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An Ecologically Oriented Operation Strategy for a Multi-Reservoir System: A Case Study of the Middle and Lower Han River Basin, China

Hao Wang [a], Xiaohui Lei [a,*], Denghua Yan [a], Xu Wang [a], Shuyue Wu [b], Zhengjie Yin [c], Wenhua Wan [b]

[a] State Key Laboratory of Simulation and Regulation of the Water Cycle in River Basins, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, China
[c] Water Resources Department, Yangtze River Scientific Research Institute, Wuhan 430010, China

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ABSTRACT

Constructing and operating a multi-reservoir system changes the natural flow regime of rivers, and thus imposes adverse impacts on riverine ecosystems. To balance human needs with ecosystem needs, this study proposes an ecologically oriented operation strategy for a multi-reservoir system that integrates environmental flow requirements into the joint operation of a multi-reservoir system in order to maintain different ecological functions throughout the river. This strategy is a combination of a regular optimal operation scheme and a series of real-time ecological operation schemes. During time periods when the incompatibilities between human water needs and ecosystem needs for environmental flows are relatively small, the regular optimal operation scheme is implemented in order to maximize multiple human water-use benefits under the constraints of a minimum water-release policy. During time periods when reservoir-induced hydrological alteration imposes significant negative impacts on the river's key ecological functions, real-time ecological operation schemes are implemented in order to modify the outflow from reservoirs to meet the environmental flow requirements of these functions. The practical use of this strategy is demonstrated for the simulation operation of a large-scale multi-reservoir system which located in the middle and lower Han River Basin in China. The results indicate that the real-time ecological operation schemes ensure the environmental flow requirements of the river's key ecological functions, and that adverse impacts on human water-use benefits can be compensated for by the regular optimal operation scheme. The ecologically oriented operation strategy for a multi-reservoir system that is proposed in this study enriches the theoretical application of the multi-reservoir system joint operation which considers environmental flow requirements.

1. Introduction

Reservoirs are one of the most efficient tools for basin water resource development and management. As of 2017, the number of large dams in the world was greater than 58 000, of which about 24 000 are located in China [1]. The joint operation of multi-reservoir systems has received a considerable amount of attention [2–4]. Multi-reservoir joint operation means that decisions to release water from a reservoir depend not only on the state of that reservoir, but also on the states of the other reservoirs within the system, thus improving the operational effectiveness and efficiency of the whole system [4]. The majority of the studies on multi-reservoir system joint operation focus on developing methods to satisfy human water needs; the explicit inclusion of environmental flow requirements has received less attention [5]. Constructing and operating a multi-reservoir system blocks rivers and forms impoundments in basins, causing changes in river flow regimes from upstream to downstream and imposing negative impacts on riverine ecosystems [6–8].

The concept of environmental flows was developed to define the volume of water that should remain in a river, and the variation of this water over time that is required to sustain specified ecosystem conditions [9]. When considered in reservoir management, environmental flow requirements often involve meeting minimum flow requirements. They can easily be translated into a minimum

* Corresponding author.
E-mail address: lxh@iwhr.com (X. Lei).

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water-release policy and integrated into currently used operation rules [5,10]. However, this method neglects the important role flow variability plays in maintaining the ecological health of a river. It is widely agreed that river flow regimes, which include the magnitude, frequency, duration, timing, and rate of change of river flows, are dominant control factors of the structure and function of a riverine ecosystem and of the adaptations of its biota [11].

Incorporating environmental flow requirements into multi-reservoir system operation is an effective way to restore riverine ecosystems [12]. Richter and Thomas [12] proposed a conceptual framework for planning and implementing a dam reoperation project to restore nature flow characteristics that benefit the riverine ecosystem. Many studies have been devoted to improving reservoir operation methods in order to mimic the nature flow regime [10]. For example, Yin et al. [13] combined reservoir operation rule curves and the minimum water-release policy into a regular optimal operation scheme that minimized both the hydrological alteration of the downstream river and the water supply shortage. Steinschneider et al. [14] estimated the environmental flow requirements at key locations throughout a basin, and proposed an optimal operation model for a large-scale reservoir system in order to examine the trade-offs between ecological targets and traditional reservoir objectives. The full use of forecast information has become an effective way to improve the efficiency of reservoir system operation [15,16]. Several studies have incorporated forecast information into reservoir ecological operation. For example, Yin et al. [17] proposed three environmental flow management strategies for wet, normal, and dry years, respectively. These strategies were coupled with reservoir-operating rule curves to form a reservoir operation approach that optimized environmental flow provision under given water supply constraints. Wang et al. [18] proposed a reservoir operation decision framework that considers multiple anthropogenic water uses and environmental flow requirements. This framework was demonstrated for instances with forecasted stream flow information.

Although many studies incorporate environmental flow requirements into reservoir operation, the effort seldom focuses on identifying key ecological functions throughout a river and integrating their environmental flow requirements into currently used multi-reservoir system operation rules. In this study, we propose an ecologically oriented operation strategy for a multi-reservoir system that combines a regular optimal operation scheme with a series of real-time ecological operation schemes. This strategy was demonstrated for the simulation operation of a large-scale multi-reservoir system located in the middle and lower Han River Basin.

The rest of this study is organized as follows: Section 2 provides a conceptual description of the ecologically oriented operation strategy for a multi-reservoir system. Section 3 describes the multi-reservoir system located in the middle and lower Han River Basin. The regular optimal operation scheme and the real-time ecological operation schemes for this system are described in Sections 4 and 5, respectively. Section 6 provides the results, and the conclusion is drawn in Section 7.

2. Conceptual description of the ecologically oriented operation strategy

The proposed ecologically oriented multi-reservoir system operation strategy specifies the environmental flow requirements of different ecological functions throughout a river and integrates them into currently used multi-reservoir system operation rules. To balance human needs with ecosystem needs, the multi-reservoir system operation is divided into two stages (Fig. 1). We denote the stage during which conflicts between human water needs and ecosystem needs for environmental flows are relatively small as the regular operation stage, and the stage during which the reservoir operation imposes significant negative impacts on the river's key ecological functions as the ecological operation stage. Within each stage, different sub-strategies are adopted.

During the regular operation stage, a regular optimal operation scheme is adopted, and environmental flow requirements are considered via a minimum water-release policy. The concept of eco-hydrological division is applied to identify the main ecological functions of different river reaches, and corresponding methods are used to estimate the minimum environmental flows required by these functions. Currently used regular operation rules for multi-reservoir systems are optimized in order to maximize comprehensive human water-use benefits under the minimum water-release constraint. Multi-objective optimization methods are applied to examine the trade-offs between multiple human water-use benefits that include water supply, flood control, power generation, and so forth. A recommended solution can be derived based on the preference of decision-makers.

During the ecological operation stage, a series of real-time operation schemes are established, with achieving the ecological

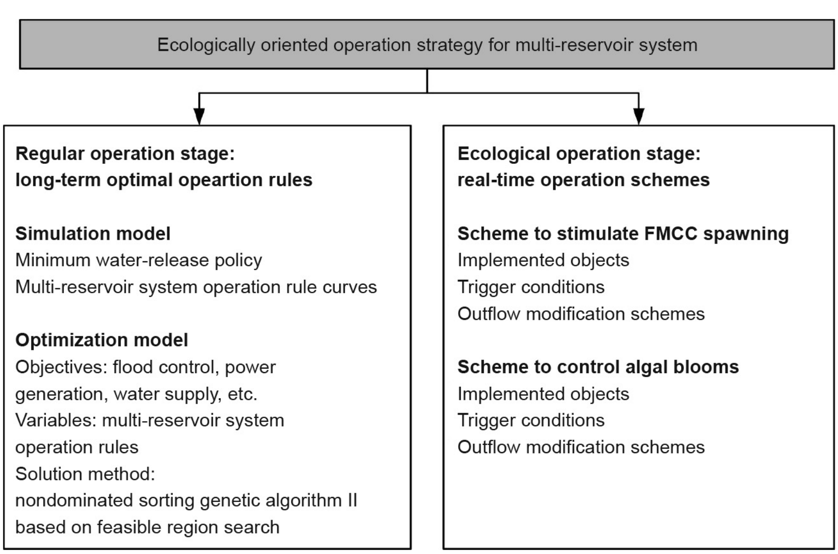

Fig. 1. Conceptual description of the ecologically oriented operation strategy for a multi-reservoir system. FMCC: four major Chinese carp.

targets being a priority. We mainly focus on restoring the river ecological processes that have important ecological functions and are significantly influenced by reservoir-induced hydrological alteration. Hydrological-ecological related knowledge and modeling methods are utilized to establish the quantitative relationships between the hydrological indicators describing the flow regimes and the ecological indicators describing the ecological status. Environmental flow requirements can be specified as a numerical range within which the flow component is to be maintained; or, they can be expressed as threshold limits for specific flow characteristics. Corresponding real-time operation schemes are set to modify the outflow from reservoirs to meet these environmental flow requirements. These real-time operation schemes are implemented with the support of ecological and hydrological forecast information, in order to capture the timing of the environmental flow events and adapt to the variability of available water resources.

Thus, during the ecological operation stage, the real-time ecological operation schemes can ensure the environmental flow requirements of the river's key ecological functions. On a long-term scale, the adverse impacts of the real-time ecological operation on human water-use benefits can be partly compensated for by the regular optimal operation scheme. The key methods adopted by each sub-strategy are demonstrated in the form of a case study in Sections 4 and 5.

3. System description

The Han River is the biggest tributary of the Yangtze River, with a mainstream length of 1577 km and a drainage area of 1.59×10^5 km^2. A multi-reservoir system in the middle and lower Han River Basin that contains 16 large- or medium-sized hydropower stations was selected as our case study (Fig. 2). In this system, the Danjiangkou Reservoir serves multiple objectives, including flood control, water supply, and power generation. The main function of the other reservoirs is power generation. The total installed capacity of the system is 3071.5 MW. The Danjiangkou Reservoir is the water source for the Middle Route of the South-to-North Water-Transfer Project (SNWTP), which annually delivers 9.5×10^9 m^3 of water to Beijing, Tianjin, Hebei, and Henan. The Yangtze River–Han River Water-Transfer Project (YHWTP) is an auxiliary project of the SNWTP, which delivers 3.7×10^9 m^3 of water from the upper reaches of the Yangtze River into the river reaches below Xinglong Reservoir of the Han River in order to compensate for the loss of water resources.

Many studies have analyzed the impacts of this multi-reservoir system on the ecological-hydrological conditions of the Han River Basin. From 1933 to 2008, the natural inflow of the middle and lower reaches of the Han River showed a downward trend, and the construction of reservoirs and the SNWTP intensified this decrease trend [19]. The decline of flow discharge disturbed the river biological community and caused the frequent breakout of algal blooms. In addition, the middle and lower reaches of the Han River are the major habitats of the four major Chinese carp (FMCC): the black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), and bighead carp (*Hypophthalmichthys nobilis*). Rapid streamflow rises serve as the cues for FMCC spawning. However, the constructing and operating of the reservoirs reduces the size and

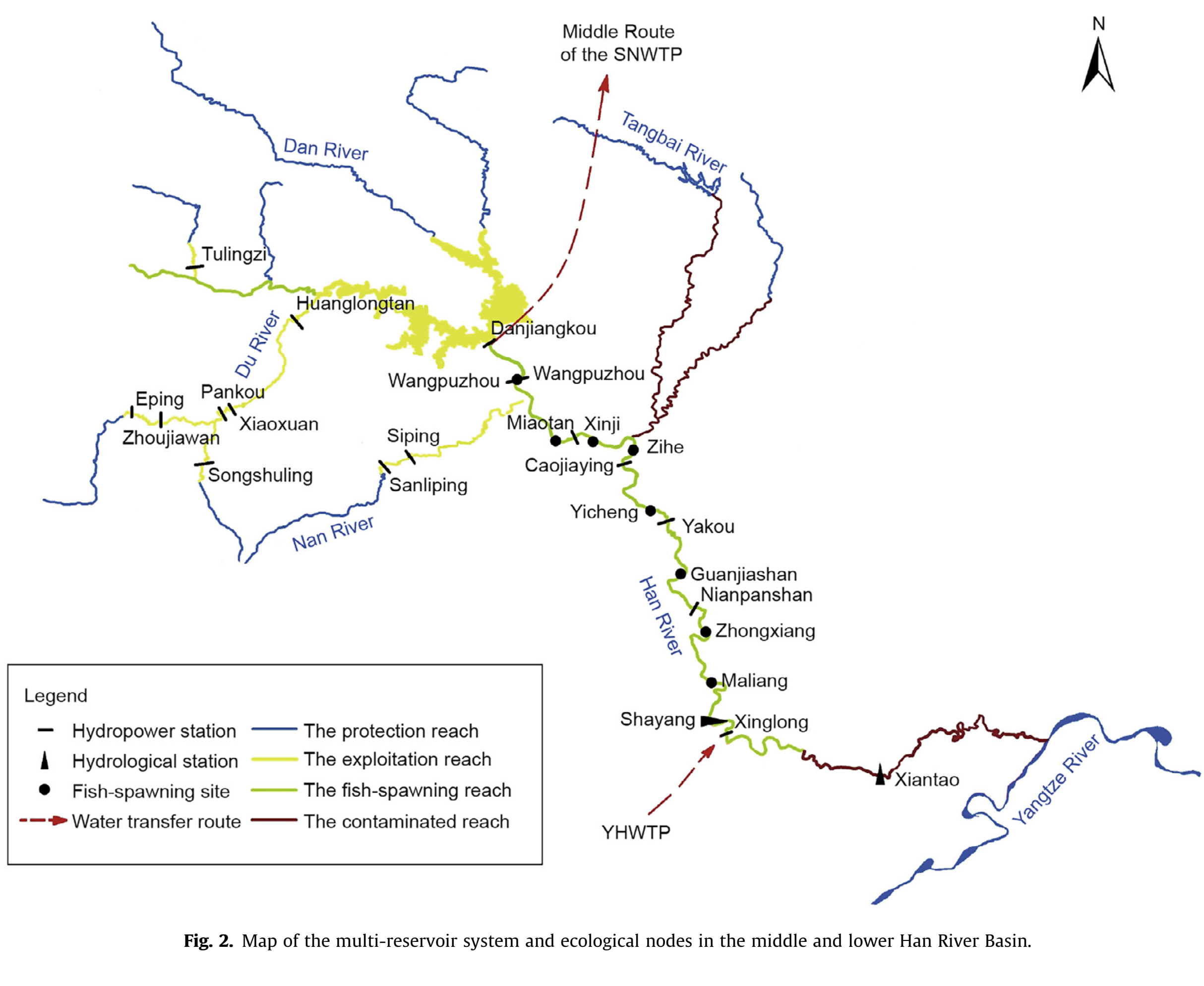

Fig. 2. Map of the multi-reservoir system and ecological nodes in the middle and lower Han River Basin.

duration of streamflow rises [20]. According to observational data, three spawning sites for the FMCC have disappeared from the middle and lower reaches of the Han River, and the number of fish eggs has decreased from 5.0×10^8 individuals (ind) in the 1970 s to 3.2×10^7 ind in 2007 [21].

The historical streamflow (water level) data used in this study were obtained from the main hydrological stations in the middle and lower reaches of the Han River. The data series range from 1929 to 2016. Data on FMCC reproduction events were collected from three surveys of fish resources that were conducted from 1977 to 1978, in 2004, and from 2006 to 2007 by Institute of Hydroecology, Ministry of Water Resources and Chinese Academy of Sciences. Algal bloom breakout monitoring data from 1992 to 2012 were obtained from the water-quality monitoring sections.

4. Regular optimal operation scheme

4.1. Simulation model

Since the multi-reservoir system in the middle and lower reaches of the Han River has multiple operation targets, this system was divided into two sub-systems. The Danjiangkou Reservoir, an annual regulation reservoir that is located in the upstream of the system, undertakes most of the flood-control tasks of the system. Its flood-control target is to ensure the safety of Nianpanshan Hydropower Station which lies downstream, when the Danjiangkou Reservoir encounters a 100 year flood. All of the reservoirs in the system have the function of power generation. The top layer of the system was the Danjiangkou–Nianpanshan flood-control network, and the bottom layer was a network of 16 hydropower stations. In the simulation operation model, the flood-control simulation operation took the design flood as the input, with a time step of 6 h. The power generation simulation operation and the water supply simulation operation took the historical streamflow as the input, with a daily time step.

4.1.1. Human water-use operation rules

The regular operation of the multi-reservoir system is implemented with the guidance of operation charts. Ten operation charts are currently used in the multi-reservoir system, including one flood-control operation chart and one water supply operation chart for the Danjiangkou Reservoir, and eight power generation operation charts for the eight major hydropower stations. Each operation chart includes several operation rule curves. Based on these operation rule curves, the reservoir operation is guided by the principle of reducing the outflow by some specified rate based on the relationship between the existing water level and the rule curves. Since the operation rule curve is a polyline that connects a series of inflection points, the human water-use operation rules can be described by the water levels and by the timings of all the inflection points in all the operation charts of the system. The human water-use operation rules were described by a total of 162 decision variables.

4.1.2. Minimum release policy

Considering the hydrological situation, morphological characteristics, aquatic life, and human factors, the middle and lower reaches of the Han River were divided into four types: the protection reach, exploitation reach, fish-spawning reach, and contaminated reach (Fig. 2). According to the characteristics of these four types of river reaches, the wetted perimeter method [22], Tennant method [23], habitat simulation method [24], and environmental function-setting method [25] were respectively used to estimate the minimum flow requirements. The minimum flow requirement for the whole river was estimated as 500 $\mathrm{m^3 \cdot s^{-1}}$. This minimum flow requirement was translated into a minimum release policy and coupled with the human water-use operation rules.

4.2. Optimization model

4.2.1. Objective functions

The target for a multi-reservoir system is to maximize the flood peak deduction rate R, the average annual power generation E, and the average annual water supply W. This multiple-objective optimization problem is expressed as follows:

$$\max\{R,\ E,\ W\} \tag{1}$$

The flood peak deduction rate R, which represents the flood-control benefit of the Danjiangkou Reservoir on the downstream Nianpanshan Hydropower Station, is calculated as follows:

$$R = \left[\sum_{t=1}^{n_\mathrm{f}} (Q_{\mathrm{in},t} - Q_{\mathrm{out},t})\right] \Bigg/ \sum_{t=1}^{n_\mathrm{f}} Q_{\mathrm{in},t} \tag{2}$$

where $Q_{\mathrm{in},t}$ and $Q_{\mathrm{out},t}$ are the inflow and outflow of the Danjiangkou Reservoir during the tth time period, and $\mathrm{n_f}$ is the number of time periods that Nianpanshan Hydropower Station encounters over-level floods under the assumption that the flood-control function of the Danjiangkou Reservoir does not exist.

The average annual power generation E, which represents the power generation benefit of the multi-reservoir system, is calculated as follows:

$$E = \left(\sum_{i=1}^{M} \sum_{j=1}^{Y} \sum_{k=1}^{T} N_{ijk}\right) \Bigg/ Y \tag{3}$$

where N_{ijk} is the output of the ith reservoir on day k of year j, M is the number of reservoirs, Y is the number of years, and T is the total number of days in year j.

The average annual water supply, W, for the Middle Route Project of the SNWTP, which represents the average annual water supply benefit of the Middle Route Project, is calculated as follows:

$$W = \left(\sum_{j=1}^{Y} \sum_{k=1}^{T} \mathrm{Sup}_{jk}\right) \Bigg/ Y \tag{4}$$

where Sup_{jk} is the water supply of the Middle Route Project on day k of year j.

4.2.2. Constraints

The constraint set of the optimization model reflects the features of the system that cannot be violated due to physical or policy considerations. These include constraints on continuity requirements, storage capacities, gate and turbine discharge capacities, and so forth. Continuity equations are included in the constraint set in order to ensure that the mass balance is preserved throughout the system. Evapotranspiration is ignored in mass balance equations. Gate and turbine discharge capacities are used to constrain outflow discharge. In addition to the physical limitations of the infrastructure, the minimum water-release policy for environmental requirements is cast as a constraint.

4.2.3. Solution method

To determine the optimal operation scheme, which maximizes the overall human water-use benefits under the minimum release constraints, 162 decision variables of the operation charts required modification. The non-dominated sorting genetic algorithm II, which is based on a feasible region search (NSGA-II-FRS), was used to identify the Pareto-optimal set for these decision variables. NSGA-II is frequently employed in solving multi-objective optimization problems, and is based on an evolutionary algorithm to find the Pareto-optimal front [26]. The feasible region search method considers the graphical constraints and operation experience constraints of each inflection point on the operation rule curves, and constructs a ray-scanning formula to find feasible space for the water level at each inflection point [27]. It ensures that the population sampling, crossover, and mutation of NSGA-II are all performed within the feasible domain, which greatly improves the multi-objective optimization efficiency.

5. Real-time operation schemes

The real-time operation schemes for the multi-reservoir system in the middle and lower reaches of the Han River were set to achieve two ecological targets: stimulating FMCC spawning, and controlling algal blooms. Within the real-time operation schemes, the outflow from reservoirs was modified to meet the environmental flows required by these two ecological targets.

5.1. Real-time operation scheme considering FMCC spawning

5.1.1. Environmental flow requirements

The main spawning periods for the FMCC are from July to August each year, during which the water temperature is generally higher than 18 °C and suitable for spawning. During this period, the streamflow rises caused by floods act as cues to stimulate the spawning of the FMCC. The scale and duration of streamflow rises are two factors that determine the occurrence and scale of spawning events. The Shayang Hydrological Station, which is located in fish-spawning river reaches, was selected as a key ecological node. By analyzing the characteristics of the observed streamflow rises at Shayang Hydrological Station during the fish-spawning events in 1976, 2004, and 2007 (Table 1), the flow requirements of FMCC spawning were identified as streamflow rises with a rising rate higher than 390 $m^3 \cdot s^{-1} \cdot d^{-1}$ and a duration longer than 3 d.

5.1.2. Trigger conditions

The Danjiangkou Reservoir was chosen as the implemented object of real-time operation. Guided by the real-time operation scheme, the outflow from the Danjiangkou Reservoir is modified to synchronously increase with the river's natural streamflow rises in order to stimulate FMCC spawning. The Tangbai River is the main source of natural streamflow rises in the Danjiangkou–Shayang reach. Real-time operation is implemented when the natural flow in the Tangbai River increases to more than 230 $m^3 \cdot s^{-1} \cdot d^{-1}$ and to a duration longer than 3 d, which will create a streamflow rises of more than 390 $m^3 \cdot s^{-1} \cdot d^{-1}$ with a duration longer than 3 d at the Shayang Hydrological Station.

5.1.3. Operation schemes

In order to adapt to variability in the available water resources, three sub-schemes for wet, normal, and dry year situations were combined with the real-time operation scheme (Table 2). The choice of these sub-schemes depends on the different storage levels of the Danjiangkou Reservoir and on different reservoir inflow conditions. When water availability is abundant, the "high" scheme for a wet year is triggered and more water is released in order to ensure large-scale FMCC spawning. When water availability is limited, the "low" scheme for a dry year is triggered and less water is released in order to reduce the potential loss of human water-use benefits caused by the increased outflow.

Table 1
Characteristics of measured streamflow rises during FMCC spawning events at Shayang Hydrological Station.

Year	Characteristics of streamflow rises	
	Rate of streamflow rise ($m^3 \cdot s^{-1} \cdot d^{-1}$)	Duration (d)
1976	410.0	4
2004	1250.0	3
	458.6	8
	990.0	3
2007	393.2	6
	817.0	8

5.2. Real-time operation scheme considering algal bloom control

5.2.1. Environmental flow requirements

The breakout of algal blooms in the middle and lower reaches of the Han River is mainly concentrated in the period from January to March, and in the reaches around Zhongxiang Reservoir and near the Han River estuary. The constructing and operating of the YHWTP have increased the flow discharge below the Xinglong Reservoir, which helps to contain the breakout of algal blooms. Therefore, with the Xinglong Reservoir as the boundary, the middle and lower reaches of the Han River were divided into an upper reach and a lower reach. Shayang Hydrological Station was chosen as the ecological node of the upper reach, and the Xiantao Hydrological Station was chosen as the ecological node of the lower reach.

According to long-term investigations on algal bloom outbreaks in the middle and lower reaches of the Han River, an algal bloom tends to occur when low flow processes last for more than 7-day during the dry season (January–March). Therefore, we selected episodes of 7-day minimum flow from 1992 to 2012 as samples and calculated the probability of an algal bloom breakout at different flows. We then plotted the probability that an algal bloom will not occur against the 7 d minimum flows, as shown in Fig. 3. According to this graph, the flow thresholds that can control the breakout of algal blooms are 900 and 800 $m^3 \cdot s^{-1}$ at Shayang Hydrological Station and Xiantao Hydrological Station, respectively.

5.2.2. Triggering conditions and operation schemes

Real-time reservoir operation schemes for algal bloom control are triggered when a trend of algal bloom breakout is observed (Table 3). For the river reach above Xinglong Reservoir, if the accumulation of algae density at Shayang Hydrological Station is close to 1×10^6 ind$\cdot L^{-1}$, the outflow from the Danjiangkou Reservoir is increased to ensure that the flow discharge at Shayang Hydrological Station is greater than 900 $m^3 \cdot s^{-1}$ for 7 d. For the river reach below Xinglong Reservoir, when the accumulation of algae density at Xiantao Hydrological Station is close to 1×10^6 ind$\cdot L^{-1}$, the YHWTP and Xinglong Reservoir are jointly operated to increase outflow, thus ensuring that the flow discharge at Xiantao Hydrological Station is greater than 800 $m^3 \cdot s^{-1}$ for 7 d.

6. Results

6.1. Comparison of the simulation operation results based on the regular optimal operation scheme and the currently used scheme

Fig. 4 shows the Pareto frontier values for R, E, and W under long series historic hydrological situation based on the optimal operation scheme. A recommended solution was derived based on the preference of decision-makers. This solution ensures that the water supply of the Middle Route Project is no less than the average annual water supply based on the currently used rules, while maximizing the combined benefits of power generation and flood control. Compared with the simulation operation results based on the currently used scheme, the recommended scheme increases R by 4.24%, E by 1.41×10^8 kW·h, and W by 3.5×10^7 m^3 (Table 4).

Table 2
Real-time operation scheme considering FMCC spawning.

Sub-schemes	Hydrological year	Water level of the Danjiangkou Reservoir (m)	Reservoir inflow forecast ($m^3 \cdot s^{-1}$)	Streamflow rise target at Shayang Hydrological Station ($m^3 \cdot s^{-1} \cdot d^{-1}$)
"Low" scheme	Dry year	< 160	–	390–700
"Middle" scheme	Normal year	160 (steady or with downtrend)	< 1200	700–1000
"High" scheme	Wet year	160 (with uptrend)	≥ 1200	1000–1250

The flood-control level of the Danjiangkou Reservoir is 160 m.

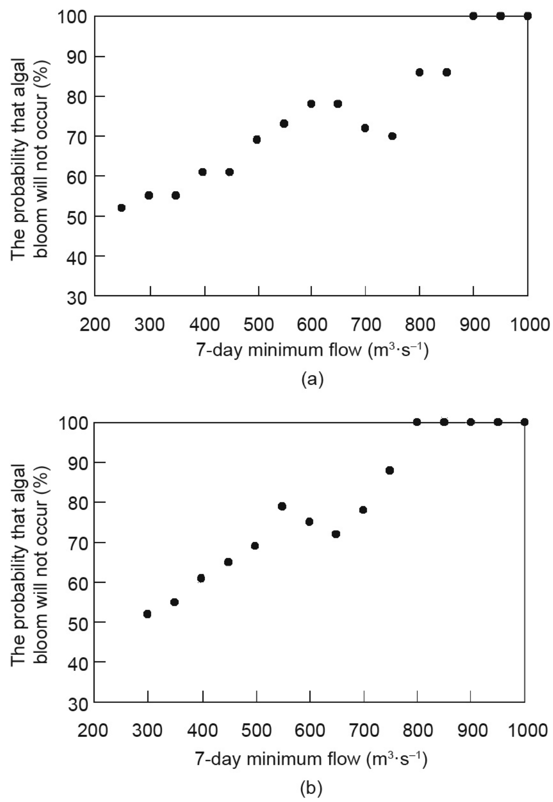

Fig. 3. Relationship between 7-day minimum flows and the probability that an algal bloom will not occur at (a) Shayang Hydrological Station and (b) Xiantao Hydrological Station.

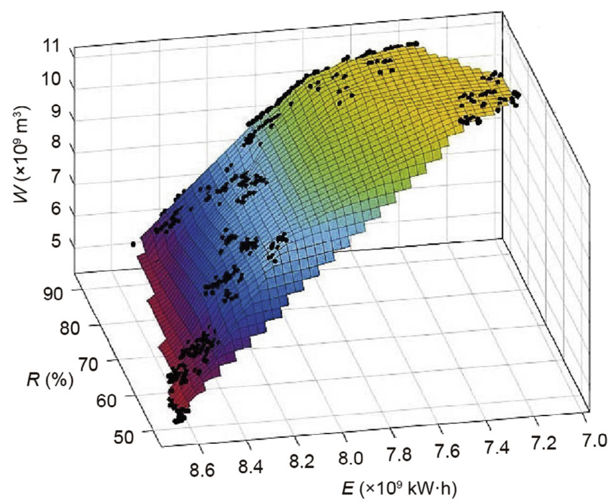

Fig. 4. Pareto frontier values for the flood peak deduction rate R, average annual power generation E, and average annual water supply W.

Table 3
Real-time operation scheme considering algal bloom control.

River reaches	Algae density ($ind \cdot L^{-1}$)	Discharge target ($m^3 \cdot s^{-1}$)	Duration target (d)
Above Xinglong Reservoir (at Shayang Hydrological Station)	1×10^6	≥ 900	≥ 7
Below Xinglong Reservoir (at Xiantao Hydrological Station)	1×10^6	≥ 800	≥ 7

Table 4
Comparison of the simulation operation results based on the recommended scheme and the currently used scheme.

Scenario	R (%)	E ($\times 10^6$ kW·h)	W ($\times 10^6$ m^3)
Recommended scheme	91.56	7842	9963
Currently used scheme	87.32	7701	9928
Difference	4.24	141	35

6.2. Impacts of real-time operation schemes on human water-use benefits

6.2.1. Impacts of the real-time operation scheme considering FMCC spawning

The real-time operation scheme considering FMCC spawning was incorporated into the regular optimal operation scheme. In order to assess the impacts of the real-time operation scheme considering FMCC spawning on human water-use benefits, the simulation operation results based on this coupled operation scheme were compared with that based on the regular optimal operation scheme, under wet, normal and dry hydrological situations (with 1968, 1976, and 1957 chosen as the wet, normal and dry typical year respectively). Under the wet, normal, and dry hydrological situations, real-time operation reduces the power generation by 3.05×10^8, 1.69×10^8, and 1.03×10^8 kW·h, respectively, and reduces the water supply by 0, 2.69×10^8, and 7.01×10^7 m^3, respectively. In general, the real-time operation scheme that targets a high streamflow rise results in greater impacts on power generation and water supply. These impacts are also affected by the reservoir inflow. If the reservoir encounters large inflow after the real-time operation, which usually happens in wet years, the water losses caused by the real-time operation can easily be compensated for.

6.2.2. Impacts of the real-time operation scheme considering algal bloom control

The real-time operation scheme considering algal bloom control was incorporated into the regular optimal operation scheme. In order to assess the impacts of the real-time operation scheme considering algal bloom control on human water-use benefits, the simulation operation results based on this coupled operation scheme were compared with the results based on the regular optimal operation scheme, under the historical hydrological situations of year 1992, 1998, 2000, 2008, and 2010 (i.e., years in which algal blooms occurred). Real-time operation results in a slight increase in the annual power generation of the Danjiangkou Reservoir, with an average increase of 1.6×10^7 kW·h. However, real-time operation reduces the annual water supply of the Middle Route Project by an average of 1.21×10^8 m^3.

6.3. Simulation operation results based on an ecologically oriented operation strategy

The recommended regular optimal operation scheme, the middle sub-scheme of the real-time operation scheme considering FMCC spawning, and the real-time operation scheme considering algal bloom control were combined into an ecologically oriented operation strategy for a multi-reservoir system. The simulation operation results based on the ecologically oriented operation strategy were compared with that based on the currently used operation scheme (Table 5). It was found that on an annual scale, losses in power generation and water supply benefits caused by real-time operation can be partly compensated for by the long-term regular optimal operation. The ecologically oriented operation strategy can thus maintain the environmental flow requirements of the river's key ecological functions while reducing potential losses in human water-use benefits as much as possible.

7. Conclusions

This study proposes an ecologically oriented operation strategy for a multi-reservoir system based on two reservoir operation stages. During the regular operation stage, a minimum water-release policy is combined with the human water-use operation rules for a multi-reservoir system in order to form a regular optimal operation scheme that maximizes multiple human water-use benefits. During the ecological operation stage, real-time operation schemes are set to modify the outflow from reservoirs in order to meet the environmental flow requirements of the river's key ecological processes. Based on the combination of the regular optimal operation scheme and the real-time operation schemes, this strategy can achieve coordination between human water needs and environmental flow requirements.

The practical use of this strategy was demonstrated for the simulation operation of a large-scale multi-reservoir system located in the middle and lower Han River Basin in China. During the regular operation stage, in comparison with the currently used operation scheme, the regular optimal operation ensures the minimum flow release and increases the comprehensive human water-use benefits of power generation, flood control, and water supply. During the ecological operation stage, the real-time operation schemes modify the reservoir's outflow from reservoirs in order to meet the environmental flow requirements of fish spawning and algal bloom control. On an annual scale, losses in power generation and water supply benefits caused by the real-time operation can be partly compensated for by the long-term regular optimal operation. This case study illustrates the feasibility of using this strategy to balance human water needs with environmental flow requirements.

Table 5
Comparison between the simulation operation results based on the ecologically oriented operation strategy and that based on the currently used scheme.

Scenarios	*E* ($\times 10^6$ kW·h)	*W* ($\times 10^6$ m^3)
Increments achieved by regular optimal operation scheme	141	35
Decrement caused by real-time operation schemes	153	390
Difference between ecologically oriented strategy and currently used scheme	−12	−355

For future improvement, the strategy can be modified in the following three aspects: ① In this strategy, the identification of the key ecological functions throughout a river was relatively empirical. More ecological-hydrological knowledge needs to be incorporated in order to make this identification more scientific. ② The real-time operation scheme was only demonstrated under historic hydrological situation, with perfect forecast as input. It is necessary to study the influence of forecast uncertainty on ecologically oriented reservoir operation, and to take these uncertainties into consideration during scheme establishment. ③ The implementation effect of this strategy was only illustrated for simulated operation. Once this strategy is applied in practice, it will be necessary to carry out long-term monitoring and evaluation on its implementation effects, and to perform continuous adjustments.

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Compliance with ethics guidelines

Hao Wang, Xiaohui Lei, Denghua Yan, Xu Wang, Shuyue Wu, Zhengjie Yin, and Wenhua Wan declare that they have no conflict of interest or financial conflicts to disclose.

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