Fuzzy Representation of Environmental Flow in Multi-Objective Risk Analysis of Reservoir Operation

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Fuzzy Representation of Environmental Flow in Multi-Objective Risk Analysis of Reservoir Operation

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Abstract: In the context of water shortages, environmental flow is the key to alleviating the negative environmental impact of reservoir operation. Environmentally, the suitable stream flow for the survival and reproduction of aquatic organisms is a varying range, although most of studies now give it a fixed value, which leads to unreasonable resource allocations. In this study, we proposed a fuzzy representation of environmental flow by using the fuzzy theory and the ecological hydraulic radius. Furthermore, we used the Three Gorges-Gezhouba cascade reservoirs as a study case and Four Major Chinese Carps as indicator species. In addition, a multi-objective operation optimization model was established, which solved by the Evolver Palisade software, and a multi-objective risk analysis method was proposed based on the design reliability and risk rate of various benefit operations. The results show that: (1) Based on the environmental flow membership function, flow ranges suitable for the aquatic organism survival and reproduction at specific locations can be determined to help guide reservoir discharge. (2) Taking environmental flow membership as an optimization objective rather than a

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constraint is conducive to formulating environmentally friendly reservoir operation schemes and make more rational use of water resources. (3) The multi-objective risk analysis can avoid the one-sidedness of a single objective and analyze the risks brought by various benefit operations. Ecological demand has long been a factor considered when formulating reservoir operation schemes. Following the environmentally friendly operation scheme is helpful to protect the environment and maximize the overall benefits of reservoirs.

Keywords： Environmental flow membership function; Multi-objective risk analysis; Triangular functions; Ecological hydraulic radius; Four Major Chinese Carps (FMCC);

1 Introduction

Reservoirs are the largest hydraulic structures which can modify stream flow. While reservoir operation provides social development with flood control safety, power support, water security and shipping convenience etc., it also causes environmental problems in the downstream such as water quality deterioration, and decline in biodiversity (Zhao et al. 2021; Volke et al. 2019). To reduce the negative environmental impact of reservoir operation, governments require managers to discharge a certain amount of water flow as environmental flow. Although scholars have not reached agreement on the definition of environmental flow, people often use hydraulic methods, hydrology methods, habitat rating methods and building block methods to calculate it (Mcgregor et al. 2018; Li et al. 2018). These four methods are simple to calculate, convenient for reservoir operation, and have been widely used in practical engineering.

However, they all set the environmental flow to a fixed value, which is inconsistent with stream flow. Tonkin et al. (2021) pointed out that stream flow is closely related to the survival of aquatic organisms. Rosa et al. (2021) believes that stream flow fluctuations can help promote the exchange of nutrients, and contribute to environment health. Therefore, how to transform the environmental flow from a fixed value to a suitable range and apply it to the formulation and decision-making of reservoir operation schemes is a problem worth studying.

Ecological hydraulic radius is a hydraulic method for calculating the environmental flow, which inherits the advantages of the hydraulics method and compensates for the lack of seasonal changes by calculating the shape of river cross-sections (Zhao et al. 2021). Unfortunately, the environmental flow calculated by this method is still a fixed value. Fuzzy theory, which is widely used in sampling technique, decision-making and evaluation etc., can solve this problem well (Cai et al. 2019; Pelissari et al. 2021). Hasanzadeh et al. (2020) used fuzzy functions to derive the membership function of water quality. Carrera et al. (2021) derived the α (judgment value) membership function with the help of fuzzy functions and realized the transformation from a fixed value to a range. The fuzzy theory is often mathematically solved by establishing a membership function of triangles, trapezoids or "S" types (Liu et al. 2021; Wu et al. 2021). Triangular functions can consider the uncertainty of parameters and give a simple method of membership function development, which is commonly used in practical engineering (Türk et al. 2021).

Usually, reservoirs with large regulating capacities are responsible for flood control and multiple benefit operations (power generation, shipping, water supply, ecology, etc.). However, the relationship between flood control and benefit operations, or within benefit operations is always complicated, which makes reservoir operation a multi-objective optimization issue (KhazaiPoul et al. 2019). To balance the objectives of power generation, shipping, water supply, etc., the multi-objective operation optimization model often has the goal of maximizing power generation, navigation flows and water supply, etc. (Li et al. 2020; Perea et al. 2020). In addition, under the promotion of sustainable development, scholars use the fixed-value environmental flow as a constraint to formulate reservoir operation schemes (Wang et al. 2020), which can only guarantee the basic water consumption requirements of the environment. Converting environmental flow from the constraint to the optimization objective in the multi-objective operation optimization model is a way to formulate an environmentally friendly operation scheme, but there are currently few studies in this area.

Affected by hydrological factors, hydraulic factors and uncertainty of engineering management, there are often differences between operation schemes and actual operation, which leads to risks in reservoir management. Currently, much reservoir operation risk analysis research focuses on dam safety standards, flood control, power generation etc. (Devkota et al. 2020). In addition, the risk analysis requires many simulations of stream flow, and operation models are mostly nonlinear. Therefore, its solution requires optimization algorithms such as genetic algorithms and the particle swarm optimization (Chen et al. 2021). Because users have different understandings of the problem and optimization algorithms, the results are greatly influenced by human factors, and they also face the problems of large computational workload and inability to obtain global optimal solutions (Bengio et al. 2020). In general, at present, risk analysis in reservoir management rarely involves multiple benefit operations.

Aquatic organisms are very sensitive to changes in stream flow, and their survival and reproduction need proper areas, and flow conditions (Nukazawa et al. 2020). In view of the above problems, we take Four Major Chinese Carps (FMCC, which consist of *Mylopharyngodon piceus, Ctenopharyngodon idellus, Hypophthalmichthys molitrix and Hypophthalmichthys nobilis*) as indicator species and Three Gorges-Gezhouba cascade reservoirs (TGGCR) as case study. This study contributes as follows:

(1) Proposing the fuzzy environmental flow based on triangular functions and the ecological hydraulic radius to calculate the suitable range of environmental flow and meet more ecological demands.

(2) Taking environmental flow membership as the optimization objective instead of the constraint in the multi-objective operation optimization model, which provides a way to formulate environmentally friendly reservoir operation schemes.

(3) Proposing a multi-objective risk analysis method based on the design reliability and risk rate, which can be used to analyze the risks brought by various benefit operations and provide more basis for reservoir management.

2 Methodology

To provide reservoir managers with a basis for formulating an environmentally friendly reservoir operation scheme and decision-making, this study involves triangular functions, the ecological hydraulic radius, the multi-objective operation optimization model, the Evolver Palisade and the multi-objective risk analysis. Among them, triangular functions and the ecological hydraulic radius are used to develop environmental flow membership functions, and the Evolver Palisade is used to solve the multi-objective optimization model.

2.1 Environmental flow membership functions

2.1.1 Triangular functions

The triangular function $M(\cdot)$ is a fuzzy subset of the membership function image in the domain X. Let a, b, c be the minimum value, the ideal value (membership is 1.0) and the maximum value of $M(\cdot)$, respectively, then the membership function can be expressed as:

$$M(x)=\begin{cases}\dfrac{x-a}{b-a} & ,a\le x\le b\\ \dfrac{c-x}{c-b} & ,b\le x\le c\\ 0, & Else\end{cases} \tag{1}$$

where,$a \le b \le c$, and $M(x)$ can only have values in $[0,1]$.

2.1.2 Ecological hydraulic radius

Due to the differences in the shape of the river cross-section (referred as to cross-section), the same flow velocity presents different flows at different locations. The ecological hydraulic radius can establish a function between flow and flow velocity with river hydraulic parameters (hydraulic radius, hydraulic gradient, etc.) and the Manning Formula (Men 2011). It assumes the flow pattern is open channel uniform flow and the flow velocity is the average velocity for the cross-section. The specific steps are as follows:

(1) According to the Manning Formula ($R = v^{\frac{3}{2}} \cdot n^{\frac{3}{2}} \cdot J^{-\frac{3}{4}}$), the hydraulic radius can be calculated, where, R is hydraulic radius; v is environmental flow velocity; n is roughness; J is hydraulic slope.

(2) According to the opening direction of the relationship curve between water surface elevation and water surface width (divided into upward type and downward type), users need to select appropriate equations to infer the function of hydraulic radius and cross-sectional area ($R \sim A$), as shown in Table 1.

(3) Calculate the environmental flow according to $Q = A \cdot v$, where Q is the environmental flow, A is the cross-sectional area.

Table 1. Parabolic equations and $R \sim A$ functions

Category	Upward type	Downward type
Parabolic equation	$y = ax^2$ $(a > 0)$	$y = a\lvert x\rvert^2 + b\lvert x\rvert$ $(a < 0, b > 0)$
$R \sim A$ function	$A = \frac{4}{3} b h^{\frac{3}{2}}$ $P = 2\int_0^{bh^{\frac{1}{2}}} \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx$	$A = \frac{aB^3}{6} + \frac{bB^2}{4}$ $P = 2\int_0^{\frac{B}{2}} \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx$

	$R=\frac{A}{P}$	$R=\frac{A}{P}$

Repeat the above steps to enumerate multiple sets of environmental flow velocity (v) and environmental flow (Q) to obtain the $v \sim Q$ curve, and the $v \sim Q$ function is obtained by fitting curve method.

2.1.3 Environmental flow membership functions

The flow that is suitable for the survival and reproduction of aquatic organisms and can protect the environment is not a fixed value, which leads to the concept of fuzzy environmental flow. The environmental flow velocity is represented by $v=(v_a, v_b, v_c)$, where v_a, v_b, v_c represent the minimum value, the ideal value and the maximum value. Then, we can calculate $M(v)$ by $Eq.1$ and $v \sim Q$ by the ecological hydraulic radius, i.e.,$v=\frac{Q}{A}$. Finally, the environmental flow membership function is deduced:

$$M(Q)=\begin{cases}\dfrac{Q-A\cdot v_a}{A\cdot(v_b-v_a)}, & A\cdot v_a \le Q \le A\cdot v_b \\ \dfrac{A\cdot v_c-Q}{A\cdot(v_c-v_b)}, & A\cdot v_b \le Q \le A\cdot v_c \\ 0, & Else\end{cases} \tag{2}$$

2.2 Multi-objective operation optimization model

Since power generation is the main source revenue for most reservoirs, we take maximizing Power Generation (PG) and maximizing Minimum Power Output (MPO) as economic optimization objectives. In addition, to formulate an environmentally friendly reservoir operation scheme, we take the environmental flow membership function as the ecological optimization objective. Based on the above 3 optimization objectives, a multi-objective operation optimization model for joint operation of cascade reservoirs was established.

2.2.1 Objective functions

(1) Maximizing PG

$$\max\left(\sum_{m=1}^{M}\sum_{t=1}^{T}E_{m,t}\right)=max\left(\sum_{m=1}^{M}\sum_{t=1}^{T}K_m I_m H_{m,t}\triangle t\right) \tag{3}$$

where: m is the number of reservoirs in joint operation, $m=1,2,\ldots,M$; t is the time period, $t=1,2,\ldots,T$; $E_{m,t}$ is the power generated by Reservoir m in Period t; K_m is the output coefficient of Reservoir m; I_m is the generation flow of Reservoir m; $H_{m,t}$ is the net water head of Reservoir m in Period t; Δt is the length of a time period.

(2) Maximizing MPO

$$max\left(\sum_{m=1}^{M}\sum_{t=1}^{T}N_{m,t}\right)=max\left(\sum_{m=1}^{M}\sum_{t=1}^{T}K_m\, Q'_{m,t}H_{m,t}\right) \tag{4}$$

where: $N_{m,t}$ is MPO of Reservoir m in Period t; $Q'_{m,t}$ is discharge flow of Reservoir m in Period t.

(3) Maximizing environmental flow membership

$$max\left[\sum_{m=1}^{M}\sum_{t=1}^{T}M_{m,t}\left(Q'_{m,t}\right)\right]=max\left[\sum_{m=1}^{M}\sum_{t=1}^{T}\begin{cases}\dfrac{Q'_{m,t}-Q'_{a,s}}{Q'_{b,s}-Q'_{a,s}} & ,Q'_{a,s}\le Q'_{m,t}\le Q'_{b,s}\\ \dfrac{Q'_{c,s}-Q'_{m,t}}{Q'_{c,s}-Q'_{b,s}} & ,Q'_{b,s}\le Q'_{m,t}\le Q'_{c,s}\\ 0, & Else\end{cases}\right] \tag{5}$$

where: $M_{m,t}(\cdot)$ is the environmental flow membership function value of Reservoir m in Period t; s is the number of river cross-sections, $s=1,2,\ldots,S$; $Q'_{a,s}$, $Q'_{b,s}$ and

$Q'_{c,s}$ are the minimum environmental flow, the ideal environmental flow and the maximum environmental flow of Cross-Section s.

2.2.2 Constraints

(1) Water flow constraint

$$Q_{m,t} = Q'_{m-1,t} + F_{m,t} \tag{6}$$

where: $Q_{m,t}$ is the inflow of Reservoir m in Period t; $F_{m,t}$ is the inflow between Reservoir m and Reservoir $(m-1)$ in Period t.

(2) Water balance constraint of cascade reservoirs

$$V_{m,t} = V_{m,t-1} + \left(Q_{m,t} - Q'_{m,t}\right) \times \Delta t \tag{7}$$

where: $V_{m,t}$ is the water storage capacity of Reservoir m at the end of Period t.

(3) Other constraints

a. Water level constraint

$$Z_{m,t}^{min} \leq Z_{m,t} \leq Z_{m,t}^{max} \tag{8}$$

where: $Z_{m,t}^{min}$, $Z_{m,t}$ and $Z_{m,t}^{max}$ are the allowable minimum water level, the current water level and the maximum allowable water level of Reservoir m in Period t, respectively.

b. PG constraints

$$I_m^{min} \leq I_{m,t} \leq I_m^{max} \tag{9}$$

where: I_m^{min} and I_m^{max} are the minimum generation flow and the maximum generation flow of Reservoir m.

c. Discharge flow constraint

$$Q'_{m,t} \le \; {Q'_m}^{max} \tag{10}$$

where: ${Q'_m}^{max}$ is the maximum allowable discharge flow of Reservoir m.

d. Ecological constraints

$$Q^{eco} \le \; Q'_{m,t} \tag{11}$$

where: Q^{eco} is the fixed-value environmental flow of the river.

e. Output constraints

$$N_m^G \le \; N_{m,t} \; \le \; N_m^E \tag{12}$$

where: N_m^G and N_m^E are the guarantee output and the expected output of Reservoir m.

f. Reservoir water balance constraint

$$V_{m,t} = V_{m,t-1} + \left(Q_{m,t} - I_{m,t} - q_{m,t}\right) \times \Delta t \tag{13}$$

where: $q_{m,t}$ is the abandoned water flow of Reservoir m in Period t.

g. The maximum water level variation per day

$$-Z_m^w \le \; Z_{m,t} - Z_{m,t-1} \le Z_m^w \tag{14}$$

where: Z_m^w is the maximum variation of the water level of Reservoir m per day.

h. Non-negativity conditions

All the aforementioned decision variables must be greater or equal to zero.

2.3 Model solving method

A nonlinear relationship exists between the objective functions and constraints of the multi-objective operation optimization model (Section 2.2), so an intelligent algorithm is needed to solve it. The Evolver Palisade (https://www.palisade.com/evolver/) is a plug-in for simulation calculation based on the

Excel Office software and allows users to build optimization models and use the built-in genetic optimization algorithm to find optimal solutions. Comparing with programming to solve the multi-objective operation optimization model, it lowers the demand for coding and has good stability. In this study, we used the Evolver Palisade for model solving, and the steps are as follows:

(1) Preliminary preparation: a. Use the fitting curve method and P-III distribution to derive the design reliability (marked as P) of the reservoir inflow flood; b. Select typical years to represent different design reliabilities.

(2) Input information: a. The optimization objectives and constraints of the multi-objective operation optimization model (totally, there are 3 operation scenarios, marked as Scenario i $(i = 1, 2, 3)$, i.e., Scenario 1 for maximizing PG, Scenario 2 for maximizing MPO, and Scenario 3 for maximizing environmental flow membership); b. The typical years with different design reliabilities.

(3) Parameter setting and solution: a. Select a scenario to simulate; b. Sett the design reliability (P), the number of iterations of the genetic algorithm (marked as $Inum^i$) and the total number of simulations (marked as $Tnum^i$); c. Start the solving program. d. Repeat the above 3 steps until 3 scenarios are simulated.

(4) Result: a. The optimization objective value of Design Reliability P in Scenario i, marked as $O^i_{P,i}$ $(i = 1, 2, 3$); b. $Tnum^i$; c. the unsatisfied number of each benefit operation for Design Reliability P in Scenario i, marked as $Fnum^i_{P,j}$ $(j = 1, 2, 3, 4)$, where, j is the benefit operation, i.e., j represents PG,

water supply, shipping and ecological operation in turn.

2.4 Multi-objective risk analysis

To provide managers with a more comprehensive basis for decision-making, we proposed a benefit evaluation value and a risk evaluation value to measure each scenario. The benefit evaluation value is calculated based on the optimization objective value ($Eq.15$), and the risk evaluation value is calculated based on the risk rate ($Eq.17$).

$$B_P^i = \sum_{i}^{3} w_{x,i} \times BO_{P,i}^i \tag{15}$$

where, B_P^i is the benefit evaluation value of Design Reliability P in Scenario i; $w_{x,i}$ $(x = 1, 2)$ is the weight value of Optimization Objective i; $BO_{P,i}^i$ is the benefit value of Optimization Objective i for Design Reliability P in Scenario i, and its calculation method is shown in $Eq.16$.

$$BO_{P,i}^i = \frac{O_{P,i}^i - min(O_{P,i})}{max(O_{P,i}) - min(O_{P,i})} \tag{16}$$

where, $O_{P,i}$ is all the value of $O_{P,i}^i$ in 3 scenarios; $min(\cdot)$ and $max(\cdot)$ represent the minimum and maximum of all values.

$$R_P^i = \sum_{j}^{4} w_{x,j} \times RT_{P,j}^i \tag{17}$$

Where, R_P^i is the risk evaluation value of Design Reliability P in Scenario i; $w_{x,j}$ $(x = 1, 2; j = 1, 2, 3, 4)$ is the weight value of Benefit Operation j; $RT_{P,j}^i$ is the risk rate of Benefit Operation j for Design Reliability P in Scenario i, and its calculation method is shown in $Eq.18$.

$$RT_{P,j}^{i} = \frac{Fnum_{P,j}^{i}}{Tnum^{i}} \tag{18}$$

In addition, to further analyze the benefits and risks brought about by various benefit operations, we used equal weight and unequal weight to calculate the benefit evaluation value and the risk evaluation value:

$$w_{x,i} = \begin{cases} w_{1,i} = \dfrac{1}{i} \\ w_{2,i} = \dfrac{D_i}{D_1 + D_2 + \cdots + D_i} \end{cases} \quad (x = 1, 2) \tag{19}$$

where, $w_{1,i}$ and $w_{2,i}$ are the equal weight and unequal weight of Optimization Objective i, respectively; D_i the design reliability of Optimization Objective i.

$$w_{x,j} = \begin{cases} w_{1,j} = \dfrac{1}{j} \\ w_{2,j} = \dfrac{D'_j}{D'_1 + D'_2 + \cdots + D'_j} \end{cases} \quad (x = 1, 2) \tag{20}$$

where, $w_{1,j}$ and $w_{2,j}$ are the equal weight and unequal weight of Benefit Operation j, respectively; $D'_j = 1 - D_j$.

3 Study area and data source

3.1 Study area

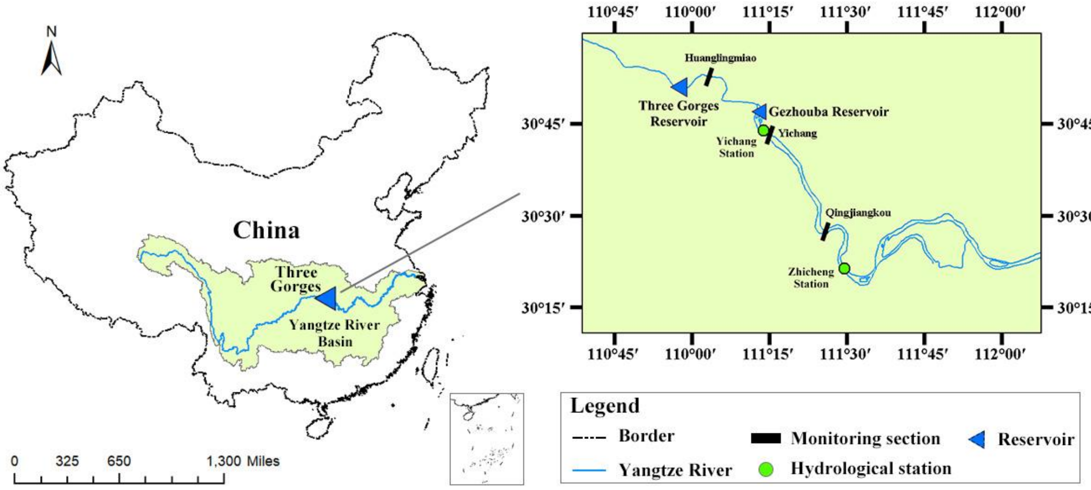


Fig. 1. Location of the Three Gorges-Gezhouba cascade reservoirs, cross-sections and hydrological stations

The Three Gorges reservoir, in the middle Yangtze River with seasonal regulation capacity, forms a join operation with the Gezhouba reservoir at 38 km downstream (Figure 1), which is called the Three Gorges-Gezhouba Cascade Reservoirs (TGGCR). The main parameters of TGGCR are shown in Table 2. In addition, according to the actual operation of TGGCR, we proposed the following operation requirements:

(1) Flood control: On the premise of ensuring the safety of TGGCR, the flow of Zhicheng Station should not exceed 80,000 m^3/s.

(2) PG: The design reliability is ⩾95%. The average output of the reservoir during the dry season is not less than the guaranteed output, i.e., the Three Gorges Reservoir is ⩾4.99 million kW, and the Gezhouba Reservoir is ⩾768,000 kW.

(3) Shipping: The water level in front of the dam of the Three Gorges Reservoir should be ⩾ 155 m, and the design reliability of the 10,000-ton vessel through Chongqing Jiulongpo Port is ⩾50% with discharge ⩾5,500 m^3/s.

(4) Water supply: The period with discharge⩾5000m^3/s is not less than 9 months, and the design reliability is ⩾75%.

(5) Ecology: The ecological operation of TGGCR mainly considers the formation of discharge conditions suitable for fish survival and reproduction. Therefore, we set the design reliability of ecological flow membership greater than 0 to be ⩾50%. Because FMCC are the main freshwater economic fishes in the Yangtze River basin of

China, we used them as indicator species. In addition, combined with the distribution of fish spawning grounds in the lower reaches of TGGCR (Figure 1), we calculated the environmental flow membership functions and environmental flow ranges suitable for FMCC survival and reproduction at three cross-sections of Huanglingmiao, Yichang and Qingjiangkou respectively.

Table 2. Main parameters of the Three Gorges-Gezhouba Cascade Reservoirs

Characteristic Parameter	Three Gorges	Gezhouba
Minimum operating water level (m)	155.0	62.0
Normal water level (m)	175.0	66.0
Flood control level (m)	145.0	—
Design flood level (m)	175.0	66.0
Check flood level (m)	180.4	67.0
Beneficial reservoir capacity (10^8 m^3)	165.0	1.11

3.2 Data source

This study involves the storage curve, discharge water level curve, PG curve and discharge curve of the Three Gorges Reservoir and Gezhouba Reservoir, which are subject to the *Joint Operation Procedure* ([2020]135, China's Ministry of Water Resources). In addition, the runoff data of Yichang hydrological station (1957～2003) before the construction of Three Gorges Reservoir is used to select the typical year.

4 Results and discussion

4.1 Determination of environmental flow velocity

The range of environmental flow velocity suitable for FMCC survival and reproduction is the basis for calculating the membership function of environmental flow.

Mu et al. (2019) divided the flow velocity suitable for FMCC survival into $< 0.9\,m/s$, $0.9\sim1.2\ m/s$ and $> 1.2\,m/s$. Yu et al. (2018) believes that the flow velocity suitable for FMCC survival and reproduction in the middle Yangtze River was $0.63\sim1.83\ m/s$. By summarizing the relevant studies, we set the environmental flow velocity range as:

$$v = (0.6,\ 0.9,\ 1.5) \tag{21}$$

where, $0.6\ m/s$ is the minimum value, $0.9\ m/s$ is the idle value, and $1.5\ m/s$ is the maximum value. The membership function of the environmental flow velocity is:

$$M(v) = \begin{cases} \dfrac{v-0.6}{0.3} & 0.6 < v < 0.9 \\ \dfrac{1.5-v}{0.6} & 0.9 < v < 1.5 \\ 0 & Else \end{cases} \tag{22}$$

4.2 Deduction of environmental flow membership functions

According to the calculation steps of the ecological hydraulic radius (Section 2.1.2), first of all, we need to analysis the opening direction of the relationship curve between water surface elevation and water surface width of Huanglingmiao, Yichang and Qingjiangkou (referred to as 3 cross-sections), as shown in Figure 2.

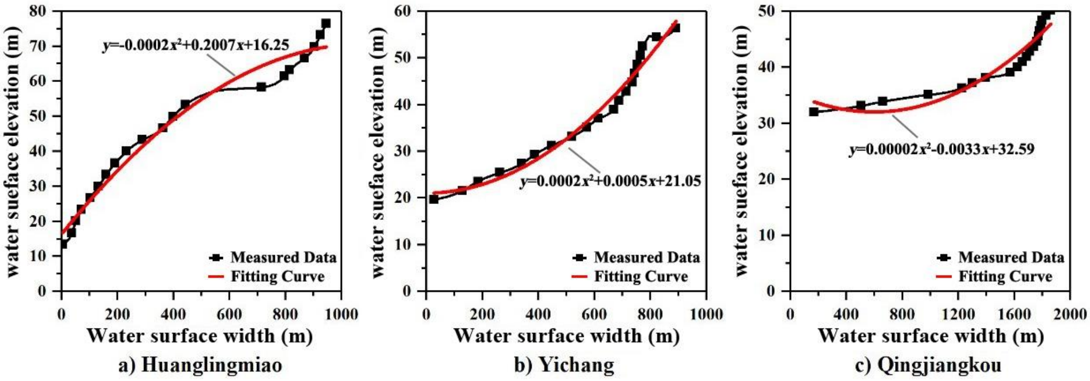


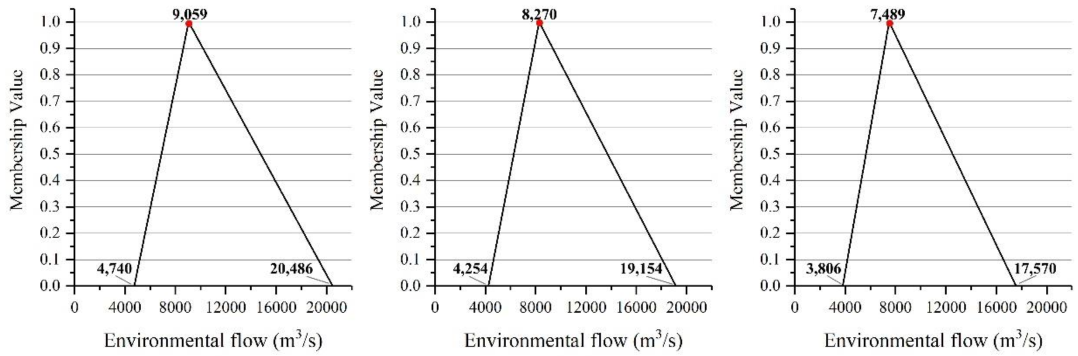
Figure 2. Fitting curve of three cross-sections

It can be seen form Figure 2 that Huanglingmiao is the downward type, while Yichang and Qingjiangkou belong to the upward type. When $n = 0.04$ and $J = 0.005$, we deduced the $Q \sim v$ fitting functions of the 3 cross-sections, which are expressed by $v_H = 0.003Q^{0.626}$, $v_Y = 0.0037Q^{0.609}$ and $v_Q = 0.0043Q^{0.599}$. Then, the environmental flow membership functions of the 3 cross-sections can be obtained, and their images are shown in Figure 3.

$$M(Q)_H = \begin{cases} \dfrac{0.003Q^{0.626} - 0.6}{0.3} & 4740 < Q < 9059 \\ \dfrac{1.5 - 0.003Q^{0.626}}{0.6} & 9059 < Q < 20486 \\ 0 & Else \end{cases} \tag{23}$$

$$M(Q)_Y = \begin{cases} \dfrac{0.0037Q^{0.609} - 0.6}{0.3} & 4254 < Q < 8279 \\ \dfrac{1.5 - 0.0037Q^{0.609}}{0.6} & 8279 < Q < 19154 \\ 0 & Else \end{cases} \tag{24}$$

$$M(Q)_Q = \begin{cases} \dfrac{0.0043Q^{0.599} - 0.6}{0.3} & 3806 < Q < 7489 \\ \dfrac{1.5 - 0.0043Q^{0.599}}{0.6} & 7489 < Q < 17570 \\ 0 & Else \end{cases} \tag{25}$$



(a) Huanglingmiao (b) Yichang (c) Qingjiangkou

Figure 3. Environmental flow membership functions of 3 cross-sections

From Figure 3, the environmental flow membership functions have realized the transformation of the environmental flow from a fixed value to a suitable range. Taking

Huanglingmiao as an example, 9,059 m^3/s is the ideal environmental flow. From 4,740 m^3/s to 9,059 m^3/s, the membership value is directly proportional to the environmental flow. On the contrary, they are inversely proportional from 9,059 m^3/s to 20,486 m^3/s. It implies that the environmental flow membership function increases the elasticity of ecological demands and provides a way for reservoir managers to optimize the ecological operation. Therefore, we suggest that the Three Gorges Reservoir should be discharged according to Huanglingmiao cross-section, and the Gezhouba Reservoir should be discharged according to Yichang cross-section.

4.3 Establishment and solution of multi-objective operation optimization model

4.3.1 Preliminary preparation

According to Section 2.3, the P-III distribution was taken as the frequency distribution, and the frequency curve of the annual average flow of the Yichang hydrological station was estimated by the fitting curve method. For the benefit operations of TGGCR, 3 typical years with P=50% (shipping and ecology), 75% (water supply) and 95% (PG) were selected. In addition, we divided one year into 36 time periods to solve the multi-objective operation optimization model, and obtained the inflow flood hydrograph of 3 typical years, as shown in Figure 4.

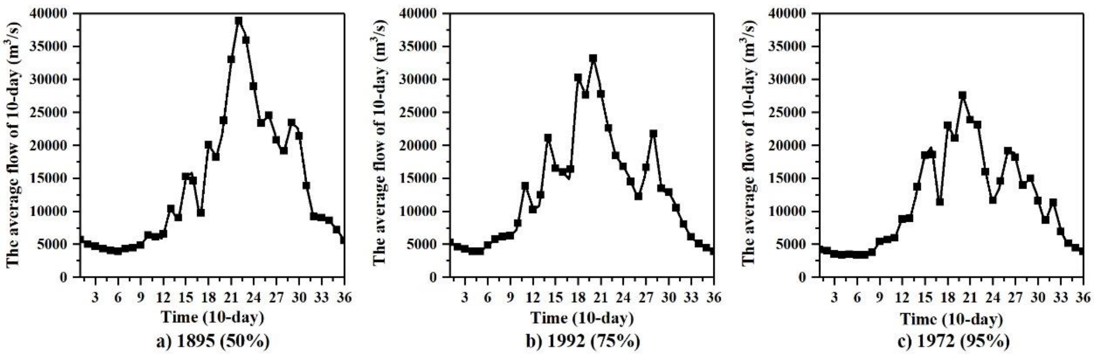


Figure 4. The flow hydrograph of 3 typical years

From Figure 4, the flood peak decreases with the increase of the design reliability, which is in line with the actual situation. The flow data for the different typical year with P=50%, 75% and 95% were used as input for the Evolver Palisade.

4.3.2 Setup parameters

In this study, we simulated 3 scenarios of TGGCR, and divided each scenario into 36 time periods, i.e., $i = 1, 2,\ 3$, $T = 36$ and $M = 2$ ($m = 1$ is the Three Gorges Reservoir and $m = 2$ is the Gezhouba Reservoir). The parameters to establish the multi-objective operation optimization model of TGGCR are shown in Table 2.

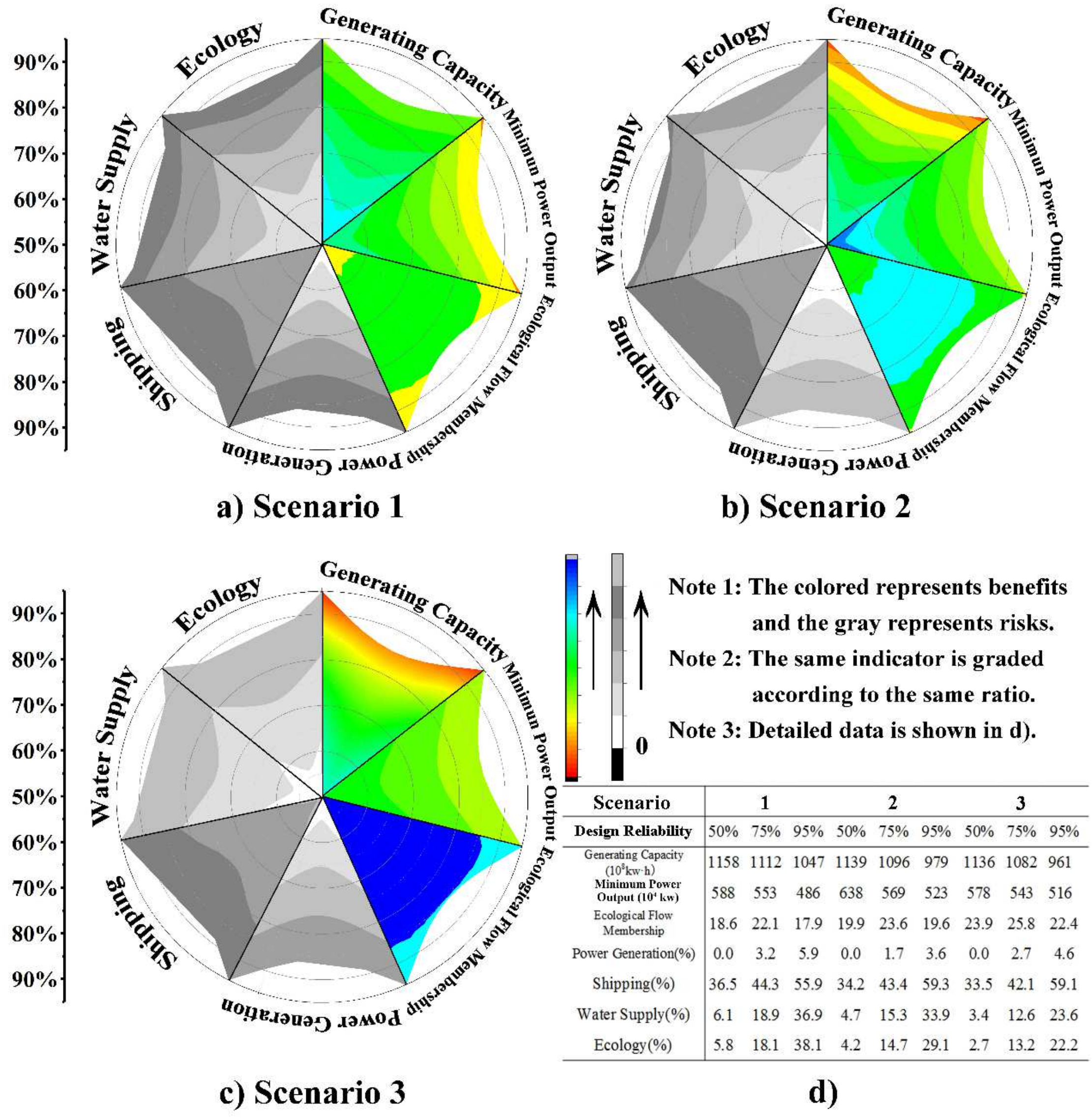
Table 2. Parameters of TGGCR multi-objective operation optimization model

Order	Parameter	Order	Parameter
1	$K_1 = K_2 = 8.5$	12	$I_1^{min} = 66.81\,m^3/s$
2	$S = 3$	13	$I_1^{max} = 31400\ \ m^3/s$
3	$Z_{1,t}^{max} = 175\ \ m\ \ (t = 1, 2, \dots, 36)$	14	$I_2^{min} = 0\ \ m^3/s$
4	$Z_{1,t}^{min} = \begin{cases} 145\ \ m\ \ (t = 18, 19, \dots, 30) \\ 155\ \ m\quad Else \end{cases}$	15	$I_2^{max} = 17935\,m^3/s$
5	$Z_{2,t}^{min} = 62\ \ m\ \ (t = 1, 2, \dots, 36)$	16	$Q_1'^{\ max} = 94000\,m^3/s$
6	$Z_{2,t}^{max} = 66\ \ m\ \ (t = 1, 2, \dots, 36)$	17	$Q_2'^{\ max} = 119470\,m^3/s$
7	$N_1^G = 4990\ \ MW$	18	$Z_1^W = 1\ \ m$
8	$N_1^E = 22500 MW$	19	$P = 50\%, 75\%, 95\%$
9	$N_2^G = 1040\ \ MW$	20	$Inum^i = 1{,}000$
10	$N_2^E = 3210\ \ MW$	21	$Tnum^i = 5{,}000$

11	$Q^{eco} = 5000 \ \ m^3/s$

4.3.3 Simulation results

After solving by the Evolver Palisade, for each scenario, we can get 18,000 (5000×36) simulation values. To preliminarily analyze the simulation results, we used $Eq. 18$ to calculate the risk rate of each benefit operation, as shown in Figure 5.



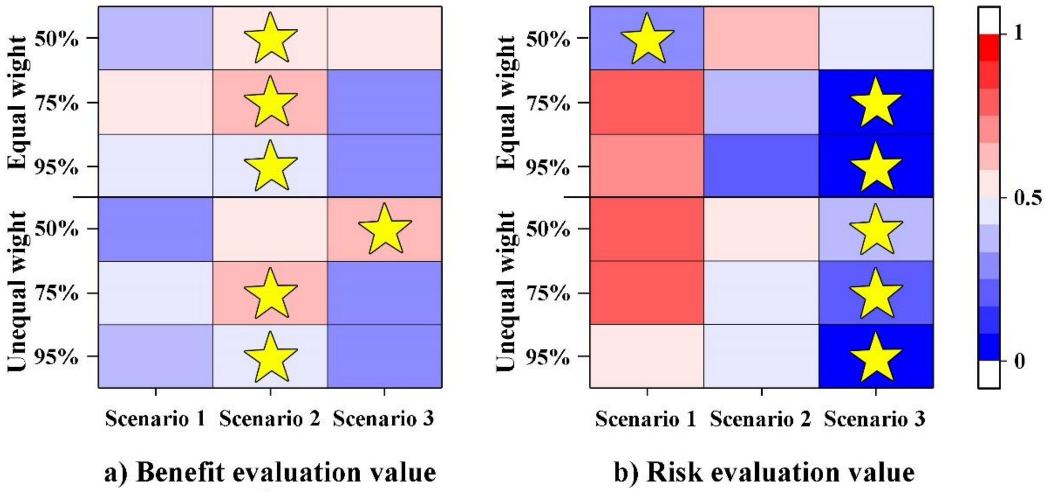
Scenario	1			2			3		
Design Reliability	50%	75%	95%	50%	75%	95%	50%	75%	95%
Generating Capacity (10^8kw·h)	1158	1112	1047	1139	1096	979	1136	1082	961
Minimum Power Output (10^4 kw)	588	553	486	638	569	523	578	543	516
Ecological Flow Membership	18.6	22.1	17.9	19.9	23.6	19.6	23.9	25.8	22.4
Power Generation(%)	0.0	3.2	5.9	0.0	1.7	3.6	0.0	2.7	4.6
Shipping(%)	36.5	44.3	55.9	34.2	43.4	59.3	33.5	42.1	59.1
Water Supply(%)	6.1	18.9	36.9	4.7	15.3	33.9	3.4	12.6	23.6
Ecology(%)	5.8	18.1	38.1	4.2	14.7	29.1	2.7	13.2	22.2

Figure 5. Simulation results of multi-objective optimization operation model

In Scenario 1 (Figure 5a), the generating capacity is the most of the 3 scenarios, but the environmental flow membership is the minimum. With the increase of the design reliability, the risk rate of benefit operation increases fastest. The fundamental reason is insufficient water resources, and the model pursues the largest amount of generating capacity, which limits other performance. Scenario 2 (Figure 5b) can guarantee certain PG benefits and ecological demands, and the risk of damage to PG requirements is the lowest. Scenario 3 (Figure 5c) can meet most ecological demands and guarantee certain MPO, but the generating capacity is the least of three scenarios. The risk rate of Scenario 3 in PG, shipping, water supply and ecology is low. Only when $P = 95\%$, the shipping will be poor. This is because the optimization model with the highest degree of environmental flow membership increases discharge flow and the output value during the dry season, so that the requirements of PG and water supply can be met. Since shipping requires that the water level in front of the dam is higher than 155 m, while the reservoir must maintain a low water level (145 m) in flood season, the risk rate is high.

4.4 Multi-objective risk analysis of benefit operations

Three scenarios are effective for each optimization objective, and reservoir managers can select operation scheme according to the actual conditions. TGGCR has the highest reliability for PG and the lowest reliability for shipping. If reservoir operation only pursues higher generating capacity, it will bring higher risks in shipping, water supply and ecology, which is not conducive to the sustainable development of reservoirs and the environment. On the contrary, if operating reservoirs properly consider ecological demands, it can effectively reduce the risk rate in the other performance, and rationally allocate resources and maximize the overall benefits. According to the calculation results in Figure 5, the benefit evaluation value and the risk evaluation value of three scenarios under the equal weight and unequal weight can be calculated, as shown in Figure 6.



Note: The one with "☆" is the most benefit or the lowest risk rate scenario in the same situation.

Figure 6 Benefit evaluation values and risk evaluation values of three scenariosFrom Figure 6, regardless of whether the weights are equal or unequal, Scenario 2 is optimal when the reliability is 75% and 95%, and Scenario 3 is optimal when the reliability is 50%. It shows that when the water resources are sufficient, maximizing MPO can bring greater overall benefits. On the contrary, when water availability is insufficient, maximizing the environmental flow membership can better resist the risk.

5 Conclusions

This study proposed a method for inferring an environmental flow membership function based on the triangular functions and ecological hydraulic radius. With the objective of maximizing PG, MPO and environmental flow membership, a multi-objective operation optimization model was established. Finally, a multi-objective risk analysis method was proposed. The following findings come from the study:

(1) Based on the environmental flow membership function, the environmental flow suitable for the survival and reproduction of aquatic organisms at river can be determined.

(2) Environmental flow membership is a concept based on the fuzzy theory. It can transform the traditional fixed value environmental flow into a range and be used as the optimization objective in the multi-objective operation optimization model of reservoir, which is conducive to the formulation of an environmentally friendly operation scheme and the rational allocation of water resources.

(3) Multi-objective risk analysis can provide more decision-making basis for reservoir managers. Whether the weights of the various benefit operations are equal, when the water resources are insufficient, maximizing the environmental flow membership can be better resisting the risk. On the contrary, maximizing MPO can obtain overall benefits.

Considering ecological demands can effectively reduce the risk brought by other benefit operations. Therefore, the operation of reservoirs should according to the environmentally friendly operation scheme, so that reasonably allocating water resources, and maximizing the overall benefits. Indeed, for large cascade reservoirs, it is not enough to select only three scenarios. If we want to further study ways to improve the overall benefits of cascade reservoirs, it is a good way to increase factors such as flood evolution and compensation operations.

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Authors' contributions

Conceptualization: J.L., J.R.L.; Methodology: J.H., P.L.; Formal analysis and investigation: J.H.; Writing - original draft preparation: J.H., P.L.; Writing - review and editing: J.L.; Funding acquisition: J.L.; Supervision: J.R.L.

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Data availability statement

Data for this study can be downloaded from the Yichang Hydrology Bureau webpage (http://www.hbycsw.com). The code and the *Joint Operation Procedure* ([2020]135, China's Ministry of Water Resources) are available from the corresponding author upon reasonable request.

Compliance with ethical standard

Declaration The authors confirm that this article is original research 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.

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Figures

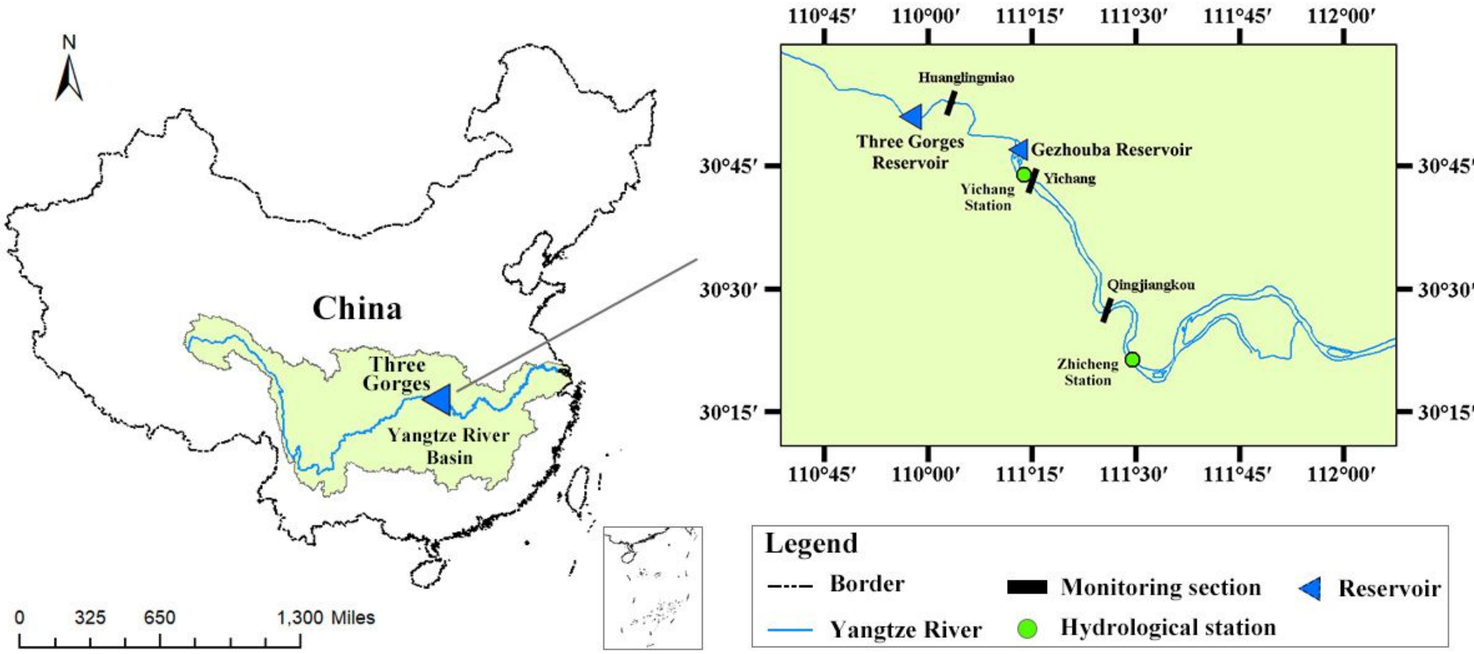


Figure 1

Location of the Three Gorges-Gezhouba cascade reservoirs, cross-sections and hydrological stations Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

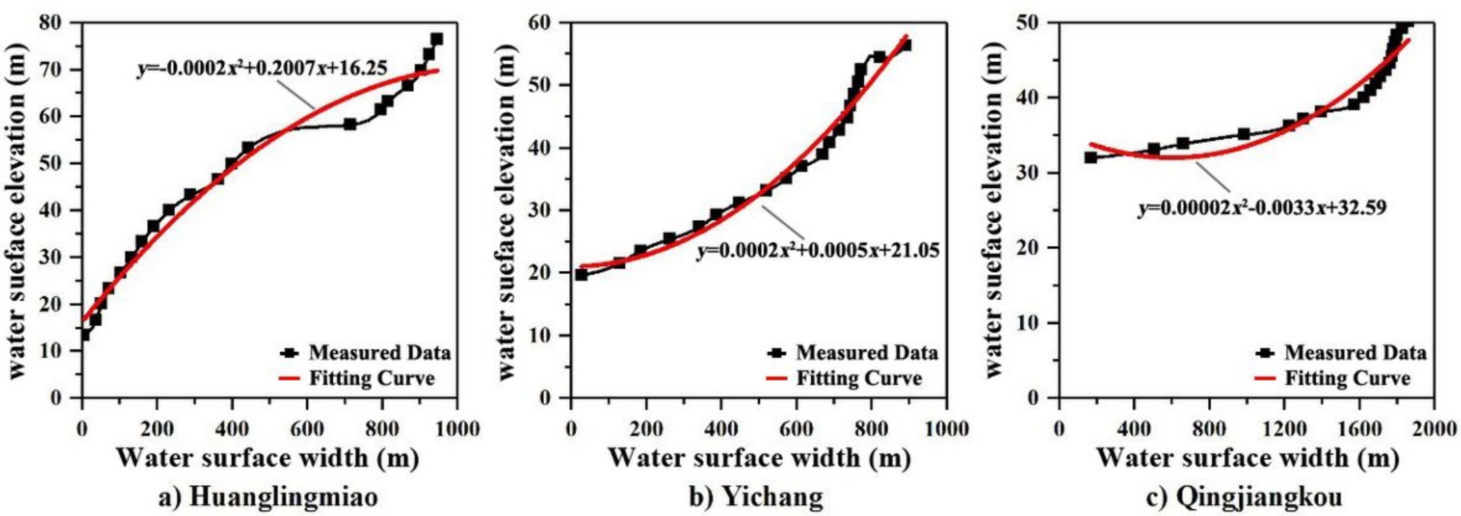


Figure 2

Fitting curve of three cross-sections

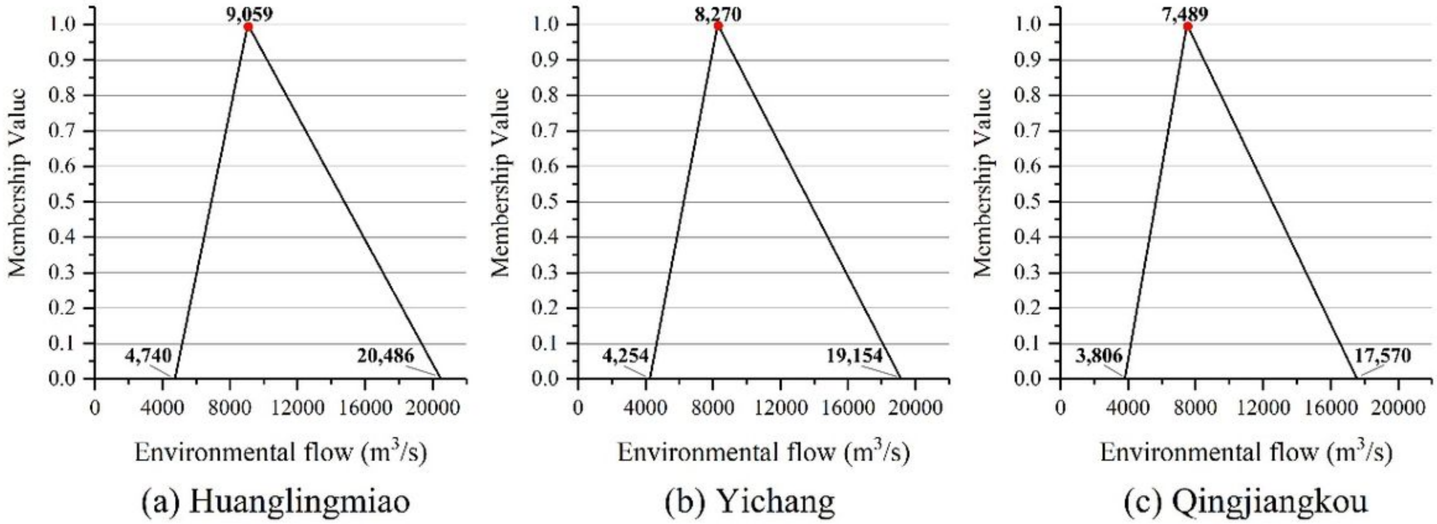


Figure 3

Environmental flow membership functions of 3 cross-sections

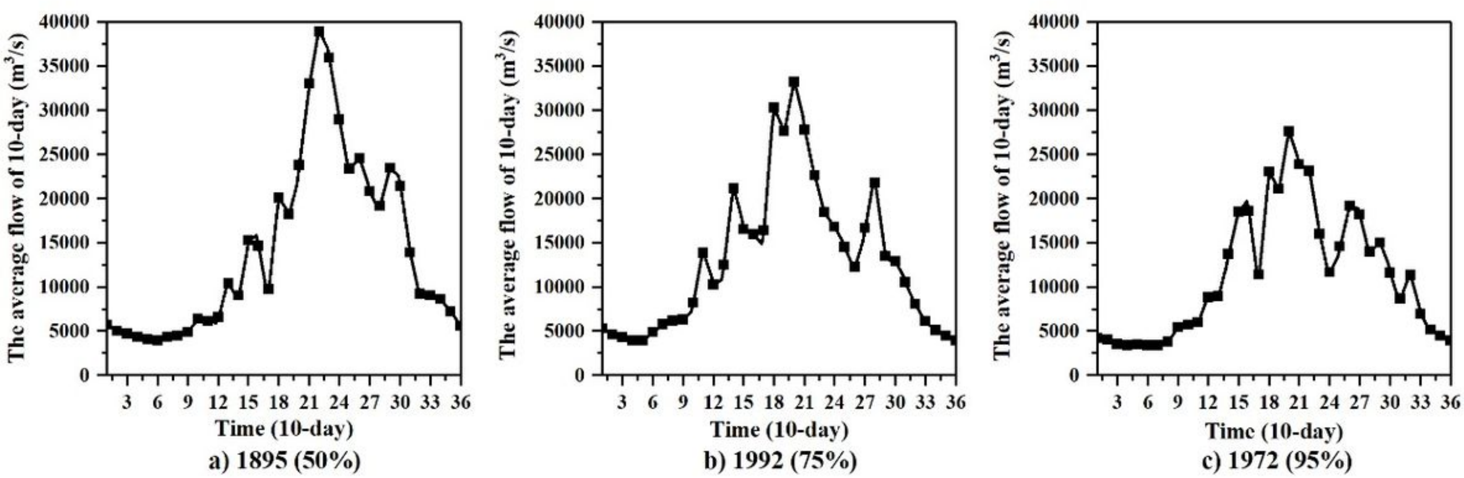
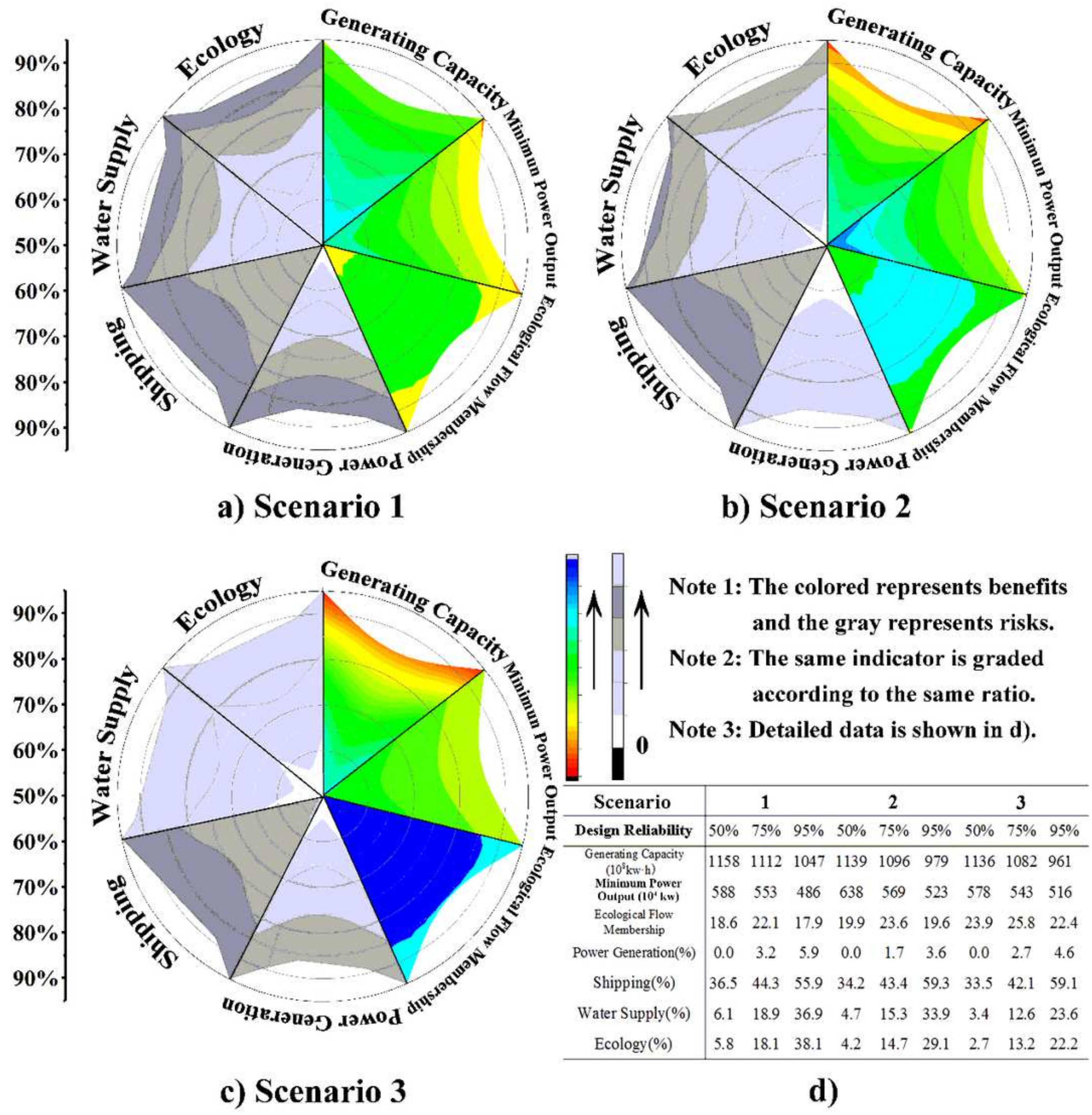


Figure 4

The flow hydrograph of 3 typical years



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Design Reliability	50%	75%	95%	50%	75%	95%	50%	75%	95%
Generating Capacity (10^8kw·h)	1158	1112	1047	1139	1096	979	1136	1082	961
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d)

Figure 5

Simulation results of multi-objective optimization operation model

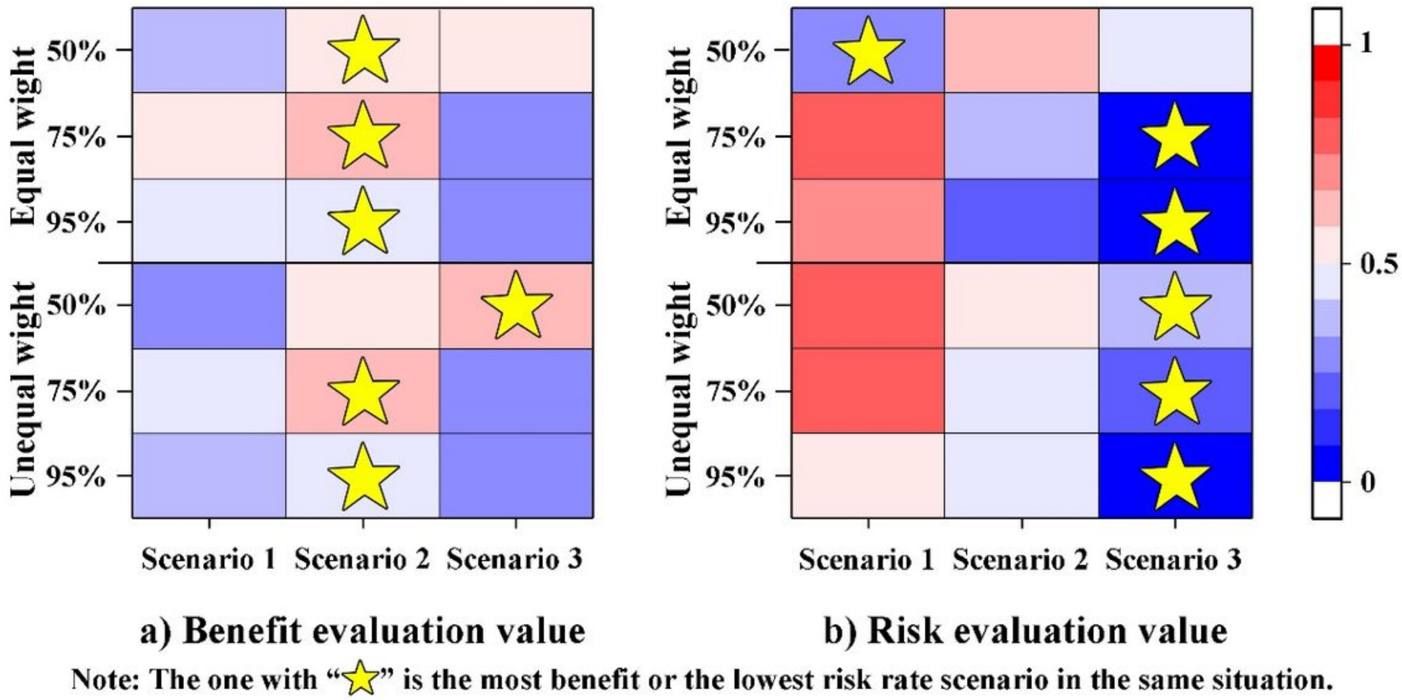

Figure 6

Benefit evaluation values and risk evaluation values of three scenariosFrom Figure 6, regardless of whether the weights are equal or unequal, Scenario 2 is optimal when the reliability is 75% and 95%, and Scenario 3 is optimal when the reliability is 50%. It shows that when the water resources are sufficient, maximizing MPO can bring greater overall benefits. On the contrary, when water availability is insufficient, maximizing the environmental flow membership can better resist the risk.