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Derivation of water and power operating rules for multi-reservoirs

Yanlai Zhou\textsuperscript{a,b}, Shengliang Guo\textsuperscript{c}, Pan Liu\textsuperscript{d}, Chong-yu Xu\textsuperscript{a,c} and Xiaofeng Zhao\textsuperscript{d}

\textsuperscript{a}State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China; \textsuperscript{b}Changjiang River Scientific Research Institute, Wuhan, China; \textsuperscript{c}Department of Geosciences, University of Oslo, Oslo, Norway; \textsuperscript{d}Hubei Provincial Water Resources and Hydropower Planning Survey and Design Institute, Wuhan, China

\textbf{ABSTRACT}

Water operating rules have been universally used to operate single reservoirs because of their practicability, but the efficiency of operating rules for multi-reservoir systems is unsatisfactory in practice. For better performance, the combination of water and power operating rules is proposed and developed in this paper. The framework of deriving operating rules for multi-reservoirs consists of three modules. First, a deterministic optimal operation module is used to determine the optimal reservoir storage strategies. Second, a fitting module is used to identify and estimate the operating rules using a multiple linear regression analysis (MLR) and artificial neural networks (ANN) approach. Last, a testing module is used to test the fitting operating rules with observed inflows. The Three Gorges and Qing River cascade reservoirs in the Changjiang River basin, China, are selected for a case study. It is shown that the combination of water and power operating rules can improve not only the assurance probability of output power, but also annual average hydropower generation when compared with designed operating rules. It is indicated that the characteristics of flood and non-flood seasons, as well as sample input (water or power), should be considered if the operating rules are developed for multi-reservoirs.

\textbf{1 Introduction}

Reservoirs are among the most effective systems for integrated water resources development and management. Currently, reservoirs have played an increasingly important role in balancing the contradiction between social development and water resources scarcity (Guo \textit{et al.} 2004, Li \textit{et al.} 2013, Urbaniak \textit{et al.} 2013). Several models and methods for reservoir operation have been proposed and reviewed (e.g. Yakowitz 1982, Yeh 1985, Simonovic 1992, Wurbs 1993). However, it is difficult to apply a single best model or method to solve the operation problem of a multi-reservoir system (Labadie 2004).

Operating rules are often used to provide guidelines for reservoir releases to maintain the best interests of a reservoir, being consistent with certain inflow and existing storage levels (Tu \textit{et al.} 2003, Chang \textit{et al.} 2005). Deriving operating rules involves optimization, fitting, refinement and simulation (Yeh 1985, Wurbs 1993, Labadie 2004, Celeste and Billib 2009, Liu \textit{et al.} 2011a, 2011b). How to select an operating rule turned out to be one of the challenges in their derivation (Saad \textit{et al.} 1994); two forms of operating rules, i.e. water operating rules (Karamouz and Houch 1982, Ostadrahimi \textit{et al.} 2012) and power operating rules (Terry \textit{et al.} 1986, Oliveira and Loucks 1997, Liu \textit{et al.} 2011a), were used to coordinate the operation among cascade reservoirs. Although the fitting method contributes to the derivation of types of operating rule for a single reservoir, the goodness-of-fit criterion for deriving operating rules in water units does not always obtain the best operating rule for cascade reservoirs.

The dimensionality problem often arises in the operation of cascade reservoirs in water units. At the same time, the efficiency of optimization algorithms is also reduced by redundancy parameters of operating rules in water units. However, the aggregation–decomposition method, which is one of the most efficient methods for converting cascade reservoirs into an equivalent reservoir, has been used to derive operating rules of cascade reservoirs. Hall and Dracup (1970) originally proposed a method of surmounting the dimensionality problem of dynamic programming (DP) for cascade reservoirs by aggregating all reservoirs into an equivalent reservoir, in which the optimal solutions for the aggregated reservoir were decomposed into individual solutions for the single reservoirs. Then Turgeon (1981) applied this concept to cascade reservoirs using stochastic DP. Valdés \textit{et al.} (1992)
aggregated reservoirs in a hydropower system in power units rather than water units. Oliveira and Loucks (1997) showed that the aggregated reservoir approach was useful for making decisions regarding total releases for water supply of cascade reservoirs. Liu et al. (2011a) studied the optimal operating rule curves of cascade reservoirs based on the aggregation–decomposition method. Similar approaches have been proposed and developed to carry out optimization, fitting, refinement and simulation of operating rules and a vast literature (Turgeon 1981, Terry et al. 1986, Valdés et al. 1992, Saad et al. 1994, Archibald et al. 1997, Lund and Guzman 1999, Koutsoyiannis and Economou 2003, Rani and Moreira 2010, Chen et al. 2013) has applied those methods to derivation of operating rules for cascade reservoirs.

Most previous studies for operating rules paid more attention to a single reservoir or cascade reservoirs rather than multi-reservoirs (including parallel reservoirs and cascade reservoirs). Since there are hydraulic connections and storage compensations between the upstream and downstream reservoirs in multi-reservoirs, derivation of operating rules will become more and more complex as the number of reservoirs is increased. Our study aims to attempt to extend the operating rules from single reservoir to multi-reservoirs. We find that the forms of the rules, i.e. the variables and function forms, allow us to deduce the best decision, and our framework allows the analysis of the optimal release schedule obtained from the deterministic optimal operation module using a multiple linear regression analysis (MLR) and artificial neural network (ANN) approach. The operating rules were further tested with observed inflows. A multi-reservoir system, consisting of the Three Gorges cascade and Qing River cascade reservoirs in the Changjiang (Yangtze) river basin of China, is selected as a case study.

The paper is organized as follows: Section 2 gives a general description of the modelling framework and then details the components of the model, i.e. a deterministic optimal operation module, a fitting operating rules module, and a testing operating rules module. In Section 3 the case study is introduced briefly and the simulation results for the multi-reservoir system are discussed. Section 4 contains the conclusions.

2 Methodology

The optimal operation of a multi-reservoir system is challenging, especially taking into consideration the inflow uncertainty. The stochastic nature of inflow can be incorporated into the optimization model either explicitly or implicitly, which generates two approaches for reservoir and hydropower stochastic optimal operation: explicit stochastic optimization (ESO) and implicit stochastic optimization (ISO). In ESO, the inflow process is directly described using its probability distributions, and then traditional optimization methods can be applied to solve the problem. One typical example of the ESO approach is stochastic dynamic programming (SDP; Karamouz and Houck 1987). Although the ESO approach may seem germane (Yeh 1985), its application in practice presents considerable difficulties. For large systems it entails a great deal of calculation that severely restricts its application. For deterministic modelling, five reservoirs is considered large-scale, but for ESO modelling, three reservoirs is large-scale (Labadie 2004). Therefore, for stochastic optimization with more than five reservoirs, it is not realistic to use the ESO approach.

The ISO approach uses a deterministic optimization method to operate the reservoir system with a series of historical or Monte-Carlo generated inflows, and then examines the optimal operating results to develop operating rules. Such rules can serve as guides to the reservoir operators in actual operation.

In ISO, the stochastic optimization is decomposed into two stages: deterministic operation and operating rule derivation. This greatly reduces model dimensionality and calculation complexity, thus making the ISO approach much more applicable than the ESO approach, especially for the actual operation of large-scale reservoirs. Therefore, in this study, the framework of deriving operating rules for multi-reservoirs under the ISO approach is proposed. The framework consists of the following three modules:

1. A deterministic optimal operation module is used to determine the optimal reservoir storage strategies, in which the Monte Carlo method is used to simulate the values of boundary conditions and coarse DP is used to determine the initial feasible solutions of the progressive optimality algorithm (POA) used to derive the optimal solutions.
2. A fitting module is used to identify and estimate the forms and variables of the preliminary operating rules using the MLR and ANN approach.
3. A testing module is used to test the fitting operating rules with observed inflows.

The details of each step are as follows.

2.1 Deterministic optimal operation module for sample generation

The deterministic optimal operation module is used to determine the optimal reservoir storage strategies for multi-reservoirs to generate as much hydropower as possible.
2.1.1 Objective function
If the multi-reservoirs can meet the water supply and initial power generation requirements, then the objective function that generates maximum hydropower is selected, i.e.:

$$\max \ HG = \sum_{i=1}^{N_t} \sum_{j=1}^{N_c} \ TOP_{t,i} \cdot \Delta t$$

where HG is the sum of the hydropower generation of the cascade reservoirs (kWh); $N_t$ ($t = 1, 2, \ldots$) is the number of time period; $N_c$ ($t = 1, 2, \ldots$) is the number of cascade reservoirs in the multi-reservoir; $TOP_{t,i}$ is the total output power of the $i$th cascade reservoirs in period $t$ (kW); and $\Delta t$ is the interval of time.

2.1.2 Constraints
The following constraints were imposed:

2.1.2.1 Firm output power constraints of the cascade reservoirs.

$$TOP_{t,i} = OPC_{t,i} - v(pFOP_t - OPC_{t,i})$$

(2)

$$OPC_{t,i} = \sum_{j=1}^{N_c} OP_{t,j}$$

(3)

where $OPC_{t,i}$ is the total output power of the $i$th cascade reservoirs in period $t$ (kW); $FOP_t$ is the $i$th cascade reservoirs’ firm output power (kW); $v$ is a variable (=1 if $OPC_{t,i} \geq FOP_t = 0$ otherwise); $p$ is a positive number for penalty; $OP_{t,j}$ is the output power of the $j$th reservoir in period $t$ (kW); and $N_c$ is the number of reservoirs in cascade reservoirs.

2.1.2.2 Water balance equation.

$$S_{t+1,j} = S_{t,j} + (I_{t,j} - D_{t,j} - ES_{t,j}) \Delta t$$

(4)

where $S_{t,j}$ is the storage of the $j$th reservoir in period $t$ (m$^3$); $I_{t,j}$ is the inflow of the $j$th reservoir in period $t$ (m$^3$/s); $D_{t,j}$ is the water discharge of the $j$th reservoir in period $t$ (m$^3$/s); and $ES_{t,j}$ is the sum of evaporation and seepage of the $j$th reservoir in period $t$ (m$^3$/s).

2.1.2.3 Reservoir water level limits.

$$W_{\text{min},t,j} \leq W_{t,j} \leq W_{\text{max},t,j}$$

(5)

where $W_{t,j}$ is the reservoir water level; and $W_{\text{min},t,j}$ and $W_{\text{max},t,j}$ the minimum and maximum water level, respectively, of the $j$th reservoir in period $t$ (m).

2.1.2.4 Comprehensive utilization of water required at reservoirs’ downstream limits.

$$D_{\text{min},t,j} \leq D_{t,j} \leq D_{\text{max},t,j}$$

(6)

where $D_{\text{min},t,j}$ and $D_{\text{max},t,j}$ are the minimum and maximum water discharge, respectively, for all downstream uses in period $t$ (m$^3$/s).

2.1.2.5 Power generation limits.

$$OP_{\text{min},t,j} \leq OP_{t,j} \leq OP_{\text{max},t,j}$$

(7)

where $OP_{\text{min},t,j}$ and $OP_{\text{max},t,j}$ are the minimum and maximum output power limitations of the reservoir, respectively, in period $t$ (kW).

2.1.2.6 Boundary conditions limit.

$$W_{1,j} = W_{\text{ini},j}$$

$$W_{N_r+1,j} = W_{\text{fin},j}$$

(8)

It is worth mentioning that the principle that the final water level $W_{N_r+1,j}$ is the same as the initial water level $W_{1,j}$ (or as close as possible) in reservoir operation is only appropriate for reservoirs with annual regulation ability, but not always suitable for reservoirs with multi-year, seasonal and daily regulation ability. Therefore, to reflect the uncertainty of the boundary conditions limit, the Monte Carlo method is used to simulate the values of $W_{\text{ini},j}$ and $W_{\text{fin},j}$ as follows:

$$W_{\text{ini},j} = W_{\text{min},1,j} + (W_{\text{max},1,j} - W_{\text{min},1,j}) \cdot \text{Rand}$$

$$W_{\text{fin},j} = W_{\text{min},N_r+1,j} + (W_{\text{max},N_r+1,j} - W_{\text{min},N_r+1,j}) \cdot \text{Rand}$$

(9)

where $W_{\text{ini},j}$ and $W_{\text{fin},j}$ are the reservoir water level of the $j$th reservoir in the initial and final time steps, respectively (m); and Rand is the random number of uniform distribution in the range [0,1].

2.1.3 Optimality algorithm
Comparison of modified DP algorithms, such as dynamic programming successive approximations (DPSA), discrete differential dynamic programming (DDDP) and POA (Yeh 1985, Labadie 2004, Guo et al. 2011, Liu et al. 2011a, Chen et al. 2013), reveals that the POA produces a better optimal solution but depends on the initial solution (Turgeon 1980, 1981, Liu et al. 2011a, Chen et al. 2013). Thus the results obtained from the coarse DP algorithm are input as the initial solution of the POA, after which a subsequent optimization routine is executed. For detailed description of the coupling between the coarse DP
algorithm and POA, readers are referred to Liu et al. (2006) and Chen et al. (2013).

2.1.4 Transformation to potential energy
An aggregated reservoir can preserve and describe some features of the multi-reservoir system without considering their interactions (Liu et al. 2011a, Chen et al. 2013). The reservoirs in a hydropower system are aggregated in energy units rather than in water units and an optimal operation policy for the equivalent aggregated reservoir is determined based on a deterministic optimal operation module. The aggregation was carried out to convert the water stored in each reservoir into energy units, based on an approach originally suggested by Arvanitidis and Rosing (1970), and applied by Turgeon (1981) and Valdés et al. (1992).

The total initial potential energy (TPE<sub>c</sub>) stored in cascade reservoirs <i>i</i> to <i>N</i><sub>c</sub> at the end of period <i>t</i> is as follows:

\[
TPE_t = \sum_{j=1}^{N_c} \sum_{i=j}^{N_c} c_i \cdot (S_{i,j} - S_{0,j})
\]

The inflow of potential energy (IPE<sub>c</sub>) to reservoirs <i>i</i> to <i>N</i><sub>c</sub> in period <i>t</i> is:

\[
IPE_t = \sum_{j=1}^{N_c} \sum_{i=j}^{N_c} c_i \cdot I_{i,j}
\]

and the outflow of potential energy (OPE<sub>c</sub>) from reservoirs <i>i</i> to <i>N</i><sub>c</sub> in period <i>t</i> is:

\[
OPE_t = \sum_{j=1}^{N_c} c_j \cdot D_{i,j}
\]

where <i>S_{0,j}</i> is the inactive storage of the <i>j</i>th reservoir (m<sup>3</sup>); <i>c_i</i> is the conversion factor of the <i>i</i>th reservoir; and <i>c_j</i> the conversion factor of the <i>j</i>th reservoir.

2.2 Fitting operating rules module
Dependent and independent variables constitute the basic framework of operating rules. Proper selection of these variables has great importance for model accuracy. There are several principles for the formulation and selection of dependent and independent variables (Ji et al. 2010a, 2010b):

(a) The dependent variable should be intuitive and easy to operate in actual operation, such as output power, OP<sub>t,j</sub>, reservoir storage at the end of the time step, <i>S_{t+1,j}</i>, and the reservoir discharge, <i>D_{t,j}</i>, for a single reservoir, as well as total output power, TOP<sub>c</sub>, total potential energy at the end of the time step, TPE<sub>c</sub>, and outflow of potential energy, OPE<sub>c</sub>, for an aggregated reservoir.

(b) Independent variables should be as comprehensive as possible, so the model can fully reflect the status of the reservoir and power station, such as inflow, <i>I_{t,j}</i>, and reservoir storage at the beginning of the time step, <i>S_{t,j}</i>, for a single reservoir, as well as total initial potential energy, TPE<sub>c</sub>, and inflow of potential energy, IPE<sub>c</sub>, for an aggregated reservoir.

(c) Variables should be independent of each other. Independence means, for instance, the reservoir storage status can be described in three ways: reservoir water level, reservoir storage status and storage energy. However, not all of them need to be adopted in the independent variables set, because they are in a one-to-one relationship.

Considering the principles above, in this paper we take reservoir output power (<i>N</i>) as a decision variable. Reservoir storage at the beginning of the time step, <i>S_{t,j}</i>, and inflow, <i>I_{t,j}</i>, are chosen as independent variables for water operating rules in a single reservoir, and inflow of potential energy, IPE<sub>c</sub>, and total initial potential energy, TPE<sub>c</sub>, are chosen as independent variables for power operating rules in an aggregated reservoir. Liu et al. (2011a) explained the meaning and calculation of independent variables in detail.

2.2.1 Water operating rules
Because of the simplicity of the water operating rules, the general forms of linear (Karamouz and Houck 1982, Ostadrahimi et al. 2012) and nonlinear operating rules (Neelakantan and Pundarikanthan 2000, Chandramouli and Raman 2001, Liu et al. 2006) have been often used in reservoir operation. Based on the results of the deterministic optimal operation module, the following linear and nonlinear water operating rules for each time period can be established:

\[
OP_{t,j} = a_0 + a_1 \cdot I_{t,j} + a_2 \cdot S_{t,j} + \varepsilon_1
\]

\[
OP_{t,j} = f(I_{t,j}, S_{t,j}) + \varepsilon_2
\]

where <i>a_i</i> (<i>i</i> = 0, 1 and 2) is the parameter of linear water operating rules; <i>\varepsilon_i</i> (<i>i</i> = 0 or 1) is the random variable of water operating rules; and <i>f(·)</i> is the nonlinear function of water operating rules.

2.2.2 Power operating rules
Based on the results of the aggregated reservoir for cascade reservoirs, the linear (Liu et al. 2011a) and nonlinear power operating rules (Turgeon 1981) for
each time period, which are used to describe the quantitative relationship between the total output power of the aggregated reservoir, TPE, and the optimal aggregated energy, can be established:

\[
\text{TPE}_t = \beta_0 + \beta_1 \cdot \text{TPE}_{t-1} + \beta_2 \cdot \text{IPE}_t + \varepsilon_3 \quad (15)
\]

\[
\text{TPE}_t = f(\text{TPE}_{t-1}, \text{IPE}_t) + \varepsilon_4 \quad (16)
\]

where \( \beta_i \) (i = 0, 1 and 2) is the parameter of linear power operating rules; and \( \varepsilon_i \) (i = 3 or 4) is the random variable of power operating rules.

2.2.3 Fitting methods
Multiple linear regression (Karamouz and Houck 1982, Liu et al. 2011a, Ostadrahimi et al. 2012) and artificial neural networks (Saad et al. 1994, Chandramouli and Raman 2001, Liu et al. 2006) are employed to develop the operating rules for multi-reservoirs. For a detailed description of MLR and ANN used in this paper, readers are referred to Liu et al. (2006).

2.3 Testing operating rules module
It is necessary to test whether the operating rules are able to deduce the best decision, because the operating rules are the approximate quantitative relationships among reservoir variables. The operation period is divided into calibration and validation periods.

2.3.1 Testing water operating rules
Once the water operating rules have been determined, their performance can be evaluated and assessed by tests with observed inflows in the calibration and verification periods.

2.3.2 Testing power operating rules
The decomposition method is aimed at decomposing the total output power of an aggregated reservoir and maximizing the total initial potential energy at the end of period \( t \) for a multi-reservoir system. The objective function that generates maximum total potential energy, TPE\(_{t+1}\), for the end period is selected, maxTPE\(_{t+1}\) subject to output power of the multi-reservoir system limit constraint TOP\(_t\) = \( \sum_{j=1}^{N_0} \text{OP}_{t,j} \), where TOP\(_t\) is the simulation output power of the \( j \)th reservoir in period \( t \) (kW). Other limit constraints are the same as equations (2)–(9).

Although POA is applied to sample generation for the operating rules, the genetic algorithm (GA) is selected as the optimal algorithm for testing the operating rules. Compared with POA, the combination of MLR, ANN and GA is easily applied to derive operating rules effectively (Chang and Chang 2001, Naresh and Sharma 2001). A general flowchart of the genetic algorithm is shown in many studies in the literature (e.g. Oliveira and Loucks 1997, Hinčal et al. 2011, Liu et al. 2011a). The GA is used to solve the whole model, including maxTPE\(_{t+1}\) and equations (2)–(9).

2.3.3 Evaluation criteria
Different disciplines have different performance indices. For example, the oldest and most widely used performance criteria for water resources systems are reliability, resiliency and vulnerability (Hashimoto et al. 1982, Moy et al. 1986). Criteria such as the Nash-Sutcliffe efficiency, root mean square error and relative error are used to evaluate the prediction abilities of hydrological models (Bennett et al. 2013). For particular reservoirs or a system of hydropower stations, the assurance probability of output power and mean hydropower energy, for example, are used to compare the performance of different operation schemes and models (Liu et al. 2006). Therefore, three evaluation criteria were selected to compare the performance of the different schemes for the multi-reservoir system: (a) the assurance probability of output power, \( P \); the mean hydropower energy, MHE; and the Nash-Sutcliffe efficiency index, \( R^2 \). The three indices are defined as follows:

\[
P = \frac{n}{N_t} \times 100\% \quad (17)
\]

\[
\text{MHE} = \frac{1}{N_y} \sum_{i=1}^{N_i} \sum_{y=1}^{N_y} \text{TPE}_{t,i} \cdot \Delta t \quad (18)
\]

The Nash-Sutcliffe efficiency index is used to assess the performance of these two fitting methods, and is given by:

\[
R^2 = 1 - \frac{\sum_{i=1}^{N_y} (\text{OP}_i - \text{MOOP})^2}{\sum_{i=1}^{N_y} (\text{OOP}_i - \text{MOOP})^2} \times 100\% \quad (19)
\]

where MHE is the mean hydropower energy in simulation years (kWh); \( n \) is the number of occurrences of TOP\(_{t,i} \geq \text{FOP}_i \); OOP\(_i\) is the optimal output power in year \( i \) for a single or aggregated reservoir (MW); OP\(_i\) is the simulated output power in year \( i \) for a single reservoir or aggregated reservoir (MW); MOOP is the mean of optimal output power in year \( i \) for a single or aggregated reservoir (MW); and \( N_y \) is the number of years.
3 Case study

3.1 Three Gorges cascade and Qing River cascade reservoirs

A multi-reservoir system consisting of the Three Gorges cascade reservoirs (Three Gorges, Gezhouba) and the Qing River cascade reservoirs (Shuibuya, Geheyan, Gaobazhou) in the Changjiang River basin of China, as shown in Fig. 1, is selected as a case study.

The Three Gorges Reservoir (TGR) is a vitally important and backbone project in the development and harnessing of the Changjiang River in China. The upstream of the Changjiang, with main course length of about $4.5 \times 10^3$ km and a drainage area of $1.0 \times 10^6$ km$^2$, is intercepted by the TGR. The TGR is the largest water conservancy project ever undertaken in the world, with a normal pool level at 175 m and a total reservoir storage capacity of $39.3 \times 10^9$ m$^3$, of which $22.15 \times 10^9$ m$^3$ is flood control storage and $16.5 \times 10^9$ m$^3$ is a conservation regulating storage volume, accounting for approximately 3.7% of the dam site mean annual runoff of $451 \times 10^9$ m$^3$.

The Gezhouba Reservoir is located at the lower end of the TGR in the suburbs of Yichang City, 38 km downstream of the TGR. The dam is 2606 m long and 53.8 m high, with a total storage capacity of $1.58 \times 10^9$ m$^3$ and a maximum flood discharging capability of 110 000 m$^3$/s.

The Qing River is one of the main tributaries of the Changjiang River and its basin area is 17 600 km$^2$. The mean annual rainfall, runoff depth and annual runoff are approximately 1460 mm, 876 mm and 423 m$^3$/s, respectively. The total length of the mainstream is 423 km, with a hydraulic drop of 1430 m. Along the Qing River, a three-step cascade of reservoirs (Shuibuya, Geheyan and Gaobazhou) has been constructed from upstream to downstream. The main functions of these cascade reservoirs are power generation and flood control. The characteristic parameter values of these five reservoirs are given in Table 1.

3.2 Results and discussion

The multi-reservoirs are composed of the Three Gorges cascade reservoirs and Qing River cascade reservoirs. The Gezhouba and Gaobazhou reservoirs are runoff hydropower plants with small regulation storages; therefore, water operating rules are applied to simulate the operation of the TGR, and water and power operating rules are applied to simulate the operation of the Shuibuya and Geheyan reservoirs. Aside from the water and power operating rules, two other schemes, conventional operation and optimal operation rules, are also implemented to simulate the operation of the multi-reservoirs for comparative purposes. The operation period with 60 years of observed inflow (from

![Figure 1. Location of the Three Gorges cascade and Qing River cascade reservoirs.](image)

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Unit</th>
<th>TGR</th>
<th>Gezhouba</th>
<th>Shuibuya</th>
<th>Geheyan</th>
<th>Gaobazhou</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total storage</td>
<td>$10^9$ m$^3$</td>
<td>393</td>
<td>15.8</td>
<td>42</td>
<td>34</td>
<td>54</td>
</tr>
<tr>
<td>Flood control storage</td>
<td>$10^8$ m$^3$</td>
<td>225.5</td>
<td>—</td>
<td>5.0</td>
<td>5.0</td>
<td>—</td>
</tr>
<tr>
<td>Crest elevation</td>
<td>m</td>
<td>185</td>
<td>70</td>
<td>409</td>
<td>206</td>
<td>83</td>
</tr>
<tr>
<td>Normal water level</td>
<td>m</td>
<td>175</td>
<td>66</td>
<td>400</td>
<td>200</td>
<td>80</td>
</tr>
<tr>
<td>Flood limited water level</td>
<td>m</td>
<td>145.0</td>
<td>—</td>
<td>391.8</td>
<td>192.2</td>
<td>—</td>
</tr>
<tr>
<td>Install capability</td>
<td>MW</td>
<td>22400</td>
<td>2715</td>
<td>1840</td>
<td>1212</td>
<td>270</td>
</tr>
<tr>
<td>Annual generation</td>
<td>$10^9$ kWh</td>
<td>84.7</td>
<td>15.7</td>
<td>3.41</td>
<td>3.04</td>
<td>0.93</td>
</tr>
<tr>
<td>Regulation ability</td>
<td>—</td>
<td>Seasonal</td>
<td>Daily</td>
<td>Multi-years</td>
<td>Annual</td>
<td>Daily</td>
</tr>
</tbody>
</table>
1951 to 2011) is divided into a calibration period (1951–1991) and a validation period (1992–2011), and the time interval is 10 days.

The designed operating rules can be regarded as a standard operating policy (SOP in Table 2). Only the designed operating rule curves of the TGR and Shuibuya Reservoir are described briefly; the designed operating rule curves of the TGR are shown in Fig. 2. From the end of May to the beginning of June, the reservoir water level will be lowered to 145 m (flood limited water level, FLWL). In October, the reservoir water level will be raised gradually to the normal pool level of 175 m. From November to the end of April in the following year, the reservoir water level should be kept as high as possible to generate more electrical power. The reservoir water level will be lowered further, but should not fall below 155 m before the end of April to satisfy navigation conditions. The designed operating rule curves of the Shuibuya Reservoir are shown in Fig. 3, in which the whole storage space is divided into five operational zones. If the water level rises to FLWL or into the flood prevention zone during the flood season, the reservoir is operated according to designed flood control rules. Otherwise, the hydropower plant is operated between the upper and lower basic guide curves. The designed operating rules do not acknowledge the potential for coordinated operation between the multi-reservoirs. Due to the potential profits when compared with the deterministic optimal operation (DOO in Table 2), it is feasible to jointly operate the multi-reservoirs to improve the hydropower benefits and generation assurance rate. The DOO is based upon the observed inflow series and can be seen as an ideal operation in theory.

Two fitting methods are used to derive the water and power operating rules based on the results of the deterministic optimal operation. One is multiple linear regression analysis, i.e. the linear water and power operating rules are derived from MLR analysis of the optimal release schedule in the calibration period. The other is the ANN method, in which the nonlinear water and power operating rules are derived by analysing the optimal release schedule in the calibration period.

Figure 4 shows that the fitting accuracy of operating rules in the flood season is better than that of operating rules in the non-flood season in both the TGR and the Qing River cascade reservoirs (QRCR). The fitting accuracy of nonlinear operating rules ($R^2 = 95.95\%$ in TGR and $R^2 = 96.13\%$ in QRCR) is better than that of linear operating rules ($R^2 = 89.89\%$ in TGR and $R^2 = 88.52\%$ in QRCR) in the non-flood season; however, the fitting accuracy of nonlinear operating rules ($R^2 = 99.86\%$ in TGR and $R^2 = 98.77\%$ in QRCR) in the flood season is even higher.

### Table 2. Comparison of operation results with observed inflow from 1951 to 2011.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Scheme</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P (%)</td>
<td>MHE (10^9 kWh)</td>
<td>$R^2$ (%)</td>
</tr>
<tr>
<td>Three Georges cascade</td>
<td>SOP 95</td>
<td>96.06</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>DOO 98</td>
<td>100.98</td>
<td>—</td>
</tr>
<tr>
<td>Qing River cascade</td>
<td>SOP 95</td>
<td>8.30</td>
<td>—</td>
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<tr>
<td></td>
<td>DOO 98</td>
<td>9.31</td>
<td>—</td>
</tr>
<tr>
<td>Mixed multi-</td>
<td>SOP 95</td>
<td>104.36</td>
<td>—</td>
</tr>
<tr>
<td>reservoirs</td>
<td>DOO 98</td>
<td>110.29</td>
<td>—</td>
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<tr>
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<td>NWOR 97</td>
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<tr>
<td></td>
<td>NWOR-NPOR 97</td>
<td>108.07</td>
<td>97.39</td>
</tr>
</tbody>
</table>

![Figure 2. Designed operating rule curves of the Three Gorges Reservoir (I: flood control zone; II: install output power zone; III: firm output power zone; and IV: lower output power zone).](image-url)
approximates to that of linear operating rules ($R^2 = 99.58\%$ in TGR and $R^2 = 92.36\%$ in QRCR) in the flood season. The NWOR scheme can perform better than the LWOR scheme for the TGR, and NPOR can perform better than LPOR for the QRCR. The explanations are as follows:

(a) Influenced by the hydrological differences between flood season and non-flood season, the linear characteristic of operating rules is noticeable in the flood season; however, the nonlinear characteristic of operating rules is noticeable in the non-flood season.

(b) The ANN method shows not only the linear characteristics but also the nonlinear characteristics, while the MLR analysis only represents linear characteristics.

As a further visual analysis, surfaces for nonlinear operating rules are shown in Figs 5 and 6, which show that the linear characteristics of operating rules are more remarkable than the nonlinear characteristics for the TGR in October, and the nonlinear characteristics of operating rules are more remarkable than the linear characteristics in January. However, the linear characteristics of operating rules are more remarkable than the nonlinear characteristics for the aggregated reservoir in October, and the nonlinear characteristics of operating rules are more remarkable than the linear characteristics in January and in the interim period in May.

The performance of the NWOR-NPOR scheme (i.e. nonlinear water operating rules for the TGR and

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**Figure 3.** Designed operating rule curves of the Shuibuya Reservoir (I: flood control zone; II: install output power zone; III: increasing output power zone; IV: firm output power zone; and V: lower output power zone).

**Figure 4.** Fitting accuracy of operating rules in the calibration period. LWOR and NWOR: linear and nonlinear water operating rules, respectively, for the TGR; LPOR and NPOR are the linear and nonlinear power operating rules for the Qing River cascade reservoirs, respectively.
nonlinear power operating rules for the QRCR) is given in Table 2. Table 2 shows that \( P \) and MHE are improved in the NWOR-NPOR scheme when compared to the standard operating policy (SOP) scheme. For the calibration period, the NWOR-NPOR scheme can generate \( 3.71 \times 10^9 \) kWh more power (an increase of 3.55\%) than the SOP scheme; \( P \) increased from 95\% to 97\% and \( R^2 = 97.39\% \) for the multi-reservoir. For the validation period, the NWOR-NPOR scheme can generate \( 3.18 \times 10^9 \) kWh more power (an increase of 3.05\%) compared with the SOP scheme; \( P \) increased from 94\% to 96\% and \( R^2 = 97.24\% \) for the multi-reservoir. It is shown that the combination of water and power operating rules can improve not only the

![Figure 5. Comparison of surfaces for operating rules in the TGR.](image-url)
assurance probability of output power but also the mean hydropower generation, when compared with the designed operating rules.

4 Conclusions

The combination of water and power operating rules, which are modifications of the single water or power operating rules, was proposed and developed. The Three Georges cascade reservoirs and Qing River cascade reservoirs were selected as a case study. The main conclusions are summarized as follows:

(1) The characteristics of flood and non-flood seasons, and sample input (water or power) should be considered if operating rules are being derived for multi-reservoirs.

Figure 6. Comparison of surfaces for operating rules in the QRCR.
(2) The combination of water and power operating rules can improve not only the assurance probability of output power but also the mean hydropower generation compared to the designed operating rules. The mixed water and power operating rules are effective and efficient for operation of multi-reservoirs because of their better performance compared to the designed operating rules.

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