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Developing a comprehensive evaluation method for Interconnected River System Network assessment:

A case study in Tangxun Lake group

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Abstract: The Interconnected River System Network (IRSN) plays a crucial role in water resource allocation, water ecological restoration and water quality improvement. It has become a key part of the urban lake management. An evaluation methodology system for IRSN project can provide important guidance for the selection of different water diversion schemes. However, few if any comprehensive evaluation systems have been developed to evaluate the hydrodynamics and water quality of connected lakes. This study developed a comprehensive evaluation system based on multi-indexes including aspects of water hydrodynamics, water quality and socioeconomics. A two-dimensional (2-D) mathematical hydrodynamics and water quality model was built, using NH_3-N, TN and TP as water quality index. The IRSN project in Tangxun Lake group was used as a testbed here, and five water diversion schemes were simulated and evaluated. Results showed that the IRSN project can improve the water fluidity and the water quality obviously after a short time of water diversion, while the improvement rates decreased gradually as the water diversion went on. Among these five schemes, Scheme V showed the most noticeable improvement in hydrodynamics and water quality, and brought the most economic benefits. This comprehensive evaluation method can provide useful reference for the implementation of other similar IRSN projects.

Keywords: Interconnected River System Network (IRSN); comprehensive evaluation system; hydrodynamic and water quality model; water environment improvement; Tangxun Lake group

1 Introduction

In urban systems, lakes play a key role in maintaining ecological balance by providing water supply, regulating runoff, adjusting climate, defending flood and conserving biodiversity. However, with the acceleration of the urbanization process and the increasing of urban population density, more and more urban lakes have been encroached upon and become fragmented (Tan *et al*., 2012). Meanwhile, industrial and municipal wastewater exacerbates

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the pollution problems in these water bodies. Both of the hydraulic and quality conditions degrade the regulating function of urban lakes and influence ecosystems balance. Most urban lakes' water quality cannot meet the daily functional requirements (Chen, 2010), poses serious threats to the ecological security and the health of urban residents.

The concept of the Interconnected River System Network (IRSN) is proposed to provide a new approach for solving the environmental problems of water networks (Zuo *et al*., 2011). By enhancing the hydraulic liquidity and continuity in water bodies, IRSN can help improve water bodies' self-recovery ability and realize the long-term health and stability. This method has been widely applied in projects of water resource allocation, water ecological restoration and water quality improvement (Cui *et al*., 2011; Li *et al*., 2011). Many scholars have analyzed the effect of the IRSN project, but both technical theory and assessment methods of IRSN still remain in the exploratory stage (Li *et al*., 2011). Kang Ling *et al*. (2012) established a hydrodynamic and water quality model to analyze the water quality improvement of COD, TN and TP under three schemes. Xie *et al*. (2009) demonstrated that water transfer project could effectively decrease the TN, TP and Chl-a concentration of Chaohu Lake. To evaluate the performance of different water diversion cases, Chen *et al*. (2015) used multi-indexes including water quality improvement rate, category change index and concentration change index. Besides the water quality indicators mentioned above, other useful indicators are used to evaluate hydrodynamics improvement. Li *et al*. (2011, 2013) used the water age to describe spatiotemporal environmental benefits in the water transfer process. The concept of water exchange rate was applied to analyze the river network's hydrodynamics of multiple water diversion plans (Lu *et al*., 2015). The cost and benefit evaluation indexes are also applied to determine the optimal diversion flow discharge of IRSN projects (Liu J M *et al*., 2014). Xie *et al*. (2015) used the river water surface curve, the water area ratio and the ecological water requirement to estimate the flood control effect, the ecological effect and the water landscape effect of the IRSN in Chaozhou City. Cui *et al*. (2017) proposed a river network connectivity assessment method based on the concept of structural connectivity and functional connectivity.

Most previous studies used a single index to evaluate the hydrodynamics or water quality effect and determine the optimal connectivity scheme, and few if any considered both the hydrodynamics and water quality to give an overall evaluation for the IRSN projects. In this paper, a comprehensive evaluation system was built based on multiple evaluation indexes, including water hydrodynamics, water quality and socioeconomics. And a two-dimensional (2-D) mathematical hydrodynamic and water quality model was built. We use the Tangxun Lake group as a testbed to test this evaluation system under different IRSN schemes.

2 Study area

The Tangxun Lake is the largest urban lake in China, with a water surface area of 52.19 km^2 and a storage capacity of 32.85 million m^3. It is located in the middle and lower reaches of the Yangtze River, and serves as the backup water source area for Wuhan, the capital city of Hubei Province. The Tangxun Lake Basin is a complicated water network system consisting of rivers and lakes (Figure 1).

With accelerating urbanization and increasing pollutants in recent decades, water quality

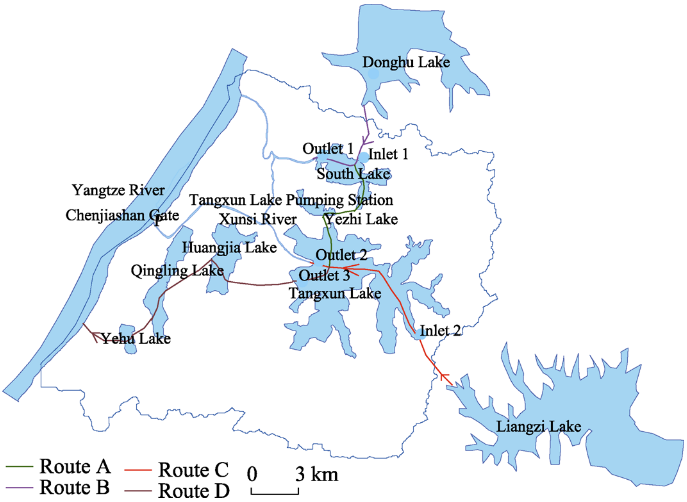


Figure 1 Sketch of the Interconnected River System Network project of the Tangxun Lake group

in Tangxun Lake deteriorated gradually (Chu *et al.*, 2009; Yang *et al.*, 2009). According to the National Surface Water Quality Standards of China (GB3838-2002), the average water quality of the lake could meet Grade IV during 2011–2013, but it has deteriorated to Grade V since 2014. The water quality of the surrounding lakes such as South Lake, Yehu Lake and Yezhi Lake is even worse than Grade V (WMWA, 2011–2016). These surrounding lakes are in the moderate eutrophication stage and they cannot meet the basic ecological function requirements. To improve water quality and alleviate eutrophication, the IRSN project was put forward by the Wuhan Municipal Government. This project is designed to reestablish the hydraulic connection of the Tangxun Lake group to the Dadonghu Lakes and the Liangzi Lake via some existing and newly-built channels (see Section 5.1 for more details).

3 Methodology

3.1 The DEM-based parallel computing hydrodynamic and water quality model

The Tangxun Lake is a typical shallow lake with a mean water depth of 1.5–3.3 m, and the bottom slope is about 0.005. The horizontal scale is greater than the vertical scale. We only consider the 2-D horizontal water flow simulation with an evenly distributed water flow in the vertical direction. This 2-D hydrodynamic and water quality model is based on the continuity equation, momentum equation and transport equation to simulate the flow field and water concentration (Zhang *et al.*, 2008; Zhang *et al.*, 2012).

(1) Hydrodynamic model

The continuity equation and momentum equations can be expressed as:

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=q \tag{1}$$

$$\begin{aligned}\frac{\partial hu}{\partial t}+u\frac{\partial hu}{\partial x}+v\frac{\partial hu}{\partial y}&=fhv-g\frac{\partial h^2}{\partial x}-gh\frac{\partial z}{\partial x}-gn^2\frac{u\sqrt{u^2+v^2}}{h^{1/3}}+\\&\quad\frac{\partial}{\partial x}\left(\varepsilon_x h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_x h\frac{\partial u}{\partial y}\right)+\frac{C_a\rho_a W_x(W_x^2+W_y^2)^{1/2}}{\rho}\end{aligned} \tag{2}$$

$$\frac{\partial hv}{\partial t}+u\frac{\partial hv}{\partial x}+v\frac{\partial hv}{\partial y}=-fhu-g\frac{\partial h^2}{\partial y}-gh\frac{\partial z}{\partial y}-gn^2\frac{v\sqrt{u^2+v^2}}{h^{1/3}}+ \\ \frac{\partial}{\partial x}\left(\varepsilon_y h\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y h\frac{\partial v}{\partial y}\right)+\frac{C_a\rho_a W_y(W_x^2+W_y^2)^{1/2}}{\rho} \tag{3}$$

where x and y represent vertical and horizontal length of water area, respectively; t is time; q is interzone inflow quantity; u and v represent vertical and horizontal velocity of the water, respectively; h is water depth; z is water level; g is the gravitational constant; f is the Coriolis force constant; n is roughness coefficient; C_a is the wind resistance coefficient; ρ and ρ_a are the density of water and wind, respectively; ε_x and ε_y are vertical and horizontal eddy viscosity coefficients, respectively; W_x and W_y are vertical and horizontal wind speed, respectively.

(2) Water quality model

The mass transport equation can be expressed as:

$$\frac{\partial hc}{\partial t}+u\frac{\partial hc}{\partial x}+v\frac{\partial hc}{\partial y}=\frac{\partial}{\partial x}\left(E_x\frac{\partial hc}{\partial x}\right)+\frac{\partial}{\partial y}\left(E_y\frac{\partial hc}{\partial y}\right)+h\sum S_i \tag{4}$$

where c is concentration of water quality index; Ex and Ey are the sum of the molecular diffusion coefficient, the turbulent diffusion coefficient and the dispersion coefficient in the x, y direction, respectively; $\sum S_i$ is the source and sink terms of water quality index.

The FVM method (Patankar, 1980) was used to discretize the equations, and the equations were solved using the Tri-Diagonal Matrix Algorithm method (TDMA) and the Alternating Direction Implicit method (ADI). The details of these methods can be found in Tao's study (2001).

3.2 The IRSN scheme evaluation method

In this study, we propose a comprehensive evaluation system based on the aspects of water hydrodynamics, water quality and socioeconomics to evaluate the IRSN effects and determine the optimal connectivity scheme. Mean flow velocity, maximum flow velocity and stagnant water ratio are selected as hydrodynamic indexes. Water quality improvement rate, concentration change index, water quality category ratio and water standard exceeding ratio are selected as water quality indexes. Economic benefits, costs and the net benefits are selected as the socioeconomic indexes. These indexes can reflect the improvement of the lakes from different perspectives, and the implications of the indexes are shown in Table 1.

3.2.1 Water quality improvement rate

The water quality improvement rate (Zhai *et al*., 2008) can be expressed as:

$$R_i=\frac{C_{bi}-C_{ai}}{C_{bi}}\times 100\% \tag{5}$$

where R_i is the water quality improvement rate of the i-th water quality index; C_{bi} is the mean concentration of the i-th water quality index before water diversion; C_{ai} is the mean concentration of the i-th water quality index after water diversion.

If $R_i>0$, the water quality is improved after water diversion; while if $R_i<0$, the water quality becomes worse after water diversion. The larger the R_i is, the better the water quality is.

Table 1 Evaluation system of IRSN scheme

Index categories	Indexes	Units	Implications
Hydrodynamic evaluation indexes	Mean flow velocity	m/s	Reflecting the water renewable capability and the self-purification ability.
	Maximum flow velocity	m/s	Representing the maximum flow velocity of the lake.
	Stagnant water ratio	%	The proportion of the stagnant water area (the velocity less than 0.0006 m/s) to the total area.
Water quality evaluation indexes	Water quality improvement rate	%	Reflecting the change trend of water quality indexes in lakes.
	Concentration change index	–	Reflecting the improvement of water quality in lakes, and the larger concentration change index is, the better the water quality becomes.
	Water quality category ratio	%	Reflecting the spatial distribution of water quality before and after water diversion.
	Water standard exceeding ratio	%	Reflecting the exceeding standard ratio of each pollutant before and after diversion.
Socioeconomic indexes	Economic benefits	yuan	Reflecting the environmental benefits of water quality improvement in lakes.
	Costs	yuan	Reflecting the costs incurred in the operation of the project.
	Net benefits	yuan	It is the difference between economic benefits and costs. The greater the net benefits, the better the water diversion effect.

3.2.2 Concentration change index

The concentration change index (Zhai *et al.*, 2008) can be expressed as:

$$P = \frac{2}{n}\sum_{i=1}^{n}\frac{C_{bi} - C_{ai}}{C_{bi} + C_{ai}} \tag{6}$$

where P is the concentration change index; C_{bi} is the mean concentration of the i-th water quality index before water diversion; C_{ai} is the mean concentration of the i-th water quality index after water diversion; n is the total number of water quality indexes.

P reflects the changes of various water quality indexes comprehensively. If $P>0$, the water quality is improved after water diversion; while if $P<0$, the water quality becomes worse after water diversion. The larger the P is, the better the water quality becomes.

3.2.3 Water standard exceeding ratio

The water standard exceeding ratio is the proportion of the water area whose water quality exceeds the standard in the total lake area. The water quality management target of the Tangxun Lake is Grade III, so the water standard exceeding ratio of the Tangxun Lake refers to the proportion of the water area whose water quality is worse than Grade III in the total lake area. The water quality management target of both the Qingling Lake and the Huangjia Lake is Grade III, and the target of both the South Lake and the Yehu Lake is Grade IV. The water standard exceeding ratio is defined as:

$$T = \frac{1}{n}\sum_{i=1}^{n}\frac{A_i}{A} \tag{7}$$

where T is the water standard exceeding ratio; A_i is the area that the i-th water quality index exceeds the standard; A is the total lake area; n is the total number of water quality indexes.

3.2.4 Cost and benefit evaluation method

This paper evaluates the diversion benefits of different schemes by improving the cost and benefit evaluation method proposed by Liu J M *et al.* (2014). Economic benefits in this paper only involve the environmental benefits which are brought by the reduction of pollution abatement costs due to the decrease of pollutant concentration in lakes. The ecological, landscape and other benefits are not considered. The environmental benefits are calculated using the pollution charges standard characterization (PCSC) method (Tan *et al.*, 2007), and the method can be expressed as:

$$B = P_b / \alpha \tag{8}$$

where B is the economic benefits, which represents the reduction of pollution abatement costs after the diversion; α is the adjustment coefficient, which represents the compensation degree to which the pollution charges compensate to the environmental pollution. The annual pollution charge is about 1/30 of the environmental protection investment (Jiang, 2014), so the adjustment coefficient is 1/30. P_b is the reduction of pollution charges after the diversion, and it can be calculated based on the pollution equivalent method.

$$P_b = \sum_{i=1}^{3} R_i N_i = \sum_{i=1}^{3} R_i \times \frac{M_{bi} - M_{ai}}{K_i} \tag{9}$$

where N_i is the reduction of pollution equivalent amount of the i-th water quality index; R_i is the charge standards of each pollution equivalent, and the charge standards of NH_3-N, TN and TP are 1.4 yuan, 0.7 yuan and 0.7 yuan, respectively (Wang, 2003; NDRC, 2014); M_{bi} is the total amount of the i-th pollutant before the diversion (kg); M_{ai} is the total amount of the i-th pollutant after the diversion (kg); K_i is the pollution equivalent value of the i-th pollutant (kg). The pollution equivalent values of NH_3-N, TN and TP are 0.8 kg, 0.8 kg and 0.25 kg, respectively (Wang, 2003).

The costs in this paper refer to the operating costs of the pumping station, and the construction costs of the IRSN project are not taken into account. The costs can be calculated as:

$$C = P_c \times Q \times T \tag{10}$$

where C is the operating costs; P_c is the operating costs per flow discharge (yuan/m^3); Q is the water diversion flow discharge (m^3/s); T is the water diversion time (s).

$$P_c = \frac{f \rho g H_{st}}{3600000 \eta_{st}} \tag{11}$$

where f is the local electricity price (yuan/kWh); ρ is the water density (kg/m^3); g is the gravitational acceleration; H_{st} is the net head of the pumping station (m); η_{st} is the efficiency of the pumping station.

According to the Power Grid Sales Tariff in Hubei Province (implemented since June 1, 2016), the electricity price of general business is 0.85 yuan/kWh. With reference to the basic parameters of the Tangxun Lake pumping station, the working head is taken to be 6 m, and the pump efficiency η_{st} is 80%. The value of P_c is calculated to be about 0.017 yuan/m^3.

The net benefits (E) are the difference between the economic benefits (B) and the costs (C). If the value of E is greater than 0, the economic benefits are greater than the costs, indicating that the scheme is feasible. The greater the net benefits are, the more effectively can the scheme achieve the goal of improving the water environment.

4 Model setup

4.1 Mesh generation

In this study, the DEM grid data, with a resolution of 30 m×30 m, was used as the grid of the simulation domain. The data was generated using the spatial interpolation methods based on the underwater topographic map of the Tangxun Lake group (Figure 2). The Tangxun Lake, the South Lake, the Huangjia Lake, the Yehu Lake, the Yezhi Lake and the Qingling Lake were divided into 44,526, 8200, 7449, 1527, 1805 and 7540 valid grid cells, respectively.

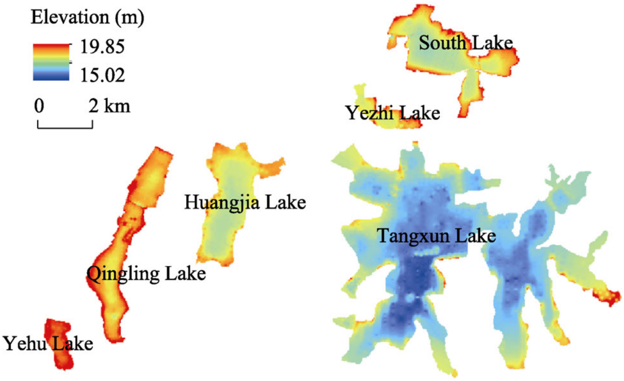


Figure 2 The underwater topographical map of the Tangxun Lake group

4.2 Initial and boundary conditions

The lakes mentioned above are typical shallow lakes with wind- driven currents. The dominant wind direction near the lakes is southeast, with a mean velocity of 2.8 m/s. The time step was set to 3600s. During the simulation period, the first day's concentration field, which was interpolated according to the data of the nine sampling sites (Figure 3), was set as the initial concentration. The normal water level of the lakes was set as the initial water level. The initial flow velocity was set to 0 m/s. According to the actual water quality situation of the Tangxun Lake group, NH_3-N, TN and TP were chosen as the water quality indexes.

The boundary conditions include inlets, outlets and the inputs of point source and non-point source. The inflow boundary is determined by flow discharge, and the outflow boundary is determined by water level. There are many sewage outlets around the Tangxun Lake group. In the simulation, these sewage outlets were integrated into 23 sewage outlets (Figure 3), and the measured data of point source concentration were used. The urban non-point source pollution has become the main causation of water pollution, and it is mainly caused by runoff scouring. The Tangxun Lake Basin was divided into 24 sub-basins based on the topographic data, and each sub-basin was generalized as a catchment inlet. The locations are

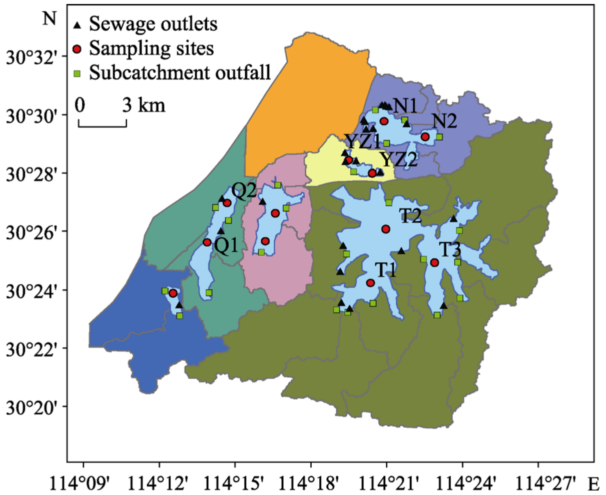


Figure 3 Location of sampling sites and sewage outlets in the Tangxun Lake group

shown in Figure 3. The average annual total non-point source pollutants of NH_3-N, TN and TP in the Tangxun Lake Basin are 93.5 t, 204.5 t and 74.2 t, respectively (Wang *et al*., 2012). Due to lack of measured data, the non-point source pollution concentration of each sub-basin was simulated on the basis of the annual total non-point source pollutants. The temporal non-point source pollution concentration was calculated according to the rainfall process, and the spatial non-point source pollution concentration was calculated according to the sub-catchment's area. The flow discharge of the sub-basins was calculated via the runoff coefficient method (Zhang *et al*., 2015), and the runoff coefficient was set to 0.49 according to Wang *et al*. (2012). Daily precipitation data were obtained from the Wuhan station which is in the vicinity of the lakes.

4.3 Model calibration and verification

Model calibration was conducted from February 10 to March 3, 2014 according to the actual situation of the Tangxun Lake group before water diversion. The boundary conditions include the inputs of point source and non-point source and two outlets. One of the outlets is located in the Tangxun Lake, and the other is in the South Lake. The model calibration parameters were shown in Table 2. The simulated and measured values at nine stations (Figure 4) showed that the mean relative errors of NH_3-N, TN and TP were 8.9%, 10.27% and 13.39%, respectively.

Table 2 The calibration parameters in hydrodynamic and water quality model

Parameter name	Value	Parameter name	Value
Coriolis force constant	7.27×10^{-5} s^{-1}	Wind resistance coefficient	0.0012
Horizontal diffusion coefficient	0.5 m^2/s	Vertical diffusion coefficient	0.8 m^2/s
Horizontal eddy viscosity	8.9 m^2/s	Vertical eddy viscosity	8.9 m^2/s
Roughness	0.02	NH_3-N degradation coefficient	0.05 d^{-1}
TP degradation coefficient	0.008 d^{-1}	TN degradation factor	0.015 d^{-1}

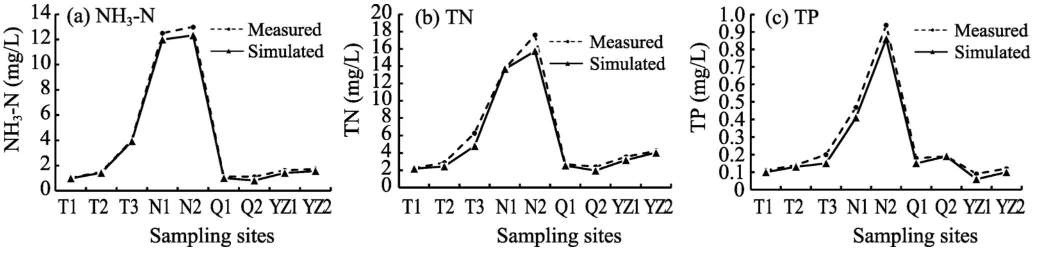


Figure 4 Simulated and measured values at nine stations during model calibration

The model was verified by the measured data of the sampling sites in June 2014. The result (Figure 5) showed that the simulated values were very close to the measured data. The

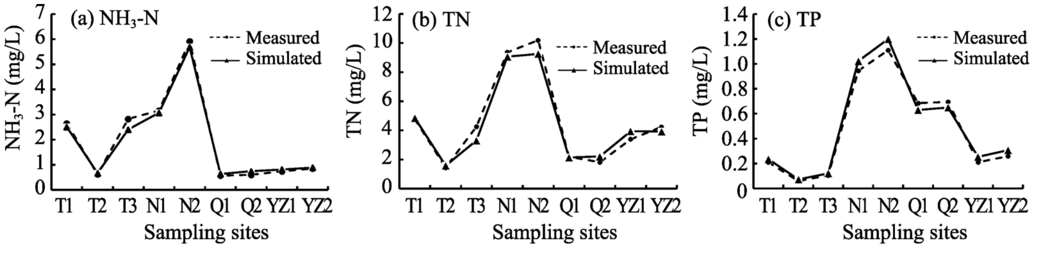


Figure 5 Simulated and measured values at nine stations during model verification

mean relative errors of NH_3-N, TN and TP were 9.18%, 11.14% and 14.56%, respectively, indicating that the model was reasonable and can be used as an effective tool for the IRSN scheme evaluation.

5 Evaluation of the IRSN scheme of the Tangxun Lake group

5.1 Connectivity scheme

According to the Lakes Planning of Wuhan, the Tangxun Lake water system will be connected with the Donghu Lake water system and the Liangzi Lake water system, thus finally forming an interconnected water network of the Yangtze River, the Donghu Lake, the Liangzi Lake, the Tangxun Lake and the Jinshui River. Fresh water from the Donghu Lake is diverted into the Tangxun Lake via Inlet 1, and fresh water from the Liangzi Lake is diverted into the Tangxun Lake via the Dongba River and Inlet 2. One part of the water is eventually discharged from the Tangxun Lake and the South Lake to the Yangtze River via Outlet 1 and Outlet 2, respectively, and another part of the water is discharged via the newly built Outlet 3 to the Huangjia Lake and the Qingling Lake (Figure 1).

With reference to the current water diversion projects in China, the water diversion flow discharge is set to 40 m^3/s. Five connectivity schemes with different water transfer routes were formulated to evaluate the water transfer project's impact on the hydrodynamics and water quality of the Tangxun Lake group (Table 3).

Table 3 The IRSN schemes of the Tangxun Lake group

Connectivity schemes	Flow discharge (m^3/s)		Outlets	Water diversion routes
	From Donghu Lake	From Liangzi Lake		
Scheme I	40	0	Outlet 1, Outlet 2	Route A, Route B
Scheme II	0	40	Outlet 2	Route C
Scheme III	40	40	Outlet 1, Outlet 2	Route A, Route B, Route C
Scheme IV	0	40	Outlet 2, Outlet 3	Route C, Route D
Scheme V	40	40	Outlet 1, Outlet 2, Outlet 3	Route A, Route B, Route C, Route D

The water transfer routes were as follows:

(1) Route A: the Donghu Lake → the South Lake → the Yezhi Lake → the Tangxun Lake → the Xunsi River (the Qingling River) → the Tangxun Lake Pumping Station (the Chenjiashan Gate) → the Yangtze River;

(2) Route B: the Donghu Lake → the South Lake → the Xunsi River → the Yangtze River;

(3) Route C: the Liangzi Lake → the Dongba River → the Tangxun Lake → the Xunsi River (the Qingling River) → the Tangxun Lake Pumping Station (the Chenjiashan Gate) → the Yangtze River;

(4) Route D: the Tangxun Lake → the Huangjia Lake → the Qingling Lake → the Yehu Lake → the Shili Channel → the Haikou Pumping Station → the Yangtze River.

The annual mean value of the sampling sites' water quality measured data in 2014 was set as the initial concentration. The target water quality of the Donghu Lake is Grade III, and it was set as the water quality of the water discharged from the Donghu Lake. According to GB3838-2002, the corresponding concentration of NH_3-N, TN and TP were 1.0 mg/L, 1.0

mg/L and 0.05 mg/L, respectively. The current water quality of the South Lake is worse than the Tangxun Lake, so the water from the South Lake should be treated to correspond with the standard of Grade III before it was discharged to the Tangxun Lake for fear that the water quality of the Tangxun Lake might be worse than before. The current water quality of the Liangzi Lake is Grade II, and it was set as the water quality of the water discharged from the Liangzi Lake. Similarly, the corresponding concentration of NH_3-N, TN and TP were 0.5 mg/L, 0.5 mg/L and 0.025 mg/L, respectively. The outflow boundary is determined by the normal water level of the lakes.

5.2 Connectivity scheme assessment

5.2.1 Hydrodynamic analysis

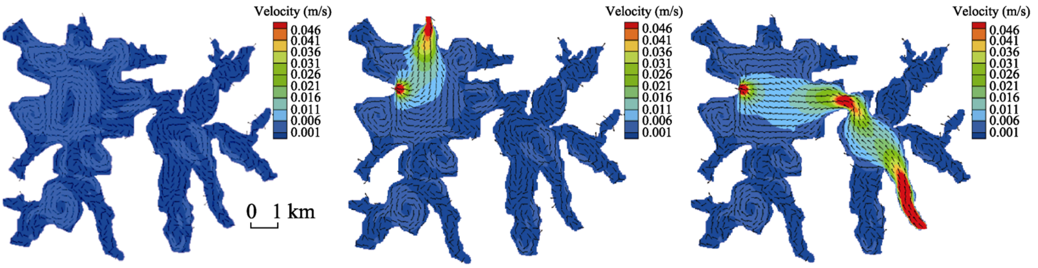
The hydrodynamic effects of the five schemes were simulated by the model set up in this study. The flow velocity of the Tangxun Lake group before and after water diversion is shown in Table 4. Before water diversion, the overall water liquidity of the lakes was weak. The mean flow velocity was 0.0015 m/s and the stagnant water ratio was 31.4%. After the diversion, the overall liquidity of the lake group improved to a certain degree. The mean and maximum flow velocity of the lake group increased, and the stagnant water ratio decreased obviously. More specifically, the mean flow velocity of both Scheme I and II is no more than 0.006 m/s, indicating that these two schemes have a little impact on the hydrodynamic process. As for Scheme V, the overall liquidity of the lake group improved greatly after the diversion. The mean flow velocity increased to 0.0087 m/s, and the stagnant water ratio decreased to 21.6%.

Table 4 The flow velocity and stagnant water ratio under different schemes

Schemes	Mean flow velocity (m/s)	Maximum flow velocity (m/s)	Stagnant water ratio (%)
Before diversion	0.0015	0.0065	31.4
Scheme I	0.0051	0.483	29.9
Scheme II	0.0056	0.690	24.8
Scheme III	0.0079	0.666	23.7
Scheme IV	0.0084	0.749	23.0
Scheme V	0.0087	0.743	21.6

The spatial distribution of the flow field in the Tangxun Lake was analyzed, as shown in Figure 6. At present, surface wind-forcing is the dominant factor that influences the water flow pattern of the Tangxun Lake. Before water diversion, there were numerous wind-driven circulations in the lake and the velocity was very slow (Figure 6a). For Scheme I, the improvement of the lake's water liquidity was not obvious (Figure 6b). Since the distance between the inlet and the outlet is short, the water replacement area is limited to the northwest of the lake. For Scheme II, the flow field distribution of the Tangxun Lake changed significantly. There was a directional water movement from the southeast near the inlet to the northwest near the outlet. By enhancing the water exchange and increasing the flow velocity, Scheme II had a positive impact on the lake, especially the areas near the inlet and outlet. However, there were some lake regions such as the south bay and the northeast bay that had no obvious changes. It was because these areas were so far from the inlet and outlet that it was hard for fresh water to reach there. Scheme III combined the water transfer routes of schemes I and II, which had more obvious impact on the water exchange of the lake. Scheme V added a water transfer route to connect the Huangjia Lake and Qingling Lake based on Scheme III. Compared with the other four schemes, the improvement of the lake's water liquidity under Scheme V was the most obvious and the water replacement area was the largest, indicating that additional water inlets and outlets can accelerate the water flow in lakes and reduce the area of stagnant water.

(a) Before diversion (b) Scheme I (c) Scheme II



(d) Scheme III (e) Scheme IV (f) Scheme V

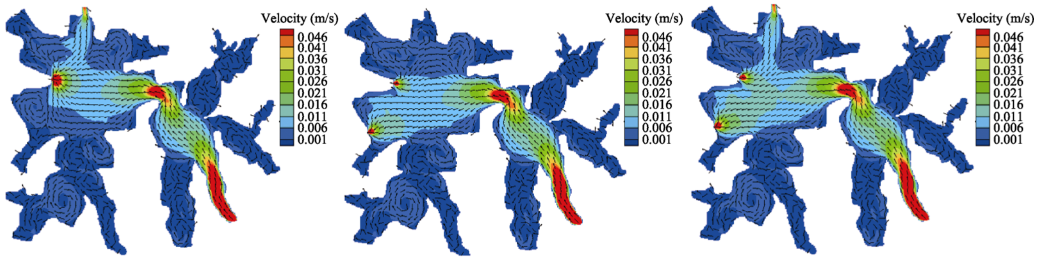


Figure 6 Spatial distributions of flow field under different schemes

5.2.2 Water quality analysis

The water quality of the Tangxun Lake, the South Lake, the Huangjia Lake, the Qingling Lake and the Yehu Lake under the five schemes was simulated. The results (Figure 7) show that the water standard exceeding ratio under Scheme I slowly increased with the diversion

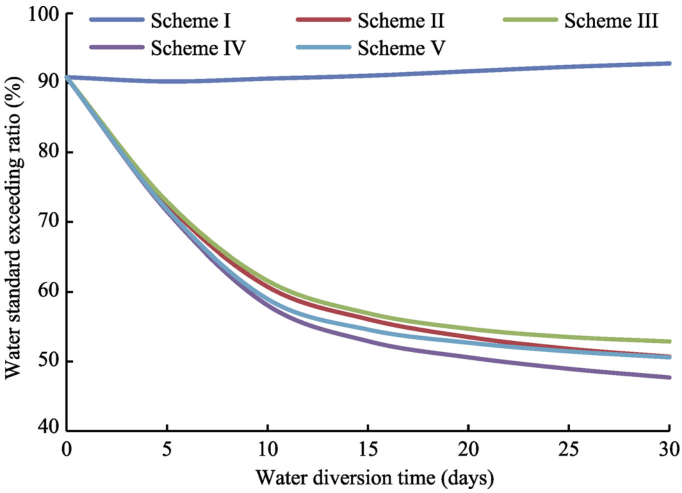


Figure 7 Time-variation of the water standard exceeding ratios of the Tangxun Lake under different schemes

time increasing, indicating that the water quality of the Tangxun Lake may become worse. For schemes II–V, the water standard exceeding ratio decreased with the diversion time increasing, and the decreasing range got smaller gradually. Specifically, the lake's water quality situation improved significantly 10 days after water diversion, and it tended to be stable 20 days later.

Furthermore, the water quality improvement rate, the concentration change index and the water quality category ratio of the lakes 20 days later after water diversion were analyzed, as shown in Table 5. It can be seen that the water quality in the South Lake improved obviously after the water was diverted from the Donghu Lake under Scheme I, and the water quality improvement rates of NH_3-N, TN and TP were 31.21%, 38.85% and 55.97%, respectively. The water standard exceeding ratio reduced from 98.03% before water diversion to 32.89%. Relatively, Scheme I had less effects on the water quality of the Tangxun Lake. For Scheme II, the water quality of the Tangxun Lake improved significantly. However, for the reason that Scheme II only diverted water from the Liangzi Lake and water can hardly flow to the South Lake located in the upstream of the Tangxun Lake, Scheme II almost had no effect on the water quality of the South Lake. Scheme III diverted water from both the Donghu Lake and the Liangzi Lake, and the water quality of both the South Lake and the Tangxun Lake improved significantly. The proportion of grades I–III increased obviously, and the proportion of Grade V and worse than Grade V decreased to some extent. Schemes IV and V were designed to connect the Tangxun Lake and the South Lake with the downstream lakes through the newly-built channels. As a result, the water quality of the Huangjia Lake and the

Table 5 Water quality of the Tangxun Lake group before and after IRSN under different schemes

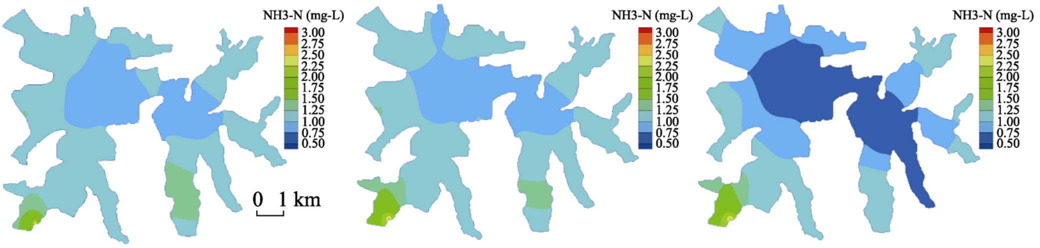
Schemes	Lakes	Water quality improvement rate (%)			Concentration change index	Water quality category ratio (%)				Water standard exceeding ratios (%)
		NH_3-N	TN	TP		I~III	IV	V	Worse than Grade V	
Before diversion	TXL	–	–	–	–	9.18	23.78	40.38	26.66	90.82
	SL	–	–	–	–	0	1.97	6.93	91.1	98.03
Scheme I	TXL	–1.32	12.54	10.81	0.078	8.33	49.97	23.89	17.8	91.67
	SL	31.21	38.85	55.97	0.543	4.57	62.54	16.4	16.49	32.89
Scheme II	TXL	16.51	31.42	30.63	0.305	46.49	28.69	13.98	10.84	53.51
Scheme III	TXL	15.85	33.5	32.43	0.321	45.31	31.48	13.37	9.83	54.69
	SL	31.21	38.85	55.97	0.543	4.57	62.54	16.4	16.49	32.89
Scheme IV	TXL	17.17	31.32	31.53	0.311	49.41	25.28	13.51	11.79	50.59
	HJL	21.52	14.87	51.72	0.366	6.91	15.25	43.45	34.39	93.09
	QLL	2.33	–1.6	–62.14	–0.298	21.03	19.03	29.74	30.2	78.97
	YL	27.71	2.13	36.57	0.264	0	33.33	50.6	16.07	66.67
Scheme V	TXL	16.04	32.65	31.53	0.313	47.31	28.66	12.93	11.1	52.69
	SL	31.21	38.85	55.97	0.543	4.57	62.54	16.4	16.49	32.89
	HJL	17.63	22.97	52.47	0.388	0.04	23.91	48.32	27.72	99.96
	QLL	2.37	–0.85	–62.03	–0.295	22.52	19.07	32.03	26.38	77.48
	YL	27.76	2.2	36.83	0.265	0	33.35	50.57	16.08	66.65

Note: TXL, SL, HJL, QLL and YL represent the Tangxun Lake, the South Lake, the Huangjia Lake, the Qingling Lake and the Yehu Lake, respectively.

Yehu Lake also improved after water diversion. Generally, the water quality of the Huangjia Lake was slightly worse than that of the Qingling Lake. For this reason, the water quality of the Qingling Lake deteriorated after water diversion.

The spatial distribution of the concentrations of NH_3-N, TN and TP in the Tangxun Lake under different schemes was analyzed, as shown in Figures 8–10. After water diversion, the enhancement of the lake's water liquidity accelerated the diffusion and degradation of pollutants. As a result, the water quality in most areas of the lake improved, while the improvement of water quality in the southern area of the lake was not obvious. Among these

(a) Before diversion (b) Scheme I (c) Scheme II



(d) Scheme III (e) Scheme IV (f) Scheme V

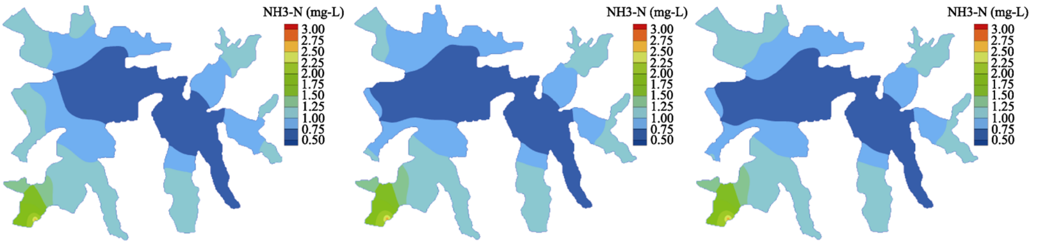
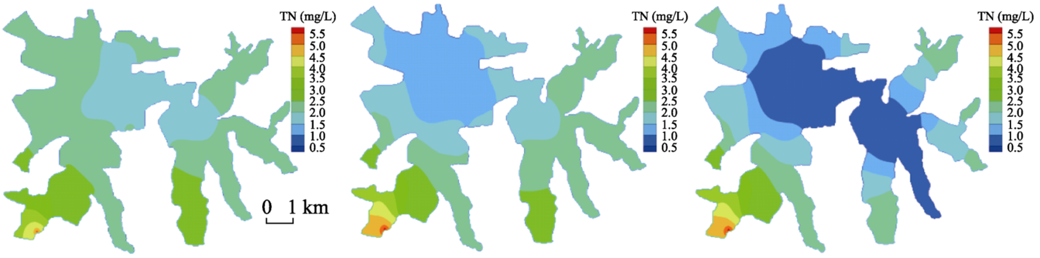


Figure 8 Spatial distributions of NH_3-N concentration 20 days later after the diversion under different schemes

(a) Before diversion (b) Scheme I (c) Scheme II



(d) Scheme III (e) Scheme IV (f) Scheme V

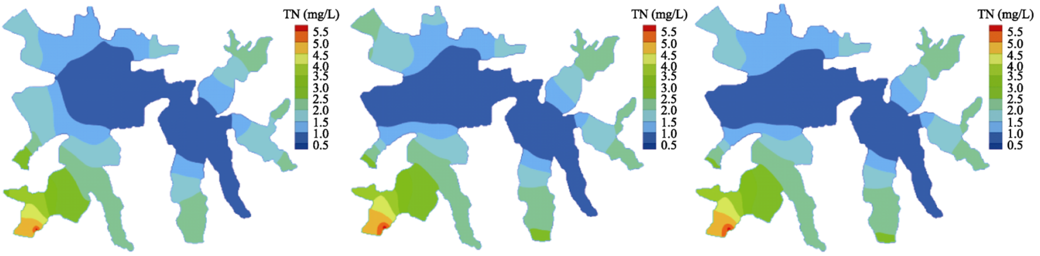


Figure 9 Spatial distributions of TN concentration 20 days later after the diversion under different schemes

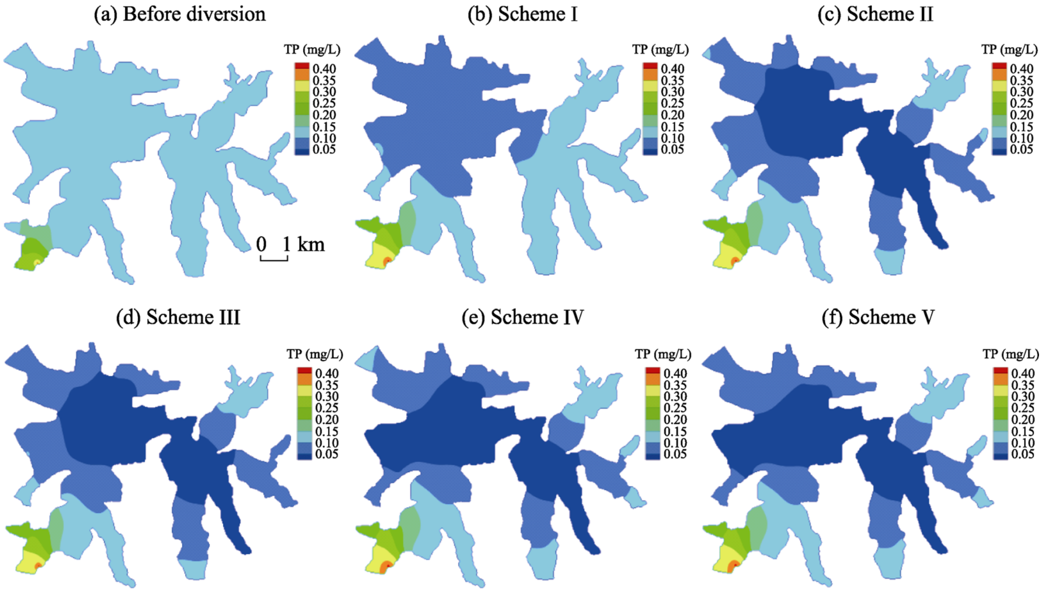


Figure 10 Spatial distributions of TP concentration 20 days later after the diversion under different schemes

five schemes, Schemes IV and V had the most obvious effects on the improvement of the lake's water quality. Under Scheme I, the scope of the regions where the water quality improved was smaller, and most of these regions were near the inlets and outlets of the water diversion routes.

Compared with the distribution of flow field, it is suggested that the water liquidity may have great effects on the water quality improvement. The improvement of water quality in the regions with larger flow velocity was more obvious, such as the regions near the water transfer inlets and outlets. However, there was only a slight change of water quality in the southern part of the lake due to the long distance to the inlet and outlet. In these regions, the water replacement rate was low and the water liquidity was still weak. What was worse, the concentrations of the NH_3-N, TN and TP in the southwest of the Tangxun Lake increased due to the continuous sewage discharge from the two sewage outlets.

5.2.3 Water diversion benefits assessment

Setting up more water inlets can effectively improve the lakes' water quality, while the costs will increase correspondingly. In this paper, the cost and benefit evaluation method was used to evaluate the feasibility of different schemes. According to the simulated pollutants of the five lakes before and after water diversion, relevant indexes were calculated via Eqs. 8–11, as shown in Table 6. It can be seen that the net benefits of the five schemes are all greater than 0, indicating that all these five schemes are feasible. Schemes III and V diverted water from the Donghu Lake and the Liangzi Lake simultaneously, which has a remarkable effect on reducing the pollutant concentration and can bring enormous economic benefits. In general, the net benefits of Scheme V are approximate 155.98×10^4 yuan, which is the most among all the schemes.

5.2.4 Optimal connectivity scheme

In order to determine the optimal connectivity scheme, indexes from the aspects of water hydrodynamics, water quality and socioeconomics were chosen as the evaluation indexes, and then a comprehensive evaluation system was established. The mean flow velocity and stagnant water ratio were selected to evaluate the hydrodynamics of the lakes. The water quality improvement rate and the concentration change index were selected to evaluate the water quality. The net benefits were selected as the socioeconomic indicator.

Table 6 Benefits and investments under different schemes

Schemes	Total flow discharge (m^3/s)	Water pollutants (kg)			Economic benefits ($\times 10^4$ yuan)	Costs ($\times 10^4$ yuan)	Net benefits ($\times 10^4$ yuan)
		NH_3-N	TN	TP			
Before diversion	–	133821.2	212388.9	18383.1	–	–	–
Scheme I	40	119334.1	174779.1	14984.7	203.33	117.50	85.83
Scheme II	40	122782.3	167619.4	16223.4	193.62	117.50	76.11
Scheme III	80	107856.8	144923.0	13418.5	355.11	235.01	120.11
Scheme IV	40	119391.0	165971.8	14044.5	234.05	117.50	116.54
Scheme V	80	105319.4	143262.0	11252.8	390.99	235.01	155.98

It can be seen from the evaluation results (Table 7) that the lakes under Scheme V have the largest mean flow velocity and the lowest stagnant water ratio. In addition, the lakes under Scheme V have the largest water quality improvement rate and the largest concentration change index. As for the aspect of the socio-economic indexes, it is still Scheme V that can bring the most net benefits. Moreover, Scheme V can improve both the hydrodynamic condition and the water quality condition of the six lakes simultaneously by diverting water from the Donghu Lake and the Liangzi Lake. In summary, Scheme V is chosen as the optimal scheme.

Table 7 Comprehensive evaluation results of the five schemes

Schemes	Hydrodynamic evaluation indexes		Water quality evaluation indexes				Socio-economic index
	Mean flow velocity (m/s)	Stagnant water ratio (%)	Water quality improvement rate (%)			Concentration change index	Net benefits (million)
			NH_3-N	TN	TP		
Scheme I	0.0051	29.9	2.85	12.66	13.57	0.114	85.83
Scheme II	0.0056	24.8	10.61	20.19	19.68	0.196	76.11
Scheme III	0.0079	23.7	13.88	26.13	27.46	0.271	120.11
Scheme IV	0.0084	23.0	14.23	21.61	19.9	0.213	116.54
Scheme V	0.0087	21.6	16.78	28.02	26.62	0.281	155.98

6 Conclusions and discussion

In this paper, a comprehensive evaluation system based on evaluation indexes from the aspects of water hydrodynamics, water quality and socioeconomics was established to evaluate the IRSN effects of the lakes. A 2-D hydrodynamic and water quality model was built to simulate the flow field and water quality. We took IRSN of the Tangxun Lake group as a case study and assessed five connectivity schemes using this evaluation system. The main conclusions can be generalized as follows:

(1) The comprehensive evaluation method was successfully applied to assess the five

schemes of the IRSN project. Scheme V has the most significant improvement in both hydrodynamics and water quality and bring the most economic benefits. It is demonstrated that setting up more water inlets and outlets can accelerate water exchange and reduce the stagnant water area in lakes.

(2) The water diversion of the IRSN can improve the lakes' water environment effectively by improving water mobility to enhance the pollutant diffusion and degradation. The hydrodynamics and water quality conditions of the lakes improved obviously at the initial ten days of the water diversion. As the water quality becomes better, the improvement rate gradually decreased with the further water diversion, which was consistent with the previous studies (Liu J M *et al.*, 2014; Bi, 2014).

In this paper, we further develop the calculation process of the cost and benefit evaluation method (Liu J M *et al.*, 2014). Instead of using traditional sewage treatment charge method to calculate the pollution abatement costs, we adopted the PCSC method and utilized the concept of pollution equivalent with consideration of multiple pollutants. Moreover, traditional methods (Liu J M *et al.*, 2014) estimated the operating costs per flow discharge with the existing pump station as the reference, but there had not been any specific quantitative calculation method. This study presents a quantitative method to calculate the operating costs per flow discharge based on its relationship with the pump station head and the electricity price, which can provide a more reliable support for the calculation of the operating costs.

The IRSN will change the flow pattern and water quality of lakes, thus changing the living environment of aquatic ecosystems including aquatic plants, phytoplankton, zooplankton and zoobenthos (Xia *et al.*, 2012; Liu B J *et al.*, 2014). In the future research, we also need to consider the water ecosystem into our evaluation system. It is necessary to combine the water ecological model with the hydrodynamic and water quality model to assess the benefits from the IRSN projects.

The connectivity has become an important indicator of river health and water resources utilization (Wu *et al.*, 2007; Xia *et al.*, 2012). The essence of maintaining water connectivity is to maintain the liquidity and continuity of water in rivers and lakes, so as to enhance the lakes' self-recovery ability and realize the long-term health and stability of the lakes. In the implementation process of the IRSN projects, it is essential to take some other measures such as ecological restoration and sewage interception project at the same time to achieve the purpose of improving the lakes' ecological environment comprehensively.

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