method of water supply using the concept of compensation regulation. Thus, the compensative regulation method is a special case of the storage allocation rule using target storage curves. The approach of the optimization method to the curves should be more reasonable.

5. CONCLUSIONS

This article proposes a joint operating rule including a hedging rule based on an aggregation reservoir and a storage allocation rule based on target storage curves. The forms of target storage curves are identified by the optimal storage strategy of the

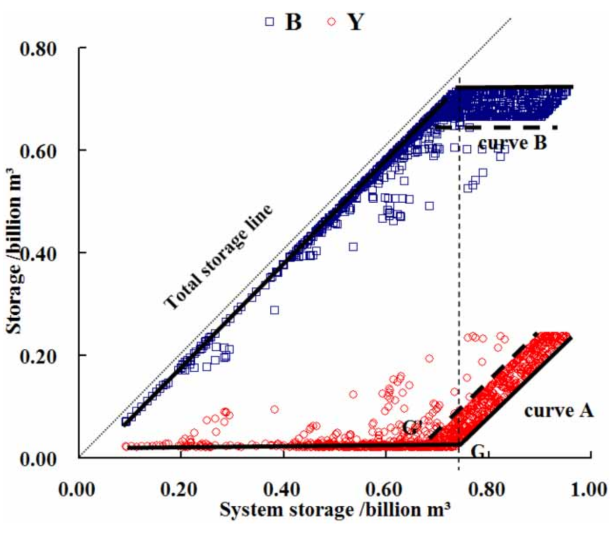


Figure 12 | Storage distribution of compensation regulation.

deterministic optimization model. A simulation–optimization model is established to refine the curves employing the B and Y reservoir systems in northern China as a case study.

Based on the analysis of results derived from different rules using observed and synthetic inflow, the following conclusions can be reached. First, the proposed rule produces a satisfactory result for a water-supply system in contrast with other methods. Second, the system storage distribution of target storage curves shares good consistency with that of the DP method, while each reservoir can reach full capacity or empty simultaneously. Third, the storage allocation rule based on target storage curves can achieve high synchronism of the SR for multi-reservoirs in parallel. The new joint operating rules provide an effective method to handle the problem of a water supply system with complex hydraulic characteristics.

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AUTHOR CONTRIBUTIONS

Hongbin Fang developed the target storage curves with the hedging rule and wrote the manuscript; Xinjie Li provided suggestions on the data analysis and manuscript preparation. Wenxiu Shang gave important advice on writing. Liang Wang revised the manuscript. All authors reviewed and approved the manuscript.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICTS OF INTEREST

The authors declare there is no conflict of interest.

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