Multi-objective optimization of the Three Gorges cascaded reservoirs operation with emphasis on electricity generation and ecological requirements
Yue Zhao, Huan Ying and Jianzhong Zhou

ABSTRACT
The operations of reservoirs produce enormous economic and social benefits but also impact species composition and habitat distribution of the riverine ecosystem. Hence, the realization of conservation and restoration of the ecosystem calls for reservoir reoperation. It is a widespread consensus that providing suitable ecological flow (SEF) for ecosystems is a useful way to cushion adverse effects. In contrast to the conventional methods that take a minimum ecological flow as a constraint, studies have been conducted to establish multi-objective operation models with an ecological objective recently. This paper considers two cascaded reservoirs: the Three Gorges Project (TGP) and the Gezhouba Dam in the middle Yangtze River. By concentrating on urgent ecological problems such as the reproduction of four major species of Chinese carp and the propagation of Chinese sturgeon, a series of monthly SEF was synthesized. Afterward, a long-term multi-objective optimization model that maximizes power generation and minimizes the water volume that violates ecosystem water requirements was developed to study the relationship between the two objectives. The non-dominated sorting genetic algorithm II method was applied to solve the proposed model. The optimized results show that according to the present water control operating regulations, the monthly amount of released water of TGP can be sufficient for ecosystem requirements except in October. The ecological model is better in improving the river ecosystem, but at the expense of power generation loss. Moreover, this method provides a set of operational non-dominated schemes between the target objectives for decision-makers to select and could be useful for water resource management of reservoirs.

Key words | ecological water requirement, multi-objective optimization, NSGA II, ecological reservoir operation, Three Gorges cascade

INTRODUCTION
The construction and operation of reservoirs have played a very considerable role in flood control, electricity generation, water supply and navigation (Wu et al. 2012). Meanwhile, their adverse effects on river ecosystems, such as wetland degradation and the sharp reduction of fish stocks, have been brought about due to the alternations of natural flow and river habitat fragmentation. Conventional reservoir operation predominantly focuses on maximizing social-economic benefits (Labadie 2004).

In the meantime, riverine ecosystem problems get surprisingly little attention, so that the structure and function of river ecosystems have degenerated gradually. To avoid or at least mitigate the negative impacts of dams on river ecosystems, it is imperative to adjust the dispatching mode of reservoirs.

It has been demonstrated that the hydrological regime is the decisive element in maintaining the integrity of the river ecosystem, and the severe disturbance to the natural
hydrological regime is considered to be the primary cause of ecosystem deterioration (Whiting 2002). Hence, ecological requirements are typically addressed by meeting minimum instream flow incorporated as a certain constraint in traditional reservoir operations (Castelletti et al. 2008). However, because of the complexity of ecosystems, it is difficult to determine the ecological flow reasonably and objectively, while considering aquatic species as much as possible. As a consequence, for the harmonious progress of both sustainable development and human interests, optimization of reservoir operation with a constraint or an objective of ecological water requirements (EWR) has been developed to reconcile these conflicting demands in the past decade.

Bednarek & Hart (2005) assessed the impacts of modifying dam operations by increasing the minimum flows on physico-chemical conditions and benthic macroinvertebrate assemblages. Nevertheless, Richter et al. (1997) indicated that the discharge requirement of a river ecosystem was far more complex than the representation of minimum ecological flow. Therefore, it is argued that ecological flow should change seasonally and the concept of alternations between regulated discharge and natural flow is recommended to evaluate the impacts on river ecosystems (Poff et al. 1997). Dittmann et al. (2009) evaluated the degree to which a natural flow regime was modified by reservoir operations using the indicators of hydrologic alteration (IHA) and range of variability approach (RVA) for a multi-objective reservoir operation with emphasis on flood control and ecology. Chen et al. (2012) used an index of flow alteration proposed to quantify the difference between the regulated hydrological regime and the natural hydrological regime as an additional constraint in the model on reservoir safety. These encouraging studies provide more rational methods for quantifying ecosystem requirements. However, there is little work that attempts to consider crucial aquatic species and pressing ecological problems synchronously.

Following the increasing concerns for the health of aquatic ecosystems influenced by reservoirs, the aim is to present an innovative method which concentrates on key aquatic species and urgent ecological concerns. Taking the Three Gorges cascade as a case study, the degree of violation of suitable ecological flow (SEF), which is obtained by synthesizing various kinds of ecological requirements, is set as an objective in the multi-objective optimization model. By using a multi-objective genetic algorithm (MOGA), we study an optimal trade-off between electricity generation and EWR, and analyze the practicability and effectiveness of the proposed model.

**CASE STUDY**

The Three Gorges cascade is located at the middle reaches of the Yangtze River (Yichang City, Hubei province, China). The cascade consists of a diversion-type reservoir (the Three Gorges Project, TGP) and a runoff hydroelectric station (Gezhouba Dam). A sketch map of the studied cascade is presented in Figure 1. The average annual rainfall over the catchment is 1,203.7 mm, with 75% of the rainfall occurring during the flood season (June–September) (Qin et al. 2010). Owing to the strong seasonality of rainfall, the inflow discharges of TGP have significant seasonal variation. The foremost task for TGP is to provide flood control for its downstream areas in the flood season. In addition to this, TGP also plays a huge role in power generation, water supply and navigation. The Gezhouba project is located 38 km downstream of TGP. It is an anti-regulating and runoff hydroelectric station, and has little influence on the released discharge of TGP, so that the ability to regulate the hydrologic process of the downstream river can be ignored. Moreover, there are no tributaries flowing into the Yangtze River between TGP and Gezhouba Dam. As a consequence, we can assume that the released discharge of Gezhouba Dam is equal to that of TGP. The main parameters of TGP and Gezhouba Dam are displayed in Table 1.

Since the impoundment of TGP began in 2003, the natural water flow has been radically changed. In the lower regime, for power generation, the flood peak from upstream is blocked to be released smoothly so that there is less fluctuation of water level. Moreover, in the impoundment period, the conflict between water consumption and water storage has emerged gradually. These drastic alterations significantly affect the health of the ecosystem and cause lots of ecological problems such as the reduction in four major species of Chinese carp (FMCC) and Chinese sturgeon.
However, the previous operation of the Three Gorges cascade was predominately oriented to the social and economic benefits, while the protection of the river ecosystem earned little attention from river managers. Nowadays, people are aware of the importance of ecosystem health, which is the fundamental factor for sustainable utilization and management of water resources. Therefore, it is essential to change the concept of operation by considering the water requirements of the ecosystem.

**Table 1 | Main characteristics of the Three Gorges reservoir and Gezhouba project**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>TGP</th>
<th>Gezhouba Dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulation ability</td>
<td>Seasonal regulation</td>
<td>Daily regulation</td>
</tr>
<tr>
<td>Released discharge range (m$^3$/s)</td>
<td>[4,500, 98,800]</td>
<td>[4,500, 86,000]</td>
</tr>
<tr>
<td>Dead water level (m)</td>
<td>135</td>
<td>63</td>
</tr>
<tr>
<td>Electricity generation coefficient</td>
<td>8.8</td>
<td>8.5</td>
</tr>
<tr>
<td>Upriver water level range (m)</td>
<td>[145, 175]</td>
<td>[63, 66.5]</td>
</tr>
<tr>
<td>Installed capacity of plant (MW)</td>
<td>22,500</td>
<td>2,715</td>
</tr>
<tr>
<td>Firm output of plant (MW)</td>
<td>4,990</td>
<td>768</td>
</tr>
<tr>
<td>Water head range (m)</td>
<td>[61, 113]</td>
<td>[6, 27.8]</td>
</tr>
</tbody>
</table>

**EWR IN THE MIDDLE YANGTZE RIVER**

**EWR for river ecosystems**

The Yangtze River is a seasonal stream, and there is a tremendous divergence in its runoff between the flood and dry seasons. The Tennant method, which is applicable for rivers with stable discharge, is not appropriate for computing the ecological flow of the Yangtze River. In this study, a hydrological method that synthesizes a monthly frequency computation method (Li et al. 2007) and RVA was applied (Gu 2011). This method takes the 25th and 75th percentile values of the monthly average discharge series as the lower and upper bounds of SEF. According to the runoff data of Yichang hydrological station, located 5.9 km downstream from Gezhouba Dam, from 1882 to 2003, the range of suitable monthly ecological flow was obtained (Figure 2). It is considered that the ecosystem will be adversely affected when the release discharge of TGP is outside that range.

**Reproduction of the FMCC**

The FMCC denotes the artificially reared black carp, grass carp, silver carp and bighead carp, which are the important commercial fish species in the Yangtze River. Their main
Spawning grounds are situated in the middle reaches of the Yangtze River. However, because of the TGP impoundment, some spawning sites in the Three Gorges reservoir have been lost, and the water temperature in the spawning grounds reaches 18°C, which is the lowest temperature for FMCC spawning, 10 days later at the end of April. In addition, the flood peak, which is an imperative stimulation for spawning, is blocked to be released smoothly for power generation. Under these negative effects, egg production of FMCC has gradually declined over recent years according to field investigation (Yi et al. 2013). To ameliorate the spawning conditions, the SEF process containing ‘artificial flood peak’ is represented.

May and June are the fastigium of FMCC propagation. TGP maintains a water level at the flood limit of 145 m in June, and the natural flow process is slightly changed consequently. In this study, the spontaneous flow process in May was analyzed as divided into environmental flow components (EFCs) by using the EFCs calculation algorithm in the IHA software. EFCs contain five events: extreme low flow, low flow, high flow pulse, small flood, and large flood. This delineation of EFCs is based on the realization by ecologists that river hydrographs can be divided into a repeating set of hydrographic patterns that are ecologically relevant. More specific details about the EFCs calculation algorithm are provided in the user manual for the IHA software (TNC 2005).

First, we classified the historical daily flow series into the environmental flow components by the EFCs calculation algorithm; next, the hydrologic parameters of each event within a year were analyzed, and then repeated in all historical years; and lastly, the statistical result of these parameters for each environmental flow event was obtained. The result shows that the flow process of FMCC reproduction is composed of low flow event and high flow pulse event (Zhao et al. 2012b). Based on the RVA framework, the 25th, 50th and 75th percentile values of each hydrologic parameter of these two events were obtained (Table 2).

![Figure 2](image)  Range of monthly SEF.

**Table 2 | Result of hydrologic parameters of each event in May (ignore the extreme low flow event)**

<table>
<thead>
<tr>
<th>EFC type</th>
<th>Hydrologic parameters</th>
<th>25th percentile value</th>
<th>50th percentile value</th>
<th>75th percentile value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flow</td>
<td>Duration (days)</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Minimum (m³/s)</td>
<td>7,645</td>
<td>9,275</td>
<td>11,200</td>
</tr>
<tr>
<td></td>
<td>Maximum (m³/s)</td>
<td>8,700</td>
<td>11,100</td>
<td>13,275</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Start Julian date</td>
<td>134</td>
<td>138</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>Rise rate (m³/s/d)</td>
<td>168</td>
<td>330</td>
<td>470</td>
</tr>
<tr>
<td></td>
<td>Fall rate (m³/s/d)</td>
<td>250</td>
<td>360</td>
<td>565</td>
</tr>
<tr>
<td>High flow pulse</td>
<td>Duration (days)</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Minimum (m³/s)</td>
<td>8,400</td>
<td>10,100</td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td>Maximum (m³/s)</td>
<td>13,100</td>
<td>15,400</td>
<td>17,900</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Start Julian date</td>
<td>133</td>
<td>137</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>Rise rate (m³/s/d)</td>
<td>1,250</td>
<td>1,500</td>
<td>1,990</td>
</tr>
<tr>
<td></td>
<td>Fall rate (m³/s/d)</td>
<td>800</td>
<td>1,080</td>
<td>1,350</td>
</tr>
<tr>
<td></td>
<td>Time interval (days)</td>
<td>9</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Rise duration (days)</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Fall duration (days)</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
Afterward, these parameters were used to determine the suitable flow process for FMCC spawning. The 25th and 75th percentile values of minimum and maximum value, rise and fall rate were used to rebuild minimum and maximum flow process, respectively; meanwhile, the others were set to the 50th percentile values. In rebuilding process, the priority was given to the rise rate and the duration of high flow pulse, which are the sufficient conditions for FMCC propagation, and other parameters could be slightly changed. As shown in Figure 3, three artificial flood peaks exist in the entire flow process to stimulate the propagation of the FMCC. In addition, the lower and upper bounds of the SEF process in May are clearly displayed. When averaging the daily flow rates in May, the range of average monthly SEF is from 11,800 to 16,600 m³/s.

**Spawning of the Chinese sturgeon**

The Chinese sturgeon, which is endangered and classified as a first-grade state protection animal in China, used historically to propagate in the lower reaches of Jinsha River and upper reaches of the Yangtze River from mid-October to early November. However, the migratory route was blocked after damming by the Gezhouba water conservancy pivot in 1981, and the fish was forced to spawn in the new spawning ground mainly distributed in the 4-km-long mainstream that is less than 1% of the historical site from Gezhouba Dam to Miaozui in the middle Yangtze River (Wei et al. 1998). As a result, the population quantity of Chinese sturgeon fell gradually from then on. After reservoir filling and power generation of the TGP in 2003, the monthly average discharge for October decreased from 17,290 m³/s (period 1981–2003) to 13,290 m³/s (period 2003–2008) and the mean flow for November slightly decreased. The noticeable decline of the discharge in October had more adverse effects on the natural reproduction of Chinese sturgeon.

To acquire the ecological water requirement for Chinese sturgeon propagation, a fuzzy logic-based eco-hydrodynamic model using instream flow incremental methodology (Bovee 1982), which is established by coupling a two-dimensional hydrodynamic model and a fish habitat module, was applied. This research was accomplished in previous studies, and more specific details about the procedure have been provided by Zhao et al. (2013) and Zhou et al. (2014). Weighted usable area (WUA), which is a mathematical variable in habitat models, is assumed to be associated positively with fish biomass. The relationship between WUA and discharge at the Chinese sturgeon spawning site is depicted in Figure 4. After the combination of finding the curve inflection points and obtaining expert advice (Yang et al. 2010), it is suggested that the ecological water requirement for Chinese sturgeon spawning is from 10,000 to 17,000 m³/s in spawning periods.

**Saline water intrusion at the Yangtze estuary**

Saline water intrusion in the Yangtze estuary usually occurs from November to the following April. In this period, the
decline of runoff causes the seawater to flow backward, and the security of the water supply in Shanghai is seriously affected. The upper stream inflow influenced by TGP operation is one of the decisive factors for saline water intrusion. Generally, the discharge of the Datong hydrological station, which can represent the water flow of the Yangtze River entering the sea, is used as the indicator of saline water intrusion control. Chen et al. (2011) used a statistical model and combined it with the calculation results of a mathematical model of multi-salinity to determine the monthly critical flow process of Datong hydrometric station from October to the following April. Zhao et al. (2012a) comparatively analyzed the runoff variation tendency between Yichang and Datong hydrometric stations from October to the following April, and presented the runoff relationship during this period. Combining these two results, the monthly flow requirements at Yichang hydrometric station for controlling saline water intrusion were calculated and displayed (Table 3).

Dissolved gas supersaturation

Supersaturation of dissolved gas is due to a lot of air being involved in the reservoir releasing water when the water flows through the spillway to the stilling basin and downstream river. Generally, this phenomenon only occurs during flood periods, and its primary hazard is that it easily causes fish to suffer from ‘gas bubble disease’. Chen et al. (2009) established a mathematical model of dissolved oxygen to simulate and predict the evolution of the supersaturation of dissolved oxygen under different discharges in the middle Yangtze River. The result shows that when the outflow of TGP exceeds 30,000 m³/s, it will cause a peak of dissolved gas supersaturation. Hence, the released discharge of TGP should be less than 30,000 m³/s in flood seasons.

The integrated monthly EWR

Considering the water requirements above, the monthly SEF ranges at Yichang hydrological station were obtained (Table 4). In the process, the highest lower bound (LB) and lowest upper bound (UB) were selected to form the ecological flow range. If there is a conflict between two demands, first priority should be given to the propagation of FMCC and Chinese sturgeon. Second priority is given to the water requirements for river ecosystem and dissolved gas supersaturation. Finally, we consider the saline water intrusion because it occurs too far away from TGP.

Table 3 | Average runoff and water requirements for controlling saline water intrusion at Yichang and Datong stations from October to the following April

<table>
<thead>
<tr>
<th>Month</th>
<th>Average runoff at Datong station (m³/s)</th>
<th>Average runoff at Yichang station (m³/s)</th>
<th>Proportion (%)</th>
<th>Water requirement at Datong (m³/s)</th>
<th>Water requirement at Yichang (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>32,690</td>
<td>17,730</td>
<td>54.2</td>
<td>16,000</td>
<td>8,672</td>
</tr>
<tr>
<td>November</td>
<td>22,840</td>
<td>9,970</td>
<td>43.7</td>
<td>15,000</td>
<td>6,555</td>
</tr>
<tr>
<td>December</td>
<td>14,240</td>
<td>5,830</td>
<td>40.9</td>
<td>13,500</td>
<td>5,521</td>
</tr>
<tr>
<td>January</td>
<td>10,960</td>
<td>4,290</td>
<td>39.1</td>
<td>12,000</td>
<td>4,692</td>
</tr>
<tr>
<td>February</td>
<td>11,750</td>
<td>3,860</td>
<td>32.9</td>
<td>12,000</td>
<td>3,948</td>
</tr>
<tr>
<td>March</td>
<td>16,160</td>
<td>4,390</td>
<td>27.2</td>
<td>14,000</td>
<td>3,808</td>
</tr>
<tr>
<td>April</td>
<td>23,800</td>
<td>6,640</td>
<td>27.9</td>
<td>18,000</td>
<td>5,022</td>
</tr>
</tbody>
</table>

Note: the proportion denotes the percentage of average runoff at Yichang station in that at Datong station.

PROBLEM FORMULATION

Objective function

In this paper, the multi-objective ecological operation comprises two objective functions: (1) to maximize the total power generation of the Three Gorges cascade during dispatching periods, while satisfying all kinds of constraints; and (2) to release water from the Three Gorges reservoir in a manner that meets the EWR as far as possible. In this study, the dispatching period is set to be 1 year.
Mathematically, the objective functions are described as follows:

(1) The economic benefit objective function

\[ E = \text{Max} \sum_{t=1}^{T} \sum_{i=1}^{N} A_i \cdot Q_{i,t} \cdot H_{i,t} \cdot \Delta t \]  

(1)

where \( E \) is the total power generation of the cascade hydropower system (kWh); \( T \) denotes the whole schedule period count within a year, \( T = 12; \) \( N \) is the number of hydro stations in the Three Gorges cascade, \( N = 2; \) \( A_i \) indicates the power generation coefficient of reservoir \( i \) (N/m³); \( Q_{i,t} \) and \( H_{i,t} \) are the turbine release water discharges for power generation (m³/s) and average head (m) of reservoir \( i \) at time period \( t \), respectively; \( \Delta t \) is the length of one dispatching period.

(2) The ecological benefit objective function

The minimum shortage and excess of ecological water requirement in the downstream watercourse is considered as the target function:

\[ F = \text{Min} \sum_{t=1}^{T} \sum_{i=1}^{N} (WV_{i,t}) \cdot (WV_{i,t}) = \]

\[ \begin{cases} (EWR_{i,t}^\text{min} - (Q_{i,t} + S_{i,t})) \cdot \Delta t & \text{if} \quad Q_{i,t} + S_{i,t} < EWR_{i,t}^\text{min} \\ 0 & \text{if} \quad Q_{i,t} + S_{i,t} \in [EWR_{i,t}^\text{min}, EWR_{i,t}^\text{max}] \\ ((Q_{i,t} + S_{i,t}) - EWR_{i,t}^\text{max}) \cdot \Delta t & \text{if} \quad Q_{i,t} + S_{i,t} > EWR_{i,t}^\text{max} \end{cases} \]

\( \forall t \in T \)  

where \( WV_{i,t} \) is the shortage or excess of ecological water requirement in the downstream river channel of reservoir \( i \) at time period \( t \) (m³); \( EWR_{i,t}^\text{min} \) and \( EWR_{i,t}^\text{max} \) are the minimum and maximum eco-environment water requirements of the downstream water course (m³/s), respectively; \( S_{i,t} \) denotes the abandoned water of reservoir \( i \) at time period \( t \) (m³/s).

Constraints

The multi-objective optimization of the hydropower ecological schedule is subjected to the following constraints:

(1) Hydraulic connection

\[ I_{i,t} = Q_{i,t-1} + S_{i,t-1} + R_{i,t} \quad \forall t \in T \]

(3)

where \( I_{i,t} \) and \( R_{i,t} \) are total inflow rate (m³/s) and local inflow rate (m³/s) of hydro plant \( i \) in period \( t \), respectively. In this study, because of the long schedule period, the water transport delay is much shorter so that it is not considered for simplification in the practical calculation.

(2) Reservoir mass balance equation

\[ V_{i,t} = V_{i,t-1} + (I_{i,t-1} - Q_{i,t} - S_{i,t}) \cdot \Delta t \quad \forall t \in T \]

(4)
where $V_{i,t}$ is reservoir storage volume at the end of period $t$. Owing to the short distance between the two reservoirs of the Three Gorges cascade, natural leakage and evaporation of water can be neglected.

(3) Hydro plant power constraints

$$P_{i,t}^{\text{min}} \leq P_{i,t} \leq P_{i,t}^{\text{max}} \quad \forall t \in T$$

where $P_{i,t}^{\text{min}}$ and $P_{i,t}^{\text{max}}$ denote the minimum and maximum power generation of the $i$th hydro plant in the $t$th period, respectively.

(4) Reservoir water level limits

$$Z_{i,t}^{\text{min}} \leq Z_{i,t} \leq Z_{i,t}^{\text{max}} \quad \forall t \in T$$

$$Z_{i,\text{start}} = Z_{i,\text{end}}$$

where $Z_{i,t}^{\text{min}}$ and $Z_{i,t}^{\text{max}}$ are the minimum and maximum upriver water levels of reservoir $i$ in period $t$, respectively; $Z_{i,\text{start}}$ and $Z_{i,\text{end}}$ are the initial water level and terminal water level of the dispatching period.

(5) Hydro plant discharge rate constraints

$$Q_{i,t}^{\text{min}} \leq Q_{i,t} \leq Q_{i,t}^{\text{max}} \quad \forall t \in T$$

where $Q_{i,t}^{\text{min}}$ and $Q_{i,t}^{\text{max}}$ denote the lower and upper water discharge of the $i$th hydro plant in the $t$th period, respectively.

**Model solving by MOGA**

There are numerous techniques for solving reservoir multi-objective optimization models, such as dynamic programming, genetic algorithm and differential evolution algorithm (Tang & Luh 1995; Orero & Irving 1998; Sinha et al. 2003). The MOGA used in this study is the non-dominated sorting genetic algorithm II (NSGA II), which was first conceived by Deb et al. (2002). The algorithm uses population-based evolutionary algorithms in searching for the Pareto-optimal solutions of a multi-objective problem, which can be obtained in a single run (Shiau 2009). It has been demonstrated to have special advantages in reservoir management, and the capability of solving multi-objective optimization models for reservoir operation has been well tested (Reed et al. 2003; Prasad et al. 2004; Kim et al. 2006).

**LONG-TERM MULTI-OBJECTIVE OPTIMAL ECOLOGICAL OPERATION FOR THE THREE GORGES CASCADE USING NSGA II**

The details of the proposed NSGA II for dealing with long-term multi-objective optimal ecological operation for the Three Gorges cascade are introduced in this section.

**Individuals encoding strategy**

In this paper, every individual vector is expressed as a group of water levels as the decision variables for the convenience of handling constraints and calculating objective functions. Because of the intervals of the schedule periods, there are $D$ values of water levels in the hydro plants of the Three Gorges and Gezhouba Dam.

$$X = \begin{bmatrix} x_{0}^{0} & x_{0}^{1} & \cdots & x_{0}^{D} \\ x_{1}^{0} & x_{1}^{1} & \cdots & x_{1}^{D} \end{bmatrix}$$

where upper and lower rows denote the water levels of TGP and Gezhouba Dam, respectively.

**Dimensionless conversion of the objective values**

When calculating crowding distance, because of the different dimensions of the different objective function values that it is needed to sum, it is necessary to transform them into dimensionless quantities by the following equations:

$$E_1 = (E - E_{\text{min}})/(E_{\text{max}} - E_{\text{min}})$$

$$F_1 = (F - F_{\text{min}})/(F_{\text{max}} - F_{\text{min}})$$

in which $E_{\text{min}}$ and $E_{\text{max}}$ are the minimum and maximum total power generation in the current population, respectively; $F_{\text{min}}$ and $F_{\text{max}}$ are the minimum and maximum values of the ecological benefit objective function, respectively.
SIMULATION RESULTS AND DISCUSSION

The NSGA II was applied to deal with three typical hydrological conditions, corresponding to dry (70% water frequency), average (50% water frequency) and wet (30% water frequency) flow years (Figure 5). Figure 6 shows the Pareto fronts for these three typical years. In general, it can be seen that there is an inverse relationship between the power generation of the Three Gorges cascade and violation of EWR, which means that to improve the cascade’s power generation, the violative volume of downstream EWR will increase. Furthermore, the non-dominated solutions for the dry year distribute less evenly than those for the average year and wet year, which illustrates there is not enough regulative space to balance power efficiency and ecological benefit when water inflow is insufficient. Moreover, it is clear that minimum hydropower production increases as the total water inflow becomes larger. The maximum hydropower production is $1,072.68 \times 10^8$ kWh, $1,143.03 \times 10^8$ kWh and $1,206.34 \times 10^8$ kWh for the dry, average and wet years, respectively. The sum of the volume of water shortage and excess for downstream requirements has a different trend with water inflow increasing. It is smaller for the average year with a minimum value of $56.82 \times 10^8$ m$^3$ than those for other typical years, which means the reservoir operation has a smaller influence on the ecosystem in the average year.

The relations between the two objectives after normalization are shown in Figure 7. For the dry year, when the ecological objective increases from 0 to 0.95, power generation decreases from 1 to 0.36 at a steady rate. Upgrading the ecological objective from 0.95 to 1 incurs a sharp decline of power generation. For the average year, when the ecological objective increases from 0 to 0.1, power generation only decreases from 1 to 0.96. At this stage, the ecological objective improves at less cost of power generation loss. If the ecological objective continues to increase, power generation will decline at a sharper rate. For the wet year, when the ecological objective increases from 0 to 0.23, power generation only decreases from 1 to 0.88 gradually. Upgrading the ecological objective from 0.23 to 1 incurs a sharp decline of power generation. Therefore, the operation of TGP should be adjusted to gain higher ecological benefit at a lower loss in power generation.

Further, the schemes that have the maximum and minimum power generation for these three typical years are set as scheme 1 and scheme 30, respectively, to analyze the specific monthly discharge processes. The detailed discharge processes, outputs and water level processes of TGP of typical schemes (scheme 1 and scheme 30) are shown in Figures 8–10, respectively. For all the typical years, we can notice that the monthly released discharges
of the Three Gorges hydropower station from January to March are nearly the same, and they all exceed the upper limits of EWR. This is because the main scheduling task is to meet the minimum guaranteed output of 4,990 MW in this period. If the released discharges increase during this period, it can cause a decline of water head in the following months and decrease annual power generation. Meanwhile, it can also increase the water excess of the ecological demand so that the ecological objective becomes worse.

In April and May, the TGP enters into the pre-flood falling stage as the water inflow starts to increase gradually. For the dry year, as depicted in Figure 8(a), the average released flow during this period of scheme 1 is similar to that of scheme 30, and the discharges of both schemes can meet the ecological water demand. As can be seen from Figure 9(a), the outputs in April of the two schemes are still equal to the minimum guaranteed output, because the increase of the released discharge in April will lead to a decline of total power generation and cannot make the ecological objective better. For the average year, because of the
increase of water inflow and the water level demanded at the end of May, the reservoir discharges water in accordance with the minimum guaranteed output in April and will make the discharge exceed the upper limit of the ecological water demand for May. Hence, increasing the outflow for April makes the monthly discharge for May more suitable for the ecosystem, and improves the ecological objective at the expense of power generation loss, which is more evident for the wet year.

The flood season of the Three Gorges reservoir begins in June. During this season, flood control becomes the most important task for TGP. According to the present water control operating regulations of TGP, the reservoir starts to fill at flood recession in the middle of September, and the upstream water level of the dam cannot exceed 156 m at the end of the month. The reservoir water level then continuously rises to 175 m before November. In this study, the water level at the end of September is set as a range from 145 to 156 m. It can be seen in Figure 10, in flood season, that TGP maintains the water level at the flood limit level 145 m until the end of August so that the released discharge is equal to the water inflow, which makes the released flows of the two schemes the same. For the average and wet years, because of the abundant water inflow, the reservoir water level can reach 156 and 175 m at the end of September and November, respectively, without impacting on the health of the downstream river ecosystem. However, for the dry year, the upper water level at the end of September in scheme 1 reaches 156 m, which leads to water shortage for the river ecosystem. In scheme 30, the upper water level only rises to 150.8 m to meet the ecological water demand in September at the cost of power generation loss. In addition, released discharges of these two schemes can both provide enough water for Chinese sturgeon spawning in October. In the remaining two months, TGP maintains the high water head for power generation to achieve maximum economic benefits while the EWR can be met.

From what has been discussed above, to some extent the present operation of TGP changes the water distribution throughout the year, and adversely affects the health of downstream river ecosystems. The optimized scheduling of the reservoir with ecological considerations will thus be beneficial to the protection of the river ecosystems. In practical application, the water inflow forecasting may not be so accurate and need to be modified with time. Since NSGA II obtains trade-offs, we can use it to re-generate alternative schemes according to the modified water inflows in time. After a set of non-dominated schemes have been generated, river managers can pick out a compromise scheme as the scheme to be implemented, according to actual requirements.

CONCLUSIONS

The conservation and restoration of river ecosystems affected by reservoirs have attracted increasing attention in recent years in China. In this study, our attention concentrated on the ecological problems in the middle Yangtze River caused by the impoundment and operation of TGP, such as the reproduction of the FMCC, the propagation of Chinese sturgeon, dissolved gas supersaturation and saline water intrusion at the Yangtze estuary. To realize the harmonious development of economy and ecological environment,
a multi-objective ecological operation model of the Three Gorges cascade reservoirs, which takes maximizing power generation and minimizing water volume that violates EWR as two objectives, was established based on the analysis of flood control and calculation of EWR in the downstream watercourse. To solve the problem effectively, NSGA II was applied. The result of the optimization is a set of effective non-dominated schemes between the target objectives, which exposes conflicting objectives and allows for transparent decision-making. It was found that according to the present water control operating regulations, the monthly amount of released water from TGP is sufficient for ecosystem requirements. In addition, the simulation results show that loss in electricity generation by the Three Gorges cascade hydropower stations would occur if provide more suitable water flow were provided for downstream ecosystems. For it to be more useful in the real-world water resource management of reservoirs, the dispatch interval should be set as a way to consider more hydrological and hydrodynamic requirements besides the flux of the ecosystem in further work.

REFERENCES


First received 5 September 2014; accepted in revised form 16 February 2015. Available online 4 March 2015