Multi-objective game theory optimization for balancing economic, social and ecological benefits in the Three Gorges Reservoir operation

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Abstract
Reservoir operation is an important and effective measure for realizing optimal allocation of water resources. It can effectively alleviate regional scarcity of water resources, flood disasters and other social problems, and plays an important role in supporting sustainable strategic development of water resources. Coordinating the stakeholders is key to the smooth operation of a multifunctional reservoir. This research examines the competition among stakeholders of a multi-objective ecological reservoir operation aiming to provide for economic, social and ecological demands. A multi-objective game theory model (MOGM) specified 10-day water discharge to meet the triple water demands (power generation, socio-economic consumption and environment) for multi-purpose reservoir operation. The optimal operation of the Three Gorges Reservoir (TGR), with the ecological objective of providing comprehensive ecological flow demanded for some key ecological problems that may occur in the middle and lower reaches of the Yangtze River, was chosen as a case study. Discharged water calculated by the MOGM and a conventional multi-objective evolutionary algorithm/decomposition with a differential evolution operator was then allocated to different demands. The results illustrate the applicability and efficiency of the MOGM in balancing transboundary water conflicts in multi-objective reservoir operation that can provide guidance for the operation of the TGR.

1. Introduction
With rapid urbanization and industrialization, water shortage has become a significant challenge affecting sustainable regional development [1]. A reasonable water allocation from transboundary river basins is effective in enhancing water use efficiency and mitigating possible conflicts between economic development and environmental conservation [2]. Conventional reservoir operations management is oriented to economics, whilst other aspects, including the ecological and environmental impacts, are neglected [3]. Therefore, the operation and management of reservoirs needs to be further optimized. While ensuring hydropower generation benefits, it is necessary to meet the environmental demand for river water to preserve freshwater ecosystems while at the same time ensuring the social demands of the reservoir and downstream regions for domestic, industrial and agricultural water [4–6].

When designing, operating or managing a water conservation project, water utilization and allocation can facilitate hydropower generation, flood control, agricultural irrigation and shipping [7–10]. China has built the Three Gorges Project, which is the world’s largest and most complex hydraulic engineering operation [11], to help over 450 million people benefit from clean energy and water diversion [12]. However, such a project confronts challenges related to disruption of the water cycle balance, and operational strategies often induce water conflicts associated with a variety of physical, environmental
[13, 14], financial, socio-economic and political issues [15, 16].

Following their individual responsibilities, the managers of water conservancy facilities (e.g. the reservoir operator and proprietors of diversion projects) prioritize their economic revenues first and then consider social and ecological interests to improve their social impact [17, 18]. The local government has performed as a leader to implement and manage water transfer projects, but prefers the water supply of reservoirs to be used to promote local socio-economic development [13]. Despite having many economic and social benefits for the reservoir operator and local government, the project may bring some negative environmental impacts. Hence, it is imperative for catchment administrators to balance the uneven distribution of water resources and preserve the health of riverine ecosystems [14, 19]. However, giving full consideration to these objectives together with management performance is a complex issue, since the outcomes do not usually match, and may conflict [20]. As optimization algorithms do not necessarily clearly reflect the real interests of stakeholders within a river basin, the application of advanced multi-objective evolutionary algorithms (MOEAs) may not effectively solve conflicting objectives in the water resources management problem [20]. As a result, the obtained decisions may cause conflict among the involved stakeholders [21]. To overcome such issues, game theory provides an insight into seeking trade-offs among strategic actions by different stakeholders [22, 23] who choose to recognize the interests of other stakeholders [20].

Game theory is a logic tool for studying the possible conflicts of involved players, with the aim of obtaining equilibrium regarding various strategic actions [24]. In recent years, a number of in-depth studies have been conducted on watershed management using game theory [15, 25–27]. In terms of the transboundary allocation of water resources, studies have mainly focused on game-theoretic compromise in conflicts between water-claiming stakeholders. For instance, Ai et al [28] introduced game theory to maximize the income generated by the operation of cascaded reservoirs. Skardí et al [29] established a cooperative Nash bargaining game to investigate the best watershed management practice regarding cost sharing among landowners of a sub-basin. Based on evaluation criteria including fairness and efficiency, Madani and Hooshyar [30] proposed a game theory–reinforcement learning based game to seek the optimal operational scheme for reservoir groups in terms of their economic revenues. Estalaki et al [31] placed emphasis on the watershed environment by using an evolutionary game to model the interactions among waste load dischargers. Oftadeh et al [32] further constructed a two-player ultimatum game to address the basin water conflicts between environmental reclamation and economic satisfaction. Zeng et al [33] proposed a game hybrid with mathematical programming to enhance transboundary water allocation by reducing the costs for water supply and removal of pollution. Zarei et al [34] applied a proportional game to optimize water resource allocation from reservoirs to agricultural, urban and industrial services. To reduce eutrophication potentials of the river–reservoir systems, Hasanzadeh et al [35] applied the Stackelberg game and Nash bargaining to obtain the trade-offs between Department of Environment and aquaculture units.

These previous studies have indicated that game theory is useful in helping stakeholders to coordinate their common interests. In the field of transboundary water resource management in particular, the above studies were mainly constructed models oriented to economic cost or benefit [33] and seldom took environmental performance into full consideration. This study proposes a multi-objective game-theory model (MOGM) to examine the conflicts among stakeholders involved in reservoir operations management, by maximizing the economic incomes, water supply for social development and ecological water demands to provide an optimal scheduling scheme for sustainable reservoir operation. The optimal operation of the Three Gorges Reservoir (TGR), where necessary ecological flow is provided for the middle and lower reaches of the Yangtze River, is taken as a case study to demonstrate application of the model. A conventional MOEA is compared with the MOGM to reflect the conflicting preferences of stakeholders. To illustrate the fulfillment of allocated water by the two algorithms, optimal reservoir operation seeks to meet different objective demands using the highest reliability index and resiliency index [34] as well as the lowest vulnerability index [36], and to prevent reduction of reservoir volume to lower than the permitted values. Moreover, the scheduling schemes obtained using the proposed model are compared with the actual scheduling schemes of the reservoir to highlight its advantages in effectiveness in mitigating ecological issues. It is expected that the study may provide an optimal scheduling scheme to optimize reservoir operation management and ultimately mitigate conflicts about water resources.

2. Case study

The above analysis implies that there are a number of interests and conflicts among the reservoir operator, local government and catchment administrator of reservoir operation, and a three-player game can be set up. The reservoir operator, which is motivated by profit, is reluctant to take on more corporate social responsibility and instead has to act under basic policy constraints [37]. The catchment administrator or watershed management committee must plan for discharges with due regard to maintaining the basic function of the ecological river environment [38].
The planned water volume, known as the ecological flow, should prevent the outbreak of key ecological problems in the river [39]. Local governments, especially the government department of riparian cities near the dam site, may perceive possible economic losses due to water shortages for industrial, agricultural and domestic water usage [40]. Generally, using the industrial and agricultural water to protect the river’s basic ecological flow will have a significant impact on the safety of socio-economic water supply [41]. The MOGM will provide a strategic model by considering all the above actions in order to examine trade-off strategies for mitigating possible conflicts among the three stakeholders.

2.1. Study area and data

2.1.1. The Yangtze River Basin

The Yangtze River, with a total length of 6397 km and a drainage basin area of 1.8 million km², is divided into three parts, upstream, midstream and downstream, by Yichang and Hukou sections [42]. The Yangtze River Basin is situated in a subtropical monsoon climate region, which has a high rainfall and warm climate, with an average rainfall of 1082 mm and a rainy season from April to October each year, during which the amount of rainfall can reach 85% of the annual rainfall [43]. The TGR, located in the upper reaches of the Yangtze River, has a storage capacity of 39.3 billion m³, with an installed capacity of 18 200 MW and annual electricity generation of 84.7 billion kWh [42]. According to daily reservoir outflow data from 2003 to 2016, the minimum and maximum release flow rates of the reservoir are 1580 and 98 800 m³ s⁻¹, respectively. This work took the main stream of the middle and lower reaches of the Yangtze River and its estuary as the study area, as shown in figure 1. According to the Hydrological Yearbook for the Yangtze River Basin, the total socio-economic water demand in the section from Yibin to Yichang of the Yangtze River in 2020 is estimated to be about 100.58 × 10⁸ m³, and the reservoir impoundments provide water supply to the reservoir region and downstream cities. Although the dam construction and operation changed the natural downstream hydrological regime and block river connectivity, the negative effects can be effectively mitigated by coordinating reservoir operation schemes.

2.1.2. Operational schedule of the TGR

Between January and May, the scheduling scheme of the TGR is to maintain an increase in reservoir discharge of 1000–2000 m³ s⁻¹. During September, the early storage period, the reservoir discharge flow should be kept above 10 000 m³ s⁻¹ for flood safety. In October, the storage period, the minimum discharge of the reservoir is controlled to 8000 m³ s⁻¹ [44]. The reservoir discharge to ensure flood control was set as 35 000 m³ s⁻¹ [42]. The range of reservoir discharge for ensuring normal navigation is controlled within 5000 and 56 700 m³ s⁻¹ [42].

2.1.3. Data

The data used in this study included the ecological flow ranges and reservoir inflow and outflow data.
The ecological flow data were referenced by a large literature review and existing measured data. The daily inflow and outflow data for the TGR from 2003 to 2016 used to trigger and validate the operational models were obtained from the website of the China Three Gorges Corporation (www.ctgpc.com.cn).

2.2. Comprehensive ecological flow requirement

The key ecological problems of concern to the catchment administrator are characterized as those having a significant impact on river structure and ecological function as well as sensitivity to runoff changes. The period corresponding to the onset of key ecological problems is defined as the critical period. Since the impoundment of the TGR, a series of ecological problems have occurred in the middle and lower reaches of the Yangtze River, such as a significant decrease in the abundance of eggs and larvae of four major Chinese carp (FMCC), remarkable changes in natural hydrological regimes, supersaturation of dissolved gas in the released flow and the intrusion of salt water into the Yangtze Estuary. How to reduce the adverse effects of the development of water resources on the river ecosystem by revising the reservoir operation scheme has become the focus of the watershed management department.

2.2.1. Reproduction of the FMCC

The FMCC comprise Mylopharyngodon piceus, Clenopharyngodon idellus, Hypophthalmichthys molitrix, and Aristichys nobilis; these are important commercial fish species in the Yangtze River and their population dynamics can mirror the health of the Yangtze ecosystem [39]. Their main spawning grounds are located in the middle reaches of the Yangtze River next to the Three Gorges Dam [45]. However, after impoundment of the TGR, the number of fry of FMCC in the Jianli section of the Yangtze River has declined sharply, possibly because hydrological alterations caused by operation of the dam have affected spawning and reproduction [46]. Using the ‘ecological flow component’ calculation module in the Indicators of Hydrologic Alteration (IHA) software, Zhao et al [45] analyzed the natural flow process at the Yichang Hydrological Station in May before and after the impact of TGR operation. The results showed that the artificial flood peak in the whole flow process can stimulate the natural reproduction of FMCC when the average flow of the Yichang section in May ranges from 11 800 to 16 600 m$^3$ s$^{-1}$. According to the dynamic relationship of discharge between different hydrological sections [47], when the discharge volume rate of the TGR varies between 11 609 and 16 260 m$^3$ s$^{-1}$ in May, it can promote the reproduction of FMCC in the middle reaches of the Yangtze River.

2.2.2. Alterations of the hydrological regime

Natural hydrological regimes of river ecosystems represent the most suitable and undisturbed hydrological conditions for aquatic organisms [48]. Such regimes are an important driving force in the maintenance of ecological integrity and biodiversity of the downstream parts of the river [49]. Using IHA and the histogram matching approach, Yu et al [48] developed an improved range of variability approach to calculate the allowable range of alteration of the runoff process at the Yichang section after the construction and operation of the TGR. The ecological flows for maintaining the natural flow regime in the middle and lower reaches of the Yangtze River were thus obtained.

2.2.3. Dissolved gas supersaturation

When the reservoir releases water flows through the spillway to the stilling basin and downstream river, large amounts of air will be carried into the water, resulting in supersaturation of dissolved gas [50]. High levels of dissolved gas may remain hundreds of kilometers downstream of the reservoir due to the very slow recovery of the supersaturated dissolved gas in the channel [51]; this can cause fish to suffer from ‘gas bubble disease’ or die [52]. Chen et al [53] developed a mathematical model to simulate the evolution of supersaturation of dissolved gas, and the simulation results showed that when the discharge rate of the TGR from June to July was less than 30 000 m$^3$ s$^{-1}$ it was conducive to alleviating the influence of flood discharge of the TGR on supersaturation of dissolved gas in the downstream water body during the spawning periods of FMCC.

2.2.4. Salinity requirements of the estuarine indicator species

Fish are a good indicator of the aquatic ecosystem at the end of a river ecosystem and can reflect the comprehensive ecological conditions of the river. Wang et al [8] applied an analytical model of intrusion of salt water in alluvial estuaries to simulate the quantitative relationship between salinity and freshwater inflows. Based on the salinity requirements of the indicator species, including Acipenser sinensis Gray, Collichthys lucidus, Ostrea plicatula and Eriocheir sinensis H. Milne-Edwards, the habitats of which are situated in the Yangtze Estuary, environmental flows for sustaining freshwater and estuarine ecosystems were determined.

Considering the ecological flow requirements for the above key ecological problems, we obtained the comprehensive ecological flow for the TGR discharge section (table 1, figure 2). The maximum lower bound and minimum upper bound of ecological flow in each critical period are selected as the comprehensive ecological flow range for the ecological problems in this period. If there is a conflict between different ecological requirements, the priorities of different key ecological problems are determined by the distance from the dam site to the critical area where they occur. Accordingly, the first priority should be given...
Table 1. Monthly ecological flow requirements at the discharge section of the Three Gorges Reservoir for comprehensive key ecological problems (m$^3$ s$^{-1}$).

| Time period (month) | FMCC reproduction | Natural hydrological regime | Dissolved gas supersaturation | Maintaining salinity requirements of the indicator species | Synthetic ecological flow |
|---------------------|-------------------|-----------------------------|-------------------------------|-----------------------------------------------------------|---------------------------|
|                     | LB                | UB                          | LB                            | UB                                                        | LB                        |
| 1                   | —                 | 3618                        | 4711                          | —                                                         | —                         |
| 2                   | —                 | 3227                        | 4379                          | —                                                         | 3618                      |
| 3                   | —                 | 3137                        | 4517                          | —                                                         | 4711                      |
| 4                   | —                 | 4654                        | 7267                          | —                                                         | 3227                      |
| 5                   | 11 609            | 6717                        | 12 868                        | 4532                                                      | 4379                      |
| 6                   | —                 | 14 223                      | 21 319                        | 19 043                                                    | 3137                      |
| 7                   | —                 | 22 268                      | 36 884                        | 11 542                                                    | 4654                      |
| 8                   | —                 | 16 961                      | 31 972                        | 27 885                                                    | 7267                      |
| 9                   | —                 | 15 290                      | 32 775                        | 24 539                                                    | 22 268                    |
| 10                  | —                 | 13 281                      | 20 894                        | 24 539                                                    | 16 961                    |
| 11                  | —                 | 7867                        | 11 591                        | 27 885                                                    | 27 885                    |
| 12                  | —                 | 4989                        | 6865                          | 24 539                                                    | 11 591                    |

LB, lower bound; UB, upper bound.
to the reproduction of the FMCC, the main spawning grounds of which are situated closer to the Three Gorges Dam [45]. The second priority is to alleviate the alterations of the hydrological regime and dissolved gas supersaturation in river ecosystems which may occur in the middle reaches of the Yangtze River from Yichang and affect an area of more than 400 km². Finally, we need to consider the amount of water needed for saltwater intrusion into drinking water sources and salinity to maintain indicator species in the estuary, as they occur far from the dam.

3. Method

3.1. Multi-objective programming for reservoir operation

Three major objectives of reservoir operation are considered in this study, i.e. maximizing hydropower energy production, minimizing socio-economic water deficits and minimizing ecological flow deficits. In such a context, these three objectives are analyzed in the following sections.

3.1.1. Economic objective

The economic objective of concern to the reservoir operator is to maximize the annual hydropower generation, expressed as follows:

\[
\max F = \sum_{t=1}^{T} k \times \alpha \times q_t \times h_t \times \tau_t
\]

Here \( F \) is the maximum output of hydropower generation (kWh), \( k \) is the conversion factor, \( \alpha \) is the output coefficient of hydropower, ranging from \( 8.0 \times 10^3 \) to \( 8.8 \times 10^3 \, \text{N m}^{-3} \) [54]. \( q_t \) refers to the reservoir discharge during the \( t \)th time period (m³ s⁻¹), \( h_t \) is the average water head of the reservoir during the \( t \)th period (m), \( \tau_t \) denotes the duration of the \( t \)th dispatching period (s), \( T \) implies the whole schedule period within a year, \( z_{up} (q_t) \) represents the relationship between upstream water level and discharge flow, \( z_{down} (q_t) \) represents the relationship between tail water level and discharge flow and \( z_{loss} \) represents the water head loss of the reservoir.

3.1.2. Social objective

The social objective of concern to the local government is to minimize deficient and excessive socio-economic water demand in the region covered by the reservoir, given as follows:

\[
\min S = \sum_{t=1}^{T} WS_t
\]

\[
WS_t = \begin{cases} R_t - Q_t - (q_t + sp_t) \times \tau_t & \text{if } Q_t + (q_t + sp_t) \times \tau_t \leq R_t \quad \forall t \in T. \\ Q_t + (q_t + sp_t) \times \tau_t - R_t & \text{if } Q_t + (q_t + sp_t) \times \tau_t > R_t \quad \forall t \in T. \end{cases}
\]

Here \( WS_t \) represents the deficient and excessive water demand in the region covered by the reservoir during the \( t \)th time period (m³), \( R_t \) and \( Q_t \) represent, respectively, the water demand and water storage of the region covered by the reservoir during the \( t \)th period (m³) and \( sp_t \) is the overflow water from the reservoir during the \( t \)th period (m³ s⁻¹).

3.1.3. Ecological objective

To mitigate adverse impacts of reservoir operation on the river ecosystem and facilitate economic and social development, ecological performance is taken into account in this study to minimize deficient and excessive ecological flow demand by regulating the reservoir discharge [37, 42], given as follows:

\[
\min E = \sum_{t=1}^{T} WE_t
\]

\[
WE_t = \begin{cases} \left[ EF_t^{\text{min}} - (q_t + sp_t) \right] \times \tau_t & \text{if } q_t + sp_t < EF_t^{\text{min}} \\
0 & \text{if } EF_t^{\text{min}} \leq q_t + sp_t \leq EF_t^{\text{max}} \forall t \in T \\
\left[ (q_t + sp_t) - EF_t^{\text{max}} \right] \times \tau_t & \text{if } q_t + sp_t > EF_t^{\text{max}}. \end{cases}
\]
Here \( W_{E_t} \) represents the deficient and excessive ecological flow in the downstream river section during the \( t \)th period (m\(^3\)) and \( E_{min}^{t} \) and \( E_{max}^{t} \) represent, respectively, the minimum and maximum ecological flows required by the downstream river section during the \( t \)th period (m\(^3\) s\(^{-1}\)).

### 3.1.4. Constraints

The above objectives are subjected to the following constraints.

#### The water balance:

\[
V_{t+1} = V_t + (I_t - q_t - S_{p_t}) \times \tau_t 
\]

where \( V_{t+1} \) and \( V_t \) are the water storage at the end of the \((t + 1)\)th and \( t \)th periods (m\(^3\)), respectively, and \( I_t \) is reservoir inflow during the \( t \)th period (m\(^3\) s\(^{-1}\)).

#### Shipping discharge constraint:

\[
q_t \geq Q_h 
\]

where \( Q_h \) denotes the reservoir discharge to ensure common navigation during the \( t \)th period (m\(^3\) s\(^{-1}\)).

#### Discharge flow constraint:

\[
Q_{t,min} \leq q_t \leq Q_{t,max} 
\]

where \( Q_{t,min} \) and \( Q_{t,max} \) denote the minimum and maximum discharge of the reservoir during the \( t \)th period to maintain safety (m\(^3\) s\(^{-1}\)).

#### Reservoir storage constraint:

\[
V_{t,min} \leq V_t \leq V_{t,max} 
\]

where \( V_{t,min} \) and \( V_{t,max} \) imply the constraints of the minimum and maximum water storage of the reservoir during the \( t \)th period (m\(^3\)).

#### Non-negative constraint:

\[
q_t \geq 0. 
\]

### 3.2. Multi-objective game-theory model

Game theory is employed to examine the operation of the multi-purpose water reservoir with the aim of mitigating the conflicts between the economic, social and environmental demands. In such a context, three players are involved: the operator of the hydropower station, local government and the catchment administrator. Game theory is further applied to solving the proposed multi-objective program by seeking Nash equilibrium between economic, social and environmental performance.

From the solution of the decision variables (discharge flow) \( q_t \), \( F_{max} \) can be determined from \( F(q_t) \). On the other hand, for the minimum of social and environmental benefits, \( S_{min} \) and \( E_{min} \) can be obtained from equations (2) and (3), respectively.

Generally, each player wants to obtain the maximum \( (F_{max}, S_{max} \) or \( E_{max} \) or minimum values \( (F_{min}, S_{min} \) or \( E_{min} \)) from the optimization of each single objective.

The range of the minimum and maximum values \( (F, S \) and \( E) \) for each player are given as follows.

For the power generation operator

\[
F_{min} \leq F(q_t) \leq F_{max}. 
\]

For local government

\[
S_{min} \leq S(q_t) \leq S_{max}. 
\]

For the catchment administrator

\[
E_{min} \leq E(q_t) \leq E_{max}. 
\]

The results of the MOGM for each player can be represented by \((F(q_t), S(q_t), E(q_t))\). Each player sets the expected objective values as \( F_{goal}, S_{goal} \) and \( E_{goal} \), respectively. In such a context, they can be incorporated as the constraints in the three objective optimizations, as follows.

For the power generation operator, the strategic action is

\[
\begin{align*}
\text{Max } F &= F(q_t) \\
\text{s.t. } \begin{cases} 
S(q_t) &\leq S_{goal} \\
E(q_t) &\leq E_{goal} \\
\forall t \in T 
\end{cases} \\
\text{equations } (5) - (9)
\end{align*} 
\]

For the local government, the strategic action is

\[
\begin{align*}
\text{Min } S &= S(q_t) \\
\text{s.t. } \begin{cases} 
F(q_t) &\geq F_{goal} \\
E(q_t) &\leq E_{goal} \\
\forall t \in T 
\end{cases} \\
\text{equations } (5) - (9)
\end{align*} 
\]

For the catchment administrator, the strategic action is

\[
\begin{align*}
\text{Min } E &= E(q_t) \\
\text{s.t. } \begin{cases} 
F(q_t) &\geq F_{goal} \\
S(q_t) &\leq S_{goal} \\
\forall t \in T 
\end{cases} \\
\text{equations } (5) - (9)
\end{align*} 
\]
The game interval that consists of the minimum and maximum values of $F, S$ and $E$ can be divided into equal plots for each player to determine the concession value. A series of concessions and bargaining will be conducted for each player. The concession value is measured as follows:

$$C_1 = \frac{F_{\text{max}} - F_{\text{min}}}{n} \quad (15)$$

$$C_2 = \frac{S_{\text{max}} - S_{\text{min}}}{n} \quad (16)$$

$$C_3 = \frac{E_{\text{max}} - E_{\text{min}}}{n} \quad (17)$$

where $n$ is the coefficient for reasonable concession (its value should not make the objective value of each player decrease rapidly in each round of negotiation) [55]. After negotiation, the expected objective values gradually approach the MOGM results. The bargaining process will continue until the solutions of $F_{\text{final}}, S_{\text{final}}$ and $E_{\text{final}}$ can meet the following conditions:

For the power generation operator

$$F_{\text{final}} \geq F_{\text{goal}}. \quad (18)$$

For the catchment administrator

$$S_{\text{final}} \leq S_{\text{goal}}. \quad (19)$$

For the local government

$$E_{\text{final}} \leq E_{\text{goal}}. \quad (20)$$

The above solution set $(F_{\text{final}}, S_{\text{final}}, E_{\text{final}})$ is deemed to be the Nash equilibrium.

### 3.3. Multi-objective evolutionary algorithm

A MOEA is a method that simulates natural selection and biological evolution among generations to achieve global optima [11]. The MOEA based on decomposition with a differential evolution operator (MOEA/D-DE) proposed by Li and Zhang [56] has been successfully applied to the search for approximated Pareto-optimal solutions for management of reservoir operations [42]. Once a Pareto-optimal frontier is obtained by the MOEA/D-DE, multi-criteria decision-making based on fuzzy set theory is further proposed to determine the most appropriate scheduling scheme. Linear fuzzy numbers coupled with a simplified analytic hierarchy process (AHP) are applied to aggregate the performance of each alternative scheme with respect to each objective, and then all the alternatives are ranked in accordance with its aggregated performance [57]. The linear fuzzy membership function for minimized objectives is defined as [58]

$$\mu_m = \begin{cases} 
\frac{f_m - f_{m\text{min}}}{f_{m\text{max}} - f_{m\text{min}}} & \text{if } f_m < f_{m\text{min}} \\
1 & \text{if } f_{m\text{min}} \leq f_m \leq f_{m\text{max}} \\
0 & \text{if } f_m > f_{m\text{max}}.
\end{cases} \quad (21)$$

Here $f_m$ represents the $m$th objective function value related to the Pareto-optimal solution, $m = 1, 2, 3$, $f_{m\text{min}}$ and $f_{m\text{max}}$ are minimum and maximum values of $f_m$, respectively, and $\mu_m$ is the membership value of objective function $f_m$. The multi-objective optimization in this study can be transformed into minimization of all objective functions. Thus, $f_m$ will be smaller in the whole Pareto-optimal membership value.

The decision-maker’s judgment about the importance of the three objectives (economic, social and ecological) is transformed into a quantitative weight coefficient by a binary dominance matrix to determine the optimal operation scheme. After obtaining the weight $w_m$ of each objective function, equation (22) is adopted to rank the performance of each optimal solution within the Pareto solution set:

$$u_N = \sum_{m=1}^{3} \mu_m \times w_m \quad (22)$$

where $u_N$ represents the score of the $N$th Pareto-optimal solution and $N$ is the number of optimal solutions in the Pareto solution set.

### 3.4. Performance evaluation indices

Reservoir management needs to meet the water demands of all stakeholders. It is possible to evaluate the performance between the developed MOGA and the MOEA used in this study for water allocation through various indices [34, 36]. In our experimental studies, three widely used performance metrics, the volumetric reliability index [20], resiliency index [20] and vulnerability index [51], are selected to assess the reliability and stability of solutions simultaneously.

#### 3.4.1. Reliability index

The indices for water system reliability are defined such that the reservoir or water system should not violate the water demands of water users. It can be expressed as the mean ratio of discharged water to the demands [34]:

$$RV^i = \frac{1}{T} \sum_{t=1}^{T} \left( \frac{X_{\text{supplied},t}}{X_{\text{demand},t}} \right) \quad (23)$$

where $RV^i$ is the volumetric reliability index, $X_{\text{demand},t}$ and $X_{\text{supplied},t}$ represent the water demand and water supplied for the $i$th stakeholder during the $t$th period (m$^3$), respectively, and $T$ implies the total number of schedule periods.

#### 3.4.2. Resiliency index

The resiliency index indicates the ratio of the system resiliency after the failure periods (failure to satisfy water demands) to desirable periods [34].
Re = \frac{\text{No. of times } (D^{i}_t = 0 \text{ follows } D^{i}_t > 0)}{\text{No. of times } (D^{i}_t > 0)}

\begin{equation}
D^{i}_t = \begin{cases} 
X^{i}_{\text{demand}, t} - X^{i}_{\text{supplied}, t} & \text{if } X^{i}_{\text{demand}, t} > X^{i}_{\text{supplied}, t} \\
0 & \text{if } X^{i}_{\text{demand}, t} \leq X^{i}_{\text{supplied}, t}
\end{cases}
\end{equation}

where Re is the resiliency index.

3.4.3. Vulnerability index

The vulnerability index examines the severity of failure events, which can be expressed as the mean water deficit in each failure period [59].

\[
V_u = \frac{\sum_{t=1}^{T} D^{i}_t}{\text{No. of times } (D^{i}_t > 0)}
\]

where Vu is the vulnerability index (m³). The reservoir system will give a more desirable performance with larger values for the reliability and resiliency indices and a smaller value for the vulnerability index.

4. Results

4.1. Nash equilibrium scheduling

The guarantee rates with 30%, 50%, 80% and annual natural inflow data of the TGR from 2003 to 2016 were implemented by a statistical analysis to select three hydrological years to trigger the model: a wet year, 2014; a normal year, 2010; and a dry year, 2013. The 10-day inflows for the three typical years are shown in figure 3.

By taking the wet year as an example, the ranges of Nash equilibrium regarding economic objective $F$, social objective $S$ and environmental objective $E$ are from 947.74 to 949.10 (10⁶ kW h), from 425.84 to 431.89 (10⁸ m³) and from 424.86 to 460.97 (10⁸ m³), respectively, as shown in table 2.

Table 3 shows that the Nash equilibrium of the economic objective $F$ is 898.80 (10⁶ kW h), and the Nash equilibrium ranges from 392.96 to 393.27 (10⁹ m³) for the social objective $S$ and from 180.10 to 198.27 (10⁶ m³) for the environmental objective $E$ in a normal year. In a dry year, the Nash equilibrium ranges from 799.60 to 799.63 (10⁸ kWh) for the economic objective $F$, from 356.27 to 356.75 (10⁵ m³) for the social objective $S$ and from 391.87 to 392.83 (10⁸ m³) for the environmental objective $E$, respectively, as shown in table 4.

From tables 2–4 it is clear that the economic objective $F$ and social objective $S$ exhibit a strong competitive relationship. With $S$ increasing, $F$ increases when the environmental objective $E$ is set as a constant. However, the economic objective $F$ shows weak conflicts with the environmental objective $E$; as $F$ increases, $E$ decreases a little when the social objective $S$ is set as a constant. The social objective $S$ has strong competitiveness with the environmental objective $E$. When the economic objective $F$ is set as a constant, a reduction in $E$ will lead to an increase in $S$. The Nash equilibrium scheduling schemes for the wet, normal and dry years are shown in figure 4. Compared with the normal and dry years, the largest reservoir inflow gives rise to the largest payoffs for the three stakeholders in the wet year. In the dry year, a comparatively narrow game range may help stakeholders feel more comfortable in making tough decisions.

4.2. Sensitivity analysis

The sensitivity is indicated by calculating the hypervolume (HV) metric that represents the diversity and convergence of solutions according to each parameter sampled in its full feasible parameter space [42]. It is stated that the HV metric with respect to the number of function evaluations (NFEs) and population size (Pop) can visualize the efficiency and ease-of-use of the algorithm [27]. Hence, sensitivity of the MOEA/D-DE is analyzed according to the HV metric with a full set of NFE and Pop sampling. The approximation set obtained by MOEA/D-DE will be closer to the Pareto frontier with a larger HV value; thus, if the value of HV against the values of NFEs and Pop reaches its maximum, these parameter values are then considered as the best parameters to use in the optimization process. Furthermore, the wet year is selected as a representative year to conduct sensitivity analysis. The sensitivity analysis of HV metric values calculated by the MOEA/D-DE can be seen in appendix A (available online at stacks.iop.org/ERL/16/085007/mmedia). For example, if Pop is 200, the best value of HV is obtained with a NFE of 80. Also, the minimum Pop of 800 and the minimum NFE of 60 can give the best value of HV. The detailed computational process for HV can be seen in appendix B. The parameter ranges and corresponding default values for MOEA/D-DE are shown in appendix C.

4.3. Optimization scheme

According to the MOEA, we can obtain a set of Pareto alternative schemes for the multi-objective ecological
reservoir operation model. In order to direct the operation of the reservoir, we can couple the fuzzy membership function and AHP to recognize the optimal operational scheme. Using AHP, the weight of objectives was constructed. Then the performance of each Pareto-optimal solution can be ultimately assessed by multiplying the weights by the membership value of each objective and taking the total sum. In the three typical hydrological years, the Pareto-optimal solution with the maximum comprehensive performance

| Round # | Expected goal | Annual power generation (F) (10^3 kWh) | Deficient and excessive socio-economic water demand (S) (10^3 m^3) | Deficient and excessive ecological water demand (E) (10^3 m^3) |
|---------|---------------|----------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Initial | —             | —                                      | —                                                            | —                                                            |
| #0-1    | —             | 955.91                                 | 427.33                                                       | 494.82                                                       |
| #0-2    | —             | 931.77                                 | 424.65                                                       | 463.49                                                       |
| #0-3    | —             | 932.99                                 | 424.66                                                       | 431.89                                                       |
| First bargaining | #1-1 | $E^\text{B} = 954.27$ | 953.70 | 424.89 | 437.71 |
|         | #1-2 | $S^\text{B} = 424.89$ | 954.55 | 425.11 | 427.55 |
|         | #1-3 | $E^\text{B} = 437.71$ | 954.29 | 424.87 | 443.16 |
| Second bargaining | #2-1 | $E^\text{B} = 952.64$ | 952.38 | 424.98 | 443.46 |
|         | #2-2 | $S^\text{B} = 425.13$ | 952.64 | 425.22 | 443.07 |
|         | #2-3 | $E^\text{B} = 443.53$ | 952.64 | 424.90 | 443.66 |
| Third bargaining | #3-1 | $E^\text{B} = 951.01$ | 950.83 | 425.12 | 449.33 |
|         | #3-2 | $S^\text{B} = 425.36$ | 951.07 | 425.38 | 447.26 |
|         | #3-3 | $E^\text{B} = 449.34$ | 951.01 | 425.04 | 450.55 |
| Fourth bargaining | #4-1 | $E^\text{B} = 949.37$ | 949.32 | 425.14 | 455.15 |
|         | #4-2 | $S^\text{B} = 425.60$ | 949.37 | 425.69 | 450.83 |
|         | #4-3 | $E^\text{B} = 455.15$ | 949.37 | 425.34 | 455.42 |
| Fifth bargaining | #5-1 | $E^\text{B} = 947.74$ | 949.56 | 425.31 | 460.96 |
|         | #5-2 | $S^\text{B} = 425.84$ | 947.82 | 424.65 | 446.45 |
|         | #5-3 | $E^\text{B} = 460.97$ | 949.10 | 424.86 | 431.89 |

| Round # | Expected goal | Annual power generation (F) (10^3 kWh) | Deficient and excessive socio-economic water demand (S) (10^3 m^3) | Deficient and excessive ecological water demand (E) (10^3 m^3) |
|---------|---------------|----------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Initial | —             | —                                      | —                                                            | —                                                            |
| #0-1    | —             | 904.39                                 | 392.89                                                       | 234.09                                                       |
| #0-2    | —             | 888.75                                 | 392.25                                                       | 240.77                                                       |
| #0-3    | —             | 889.93                                 | 392.74                                                       | 176.25                                                       |
| First bargaining | #1-1 | $E^\text{B} = 902.99$ | 899.92 | 392.51 | 181.76 |
|         | #1-2 | $S^\text{B} = 392.51$ | 903.10 | 392.57 | 181.37 |
|         | #1-3 | $E^\text{B} = 181.76$ | 902.99 | 392.51 | 183.86 |
| Second bargaining | #2-1 | $E^\text{B} = 901.59$ | 901.11 | 392.66 | 187.26 |
|         | #2-2 | $S^\text{B} = 392.76$ | 901.62 | 392.79 | 187.23 |
|         | #2-3 | $E^\text{B} = 187.26$ | 901.59 | 392.76 | 187.88 |
| Third bargaining | #3-1 | $E^\text{B} = 900.20$ | 900.02 | 392.44 | 192.75 |
|         | #3-2 | $S^\text{B} = 393.02$ | 900.27 | 393.03 | 192.75 |
|         | #3-3 | $E^\text{B} = 192.77$ | 900.20 | 392.90 | 193.29 |
| Fourth bargaining | #4-1 | $E^\text{B} = 898.80$ | 899.68 | 392.44 | 198.24 |
|         | #4-2 | $S^\text{B} = 393.27$ | 898.81 | 392.44 | 198.27 |
|         | #4-3 | $E^\text{B} = 198.27$ | 898.80 | 392.96 | 180.10 |

Table 2. Results of the multi-objective game theory model in a wet year.

Table 3. Results of the multi-objective game theory model in a normal year.
Table 4. Results of the multi-objective game theory model in a dry year.

| Round #  | Expected goal | Annual power generation ($F$) (10^8 kWh) | Deficient and excessive socio-economic water demand ($S$) (10^9 m^3) | Deficient and excessive ecological water demand ($E$) (10^8 m^3) |
|----------|---------------|------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Initial  | —             | —                                        | —                                                            | —                                                            |
| #0-1     | —             | 805.37                                   | 358.15                                                       | 401.37                                                       |
| #0-2     | —             | 797.38                                   | 355.76                                                       | 401.15                                                       |
| #0-3     | —             | 799.30                                   | 356.09                                                       | 385.62                                                       |
| First bargaining | | | | |
| #1-1     | $F^{\text{goal}} = 803.93$ | 798.31                                   | 355.58                                                       | 384.11                                                       |
| #1-2     | $S^{\text{goal}} = 356.00$ | 803.97                                   | 357.65                                                       | 387.36                                                       |
| #1-3     | $E^{\text{goal}} = 387.42$ | 803.94                                   | 356.00                                                       | 387.49                                                       |
| Second bargaining | | | | |
| #2-1     | $F^{\text{goal}} = 802.48$ | 796.87                                   | 355.51                                                       | 386.20                                                       |
| #2-2     | $S^{\text{goal}} = 356.25$ | 803.37                                   | 357.92                                                       | 389.21                                                       |
| #2-3     | $E^{\text{goal}} = 389.22$ | 802.71                                   | 356.25                                                       | 389.45                                                       |
| Third bargaining | | | | |
| #3-1     | $F^{\text{goal}} = 801.05$ | 800.11                                   | 356.23                                                       | 391.02                                                       |
| #3-2     | $S^{\text{goal}} = 356.50$ | 802.65                                   | 357.23                                                       | 391.01                                                       |
| #3-3     | $E^{\text{goal}} = 391.02$ | 801.32                                   | 356.50                                                       | 394.78                                                       |
| Fourth bargaining | | | | |
| #4-1     | $F^{\text{goal}} = 799.60$ | 801.84                                   | 356.75                                                       | 392.62                                                       |
| #4-2     | $S^{\text{goal}} = 356.75$ | 800.59                                   | 356.74                                                       | 391.69                                                       |
| #4-3     | $E^{\text{goal}} = 392.83$ | 799.63                                   | 356.27                                                       | 391.87                                                       |

score is regarded as the optimal reservoir operation scheme.

To determine the relative importance of the three objectives (economic, social and ecological) pursued by different stakeholders in the MOEA/D-DE, a comparison matrix was established by assigning a value between 1 and 9 to represent the relative importance of a pair of objectives relative to each other [60], referring to the relevant existing literature [40, 61, 62], as follows: (a) large reservoirs with high power generation (economic benefits) more often cause disturbance of riverine ecosystems (ecological benefits); (b) the improvement in industrial and agricultural water usage guarantee levels could not provide full basic ecological river flow; (c) increased energy production (economic purpose) has little effect on flood control risk (social purpose). Hence, in this study, the water requirement for power generation is deemed to be the most important objective, followed by the ecological water demand and the socio-economic water demand. The comparison matrix and the weights corresponding to the three objective functions are shown in table 5.

Thereafter, we can obtain the optimal reservoir operation scheme sought by the multi-objective evolutionary algorithm in three hydrological years, as shown in figure 5.

5. Discussion

5.1. Operational results of different optimization strategies

In MOGM, the Nash equilibrium provides the baseline for the involved stakeholders to choose a feasible alternative. MOGM results can be compared with the optimized scheduling results obtained by MOEA/D-DE, as shown in figure 6, to analyze payoffs for the involved conflicted players. It is clear that the scheduling scheme obtained with MOGM increases annual hydropower generation and reduces the deficient and excessive socio-economic or ecological water demand. For the wet year, the annual hydropower generation increases by 0.73%, and the deficient and excessive ecological water demand decreases by 0.04%; for the normal year, the power generation increases by 0.79%, and the deficient and excessive ecological water demand decrease by 13.30%; and for the dry year, the hydropower generation increases by 1.10%, and the deficient and excessive socio-economic water demand decreases by 0.36%.
5.2. The water allocated to different objective demands

Table 6 shows the water allocated to different objective demands by the two algorithms in wet, normal and dry years, respectively. In the wet year, the RV value, based on the MOGM, representing the mean ratio of discharged water to social demands is equal to 2.46. The lowest index (1.21) is for the economic demands. This indicates that meeting the social water demands, based on the MOGM, is related to a higher probability of success. The RV for social demands by both MOGM and MOEA/D-DE is higher than that for the other two objective demands in the three hydrological years. This confirmed that the smallest weight for the social objective in AHP analysis is reasonable, because a greater volume of the social demand is provided than that of the economic and ecological demands by both algorithms. Also, compared with the MOEA/D-DE algorithm, the MOG gives a higher value of the RV index in any hydrological year, showing higher reliability of water supply.

In the wet year, the Vu values for economic and ecological demands, based on the MOGM, are equal to $13.11 \times 10^8$ and $13.32 \times 10^8$ m$^3$, respectively; while based on the MOEA/D-DE the respective values are $13.13 \times 10^8$ and $13.66 \times 10^8$ m$^3$. The same results can be seen for the other two hydrological years. This reveals that the severity of the failure events faced by the economic benefit stakeholder (the reservoir operator) is a little lower than that faced by the ecological benefit stakeholder (the catchment administrator), which is consistent with the results of AHP analysis; thus the weight of the economic objective is slightly higher than that of the ecological objective (0.4979 and 0.3669, respectively). It is also indicated that lower economic and ecological deficiencies are observed with the MOGM. The Re index of different water demands in table 6 shows that both MOGM and MOEA/D-DE meet ecological demands better than economic demands in the three hydrological years (e.g. in the wet year, Re = 0.67 and 0.33, respectively). In normal and dry years, Re values from the MOGM outperformed those of MOEA/D-DE in recovering from failures to provide the water demands of different sectors.

Moreover, the highest water demand comes from the economic sector. As table 6 shows, RV for the economic objective has a smaller value for both the algorithms than for the other two sectors in the three hydrological years. The economic objectives for annual hydropower generation in wet, normal and dry years were 949.10, 898.80 and $799.6 \times 10^8$ kWh, respectively, by the MOGM, while by the MOEA/D-DE the annual hydropower generation in the three hydrological years was 942.22, 891.77 and $790.90 \times 10^8$ kWh, respectively, indicating that the MOGM has a good performance for the other two objectives.

Comparison between the MOGM results and the optimization results obtained by the MOEA indicates that the Nash equilibrium solution is different from the Pareto optimal solution; Carraro et al [63] and Madani [15] also noted this phenomenon. The former model (MOGM) is based on the requirements of a single stakeholder; for example, for power generation operator, its strategy control equation is equation (12), rather than the overall goal of the whole system. In strategic games, each player’s main concern is to maximize his/her own interests. The MOGM supports a more realistic simulation of a stakeholder’s pursuit of his/her own maximum benefits and helps provide program managers with some planning strategies and policy insights. The MOEA focuses on maximization of the economic benefits of the system, the minimization of social impact or the minimization of ecological environment impact, and solves the problem as a single decision-making problem. In addition, the MOEA describes the reservoir operation and management problem from the perspective of optimization, and specifies the prior characteristics of maximum hydropower generation, minimum deficient and excessive socio-economic water demand and ecological water demand. However, this may be unfeasible and/or socially unacceptable, making it difficult to select strategies from multiple Pareto solutions that can satisfy all stakeholders.
Figure 6. Objective function values of operational schemes obtained with the MOGM and MOEA/D-DE in three typical hydrological years.

Table 6. Index values in allocation of water to different objective demands by the two algorithms in the three hydrological years.

| Demand      | Wet year | Normal year | Dry year |
|-------------|----------|-------------|----------|
|             | RV       | Vu (10^3 m^3) | Re       | RV       | Vu (10^3 m^3) | Re       | RV       | Vu (10^3 m^3) | Re       |
| MOGM        |          |              |          |          |              |          |          |              |          |
| Economic    | 1.21     | 13.11        | 0.33     | 1.06     | 4.51         | 0.38     | 1.03     | 17.68        | 0.24     |
| Social      | 2.46     | NaN          | NaN      | 2.26     | 8.07         | 1.00     | 2.10     | 2.69          | NaN      |
| Ecological  | 1.50     | 13.32        | 0.67     | 1.31     | 19.97        | 0.50     | 1.30     | 26.97        | 0.33     |
| MOEA/D-DE   |          |              |          |          |              |          |          |              |          |
| Economic    | 1.20     | 13.13        | 0.33     | 1.05     | 4.60         | 0.33     | 1.03     | 19.36        | 0.21     |
| Social      | 2.46     | NaN          | NaN      | 2.26     | 7.47         | 1.00     | 2.09     | NaN          | 1.00     |
| Ecological  | 1.49     | 13.66        | 0.67     | 1.30     | 20.33        | 0.50     | 1.29     | 26.94        | 0.33     |

NaN means the water supply can satisfy the water demands, with no failure periods.

In contrast, the MOGM applies a non-cooperative game framework to help water resources planning managers find compromises acceptable to economic, social and ecological interests.

Multi-objective optimization methods provide many different Pareto optimal solution sets, but these solutions can only be adopted when the decision-maker has no prior bias against the economic, social and ecological interests of stakeholders. On the other hand, with the MOGM Nash equilibrium can be reached after several rounds of games in which players focus on their own goals. Additionally, it is much easier for stakeholders to balance economic, social and ecological interests within a relatively narrow range of choices.

5.3. The multi-objective game scheduling scheme for comprehensive ecological flow demands

In order to further illustrate the improved results with the MOGM for the ecological problems that may occur in the middle and lower reaches of the Yangtze River, the optimized outflow obtained by the MOGM was compared with the actual runoff process measured at the TGR outflow section and the comprehensive ecological flow requirement for each hydrological year (figure 7).

As can be seen from figure 7, in the three typical hydrological years the 10-day released discharges of the TGR allocated by the MOGM and the actual measured flow meet the appropriate range for the ecological flow demand, except for January to April and September to October. From January to March, we note that the actual measured flow is higher than the upper bound of the comprehensive ecological flow demand, while the allocated discharges are all below the actual measured flow. This is because the main scheduling task is to maintain the natural hydrological regime in this period. Constrained by the water balance equation, MOGM increased the discharge in April to empty the storage for the upcoming flood season.

In May, the TGR enters into the pre-flood falling stage as the inflow begins to increase gradually. As can be seen from figure 7, the outputs of the MOGM
Figure 7. Suitable ecological flow, MOGM results and actual flow monitored at the outflow section of the Three Gorges Reservoir in three typical hydrological years: (a) a wet year, (b) a normal year, (c) a dry year.

scheme in May are higher than the measured flow in the three typical years. This is due to the artificial flood peaks operated for the reproduction of FMCC in this period [46].

The critical period for the supersaturation of dissolved gas downstream of the Three Gorges Dam is from June to July. During this period, flood control is also an important task for the TGR. According to the present scheduling scheme of the TGR, the release flow will be consistent with the incoming flow if the incoming flow does not exceed 35,000 m$^3$s$^{-1}$. When the inflow of the reservoir reaches 35,000 m$^3$s$^{-1}$ (and may continue to increase), flood control should be implemented to mitigate the economic losses of downstream regions [64]. The MOGM regulation presented in this study can control the water release within 30,000 m$^3$s$^{-1}$ during this period, especially in a normal year (figure 7(b)), with the aim of reducing the damage to eggs and juvenile fish caused by the supersaturation of dissolved gas. Also, this reservoir regulation can facilitate flood prevention.

The key ecological problems from August to October are maintenance of the natural hydrological regime of the downstream channels and the salinity required for estuarine indicator species. The flood control operation of the TGR is implemented from early to mid August, thus the allocated flow is nearly the same as the measured values during this period. From late August to early September, the TGR begins post-flood impoundment, and from mid September to October, the TGR starts formal impoundment until the water level increases to 175 m. In order to maintain the natural hydrological regime in this period, the MOGM scheduling scheme increases the flow rate at certain storage periods to reduce the ecological water shortage.

For all three typical years, we note that the flows allocated by the MOGM in November and December are higher than the measured water releases, which can improve the reservoir power generation efficiency while not increasing the loss of ecological benefits.

Moreover, figure 7 shows that when the actual measured flow is lower than the lower bound of the ecological flow demand, the allocated flow is higher than the actual monitored flow, indicating that the planned discharge scheme considering the multi-agent benefits is closer to the upper and lower boundary values of the appropriate ecological flow than the actual monitored value. The optimal operational schemes may not always satisfy ecological flow thresholds because the ecological objective function is defined based on minimizing deviation of released water and the comprehensive ecological flow demands [34]. As a result, there is a large amount
of redundancy in ecological water demand which is generated in a wet year, while there is a large ecological water shortage in the dry year. Consequently, the volume of deficient and excessive ecological flow demand seems to be double the volume of socio-economic water demand in wet and dry years in Figure 6.

Compared with the actual scheduling scheme, despite the multi-objective game scheduling scheme increasing the deficient and excessive ecological water demands by 12.66% in wet years, it could decrease these by 38.15% and 12.44% in normal and dry years, respectively. The reason for the increase in the deficient and excessive ecological water demands in the wet year is that emergency scheduling is added to the actual scheduling scheme for flood control [65]. Therefore, in addition to considering the conflicts between different stakeholders with different scheduling objectives, the conflicts between emergency scheduling and real-time scheduling should also be considered in follow-up research.

6. Conclusion

This study constructs a multi-objective ecological operations model of the TGR, and the ecological objective for considering the comprehensive ecological flow demand of the middle and lower reaches of the Yangtze River is provided. Then a MOGM is proposed to solve transboundary water conflicts involved in economic, social and environmental issues. In addition, the scheduling schemes obtained by the MOGM and MOEA are compared and discussed.

The results of the game theory model reflect the complex balance among economic, social and ecological benefits. Compared with the scheduling scheme obtained with the MOEA/D-DE, the Nash equilibrium solution obtained with the MOGM increased annual hydropower generation and reduced the deficient and excessive socio-economic water demand or ecological water demand in the three typical hydrological years in which competition and compromise among triple stakeholders were fully considered. The values of different evaluation indices also revealed the superiority of the MOGM. For example, the MOGM has higher values of the reliability index than the MOEA/D-DE in the three hydrological years, indicating that it has a higher probability of success. The values of the vulnerability index for economic and ecological sectors are all lower than those obtained with the MOEA/D-DE in the wet and normal years. Also, compared with the actual scheduling scheme, the multi-objective game scheduling scheme can effectively reduce the deficient and excessive ecological water demands by 38.15% and 12.44% in normal and dry years, respectively. Moreover, in the three hydrological years, the reliability index of social demands obtained with the MOGM is higher than that of the other two objective demands, indicating that a greater volume of the social demand is provided than that of economic and ecological demands. The resiliency index of different water demands shows that the MOGM meets ecological demands better than economic demands in the three hydrological years.

The study is expected to develop a multi-objective ecological operation model that can comprehensively alleviate the key ecological problems occurring downstream of the reservoir site, provide an effective optimal method for solving transboundary water conflicts and to expand the application of game theory in reservoir operation management. Future research will focus on developing nested multi-objective operation models with different time steps to carry out a short-term real-time operation scheme and using a game theory approach for treating transboundary water conflicts with different time steps and conflicts between emergency scheduling and real-time scheduling.

Data availability statement

Data can be obtained by request to the author Rui Zhao (ruizhao@swjtu.edu.cn).

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare no competing financial interest in this work.

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