Optimal operation of a multi-reservoir system for environmental water demand of a river-connected lake

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ABSTRACT

Dongting Lake, a large river-connected lake in the Yangtze River watershed, plays important roles in flood control, drought mitigation, and biodiversity conservation. Its ecosystem has recently been severely affected by upstream water resource development such as reservoir operations. In this study, an optimization model is developed for the operation of a multi-reservoir system, including the Three Gorges Reservoir (TGR) on the upper Yangtze River and 8 major reservoirs on the tributaries to Dongting Lake. The optimal target in pursuit of the ecological objective is to maximize the environmental water demand (EWD) satisfaction of the lake. A support vector regression-based model is used to predict the response of the lake level to reservoir operations. The optimization is carried out under different scenarios for both normal and dry conditions, and the results show that: (i) the existing operation policy could result in significant hydrologic alteration; (ii) in the normal condition, the proposed optimal joint operation policy could increase the general EWD satisfaction rate of Dongting Lake from 85.4% to 95.7%; and (iii) the improvement of EWD satisfaction in the normal condition is mainly affected by the TGR, while in the dry condition, the southern and western lake regions are more sensitive to the tributaries’ reservoirs.

Key words | Dongting Lake, environmental water demand, multi-reservoir system, optimal operation, river-connected lake

INTRODUCTION

River-connected lakes can be characterized as the inland waters with a direct physical and ecological connection to the main river of a watershed, and hence water can exchange freely between the main river and the lakes. Such lakes play important roles in water resources management (e.g., flood control and drought mitigation) and ecosystem services (e.g., water quality maintenance and biodiversity conservation) of watersheds. It is generally accepted that aquatic ecosystem processes are intrinsically related to hydrological regimes. The ecosystem of a river-connected lake is influenced by both the main river and lake tributaries. In particular, upstream reservoirs can significantly alter the hydrological characteristics of rivers and their connected lakes (Braatne et al. 2008), and thus may profoundly affect the structure and functioning of the ecosystem if sustainable reservoir operation is not performed (Jager & Smith 2008).

Dongting Lake, the second largest freshwater lake in China, is a typical river-connected floodplain lake, which is laterally connected to the middle reaches of the Yangtze River (the longest river in China). The lake is of great ecological importance to fisheries, wildlife and water resources. In recent years, under the influence of climate change and human activities (e.g., reservoir operation, sand mining, etc.), the lake water level during the dry season has decreased drastically (∼2 m), especially after
the impoundment of the world’s largest water resource project, the Three Gorges Reservoir (TGR), on the upper Yangtze River in 2003 (Xu et al. 2013). Such changes have resulted in or will potentially cause severe environmental degradation and water crises, which has raised concerns for the lake ecology and local water resources management (Li et al. 2012; Ye et al. 2016). To lessen the adverse effects of hydroelectric development and meet the environmental demands of this important lake, the optimization of reservoir operation is therefore clearly necessary.

Optimization methods have been applied to reservoir operation problems since the early 1950s, and operation of multi-reservoir systems has also been extensively reported (e.g., Yeh 1985; Labadie 2004; Xu et al. 2014). According to Goor et al. (2010), optimal multi-reservoir operation is generally used to determine a sequence of release decisions that maximizes the system benefits over a given period while meeting operational and institutional constraints. As the problem is often dynamic, nonlinear, multi-dimensional, multi-objective and uncertain, various optimization methods have been designed and used (e.g., dynamic programing, nonlinear programing, heuristic programing, etc.). In recent years, evolutionary algorithms, such as genetic algorithm (GA) and evolutionary programing, have become popular in engineering applications, due to their success in searching complex nonlinear spaces.

Conventional reservoir operations aim to maximize social and economic benefits. Nevertheless, there is now widespread recognition that water resources management must take account of the vulnerability of aquatic ecosystems. Accordingly, many researchers have attempted to incorporate environmental or ecological needs into reservoir operation problems. There is growing awareness that flow regime is the key driver of the ecology of rivers and associated water bodies. In the late 1990s, the concepts of ‘natural flow regime’ and ‘environmental/ecological flow regime’ were developed to mitigate negative effects of human activities (Poff et al. 1997). A variety of methods have been developed to assess environmental or ecological water requirements: for example, Vogel et al. (2007) designed an ecological flow regime to capture the natural flow variability for maintaining the functional integrity of aquatic ecosystems; more recently in China, increasing attention has been paid to the balance between human interests and ecosystem protection (Cai et al. 2013; Hu et al. 2014). Briefly speaking, relevant environmental water demand (EWD) for a water body refers to the basic or proper water (the quantity and timing) needed by the ecosystem to sustain its integrity and sustainability.

Dongting Lake and the middle reaches of the Yangtze River are now periodically regulated by the upstream reservoirs, including the TGR built on the upper Yangtze River and many reservoirs situated on the lake tributaries. The complexity of such a large-scale river-lake and multi-reservoir system presents considerable challenges for lake managers in determining optimal reservoir operation policies. Most previous research on Dongting Lake focused on the field investigation of the hydrological, hydrodynamic and ecological conditions, as well as the vulnerable river-lake interaction. The effects of reservoir operation have also been investigated, but mainly limited to the subjects of local hydrological and sediment changes, either in the Yangtze River or in Dongting Lake (Lai et al. 2013; Xu et al. 2013). As far as we are aware, the possibility of optimal multi-reservoir operations for environmental demands of the important river-connected lake has hitherto not been fully studied.

The objective of this study is to develop optimal operation policies of the upper major reservoirs to meet the EWD of Dongting Lake, which is an important step for enhancing the ecosystem management in the middle Yangtze River watershed. We develop a site-specific optimization model for the operation of a multi-reservoir system, including 9 key reservoirs on both the upper Yangtze River and the tributaries of Dongting Lake. As a preliminary and exploratory study, the optimal target is to maximize the lake EWD satisfaction, while other reservoir functions such as flood control, hydropower generation and navigation are considered in the constraints of the optimization model. A support vector regression (SVR)-based model is developed to link the response of lake water levels to reservoir operation changes. The effect of the existing operation policy on EWD satisfaction is analyzed, for both normal and dry conditions. Through a comparative study among different scenarios, the optimal joint operation policies are numerically studied. The potential improvement in EWD satisfaction rate, due to the optimal multi-reservoir operation, is finally quantitatively estimated.
MATERIAL AND METHODS

Study area

There are 2 large river-connected lakes in the Yangtze River floodplain, namely Dongting Lake and Poyang Lake. The former is slightly smaller in size, but much closer to the TGR of the Yangtze River. Dongting Lake has an internationally important wetland system, providing habitat for approximately 1,428 plant species, 114 fish species and 217 bird species (Xie et al. 2018). It is also the source of drinking water supply for millions of people, irrigates millions of hectares of fields, and sustains a number of commercially important fisheries. The lake and its catchment (111°19'–113°34'E, 28°30'–30°20'N) experience a subtropical monsoon climate, with an annual mean temperature of 18.6 °C, and average precipitation of 1,200–1,400 mm. The average water area of the lake is about 1,310 km²: around 2,691 km² during the wet season, and 709.9 km² during the dry season (Du et al. 2001). The lake level can fluctuate over a range of approximately 15.0 m, with a peak in summer and a low in winter. Dongting Lake may be generally divided into 3 lake regions, namely, the eastern, the southern, and the western lake regions (Figure 1). The annual average water volume flowing into Dongting Lake is 3.126×10¹¹ m³, of which the water from the Yangtze River accounts for 37.7%; the average inflow volume during the wet season (April to October) is 2.322×10¹¹ m³, of which water from the Yangtze River accounts for 46.9%. Its average hydraulic retention time is about 18.2 days (Pan et al. 2009).

Figure 1 | Map of Dongting Lake and location of lake gauging stations.
At the northeastern end of its eastern region, Dongting Lake is directly connected with the middle Yangtze River, through a short and narrow channel. Water exchanges frequently between the river and the lake at Chenglingji (the junction): (i) when the water level of the Yangtze River is lower, water flows from the lake into the river, and the lake level tends to decrease (i.e., emptying effect); (ii) in contrast, when the water level of the Yangtze River is higher, it can constrain the drainage of the lake (i.e., blocking effect) (Zhang et al. 2012). During the wet season, Yangtze River's water may flow into the western region via 3 diversion outlets (Songzi, Taiping, and Ouchi), and then drains from the eastern region directly back into the Yangtze River. After the impoundment in June 2003, the TGR was formed at the upper Yangtze River. Covering around 75,098.13 km² drainage area and controlling over 1 million km² (56% of the Yangtze River watershed), the TGR plays the critical roles of flood control, hydropower generation, and navigation improvement (Hayashi et al. 2008). In particular, it has a flood storage capacity of $22.15 \times 10^9 \text{ m}^3$, which can lessen the frequency of downstream flooding from once every 10 years to once every 100 years (Mao et al. 2015). It is obvious that TGR operation inevitably alters the natural hydrological regime downstream by regulating outflow discharges. In addition, the Qingjiang River, a large tributary of the Yangtze River, joins the mainstem between the TGR and the Songzi outlet.

Dongting Lake also receives water from 4 main tributaries: Xiangjiang River, Zishui River, Yuanjiang River, and Lishui River. The average annual discharges of the Xiangjiang River and Yuanjiang River are $6.43 \times 10^{10} \text{ m}^3$ and $6.53 \times 10^{10} \text{ m}^3$, respectively, which contribute to around 77.52% of the total tributary inflow. There are 26 relatively large reservoirs in the Dongting Lake catchment (Figure 2). Of these, accounting for more than 90% of the total regulation capacity of tributaries' reservoirs (Table 1), 8 major reservoirs are selected:

(i) Dongjiang Reservoir and Taoshui Reservoir on Xiangjiang River;
(ii) Zhexi Reservoir on Zishui River;
(iii) Wuqiangxi Reservoir, Fengtan Reservoir, Tuokou Reservoir and Huangshi Reservoir on Yuanjiang River;
(iv) Jiangya Reservoir on Lishui River.

Suitable hydrological, geometry and bathymetry conditions are required for this study. Most water level and inflow discharge data are provided by the Bureau of Hydrology (BOH) of Changjiang Water Resources Commission.

**Satisfaction rate of EWD**

It could be assumed that a lacustrine ecosystem has adapted to the natural hydrological regime and its specific fluctuation, due to long-term evolution. The acceptable thresholds are typically maintained in a flexible state, indicating that a short-term disturbance would not irreversibly damage the ecosystem. As shown in Figure 3, available water mass in a river-connected lake is determined by the dynamic balance between inflow and outflow. Lake water level, an indicator for the available water mass, is therefore the most important limiting factor in lake ecosystems. For Dongting Lake, an appropriate range of lake level fluctuations is necessary to favor biodiversity and ecosystem health; for example, its grass community (mostly Carex), which provides a primary habitat for fish spawning and food source for winter migratory birds, is closely related to lake levels (Xie et al. 2015). Such an appropriate range is often defined by the acceptable lowest, the highest, and the optimal levels during a given period. However, as mentioned above, Dongting Lake is suffering from a decreasing trend of available water resources in the dry season. Therefore, the lake EWD concerned in this study focuses on the acceptable lowest levels to sustain the basic ecosystem functioning.

Various methods are available for assessing environmental flow required in rivers and lakes to achieve ecological objectives, which could generally be grouped into 4 categories: hydrological methods, hydraulic rating, habitat simulation (rating), and holistic methods (Tharme 2003). Among them, hydrological methods are relatively simple, relying primarily on the use of hydrological data for making environmental flow recommendations. Based on the long-term daily observations in Dongting Lake over the past six decades, it can be straightforward to statistically characterize the lowest acceptable lake levels during the study period concerned: (i) first, the representative
Table 1  | Characteristics of TGR and 8 major reservoirs on the 4 main tributaries of Dongting Lake

| Reservoir | Location (river) | Dead water level (m) | Normal water level (m) | Utilizable capacity \((\times 10^9 \text{ m}^3)\) | Total storage capacity \((\times 10^9 \text{ m}^3)\) | Storage period  
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<tr>
<td>TGR</td>
<td>Yangtze</td>
<td>145.0</td>
<td>175.0</td>
<td>16.5</td>
<td>39.3</td>
<td>September–October</td>
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<td>Dongjiang</td>
<td>Xiangjiang</td>
<td>242.0</td>
<td>285.0</td>
<td>5.25</td>
<td>9.15</td>
<td>September–November</td>
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<tr>
<td>Taoshui</td>
<td>Xiangjiang</td>
<td>170.0</td>
<td>205.0</td>
<td>0.39</td>
<td>0.52</td>
<td>August–October</td>
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<tr>
<td>Zhexi</td>
<td>Zishui</td>
<td>144.0</td>
<td>169.5</td>
<td>2.26</td>
<td>3.57</td>
<td>August–October</td>
</tr>
<tr>
<td>Wuqiangxi</td>
<td>Yuanjiang</td>
<td>90.0</td>
<td>108.0</td>
<td>2.02</td>
<td>4.29</td>
<td>July–October</td>
</tr>
<tr>
<td>Fengtan</td>
<td>Yuanjiang</td>
<td>170.0</td>
<td>205.0</td>
<td>1.06</td>
<td>1.73</td>
<td>July–October</td>
</tr>
<tr>
<td>Tuokou</td>
<td>Yuanjiang</td>
<td>235.0</td>
<td>250.0</td>
<td>0.62</td>
<td>1.25</td>
<td>August–October</td>
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<tr>
<td>Huangshi</td>
<td>Yuanjiang</td>
<td>77.0</td>
<td>90.0</td>
<td>0.34</td>
<td>0.60</td>
<td>September–October</td>
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<tr>
<td>Jiangya</td>
<td>Lishui</td>
<td>188.0</td>
<td>236.0</td>
<td>1.16</td>
<td>1.74</td>
<td>July–October</td>
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Figure 2  | Map of Dongting Lake tributaries and location of tributary reservoirs.
hydrological gauging stations are selected for different lake regions, and a long sequence of lake level data is collected for the period concerned; (ii) those extremely low lake levels are then excluded (e.g., using the 3σ rule); (iii) the continuous distribution of EWD may be determined by the lowest historical lake level variations; the results could be further upscaled to larger time scales (e.g., several days or monthly) in accordance with intervals of optimal operation.

The optimal target in this study is defined as EWD satisfaction rate, which represents the ability of water resources to supply the necessary EWDs (Equation (1)).

\[
S_t = \frac{W_t}{W_{sto,t}}
\]

where \( W_t \) is the water resources availability in period \( t \) (m³), which can be figured out based on a specific lake level-storage curve; \( W_{sto,t} \) is the necessary water storage in accordance with EWD, in period \( t \) (m³).

Considering the spatial variability across Dongting Lake, EWDs are considered for the eastern, the southern, and the western lake regions, respectively. The water resources availability of different lake regions may be approximately reflected by the water levels of their own representative gauging stations: Station Lujiao for the eastern region; Yangliutan and Yingtian for the southern region; and Xiaohexui and Nanzui for the western region (Figure 1). If the study period is divided into \( T \) time intervals, the general EWD satisfaction rate in each lake region can be calculated as follows:

\[
S = \sum_{t=1}^{T} \left( \omega_t \frac{W_t}{W_{sto,t}} \right)
\]

where \( \omega_t \) is the weight of EWD satisfaction rate in the \( t \)th interval, and its value is dependent on how important the period is to the ecosystem.

The general EWD satisfaction rate \( S_{EWD} \) of the entire lake can be expressed as:

\[
S_{EWD} = \sum_{t=1}^{T} \left[ \lambda_t \sum_{i=1}^{N} \left( \omega_i \frac{W_{i,t}}{W_{sto,i}} \right) \right]
\]

where, \( \lambda_i \) is the weight of EWD satisfaction rate for \( N \) lake regions (\( N = 3 \)), i.e., the eastern \( (i = 1) \), the southern \( (i = 2) \) and the western \( (i = 3) \), respectively. A value of \( S_{EWD} \) larger than 100% means that the water resources could meet the necessary EWDs to sustain the lake ecosystem.

**Relationship model between lake and reservoir**

The hydrological regime of Dongting Lake is dominated by both the Yangtze River and the lake tributaries. As a linkage between source and target, accurate prediction of the response of EWD satisfaction rate (reflected by lake level...
fluctuation) to upstream multi-reservoir operation is essential for the development of the optimization model. Lake level changes are traditionally predicted using either process-based or data-driven modeling approaches (Li et al. 2015; Mao et al. 2015). Due to the high complexity of the river-lake interaction and the multi-reservoir system, the practical application of process-based models is often hampered by the lack of detailed geometry, bathymetry, and initial and boundary conditions, as well as the difficulty of model calibration. As an alternative approach, data-driven modeling techniques, such as SVR and artificial neural network, are relatively easy to use to model dynamic and nonlinear data, especially when the underlying physical relationships are not fully understood.

As traditional statistical models are usually unable to capture nonlinearity and nonstationarity correlated with hydrological forecasts, here, SVR is used to develop the relationship model between lake level and inflow (controlled by reservoir release), which is then incorporated in the optimization model to provide real-time analysis and prediction. SVR is an extension of the support vector machine (SVM) method for regression and function approximation. SVM is a relatively novel artificial intelligence-based method developed from statistical learning theory (Vapnik 1998). This type of learning machine employs the structural risk minimization principle to obtain good generalization on a limited number of learning patterns. SVM can be applied to regression problems by the introduction of an alternative loss function that is modified to include a distance measure. The basic idea of SVR is the mapping of the input data onto a higher dimensional feature space via nonlinear mapping. Then, a linear regression model is obtained and solved in this feature space (Gunn 1998). SVR has been proven to be a robust and competent algorithm for hydrological modeling and forecasting (Yu et al. 2006).

Lake level forecast can be approximately cast in the set of data \(\{(x_1, y_1), \ldots, (x_l, y_l)\}\) with the approximate function \(y = \omega^T \phi(x) + b\), where \(x \in \mathbb{R}^n\) is a feature vector (e.g., river inflow) and \(y_i \in \mathbb{R}\) is the corresponding output (e.g., lake level), and \(\phi(x)\) denotes an embedding map that projects \(x\) into a high dimensional feature space in which linear regression may be performed. The approximate function can be determined, for example, using the linear \(\varepsilon\)-insensitive SVR by minimizing the following structural risk (Vapnik 1998):

\[
\min_{\omega, b, \xi, \xi^*} \frac{1}{2} \omega^T \omega + C \sum_{i=1}^{l} (\xi_i + \xi_i^*)
\]

s.t. \(\omega^T \phi(x_i) + b - y_i \leq \varepsilon + \xi_i, y_i - \omega^T \phi(x_i) - b \leq \varepsilon + \xi_i^*, \xi_i, \xi_i^* \geq 0, i = 1, \ldots, l.\)

where \(C\) is the regularization parameter determining the trade-off between model complexity and training error (measured by the slack variables \(\xi\) and \(\xi^*\)). Due to the possible high dimensionality of \(\omega\), usually its dual optimization problem is solved instead, with a certain kernel function involved in:

\[
K(x, x_i) = \varepsilon^{-\gamma} \|x - x_i\|^2
\]

where \(\gamma\) is a kernel parameter and \(\gamma > 0\).

In summary, the development of our SVR-based lake-reservoir relationship model involves 5 main steps, as follows:

1. Normalizing the whole data set to a fixed range from 0 to 1 for river inflow, and then separating it into a training data set and testing data set randomly.
2. Deriving the dual problem to avoid explicitly computing the mapping \(\phi\) and reduce the computing complexity, in which the Gaussian kernel function is used here.
3. Using a GA to find the best error threshold \(\varepsilon\), regularization parameter \(C\) and kernel parameter \(\gamma\), during which the 3-fold cross-validation is applied to prevent the overfitting problem.
4. Training the SVR model based on the training data set to obtain the final approximate function.
5. Validating the model based on the independent testing data set.

Additionally, a well validated hydrodynamic model, including Dongting Lake and the river network in the middle Yangtze River, is used to evaluate the spatial-temporal effects of existing and potential optimal operation schemes (given by the optimization model) on lake levels. The type of process-based model is based on a generally accepted framework of hydrodynamics, in which numerical methods are used to solve continuity and momentum...
equations. The hydrodynamic model has been calibrated and validated against a series of observations, and more details are provided in Dai et al. (2013). The 1D-2D coupled hydrodynamic model is suitable for simulating the hydrodynamics of complex river-lake systems, in which the lake is modeled as a two-dimensional water body while the river network is described by the one-dimensional governing equations.

Optimization model of multi-reservoir system

The study concentrates on high-risk periods of low lake levels caused by existing reservoir operation policies. The flood period of the Yangtze River is from early June to mid-September, of which the main flood period begins in early July. The flood season of Dongting Lake is from April to September. According to the existing rule curves, the storage period of the TGR is from late September to late October, and the storage periods of most major tributary reservoirs also end in October (Table 1). In recent years, low lake levels are often observed during the storage periods of upper reservoirs; that is, the lake EWD satisfaction rate might show a decreasing trend due to inflow reduction after the flood period. It is reasonable to only consider the EWDs from late September to late October. In this study, we select the period from early July to mid-November as the optimization period for the multi-reservoir system, covering the main flood season, the storage period, and part of the after-storage period.

The objective of our optimization model is to seek for the optimal scheduling of the upper 9 reservoirs (i.e., the TGR and 8 major tributary reservoirs of Dongting Lake) to maximize the general EWD satisfaction rate of the entire Dongting Lake ($S_{EWD}$). As defined in Equation (3), $S_{EWD}$ is an integration of all EWD satisfaction rates in lake regions ($S$), and hence the objective function is formulated as:

$$\text{Maximize } S_{EWD} = \max \left\{ \sum_{i=1}^{T} \left[ w_i \sum_{j=1}^{N} \left( \lambda_j \frac{W_{i,j}}{W_{sto,i,j}} \right) \right] \right\}$$

(6)

The optimization period is further downscaled to 10-day time steps for use. There are 14 time intervals ($T = 14$) in this study, of which intervals 1–8 refer to the flood period (the weight $w_1$–$w_8 = 0$, pre-EWD stage), intervals 9–12 refer to the low lake level period ($w_9$–$w_{12} = 0.1$, 0.2, 0.3 and 0.4 respectively, EWD stage), and intervals 13–14 refer to the post-EWD period ($w_{13}$–$w_{14} = 0$). The determination of the above time weighting factors is based on experts’ knowledge of the area (i.e., professional judgment); a higher value (e.g., $w_{12}$) indicates a higher level of EWD concerns for the interval (e.g., late October). Similarly, according to the opinion of experts, the weight-importance coefficients assigned to different lake regions are: $\lambda_1 = 0.5$ (the eastern lake region); $\lambda_2 = 0.3$ (the southern lake region); $\lambda_3 = 0.2$ (the western lake region).

Constraints of the optimization model are given in Equations (7)–(9). The mass conservation of a reservoir is written as:

$$V_{i+1} - V_i = (Q_{in,i} - Q_{out,i}) \times \Delta t$$

(7)

where $V_i$ and $V_{i+1}$ are water storages of a reservoir in the $i$th and the $(i + 1)$th intervals, respectively, (m$^3$); $Q_{in,i}$ and $Q_{out,i}$ are inflow and outflow in the $i$th interval, respectively, (m$^3$/s); and $\Delta t$ is the time step in reservoir operation under consideration (10-day).

The useable storage capacity of a reservoir is represented by the water level constraints:

$$Z_{\text{min}} \leq Z_t \leq Z_{\text{max}}$$

(8)

where $Z_t$ is the reservoir water level in the $i$th interval, (m); $Z_{\text{max}}$ and $Z_{\text{min}}$ are reservoir maximum and minimum water levels, respectively, (m). Notice that $V_i$ and $Z_t$ are related to $Q_{out,i}$ through the water balance and the elevation-storage curve of the reservoir.

The reservoir release constraint is given as follows:

$$Q_{out,\text{min}} \leq Q_{out,i} \leq Q_{out,\text{max}}$$

(9)

where $Q_{out,\text{max}}$ and $Q_{out,\text{min}}$ are the maximum and minimum outflows in the $i$th interval, which are determined by the reservoir functions (e.g., hydropower generation and navigation) and downstream river capacity (e.g., flood control). The variation of $Q_{out,i}$ influences the water resources availability ($W_{i,j}$) in the objective function, which can be forecasted using the relationship model.
The above model employs the GA technique to obtain optimal solutions. GA is an adaptation procedure based on the mechanics of natural genetics and natural selection (Darwin’s evolutionary principle) (Goldberg 1989). Its principal advantage is to intelligently explore the solution space from many different points simultaneously enabling higher probability for locating a global optimum. This optimization algorithm has been widely used in water resources optimization models, including the multi-reservoir optimization problem (e.g., Oliveira & Loucks 1997; Sharif & Wardlaw 2000). In the study, the population size is 2000 and the iteration is set to be 200 generations. The method proceeds generation by generation until it is terminated when the maximum number of allowed generations is reached, or a solution to the problem is found, namely, the difference of successive iterates is less than an extremely small number specified.

However, its practical application is hindered by the difficulty in dealing with numerous variables involved in the multi-reservoir problem. There are 9 reservoirs to be optimized simultaneously in 14 intervals, implying that in total 126 variables have to be determined. To avoid the rapid increase in the numerical complexity with respect to the number of states (i.e., ‘curse of dimensionality’), the aggregation-decomposition method is applied by grouping the reservoirs on the same tributary into one aggregate (virtual) reservoir. As shown in Figure 4, the 4 tributary reservoirs on the Yuanjiang River and the two tributary reservoirs on the Xiangjiang River are aggregated respectively. An aggregate reservoir is treated as a surrogate of a group of tributary reservoirs in the aggregation step, and then the total release obtained by the model is decomposed to each reservoir according to its ratio of inflow in the decomposition step (Liang et al. 1996).

### RESULTS AND DISCUSSION

#### EWD of Dongting Lake

The long-term hydrological data observed at the 5 lake gauging stations are used to statistically estimate the lake EWDs. To minimize the effects of upper reservoirs on the natural lake level fluctuation as much as possible, we only select the observation data during the years prior to the impoundment of the TGR (1953–2002). Using the 3σ rule, the extremely dry (1963, 1966, 1971 and 1972) and extremely wet (1983 and 1989) years are excluded from the analysis. The variations of the acceptable lowest water levels (LWLs) for different lake regions are first estimated from the historical low lake levels, using the estimation method for EWD described above. Figure 5 shows a comparison of LWL estimates at 3 lake regions, with 10-day average values during September–October; note that the results from early to mid-September are also included for

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**Figure 4** | The multi-reservoir system for Dongting Lake, with aggregate reservoirs (dashed ellipse), and input variables of the relationship model.
ease of reference and comparison. In this sensitive period, the regional LWLs range between 22.58 and 31.5 m, and all exhibit a gradually decreasing tendency over time. The eastern lake region has the lowest LWLs (22.58–26.42 m), while the western has the highest values (29.23–31.5 m). The necessary water storage in accordance with EWD is correspondingly obtained using the relevant lake level-storage curve (Figure 6). Compared with the LWL results, however, the western region needs less water to sustain its ecosystem, while both the eastern and the southern regions need more water (Table 2), which is primarily due to bathymetric variation and the effects of the mainstream outside.

**Relationship modeling results**

The SVR-based lake-reservoir relationship models are developed based on historical data for typical normal and dry years, and conducted at 5 representative lake gauging stations respectively: Lujiao (the eastern); Yangliutan and Yingtian (the southern); Xiaohuezui and Nanzui (the western). For each station, lake level is treated as the output variable ($y$), and the discharges from the Yangtze River and the main tributaries are treated as the input variables ($x$). As demonstrated previously, although there are 9 reservoirs to be optimized in the system, to avoid the curse of dimensionality problem, the reservoirs on the same lake tributary have been grouped as one aggregate reservoir in the optimization solution. As such, in the optimization model, there are actually 5 solo and aggregate reservoirs to be optimized. Accordingly, the effects of the Yangtze River and the 4 main tributaries in the relationship models (Figure 4) are expressed by 6 input variables: the discharges of TGR ($x_1$), Qingjiang River ($x_2$), Xiangjiang River ($x_3$), Zishui River ($x_4$), Yuanjiang River ($x_5$) and Lishui River ($x_6$)
These input variables are closely related to upper reservoir operations. Using a representative station as an example, the daily lake level and river discharge data in a typical normal year (2007) are first selected. Statistical characteristics of the input and the output variables are shown in Table 3. After the normalization procedure, the input and output data are randomly divided into a training group (70% data) and a testing group (30% data). The training data are used to establish the regression relationship and calibrate the critical parameters (Table 4). The site-specific relationship models are successfully developed at all stations, and the performance is shown in Table 5. After that, the testing data are applied to quantitatively validate the model performance. The scatter plots of observed and predicted lake levels, for example, at 3 representative stations are shown in Figure 7 together with the coefficients of determination. In general, they all show good agreement of the model results with the measured values: at Lujiao in the eastern region, $R^2 = 0.9930$; at Yangliutan in the southern region, $R^2 = 0.9963$; and at Xiaohezui in the western, $R^2 = 0.9933$. The relationship models are also successfully developed at all stations for the typical dry year (2006), with all mean squared errors (MSEs) less than 0.01 and $R^2$ larger than 0.99. The merit of the SVR-based relationship models is that they may forecast the response of lake levels at different stations accurately and quickly, thus providing an efficient predictor for optimization modeling.

### Optimization modeling results

For the present study, it is found that wet conditions may meet the necessary lake EWDs (i.e., lake EWD satisfaction rates >100%); therefore, we demonstrate the optimization model results for two representative hydrological conditions: Case I, a normal condition; and Case II, a dry condition. These cases represent an average flow year (1974) and a low flow year (1978) based on BOH hydrological records on Yangtze River and Dongting Lake tributaries from 1953–2012. During the high-risk period (September-October), the normal condition has a mean discharge approximately 1.5 times the dry condition: 20,183.5 m$^3$/s (Case I) and 14,422 m$^3$/s (Case II) for the Yangtze River, and 3,063 m$^3$/s and 1,926.5 m$^3$/s for the lake tributaries. In each case, the modeling study is carried out for 5 scenarios:

- **Scenario 0**: without reservoirs in the study area;
- **Scenario 1**: with the existing operation schemes for all reservoirs;
- **Scenario 2**: with optimized operation schemes for all reservoirs;
- **Scenario 3**: with the existing operation schemes for some reservoirs;
- **Scenario 4**: with optimized operation schemes for some reservoirs.

### Table 2 | Water storage in accordance with EWDs of lake regions (September-October)

<table>
<thead>
<tr>
<th>Time</th>
<th>Eastern lake region (10$^9$ m$^3$)</th>
<th>Southern lake region (10$^9$ m$^3$)</th>
<th>Western lake region (10$^9$ m$^3$)</th>
<th>Total (10$^9$ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early September</td>
<td>2.783</td>
<td>1.961</td>
<td>1.298</td>
<td>6.042</td>
</tr>
<tr>
<td>Mid-September</td>
<td>2.146</td>
<td>1.897</td>
<td>1.251</td>
<td>5.294</td>
</tr>
<tr>
<td>Late September</td>
<td>1.634</td>
<td>1.579</td>
<td>0.882</td>
<td>3.548</td>
</tr>
<tr>
<td>Early October</td>
<td>1.304</td>
<td>1.433</td>
<td>0.811</td>
<td>3.548</td>
</tr>
<tr>
<td>Mid-October</td>
<td>1.076</td>
<td>1.520</td>
<td>0.743</td>
<td>3.139</td>
</tr>
<tr>
<td>Late October</td>
<td>0.929</td>
<td>1.250</td>
<td>0.685</td>
<td>2.864</td>
</tr>
</tbody>
</table>

### Table 3 | Statistics of the input (m$^3$/s) and output (m) variables in the relationship model

<table>
<thead>
<tr>
<th>Input index</th>
<th>TGR ($x_1$)</th>
<th>Qingjiang ($x_2$)</th>
<th>Xiangjiang ($x_3$)</th>
<th>Zishui ($x_4$)</th>
<th>Yuanjiang ($x_5$)</th>
<th>Lishui ($x_6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>15,889</td>
<td>392</td>
<td>2,025</td>
<td>797</td>
<td>2,012</td>
<td>434</td>
</tr>
<tr>
<td>Minimum</td>
<td>3,210</td>
<td>77</td>
<td>287</td>
<td>160</td>
<td>333</td>
<td>7</td>
</tr>
<tr>
<td>Maximum</td>
<td>61,000</td>
<td>889</td>
<td>8,420</td>
<td>8,130</td>
<td>17,600</td>
<td>3,820</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>13,380</td>
<td>239</td>
<td>1,644</td>
<td>801</td>
<td>2,102</td>
<td>591</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output index</th>
<th>Lujiao</th>
<th>Yingtian</th>
<th>Yangliutan</th>
<th>Nanzui</th>
<th>Xiaohezui</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>28.24</td>
<td>28.48</td>
<td>28.57</td>
<td>30.96</td>
<td>31.24</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>26.04</td>
<td>26.06</td>
<td>26.32</td>
<td>28.74</td>
<td>29.67</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>31.97</td>
<td>32.15</td>
<td>32.16</td>
<td>34.85</td>
<td>34.57</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.58</td>
<td>0.085</td>
<td>1.56</td>
<td>0.083</td>
<td>1.13</td>
<td></td>
</tr>
</tbody>
</table>
Scenario 2: with the optimal operation scheme for the TGR, but with the existing operation schemes for tributary reservoirs of Dongting Lake;

Scenario 3: with the existing operation scheme for the TGR, but with the optimal operation schemes for tributary reservoirs of Dongting Lake;

Scenario 4: with the optimal joint operation schemes for all reservoirs.

The above optimal operation schemes would be determined for the individual scenarios through the optimization model. Table 6 compares the predictions of EWD satisfaction rates in different scenarios of Case I. Assuming no effect of reservoirs (Scenario 0), the SVR-based model results show that the EWD satisfaction rates for all lake regions are moderately larger than 100% during the high-risk period, implying that the ‘natural’
river regimes in the normal condition can meet the environmental water requirements of the lake. However, the presence of upper reservoirs causes a marked decrease in EWD satisfaction rates. With the existing reservoir operation schemes (Scenario 1), it is estimated that all lake regions’ EWD satisfaction rates would fall within the range of 80–90%. In particular, the value for the western region significantly decreases from 139.47% to 87.14% because of the dual effects of the TGR and 4 tributary reservoirs.

<table>
<thead>
<tr>
<th>Lake region</th>
<th>Scenario 0</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>The eastern region</td>
<td>111.60%</td>
<td>82.38%</td>
<td>87.16%</td>
<td>83.64%</td>
<td>97.86%</td>
</tr>
<tr>
<td>The southern region</td>
<td>114.10%</td>
<td>89.26%</td>
<td>91.65%</td>
<td>92.22%</td>
<td>94.44%</td>
</tr>
<tr>
<td>The western region</td>
<td>139.47%</td>
<td>87.14%</td>
<td>91.83%</td>
<td>87.66%</td>
<td>92.30%</td>
</tr>
<tr>
<td>Dongting Lake</td>
<td>117.92%</td>
<td>85.40%</td>
<td>89.44%</td>
<td>87.02%</td>
<td>95.73%</td>
</tr>
</tbody>
</table>

The optimal TGR operation schemes in the normal condition, alone (Scenario 2) or jointly (Scenario 4), derived from the optimization model, are presented in Figure 8. Meanwhile, as the TGR uses the existing operation scheme in both Scenario 1 and Scenario 3, the two scenarios can produce the same baseline results, as shown in Figure 8, for comparison. To improve the EWD satisfaction rate, the TGR storage operation is proposed to be scheduled approximately one and a half months in advance (in August), and then its water levels can be kept at ∼150 m.

![Figure 8](https://iwaponline.com/hr/article-pdf/47/S1/206/367351/nh047s10206.pdf)
for about a month, and further increased up to 175 m in early November. On the other hand, the optimal operation policies for the tributary reservoirs are shown in Figure 9, including Scenario 3 and Scenario 4; their baseline results are given in both Scenario 1 and Scenario 2. Their optimization strategies are similar to that of the TGR optimization, i.e., performing the storage operation ahead of the original schedule and thus reducing the storage requirements so as to increase the release during the high-risk period. The unilateral optimization schemes (both Scenario 2 and Scenario 3) have relatively little influence. If the optimal operation is only performed for the TGR, the general EWD satisfaction rate would be increased from 85.40% to 89.44%. It is expected to be 87.02% if the optimal operation for the tributary reservoirs is solely performed. The optimal joint operation policy of the entire multi-reservoir system is illustrated by Scenario 4, which could increase the general EWD satisfaction rate from 85.4% to 95.7%. Therefore, the optimal joint operation schemes obtained from the optimization model could be considered in the aquatic ecosystem management in Dongting Lake.

The primary benefit of the optimal joint operation, compared with the existing schemes, is that the specific releases could be increased (e.g., by around 2,377 m³/s on average from the TGR) during the original storage period. As the storage capacity of the TGR (39.3 × 10⁹ m³) is much greater, it has more impact than the tributary reservoirs do on the entire lake. The TGR exerts influence in two ways: (i) increasing the inflow into Dongting Lake from the 3 diversion outlets (~0.909 × 10⁹ m³); and (ii) raising the water levels in the middle reaches of the Yangtze River (~0.3 m at Station Chenglingji), which helps to enhance the

![Operation schemes of the reservoirs on lake tributaries under different scenarios in Case I.](https://iwaponline.com/hr/article-pdf/47/S1/206/367351/nh047s10206.pdf)
‘blocking effect’ of the Yangtze River. Therefore, as shown in Table 6, the eastern and the western lake regions are more sensitive to the operation of the TGR, while the southern region is more sensitive to the operation of the tributary reservoirs.

As for the dry condition (Case II), it is found that the ‘natural’ river regimes cannot provide the necessary water storage to sustain basic ecosystem functioning (Table 7); neglecting the effects of reservoirs (Scenario 0), the EWD satisfaction rates are around 80–85% during the storage period. If the existing operation policy is adopted (Scenario 1), all lake regions’ EWD satisfaction rates are to be reduced by about 15%. The optimal reservoir operation schemes in dry condition are similarly estimated as in Case I. Similar to the normal condition, the relative optimization strategies of the TGR (Figure 10) and tributary reservoirs (Figure 11) in Case II are to enlarge the storage periods by planning the operation in advance. Table 7 summarizes the predicted EWD satisfaction rates under different scenarios of Case II, and the optimal policy in Scenario 4 is also the best one to be considered. Although the optimal operation is believed to have a positive effect on the lake ecosystem, no significant improvement in EWD satisfaction rate could be detected when compared with Case I. Due to the relatively small background discharges available, the general EWD satisfaction rate under the optimal joint operation is predicted to be 67.74%. It is interesting to note that, in the dry condition, the lake is more sensitive to the operations of tributary reservoirs, especially in the southern and western lake regions.

In conclusion, the existing operation policies cause significant hydrologic alteration. The optimal joint operation may improve the lake EWD satisfaction rates in the normal condition, approximately satisfying the

<table>
<thead>
<tr>
<th>Lake region</th>
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<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>The eastern region</td>
<td>80.67%</td>
<td>63.90%</td>
<td>66.70%</td>
<td>64.48%</td>
<td>67.32%</td>
</tr>
<tr>
<td>The southern region</td>
<td>80.24%</td>
<td>64.78%</td>
<td>63.48%</td>
<td>68.30%</td>
<td>66.69%</td>
</tr>
<tr>
<td>The western region</td>
<td>85.48%</td>
<td>70.96%</td>
<td>70.14%</td>
<td>71.49%</td>
<td>70.35%</td>
</tr>
<tr>
<td>Dongting Lake</td>
<td>81.50%</td>
<td>65.58%</td>
<td>66.42%</td>
<td>67.03%</td>
<td>67.74%</td>
</tr>
</tbody>
</table>

Figure 10 | Discharges and water levels of TGR under different scenarios in Case II.
environmental water requirements, while it has a limited role in the dry condition. The improvement of EWD satisfaction in the normal condition is mainly affected by the TGR; in the dry condition, however, the southern and western lake regions are more sensitive to the tributaries’ reservoirs.

Spatial influence of optimal operations

The foregoing demonstrations show that, the optimal operation policies may be reasonably determined by the optimization model, and the SVR-based model correctly reproduces the rapid changes of lake level. Nevertheless, those modeling results are limited to several representative stations located in different lake regions. To further illustrate the performance of the proposed optimal operation schemes, the corresponding spatial patterns of hydrodynamic change are numerically investigated using a process-based hydrodynamic model. In this 1D-2D coupled model, the lake domain is discretized using unstructured triangular grids (9,424 points and 14,289 cells). By changing the boundary conditions, the well-validated model may make projections of the detailed lake level response (in time and space) to reservoir operation changes.

Here, we present the spatial influence of optimal operations on the lake, using the simulation results in mid-October as a case study. Figure 12 compares the distributions of lake level increase caused by 3 optimal operation schemes in the normal condition (Case I). Across the simulation results for Scenarios 2–4, there is a roughly similar spatial pattern of hydrodynamic variation,
namely, the lake level improvement tends to occur in the waters closer to the rivers. With the optimal TGR operation (Scenario 2), the eastern and the western lake regions exhibit large increases in lake levels (0.08–0.4 m and 0.08–0.32 m, respectively), whereas the increase is less than 0.16 m for the southern. In Scenario 3, the improvement remains at an unsatisfactory level, in which the southern and the eastern lake regions are more prone to be affected by the optimal operation of tributary reservoirs. With the optimal joint operation (in Scenario 4), greater lake level variations are observed in most of the waters: 0.12–0.52 m in the eastern, 0.16–0.40 m in the southern, and 0.20–0.40 m in the western. Figure 13 shows the relevant spatial variation of lake level increase in the dry condition (Case II). For its Scenario 2, lake level response to the optimal TGR operation mainly occurs along the northeastern channel connected to the Yangtze River. In contrast, when the optimal operation is performed for tributary reservoirs (Scenario 3), the lake level increase can be observed in a large portion of the western and southern lake regions, particularly near the mouths of tributary rivers, ranging from 0.04 to 0.28 m. The optimal joint operation in the dry condition may raise the lake levels of most of the western and southern lake regions, up to 0.1 m and 0.35 m, respectively.

Our results show that, both for Case I and Case II, the overall spatial patterns (lake level increase) from the hydrodynamic model are generally in agreement with the relative differences (EWD satisfaction rate) at representative stations given by the SVR-based models. Although the hydrodynamic model cannot be directly applied to describe the spatial distribution of the EWD satisfaction rate, it may be used to forecast the spatial influence of the reservoir release on the propagation of lake level changes, thus introducing a feedback mechanism into the multi-reservoir optimization model.

**CONCLUSIONS**

This work presents a multi-reservoir optimization system for EWD of a river-connected lake. The elements of the ecologically oriented reservoir operation optimization are outlined. The optimal target index of EWD satisfaction rate is defined, of which EWD is estimated at representative stations in different lake regions of Dongting Lake. Station-specific SVR-based models are developed to quantitatively relate the lake and reservoirs, which are incorporated in the
optimization model to provide a real-time forecast of lake level response to reservoir operations. To meet the lake EWD, an optimization model is further developed for the operation of this multi-reservoir system; the optimal operation policies for the TGR and 8 major tributary reservoirs of Dongting Lake can be determined by reference to the optimal target index and SVR-based model results.

This study unravels the cause of abnormally low lake level periods, due to the existing operation schemes, in both normal and dry conditions. The multi-reservoir optimization system leads to valuable insights into lake EWD satisfaction changes caused by optimal operation schemes. For example, in the normal condition, the proposed optimal joint operation policy could aid greatly in risk mitigation, increasing the lake EWD satisfaction rate from 85.4% to 95.7%. On the other hand, the results show that the spatial patterns of EWD satisfaction rate and lake level fluctuation in the lake are definitely dependent on the operation schemes. The success of the multi-reservoir optimization system paves the way for the development of more comprehensive aquatic ecosystem management in Dongting Lake.

It is recognized that some important factors such as hydropower generation, navigation and irrigation have not been considered in the optimal target, which might be addressed in more refined modeling in the future.

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