Quantitative assessment of ecological operation effects based on flood pulses and ecology-economic coupling model: a case study of Three Gorges Reservoir, China

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Abstract

Flood pulses are closely related to river ecosystem health. Reservoirs bring many benefits to flood control, power generation, shipping etc., but their attenuation effects on runoff flood pulses should not be ignored. Ecological operation can effectively reduce some negative ecological impacts brought by the reservoir. However, the inability to quantitatively assess ecological effects hinders the promotion of ecological operation in reservoir management. To solve this problem, we proposed 11 flood pulse indicators (FPI), a random simulation method and an ecology-economy coupling model in this study. In addition, we used four major Chinese carps as indicator species and the Three Gorges Reservoir as a case study to test the role of flood pulses in improving the ecological operation effects of the reservoir from the fish protection perspective. The results show that: (1) FPI can be controlled by the reservoir and reflect the flood pulse characteristics of runoff. (2) Random simulation method guides managers to optimize the discharge and formulate eco-friendly operation schemes. (3) Ecology-economy coupling model helps managers analyze the relationship between ecological operation effects and economic benefits. A comprehensive assessment can improve the acceptance of ecological operation, which is conducive to the sustainable development of river ecosystem.

Key words: ecology-economic coupling model, flood pulse indicators (FPI), improved grey wolf optimizer, random simulation method, reservoir ecological operation

Highlights

- 11 flood pulse indicators that can be controlled by the reservoir have the ability to reflect the runoff flood pulse.
- The random simulation method can provide reference for the formulation of reservoir ecological operation schemes.
- The ecology-economy coupling model can quantitatively analyze the relationship between ecological operation effects and economic benefits brought by the ecological operation of reservoirs.

1. INTRODUCTION

A river is a complex ecosystem that combines natural, social and economic functions. Reservoirs bring huge benefits in flood control and benefit operations (power generation, shipping, water supply, irrigation, etc.). At the same time, they have negative impacts on attenuating the runoff flood pulses (Binh et al. 2020). In addition, operating reservoirs inappropriately will cause water quality deterioration, vegetation decline in floodplains, biodiversity reduction and other problems, which worsen the river ecosystem health (Li & Zeng 2020; Lin et al. 2021). Therefore, while maximizing flood control or economic benefits, reservoir managers should take the ecological demands into consideration. Optimizing discharge to have the characteristics of runoff flood pulses is an effective way to reduce some of the negative ecological impacts brought by the attenuation of reservoirs (Jardim et al. 2020).

To maintain river functions (biological habitats, material exchanges, natural landscapes, etc.), governments generally require reservoir managers to control the discharge based on the recommended environmental flow (Turgeon et al. 2021), which is often determined by hydrology methods, hydraulics methods, habitat simulation methods and holistic methods (Goguen et al. 2020). However, these methods ignore the importance of runoff flood pulses, because the recommended...
environmental flows are determined from the base flow (the minimum flow that meets the basic ecological function of the river) and the fixed value (Lobera et al. 2021). According to the flood pulse theory, pulses formed in the rising or falling flood are the main driving force for biological survival, ecosystem interaction and productivity (Li et al. 2020). Therefore, it is necessary to carry out a quantitative analysis on flood pulses, which can be divided into indicator selection, sample division and degree of change assessment (Du et al. 2020). The only recognized flood pulse index system is the Indicators of Hydrologic Alteration (IHA) (Cheng et al. 2019). Because the IHA is proposed to quantitatively assess the hydrological regime (the changes of precipitation, runoff, evaporation, sediment transport, water level, water quality, etc. of rivers, lakes and reservoirs with time and space), it cannot fully reflect the flood pulse characteristics of runoff. Commonly used principles for sample division are the operating year of the reservoir and the planning period (Kuriqi et al. 2019). The former focuses on measuring the impact of reservoirs on runoff, while the latter focuses on measuring the changes in runoff during the planning period. In addition, the degree of change assessment is usually performed by nonparametric test methods, such as the Mann-Whitney U and the Mann–Kendall, which have advantages in testing whether two samples with unknown distribution are consistent (Chen et al. 2017; Gu et al. 2020).

Biodiversity can be used as a measure of the river health. Studies have shown that the scale, occurrence time and frequency of flood pulses are closely related to the cyclical life activities of fish, plankton, benthic and other aquatic organisms (Mallen Cooper & Zampatti 2020). To protect the river health, more and more scholars advocate that reservoir managers should adopt ecological operation such as increasing discharge, discharging reservoir based on runoff flood pulses, discharging reservoir surface water, and so on (Soﬁ et al. 2020; Virbickas et al. 2020). Proper reservoir operation can simulate the runoff flood pulses under the premise of meeting flood control safety, and play a positive role in river health (Cruz et al. 2020). However, this positive effect has the disadvantages of being difficult to quantify, long showing period and reduced economic benefits. As a result, many reservoirs are reluctant to adopt ecological operation.

Essentially, the operation of reservoirs is a multi-objective optimization problem (Yang et al. 2021). Because of the non-linear relationships between optimization objectives, it is necessary to use optimization algorithms. Grey wolf optimizer is a meta-heuristic optimization algorithm that mimics the predation behavior of wolves. It inherits the advantages of meta-heuristic optimization algorithms, such as simplicity, flexibility, derivation-free mechanism and local optima avoidance (Dahmani & Yebdi 2020). The grey wolf optimizer is widely used in power system optimization operation, image information processing and trend prediction (Mohammadi et al. 2020).

In order to illustrate the ecological operation of the reservoir, we established an ecology-economy coupling model to analyze the relationship between ecological operation effects and economic benefits. Four major Chinese carps (FMCC, which consist of Mylopharyngodon piceus, Ctenopharyngodon idellus, Hypophthalmichthys molitrix and Hypophthalmichthys nobilis) are the representative warm-water and cool-water fishes (Zhang et al. 2021) and the Three Gorges Reservoir is a representative large-scale reservoir in the Yangtze River Basin, China. In this study, we used the FMCC as indicator species to analyze the impact of the Three Gorges Reservoir on the flood pulses of the middle Yangtze River. The specific objectives of this study are:

1. Analyzing the runoff flood pulses and finding ways to simulate it by reservoirs.
   a. Determining an index system that can reflect the runoff flood pulses.
   b. Finding a way to guide reservoir managers to optimize discharge and formulate ecological operation schemes.
2. Seeking methods to analyze the feasibility of reservoir ecological operation and the relationship between ecological operation effects and reservoir economic benefits.
   a. Establishing a multi-objective optimization model to calculate the ecological operation effects and economic benefits of the reservoir.
   b. Identifying the integration point between the improved gray wolf optimizer and the multi-objective optimization model to simulate the ecological operation of the reservoir.

### 2. STUDY AREA AND DATA

#### 2.1. Study area

The upper and middle Yangtze River is the main habitat of the FMCC. Affected by reservoirs on the main stream of Yangtze River (from Chongqing to Pengze about 1,695 km), the number of FMCC spawning grounds decreased from 36 (in the 1960s) to 14, and the annual egg production of FMCC decreased from 118.4 billion to 977 million (Yu 2018). Every year from April
to July, when the water temperature reaches or is above 18 °C, FMCC will swim up to spawning grounds to breed offspring under the stimulation of rising flood. The eggs of FMCC belong to the semi-floating type, and flood pulses prevent them from sinking death. According to statistics, the spawning grounds of FMCC in the middle Yangtze River are mainly distributed in Yichang, Yidu and Zhicheng (their locations are shown in Figure 1). The total annual egg production in 3 spawning grounds is 631.2 million, which account for 64.6% of the main stream of Yangtze River. Therefore, these areas are the main spawning grounds of FMCC, and their information is shown in Table 1.

The total amount of water resources in the Yangtze River is 975.5 billion m³, accounting for 36% of China’s river runoff. Its annual average precipitation is 1,067 mm, annual average water surface evaporation is 922 mm and annual average land surface evaporation is 541 mm. The Three Gorges Reservoir (main parameters are shown in Table 2) is the largest reservoir in the middle Yangtze River, which can directly affect the hydrology and hydraulics of Yichang, Yidu and Zhicheng spawning grounds. To find an ecological operation that can improve the FMCC production, we took the Three Gorges Reservoir as the study case and analyzed its impact on the flood pulses in the middle Yangtze River.

2.2. Data source

Yichang Station (Figure 1) is one of the main control stations in the downstream of the Three Gorges Reservoir (apart from 44 km) and is located at the junction of the upper and middle Yangtze River. About half of the runoff in the main stream comes from the upstream (area is 10,055 km²), therefore, the Yichang Station is the key to studying the flood pulses of Yangtze River. All calculating parts of this study were conducted using the daily runoff data from 1877 to 2016 of the Yichang Station.

![Figure 1](image_url) | The location of FMCC main grounds and the Three Gorges Reservoir.

<table>
<thead>
<tr>
<th>Spawning ground</th>
<th>Yichang</th>
<th>Yidu</th>
<th>Zhicheng</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Gezhouba Reservoir-Miaozui</td>
<td>Yanzhiba-Honghuatao</td>
<td>Zhicheng-Yaojiagang</td>
</tr>
<tr>
<td>Scale (km)</td>
<td>5</td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>Annual egg production (million)</td>
<td>412.54</td>
<td>189.86</td>
<td>28.8</td>
</tr>
<tr>
<td>Average water surface depth (m)</td>
<td>45.10</td>
<td>57.99</td>
<td>41.26</td>
</tr>
<tr>
<td>Average water surface width (m)</td>
<td>422.33</td>
<td>552.39</td>
<td>1,441.15</td>
</tr>
</tbody>
</table>
Station with good consistency, representativeness and reliability. In addition, we used the discharge data of the Three Gorges Reservoir from 2004 to 2016 when comparing the discharge of the reservoir with the daily runoff data of the Yichang Station. The parameters involved in the ecology-economy coupling model are all from the ‘Regulation for joint operation of Three Gorges-Gezhouba cascade reservoirs’ ([2020]135, China’s Ministry of Water Resources).

3. METHODOLOGY

To evaluate the feasibility of ecological operation and its impact on the economic benefits of the reservoir, we proposed 11 flood pulse indicators (FPI), a random simulation method and an ecology-economy coupling model. The specific contents of this study are as follows (Figure 2):

1. Proposing 11 FPI based on the IHA to quantify the runoff flood pulses.
2. Using the Mann-Whitney U method to find out the significantly changed FPI (referred to as SC-FPI) after the reservoir operated.
3. Using the random simulation method to analyze the characteristics of runoff flood pulses and provide the optimum values of SC-FPI.
4. Establishing an ecology-economy coupling model (multi-objective optimization model) to simulate the ecological operation of the reservoir with an optimization of discharge and quantify its benefits mainly from the fish protection perspective.
5. Using the improved grey wolf optimizer to solve the ecology-economy coupling model, and assessing the feasibility of the reservoir ecological operation according to the simulation results.

3.1. Flood pulse indicators (FPI)

IHA has good applicability of hydrological data (water levels and flow) and is a quantitative index system for a hydrological regime that is mature and widely used worldwide (Cheng et al. 2019). It uses 33 indicators to reflect the hydrological regime

![Figure 2](http://iwaponline.com/ws/article-pdf/22/2/1848/1010809/ws022021848.pdf)

**Table 2** | Main parameters of the Three Gorges Reservoir

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter</th>
<th>Design standard and flood peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest drawdown water level in dry season (m)</td>
<td>155</td>
<td>1,000-year flood; 98,800 m$^3$/s</td>
</tr>
<tr>
<td>Normal water level (m)</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Flood control water level (m)</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>Design flood water level (m)</td>
<td>175</td>
<td>10,000-year flood; 124,300 m$^3$/s</td>
</tr>
<tr>
<td>Check flood water level (m)</td>
<td>180.4</td>
<td></td>
</tr>
<tr>
<td>Storage capacity for flood control (billion m$^3$)</td>
<td>22.15</td>
<td></td>
</tr>
<tr>
<td>Total storage capacity (billion m$^3$)</td>
<td>39.3</td>
<td></td>
</tr>
<tr>
<td>Flood season</td>
<td>May–October</td>
<td></td>
</tr>
</tbody>
</table>
of the river from five aspects: magnitude, duration, occurrence time, frequency and change rate (Du et al. 2020). Referring to the selection principle and the ecological connotation of each indicator in IHA, we proposed 11 indicators to quantify the runoff from the base flow and the flood pulses, as shown in Table 3.

3.2. Mann-Whitney U method

Mann-Whitney U is a nonparametric test method. The information source of it is the sample rank (data size level), which is used to analyze the sample distribution. In this study, the Mann-Whitney U method was used to test the degrees of change of 11 FPI and find out SC-FPI. The inspection steps of the Mann-Whitney U method are as follows:

1. Select observation set $a_A$ and observation set $b_B$ from Sample A and Sample B, respectively ($a$ and $b$ represent the number of individuals selected from A and B, respectively).
2. Mix $a_A$ and $b_B$, and arrange their individuals in descending order.
3. Calculate the rank sum of $a_A$ and $b_B$ respectively, and denote them as $T_A$ and $T_B$.
4. Hypothesis 1 (denoted as $H_1$): the relative rank distributions of $A$ and $B$ are same.
5. Calculate statistical parameters $U_1$ and $U_2$:

$$U_1 = a_A \times b_B + \frac{a_A \times (a_A + 1)}{2} - T_A$$  
$$U_2 = a_A \times b_B + \frac{b_B \times (b_B + 1)}{2} - T_B$$  

6. Check the significance level table to obtain the critical value $U_L$.
7. Record the minimum value in Step (5) as $U_{min}$, and compare $U_{min}$ with $U_L$. If $U_{min} \leq U_L$, reject $H_1$; otherwise, accept $H_1$.

### Table 3 | FPI and its main significance

<table>
<thead>
<tr>
<th>Order</th>
<th>FPI</th>
<th>Unit</th>
<th>Main significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monthly average flow</td>
<td>$m^3/s$</td>
<td>- Base flow required by river ecosystem</td>
</tr>
<tr>
<td>2</td>
<td>Daily rising flood rate</td>
<td>$(m^3/s)/d$</td>
<td>- One of the main driving forces for the changes of physical and chemical properties of the river, such as water temperature, oxygen content, sediment content, etc.</td>
</tr>
<tr>
<td>3</td>
<td>Daily falling flood rate</td>
<td>$(m^3/s)/d$</td>
<td>- One of the main driving factors for the formation of flood pulses</td>
</tr>
<tr>
<td>4</td>
<td>Average rising flood duration</td>
<td>$h$</td>
<td>- The control factors of the basic flood pulses required by the river ecosystem</td>
</tr>
<tr>
<td>5</td>
<td>Average falling flood duration</td>
<td>$h$</td>
<td>- The average exchange period and speed of nutrients (oxygen, vitamins, organics, etc.) needed by biological growth and breeding in the river ecosystem</td>
</tr>
<tr>
<td>6</td>
<td>Average cumulative rising flow$^1$</td>
<td>$m^3/s$</td>
<td>- Average adjustment period and range of flow rising/falling in the river</td>
</tr>
<tr>
<td>7</td>
<td>Average cumulative falling flow$^1$</td>
<td>$m^3/s$</td>
<td>- To maintain the river ecosystem health, the reservoir discharge must refer to the factors</td>
</tr>
<tr>
<td>8</td>
<td>Maximum cumulative rising flow$^2$</td>
<td>$m^3/s$</td>
<td>- Maximum amplitude of flood pulses acceptable to aquatic organisms in river ecosystem</td>
</tr>
<tr>
<td>9</td>
<td>Maximum cumulative falling flow$^2$</td>
<td>$m^3/s$</td>
<td>- The largest exchange period and speed of nutrients needed by biological growth and breeding in the river</td>
</tr>
<tr>
<td>10</td>
<td>Longest rising flood duration</td>
<td>$h$</td>
<td>- The largest adjustment range of reservoir discharge rising/falling period and speed</td>
</tr>
<tr>
<td>11</td>
<td>Longest falling flood duration</td>
<td>$h$</td>
<td></td>
</tr>
</tbody>
</table>

**Note 1:** Average flow increase/decrease value in all rising/falling flood.

**Note 2:** Compare the value of each rising/falling flood to select the maximum increase/decrease value as the Maximum cumulative rising/falling flow.
3.3. Random simulation method

The random simulation method is a method to simulate the occurrence time and scale of nature according to its randomicity and determinacy. For floods, the occurrence time, flow and possibility of rising or falling are random. But for the river, some determinacies can be obtained by statistical analysis of its runoff data. After obtaining SC-FPI, we proposed a random simulation method to determine their values by analyzing runoff flood pulses, and the steps were as follows:

(1) Calculate the occurrence number of Indicator \(i, \ (i = 1, 2, \ldots, I)\) in the data, where \(i\) is \(i^{th}\) SC-FPI and \(I\) is the total number of SC-FPI. Because the distribution of Indicator \(i\) is significantly changed, only the unaffected data can be used here.

(2) Divide intervals for Indicator \(i\) based on their characteristics and the results of Step (1), and calculate the occurrence possibility of each interval (referred to as the possibility interval).

(3) Use the program to randomly generate \(X_t^i \in (0, 1), \ t = 1, 2, \ldots, T\), where: \(t\) is the current calculation period; \(T\) is the total number of calculation periods; \(X_t^i\) is a random number of Indicator \(i\) in Period \(t\).

(4) Determine the value of Indicator \(i\) in Period \(t\) based on \(X_t^i\) and its possibility intervals.

3.4. Ecology-economy coupling model

With the promotion of river health, ecological demands have become a part of reservoir operation. Based on the test results of the Mann-Whitney U method, we set the SC-FPI as ecological indicators and took the measurement parameters (generating capacity) in benefit operations as economic indicators to establish an ecology-economy coupling model.

(1) Objective Function

\[
R_t = \max \left[ \alpha_1 \sum_{t=1}^{T} B_t^e + \alpha_2 \times \left( \omega_1 \sum_{t=1}^{T} B_t^i + \omega_2 \times FFP_t \right) \right] \tag{3}
\]

where: \(t (t = 1, 2, \ldots, T)\) is the current simulation operation period, and \(T\) is the total number of \(t\). \(R_t\) is the simulation result of ecology-economy coupling model in Period \(t\). \(\alpha_1\) and \(\alpha_2\) are control parameters, i.e., \(\alpha_1 = 0, \alpha_2 = 1\) at ecological operation and \(\alpha_1 = 1, \alpha_2 = 0\) at other time. \(\omega_1\) is the weight coefficient of economic indicators, and \(\omega_2\) is the weight coefficient of ecological indicators \((\omega_1, \omega_2 = 0, 0.1, 0.2, \ldots 1\) and \(\omega_1 + \omega_2 = 1)\). \(B_t^e (e = 1, 2, \ldots, E)\) is the value of Measurement Parameter \(e\) (benefit operation) in Period \(t\), which is calculated based on the flow, power generation head and other intermediate values in Period \(t\), and \(E\) is the total number of \(e\). \(FFP_t^i\) is the value of Indicator \(i\) in Period \(t\), which is determined by the random simulation method.

Control parameters \((\alpha_1\) and \(\alpha_2)\) determine whether reservoirs adopt ecological operation, and weight coefficients \((\omega_1\) and \(\omega_2)\) determine the proportion of benefit operations and ecological operation. By the ecology-economy coupling model, managers can quantitatively analyze the feasibility of ecological operation and the relationship between ecological operation effects and economic benefits. It should be noted that the ecological operation should be adopted under the premise of flood control safety, which is reflected by constraints.

(2) Constraints

a. Water level constraint

\[
Z_t^{\min} \leq Z_t \leq Z_t^{\max} \tag{4}
\]

where: \(Z_t^{\min}, Z_t\), and \(Z_t^{\max}\) are the minimum allowable water level, the current water level and the maximum allowable water level in Period \(t\), respectively.

b. Power generation discharge constraint

\[
q_t^{\min} \leq q_t \leq q_t^{\max} \tag{5}
\]

where: \(q_t^{\min}, q_t\), and \(q_t^{\max}\) are the minimum power generation discharge, the current power generation discharge and the maximum power generation discharge in Period \(t\).
c. Water flow constraint

\[ Q_{t}^{\text{min}} \leq Q_{t} \leq Q_{t}^{\text{max}} \]  

(6)

where: \( Q_{t}^{\text{min}} \), \( Q_{t} \) and \( Q_{t}^{\text{max}} \) are the minimum allowable water flow, the current water flow and the maximum allowable water flow in Period \( t \).

d. Power generation output constraint

\[ N^G \leq N_t \leq N^E \]  

(7)

where: \( N^G \), \( N_t \) and \( N^E \) are the guarantee power generation output, the current power generation output and the expected power generation output of hydropower station.

e. Reservoir water balance constraint

\[ V_t = V_{t-1} + (Q_t - q_t - I_t) \times \Delta t \]  

(8)

where: \( V_t \) is the reservoir storage capacity in Period \( t \). \( I_t \) is the abandoned flow in Period \( t \).

f. The daily maximum water level variation

\[ -Z^w \leq Z_t - Z_{t-1} \leq Z^w \]  

(9)

where: \( Z^w \) is the maximum variation of daily operating water level.

g. Non-negativity condition

All the aforementioned decision variables must equal or exceed zero.

3.5. Improved grey wolf optimizer

The grey wolf optimizer is a meta-heuristic optimization algorithm that simulates the predation and prey allocation behavior of wolves. It abstracts the way to find the optimal model solution into three kinds of intelligent behaviors (hunting, attacking and besieging) and two kinds of updating mechanisms (‘winner is king’ and ‘strong survival’). Because the optimization operation of the reservoir is a multi-stage and nonlinear continuous optimization problem, Wang et al. (2015) improved the way of attacking and besieging in the grey wolf optimizer, which was called the improved grey wolf optimizer. The steps to solve the reservoir multi-objective optimization model by using the improved grey wolf optimizer are as follows:

(i) Initialization

Dividing the total simulation operation period into \( t \) periods, and the number of wolves is assumed to be \( n \) (\( n = 1, 2, \ldots, N \)).

Taking the reservoir operating level \( Z_t \) (at the end of Period \( t \)) as the control variable, generating a value randomly within the allowable range (in Period \( t \)). The position of Wolf \( n \) can be expressed by \( Z(n, t) \).

(ii) Hunting

Calculating the results of single-objective optimization model (referred to as model result, \( R(n, t) \)) for each position \( Z(n, t) \). If an intermediate value (power generation flow, system output, etc.) does not meet the constraints (Chapter 3.4), users should reset \( Z(n, t) \) until all intermediate values meet the constraints. \( l (l = 1, 2, \ldots, L) \) wolves with good model results are selected as candidates, and each candidate carry out \( h (h = 1, 2, \ldots, H) \) times hunting, which can be expressed as:

\[ Z_{(n,l)}^{(l,h)} = Z(n, t) + \text{rand}(-1, 1) \times a_t^h \]  

(10)

where: \( Z_{(n,l)}^{(l,h)} \) is the hunting position of Wolf \( n \) in \( h^{th} \) hunting of Period \( t \). \( \text{rand}(-1, 1) \) means randomly generating a number between \((-1, 1)\). \( a_t^h \) is the hunting scale in \( h^{th} \) hunting of Period \( t \).

If the model result of the hunting position (denoted as \( R_{(n,l)}^{(l,h)} \)) is better than the original one (\( R(n, t) \)), update \( R(n, t) \), otherwise unchanged. After all candidates have completed hunting, the wolf with the optimal model result becomes the king.
(iii) Attacking

After hearing the call from the king, the other \( N - 1 \) wolves begin to approach the position of king and carry out attacking, which can be expressed as:

\[
Z^*(n,t) = Z(n,t) + \text{rand}(0, 1) \times (Z(n,t) - Z(n,t)) \times b_t
\]

where: \( Z^*(n,t) \) is the attacking position of Wolf \( n \) in Period \( t \), \( b_t \) is the attacking scale in Period \( t \).

If the model result of the attacking position (denoted as \( R_{(n,t)} \)) is better than the original one, update \( R_{(n,t)} \), otherwise unchanged.

(iv) Besieging

As \( (N - 1) \) wolves approach the position of the king, each wolf besieges \( k \) \( (k = 0, 1, 2 \ldots, K) \) times, which can be expressed as:

\[
Z^{k+1}_{(n,t)} = \begin{cases} 
Z^k_{(n,t)} & \text{rand}(0, 1) < 0.5 \\
Z^k_{(n,t)} + \text{rand}(-1, 1) \times c_t^k & \text{rand}(0, 1) \geq 0.5
\end{cases}
\]

where: \( Z^k_{(n,t)} \) is the besieging position of Wolf \( n \) in \( k^{th} \) besieging of Period \( t \), \( c_t^k \) is the besieging scale in \( k^{th} \) besieging of Period \( t \).

(v) Competitive update

a. Strong survival: First, all wolves are arranged from large to small according to their model results. Then, under the premise of maintaining the total number (N) of wolves, \( m \) \( (m < N) \) wolves with poor model results are replaced by randomly generating new wolves.

b. Iterative update: After all wolves have undergone a round of the hunting, attacking, besieging, and competitive update of strong survival, return to the hunting until the number of iterations reaches the preset value.

4. RESULTS AND DISCUSSION

4.1. FMCC-FPI

Because the reproductive activity of FMCC is closely related to rising floods, it is suitable to take it as the indicator species to study whether 11 FPI (Table 3) have the ability to reflect the flood pulses in the middle Yangtze River. To reduce the contradiction between the ecological operation and benefit operation of the Three Gorges Reservoir, we chose to focus on the peak breeding period of FMCC (from May to July). According to the hydrological conditions required for the spawning and breeding of FMCC and the operation requirements of the Three Gorges Reservoir, we selected rising flood indicators and key falling flood indicators from 11 FPI, and expanded them into 14 FMCC-FPI by period or interval, as shown in Table 4.

4.2. Significantly changed FMCC-FPI

To analyze the influences of the Three Gorges Reservoir (began to store water and generate electricity in 2003) on flood pulses in the middle Yangtze River, the daily runoff data from 1877 to 2016 of the Yichang Station were divided into 2 types: ‘Before’ (1877–2003, 127 years) and ‘After’ (2004–2016, 13 years). ‘Before’ represents the runoff flood pulses, while ‘After’ represents flood pulses changed by reservoir construction or operation. It is helpful for management to adjust the reservoir operation by finding the SC-FPI. According to the definition, we calculated the FMCC-FPI of ‘Before’ and ‘After’ respectively, and used the Mann-Whitney U method to test their degrees of change (two-tailed progressive, referred to as progressive significance and denoted as \( p \)). The results are shown in Figure 3.

\( p \leq 0.05 \) indicates 2 groups of FMCC-FPI obey different distributions; that is, the Three Gorges Reservoir changed the flood pulses in the middle Yangtze River. The \( p \)-value of \( T_{up} \) and \( T_{down} \) are 0.01 and 0.03 respectively, and remaining FMCC-FPI are all greater than 0.05 (Figure 3). It shows that the operation of the Three Gorges Reservoir from 2004 to 2016 changed the flood pulses in the middle Yangtze River. Although it had not caused much influence on flood peaks and flood volumes, the 2004–2016 operation of the Three Gorges Reservoir shortened the average rising flood duration and the average falling flood duration for benefit operations.
Combined with the ecological connotations of FPI (Table 3), shortening the average rising flood duration and the average falling flood duration will change the basic flood pulses and hinder the material exchange and information transfer between the upstream and the downstream, rivers and their floodplains. For FMCC, if they do not fully perceive flood pulses, their spawning activity will be delayed or interrupted. Therefore, the reduced average rising flood duration and the average falling flood duration is the main hydrological factor leading to the large-scale production reduction of FMCC in the middle Yangtze River. To increase the population of FMCC in their breeding season, managers should optimize the operation of the Three Gorges Reservoir by extending the rising flood duration and the falling flood duration in discharge.

### 4.3. Application and solution of the ecology-economy coupling model

Based on the test results from the Mann-Whitney U method (Figure 3), SC-FPI are $T_{up}$ and $T_{down}$. In this study, the ecology-economy coupling model of the Three Gorges Reservoir was established by taking the rising flood duration as the ecological
indicator and the generating capacity (power generation benefit is the main economic source of the Three Gorges Reservoir) as the economic indicator.

To reduce the contradiction between economic benefits and ecological demands, the Three Gorges Reservoir only adopts the ecological operation in the FMCC breeding peak period (from May to July). The ecology-economy coupling model is used to simulate the 2004–2016 operation of the Three Gorges Reservoir (total of 13 years). Specifically, one day is used as the time-scale of simulation operation in the ecological operation, and one month is the time-scale of simulation operation in other months (August to April of the following year). The total simulation operation period is $T = 1313 \times (51 + 30 + 51 + 9)$.

(1) Economic indicator

$$B_t^1 = \sum_{t=1}^{1313} E_t = \sum_{t=1}^{1313} OC \times \bar{q}_t \times H_t \times \Delta t$$

where: $E_t$ is the power generation in Period $t$. $OC$ is a power generation output coefficient. $\bar{q}_t$ is the average power generation flow in Period $t$. $H_t$ is the average power generation head in Period $t$. $\Delta t$ is the time-scale of current simulated operation.

(2) Ecological indicator:

$$FP_t^1 = D'_t = 4000 \times \text{Avg}\left[ \sum_{y=1}^{15} \text{Avg}\left( \sum_{c=1}^{C_y} \text{Dur}_c^y \right) \right]$$

where: $D'_t$ is the rising duration in Period $t$. 4000 is a trial parameter to eliminate the magnitude of difference between the gross generation and the rising flood duration of the Three Gorges Reservoir. $y (y = 1, 2, \ldots, 13)$ is the current simulating operation year. $c (c = 1, 2, \ldots, C_y)$ is the $c$th rising flood in ecological operation of Year $y$, and $C_y$ is the total number of rising floods in Year $y$. $\text{Dur}_c^y$ is the duration of the $c$th rising flood in Year $y$. $\text{Dur}_c^y$ is determined by the random simulation method.

(3) Constraint values

Water level constraints are shown in Table 2. Other parameters come from the ‘Regulation for joint operation of Three Gorges-Gezhouba cascade reservoirs’ (2020)135, China’s Ministry of Water Resources: $q_m^{min} = 0$, $q_m^{max} = 27500 m^3/s$; $Q_m^{min} = 10000 m^3/s$, $Q_m^{max} = 102400 m^3/s$; $N^G = 4990 MW$, $N^E = 22599 MW$; $Z^w = 3 m/d$.

4.4. Determination of rising flood duration

It is necessary to know the daily rising flood rate when using the random simulation method to calculate the rising flood duration. In addition, to better compare the optimized operation with the actual operation of the Three Gorges Reservoir, we added an analysis of the falling flood duration. Therefore, we analyzed the rising flood duration, falling flood duration, daily rising flood rate and daily falling flood rate in the middle Yangtze River, as shown in Figure 4. It is worth noting that, because the 2004–2016 operation of the Three Gorges Reservoir changed the rising flood duration and falling flood duration in the middle Yangtze River (Figure 3), we used the ‘Before’ to statistic their occurrence number. In order not to affect the flood control function of the Three Gorges Reservoir, the daily rising flood rate and daily falling flood rate in discharge should be controlled within 10,000 $(m^3/s)/d$. Taking 2,000 $(m^3/s)/d$ as a grade, we divided the daily rising flood rate and daily rising flood rate into six intervals respectively (0–2,000; 2,000–4,000; 4,000–6,000; 6,000–8,000; 8,000–10,000 and $\geq$10,000).

With the help of Figure 4, the statistical characteristics of runoff in the middle Yangtze River can be analyzed. First, during the rising flood duration, 2-day is dominant, while the number of days is inversely proportional to the number of occurrences in the falling flood duration (Figure 4(a), 4(c), 4(d)). Second, the possibility of daily rising flood rate in Interval 0–6,000 $(m^3/s)/d$ is 93.3%, and Interval 0–2,000 $(m^3/s)/d$ accounts for 68.06%. In addition, the possibility of daily falling flood rate in Interval 0–6,000 $(m^3/s)/d$ is 98.3%, and Interval 0–2,000 $(m^3/s)/d$ accounts for 78.54% (Figure 4(b), 4(e), 4(f)). It is not difficult to find that the middle Yangtze River is dominated by short-duration (1–3 days), small-flood rate [0–2,000 $(m^3/s)/d$] flood pulses. Compared with the runoff in the middle Yangtze River during the peak breeding period of FMCC, the daily rising flood rate between 0 and 6,000 $(m^3/s)/d$ can be formed by the non-steady discharge runoff of the Three
Gorges Reservoir. From the perspective of fish protection, short-duration, high-frequency flood pulses can stimulate large number of FMCC to start spawning activities, and avoid the death of their semi-floating type eggs. In addition, small-flow flood pulses can also play a role in promoting nutrient exchange and hydrological regime information transmission, and provide an environment for fish growth.

In this study, we used the improved grey wolf optimizer (Section 3.5) to solve the ecology-economy coupling model of the Three Gorges Reservoir. The results of simulation operation are shown in Figure 5.
Extending the average rising flood duration and the average falling flood duration in the Three Gorges Reservoir discharge can result in the reduction of power generation (Figure 5). The main reason for this phenomenon is that, to simulate flood pulses in the middle Yangtze River, the Three Gorges Reservoir needs to increase discharge from May to July, which exceeds the maximum overcurrent capability of generator sets. Because the reservoir can only discharge through flood discharge facilities, this part of discarded flow causes the reduction of power generation. Therefore, under the premise of ecological operation from May to July, the annual average power generation is lower than fully optimized power generation \( (w_1 = 1, \ w_2 = 0) \). However, the difference between fully optimized power generation and fully optimized rising duration \( (w_1 = 0, \ w_2 = 1) \) is 6.95\( \times 10^8 \) kW·h, and the loss rate is about 0.69%, which has little effect on the power generation of the Three Gorges Reservoir. The results show that it is feasible for the Three Gorges Reservoir to adopt the ecological operation with simulating flood pulses of the middle Yangtze River during the FMCC peak breeding period.

To study the extension effects of the ecology-economy coupling model on rising flood duration and falling flood duration in the middle Yangtze River, we separately calculated the average rising flood duration and the average falling flood duration in the actual discharge of the Three Gorges Reservoir from 2004 to 2016 (in Figure 6, referred to as Three Gorges Reservoir) and the runoff data of Yichang Station from 2004 to 2016 (in Figure 6, referred to as Yichang Station), and comparing them with the simulation operation results (in Figure 6, referred to as ecological operation). The results are shown in Figure 6 and the detailed data are shown in Table 5.

As can be seen from Figure 6, when \( w_2 = 0 \) (fully optimized power generation), compared with the 2004–2016 operation of the Three Gorges Reservoir, the ecology-economy coupling model has extended the rising flood duration and the falling flood duration in the middle Yangtze River. This is because the 2004–2016 operation of the Three Gorges Reservoir also considers the requirements of shipping safety and water supply, the flood pulses is more attenuated. When \( w_2 = 0.3 \) and 0.4 respectively, the average rising flood duration \( (w_2 = 0.3) \) and the average falling flood duration \( (w_2 = 0.4) \) in the Three Gorges Reservoir discharge are close to those in the runoff data of Yichang Station (Figure 6 and Table 5). This shows when managers adopt the ecological operation with \( w_2 > 0.4 \), they can effectively simulate the flood pulses of the middle Yangtze River, increase the production of FMCC in Yichang, Yidu and Zhicheng spawning grounds (Figure 1) and play a role in protecting the river ecosystem to a certain extent. Combined with the simulation operation results (Figure 5), when managers adopt the ecological operation (from May to July) with \( w_2 = 0.4 \), the annual average power generation loss of the Three Gorges Reservoir is 2.73\( \times 10^8 \) kW·h, and the loss rate is 0.27%. But this operation can create a suitable environment for the spawning and breeding of FMCC and promote the material exchange and information transmission in the upper and middle Yangtze River.

5. CONCLUSIONS

Ecological demands have become a part of reservoir management that cannot be ignored. In this study, we took the Three Gorges Reservoir as a study case. Firstly, based on the IHA, 11 indicators were proposed to reflect the runoff flood pulses.
Then, we used the Mann-Whitney U method to test their degrees of change. Finally, an ecology-economy coupling model was established to simulate the ecological operation of the Three Gorges Reservoir and promote the sustainable development of the middle Yangtze River, and the improved gray wolf optimizer was used to solve the model.

![Figure 6](image-url)  
*Figure 6* | The extension effects of average rising flood duration and average falling flood duration by the Three Gorges Reservoir ecology-economy coupling model.

![Table 5](image-url)  
*Table 5* | The variations of annual average power generation, average rising flood duration and average falling flood duration with weight coefficient ($w_2$)

<table>
<thead>
<tr>
<th>$w_2$</th>
<th>Annual average power generation</th>
<th>Average rising flood duration</th>
<th>Average falling flood duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value (kW·h)</td>
<td>Reduced proportion</td>
<td>Value (Day)</td>
</tr>
<tr>
<td>1</td>
<td>997.26</td>
<td>0.69%</td>
<td>3.75</td>
</tr>
<tr>
<td>0.9</td>
<td>997.29</td>
<td>0.69%</td>
<td>3.69</td>
</tr>
<tr>
<td>0.8</td>
<td>997.40</td>
<td>0.68%</td>
<td>3.62</td>
</tr>
<tr>
<td>0.7</td>
<td>997.71</td>
<td>0.65%</td>
<td>3.46</td>
</tr>
<tr>
<td>0.6</td>
<td>999.44</td>
<td>0.47%</td>
<td>3.23</td>
</tr>
<tr>
<td>0.5</td>
<td>1,000.41</td>
<td>0.38%</td>
<td>3.05</td>
</tr>
<tr>
<td>0.4</td>
<td>1,001.48</td>
<td>0.27%</td>
<td>2.88</td>
</tr>
<tr>
<td>0.3</td>
<td>1,002.06</td>
<td>0.21%</td>
<td>2.69</td>
</tr>
<tr>
<td>0.2</td>
<td>1,002.96</td>
<td>0.13%</td>
<td>2.55</td>
</tr>
<tr>
<td>0.1</td>
<td>1,003.77</td>
<td>0.04%</td>
<td>2.48</td>
</tr>
<tr>
<td>0</td>
<td>1,004.21</td>
<td>0.00%</td>
<td>2.39</td>
</tr>
</tbody>
</table>

*Note:* Extended proportion of the average rising flood duration and the average falling flood duration are both compared with the Yichang Station.
The flood pulses in the middle Yangtze River have the characteristics of short duration and small flow. Jiang et al. (2019) have pointed out that the Three Gorges Reservoir has an impact on the duration and flow of flood pulses in the middle Yangtze River, which was not conducive to the river’s health. To effectively increase the production of FMCC in Yichang, Yidu, and Zhicheng spawning grounds, the Three Gorges Reservoir should simulate the flood pulses from May to July and adopt the ecological operation with the weight coefficient of ecological indicators ($w_2$) greater than 0.4, which causes the annual average power generation loss is within 0.27–0.69%. The conclusions are as follows:

(1) FPI can reflect the characteristics of runoff flood pulses, and provide reservoir controllability at the same time. Although only FMCC was used as an indicator species to test the adaptability of FPI in this study, they can be extended to the study of the relationship between flood pulses and plants, benthic organisms or chemical properties in the river.

(2) The random simulation method can provide a guide for managers to optimize the reservoir discharge, which is very important for reservoir operation and river ecosystems. In addition, because the random simulation method simulates the occurrence time and scale of things based on their randomicity and determinacy, it can be used to capture or simulate the runoff and precipitation.

(3) Ecology-economy coupling model is a good way to assess the feasibility of reservoir ecological operation. Managers can understand the relationship between ecological operation effects and economic benefits from the coupling model, and they can choose a more appropriate reservoir operation scheme.

The appropriate operation and comprehensive ecology-economy assessment can encourage the willingness of reservoir managers to adopt ecological operation. If we can accurately grasp the flood pulses of reservoir inflow flood by using mature hydrological forecasting technology, we only need to change discharge slightly (under the premise of satisfying the requirements of flood control safety) to achieve a better ecological operation effect and protection of ecosystems.

ACKNOWLEDGEMENTS

The authors would like to give special thanks to the anonymous reviewers.

AUTHORS’ CONTRIBUTIONS


FUNDING

This study is financially supported by the National Key R&D Program of China (2018YFC0407601, 2016YFC0402208, 2017YFC0405900) and the National Natural Science Foundation of China (No. 52179014, No. 51879273).

DATA AVAILABILITY STATEMENT

Data for this study can be downloaded from the Yichang Hydrology Bureau webpage (http://www.hbycsw.com). The code and the ‘Regulation for joint operation of Three Gorges-Gezhouba cascade reservoirs’ ([2020]135, China’s Ministry of Water Resources) are available from the corresponding author upon reasonable request.

DECLARATION

The authors confirm that this article is original study and has not been published or presented previously in any journal or conference.

CONFLICT OF INTEREST

None.

ETHICAL APPROVAL

Not applicable.

CONSENT TO PARTICIPATE

Not applicable.
CONSENT TO PUBLISH
Not applicable.

REFERENCES


First received 7 January 2021; accepted in revised form 3 September 2021. Available online 15 September 2021