Water transparency distribution under varied currents in the largest river-connected lake of China
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ABSTRACT
Water transparency is an important ecological indicator for shallow lakes. The largest shallow lake, Poyang Lake, as well as the most typical river-connected lake in China was selected as the research area. In view of the complicated water-sediment conditions induced by its frequent water exchange with external rivers, the dominant factors driving water transparency were determined against the field investigated data from 2003 to 2013 and a specific driving function was established. A numerical model coupling suspended sediment, Chl-a and chemical oxygen demand was developed and validated, and the spatial water transparency distributions under three typical current structures in Poyang Lake, Gravity-style, Jacking-style and Backflow-style, were quantitatively estimated. The following results stood out: water transparency in the lake varied distinctly with the current status; Backflow-style current was basically characterized by the lowest water transparency, while that under Jacking-style was the highest due to the lower sediment carrying capacity. In some outlying regions in the lake, where the water current is hardly influenced by the mainstream, the water transparency was always kept at a stable level.

INTRODUCTION
Water transparency is the distance from water surface to the invisible–visible position of a Secchi Disc, which not only describes the turbidity degree but also indicates the eutrophication level (Zhang et al. 2003; Naumenko 2007). Water transparency contributes to maintain the health and stabilization of water environment, as well as the aquatic ecosystem (Gordon & Brown 1972). Nevertheless, due to the intensive soil erosion, enhanced anthropogenic pollutant and accelerating water eutrophication, a decreasing trend of water transparency is observed in many lakes in recent years (Zhang et al. 2003; Li 2006). The reduced water transparency can affect the photosynthesis process of floating and submerged plants, change the community structure of aquatic animals, and harm the ecological balance by weakening the underwater light intensity. Water transparency is closely related to a combination of a series of environmental factors including optical attenuation, water physicochemical properties and water body compositions such as suspended particles, phytoplankton, and dissolved organic matters (Kirk 1994; Li 2006).

Given the different environmental characters in different lakes and the varied dominant factors involved in transparency fluctuation, it is hard to conduct a quantitative study to investigate the driving mechanisms of water transparency. So far, the concern on water transparency has not got broad attention. Since the late 1970s, several researchers have carried out some related works (Jonasz & Prandke 1986; Hall & Rao 1997), which provided useful information to learn the changing principles of transparency. However, most of them were traditionally performed by simple analyzing and there are still two points that have been less focused. First, the present results were generally conducted based on limited field data and suffered from not explicitly establishing a driving function for water transparency. Due to the coarse sampling frequencies and limited sampling points, it is difficult to comprehend the temporal and spatial transparency distribution for an entire water body, which are usually featured by environmental characters that are uneven in both time and space scales. Moreover, most of these studies basically aimed at isolated lakes, of which the environment characters were relatively stable, and few attention has been paid to river-connected lakes. Compared to an isolate lake, lakes of this kind are always characterized by more
complicated environmental features due to the frequent water volume and material exchange with the external rivers, such as the uneven distributed water current, wide water level fluctuation, short water age and high suspended sediment (SS) concentration (Yuan et al. 2011; Wang et al. 2014). These factors always result in a high frequency of ecological properties in river-connected lakes and make more uneven the distribution of water transparency in time and space scales. A quantitative insight into the driving mechanism of water transparency in this kind of lakes can merit the effective use of the lake landscape function, promote the restoration of aquatic community structure, and contribute to keeping the lake ecological balance.

Here, Poyang Lake, the largest freshwater lake as well as the most typical river-connected lake in China, was selected as the research area. The lake is one of the most important ecological regions recognized by the Global Natural Fund and is the important habitat for the endangered Siberian crane as more than 95% of its world population congregates here during the winter (Han et al. 2015; You et al. 2015). However, the water transparency decrease in recent years is accelerating the aquatic ecosystem degradation in Poyang Lake, and is correspondingly threatening the habitat conditions in dry seasons. The objectives of this work were to (1) explore the relationships between water transparency and different environmental factors such as SS, Chl-a and chemical oxygen demand (COD), based on the field monitored data and extract a specific driving function for water transparency in Poyang Lake, (2) develop and validate a numerical model that can yield realistic and accurate simulations of water transparency in Poyang Lake, and (3) simultaneously show water transparency distribution covering the whole lake under different flow structures, which are induced by the uneven water exchange between Poyang Lake and the external rivers. This study may provide references for policy makers who are attempting to prevent ecological degradation and improve the water quality of river-connected lakes.

METHODS AND MATERIALS

Research area

Poyang Lake (115°50'-116°44' E, 28°25'-29°45' N), the most typical river-connected lake in China, plays an important role in maintaining regional water balance and ecological safety (Ma et al. 2005; Luo et al. 2008; Sun et al. 2010). The lake is located in the north of Jiangxi Province and

Figure 1 | Location of the research area.
the southern bank of the Yangtze River (Figure 1). Due to the specific location Poyang Lake is a distinct seasonal lake with high water fluctuations, which regulates the water volume from the upper main five rivers, Gan River, Fu River, Xin River, Rao River and Xiu River, to the downstream Yangtze River (Wang et al. 2015). Overall, the lake can be divided into the north part and the south part. The former is a waterway-like lake directly connected to the external Yangtze River, of which the size is 40 km in length, 5–5 km in width, and 2.8 km at its narrowest; the south part is the main lake, of which the size is 133 km in length and 74 km at its widest (Wu et al. 2007; Gao et al. 2014). Both the water area and the storage of the lake vary evidently with seasons. The multi-year average water level of Poyang Lake is about 13.30 m, and the corresponding water area and volume were respectively 2,291.9 km² and 2.1 × 10⁹ m³. The annual rainfall in Poyang Lake is about 1,652 mm, which was mainly concentrated from March to August, accounting for about 74.4% of the total (Liu & Rosier 2008; Volpe et al. 2011; Cui et al. 2015). Referring to the field monitored data before 2003, water quality in the lake could meet grade III of China National Surface Water Environmental Quality Standards. Nevertheless, in the recent decade, a remarkable water quality deterioration has been observed in the lake due to the regional acceleration of industrialization and urbanization (Lu et al. 2012). As one of the quality indicators, water transparency in the lake is deservedly faced with a marked decline, which weakens the underwater light intensity, hinders the photosynthesis of submerged plants, and accelerates ecological degradation in the lake.

Field investigation

The materials dominating underwater light intensity and spectral distribution in shallow lakes can be classified to the following three items (Bricaud et al. 1981; Kirk 1994): (1) suspended substance, mainly composed of inorganic suspended particles and organic detritus produced by death phytoplankton; (2) phytoplankton, including different types of planktonic algae; (3) chromophoric dissolved organic matter (CDOM), made up of humic acid and aromatic polymer (Brezonik & Arnold 2011; Patrick et al. 2014). Due to the frequent water exchange between Poyang Lake and the external rivers, the suspended substance in Poyang Lake is mainly featured by SS. CDOM is a kind of inert material in water body, which is always conservative, especially in marine circumstances. However, in inland lakes, as a result of the relatively higher suspended material content, CDOM usually cannot play an evident role in light attenuation. In view of the complicated chemical composition of CDOM and the high difficulties in extraction and determination, in the present work, we determined COD index for evaluation instead (Su et al. 2003). Besides the above three main factors, water transparency can also be indirectly affected by some other environmental characters such as pH, total nitrogen (TN) and total phosphorus (TP). For example, under the situation of high pH value, phosphate will be easily transformed to insoluble tricalcium phosphate and Fe₃⁺ will be simply formed to Fe (OH)₃ suspending in the water body. High concentration of TN and TP can accelerate algae proliferation, which may to some extent generate a decrease in water transparency.

Since varied factors are involved in water transparency, we aimed to explore the relationships between water transparency and the factors of SS, Chl-a, COD, TN, TP, and pH, according to the regular and random investigated data at 19 points in Poyang Lake from 2003 to 2013 (Figure 2). In field monitoring, water samples were collected by sediment horizontal sampler at the depth of 50 cm under water surface. Samples for SS, TP, TN, COD and Chl-a were transported promptly to the laboratory following the required standard steps. Determination of the concentrations were conducted according to the ‘Monitoring and Analysis Method of Water and Waste Water’ and ‘Criterion of Investigation on Lake Eutrophication (Second Edition)’ in China. SS, Chl-a, COD, TN, TP were respectively measured by filtrating and weighing method, spectrophotometry, dichromate method, alkaline potassium persulfate oxidation-UV spectrophotometric method and ammonium molybdate spectrophotometric method. pH and water transparency were measured in the field, respectively, by portable water quality detecting instrument and Secchi Disc (Φ20 cm).

Numerical model

Water transparency is a status index influenced by the combination of several characters. The numerical description for these factors is an important foundation for water transparency simulation. Given the complicated hydrodynamic conditions in Poyang Lake, a 2-D unsteady model coupling water flow, water quality, SS and algae growth was developed for water transparency simulations.

Governing equations

Water current and water quality. The conservation forms of the 2-D shallow water equations and the convection-diffusion
equations can be written as follows \((Li & Yao 2015; Li et al. 2015):\)

\[
\begin{align*}
\frac{\partial h}{\partial t} &+ \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \\
\frac{\partial (hu)}{\partial t} &+ \frac{\partial (hu^2 + gh^2/2)}{\partial x} + \frac{\partial (huv)}{\partial y} = gh(s_{ax} - s_{fx}) \\
\frac{\partial (hv)}{\partial t} &+ \frac{\partial (hv^2 + gh^2/2)}{\partial y} = gh(s_{by} - s_{fy}) \\
\frac{\partial (hC)}{\partial t} &+ \frac{\partial (huC)}{\partial x} + \frac{\partial (hvC)}{\partial y} = \frac{\partial}{\partial x} \left( E_x h \frac{\partial C}{\partial x} \right) \\
&+ \frac{\partial}{\partial y} \left( E_y h \frac{\partial C}{\partial y} \right) - KhC + Sc
\end{align*}
\] (1)

where \(h\) is the water depth, \(t\) is the time, \(u\) and \(v\) are the depth-averaged velocity components in the \(x\) and \(y\) directions, \(g\) is the acceleration of gravity, \(s_{ax}\) and \(s_{fx}\) are the bed slope and friction slope in the \(x\) direction, \(s_{by}\) and \(s_{fy}\) are the bed slope and friction slope in the \(y\) direction, \(E_x\) and \(E_y\) are the dynamic pollutant dispersion coefficients in the \(x\) and \(y\) directions, \(k\) is the degradation coefficient, \(C\) is the depth-averaged concentration, and \(Sc\) is the source-sink vector.

SSs transport model. The general SS transport equation is as follows:

\[
\begin{align*}
\frac{\partial (hS)}{\partial t} &+ \frac{\partial (huS)}{\partial x} + \frac{\partial (hvS)}{\partial y} = \frac{\partial}{\partial x} \left( D_x^h \frac{\partial S}{\partial x} \right) \\
&+ \frac{\partial}{\partial y} \left( D_y^h \frac{\partial S}{\partial y} \right) + E - D
\end{align*}
\] (2)

where \(S\) indicates suspended sediment concentration, \(D_x^h\) and \(D_y^h\) are the dynamic dispersion coefficients for the suspended particles in the \(x\) and \(y\) directions, \(E\) is the amount of sediment raised from the riverbed and \(D\) is the amount of deposited sediment, \(E - D\) is then the source-sink vector for the SSs which can be expressed as \((Fan 2009; Francisco 2014):\)

\[
E - D = \alpha \omega (S^* - S)
\] (3)

where \(\alpha\) is the restoration-saturation coefficient, \(S^*\) is the sediment-carrying capacity of the water, and \(\omega\) is the settling velocity.
Algae growth model. The algae growth model can be written as follows:

\[
\begin{aligned}
\frac{\partial (hN)}{\partial t} + \frac{\partial (huN)}{\partial x} + \frac{\partial (hwN)}{\partial y} &= \frac{\partial}{\partial x} \left( D^e_x \frac{\partial N}{\partial x} \right) \\
&\quad + \frac{\partial}{\partial y} \left( D^e_y \frac{\partial N}{\partial y} \right) + S_N \\
\frac{\partial (hP)}{\partial t} + \frac{\partial (huP)}{\partial x} + \frac{\partial (hwP)}{\partial y} &= \frac{\partial}{\partial x} \left( D^e_x \frac{\partial P}{\partial x} \right) \\
&\quad + \frac{\partial}{\partial y} \left( D^e_y \frac{\partial P}{\partial y} \right) + S_P \\
\frac{\partial (hC_{chl-a})}{\partial t} + \frac{\partial (huC_{chl-a})}{\partial x} + \frac{\partial (hwC_{chl-a})}{\partial y} &= \frac{\partial}{\partial x} \left( D^e_x \frac{\partial C_{chl-a}}{\partial x} \right) \\
&\quad + \frac{\partial}{\partial y} \left( D^e_y \frac{\partial C_{chl-a}}{\partial y} \right) + S_{chl-a}
\end{aligned}
\]  

(4)

where \( N, P \) and \( C_{chl-a} \) are the depth-averaged concentrations of the total nitrogen, total phosphorus and Chl-a; \( D^e_x \) and \( D^e_y \) are the dynamic dispersion coefficients for \( N \) in the \( x \) and \( y \) directions; \( D^p_x \) and \( D^p_y \) are the dynamic dispersion coefficients for \( P \) in the \( x \) and \( y \) directions; \( D^i_x \) and \( D^i_y \) are the dynamic dispersion coefficients for Chl-a in the \( x \) and \( y \) directions; \( S_N, S_P, S_{chl-a} \) are the source-sink vectors for \( N, P \) and Chl-a:

\[
\begin{aligned}
S_N &= R_N - SED_N + C_N - U_N, \\
S_P &= R_P - SED_P + C_P - U_P, \\
S_{chl-a} &= (\mu - sed - d)C_{chl-a}
\end{aligned}
\]

where \( R_N \) and \( R_P \) are the amounts of nitrogen and phosphorus released from the sediment, \( SED_N \) and \( SED_P \) are the amount of deposited nitrogen and phosphorus, \( U_N \) and \( U_P \) are the amount of nitrogen and phosphorus absorbed by the algae, \( C_N \) and \( C_P \) are the additional loads on nitrogen and phosphorus sources induced by the algae catabolism, and \( \mu, sed \) and \( d \) are the algae growth, deposition and loss rates.

Model numerical solution

The water flow, water quality, SS and algae growth equations could be solved by combining the Equations (1), (2) and (4) into the following general form (Zhao et al. 1994, 1996, 2000):

\[
\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{f}(q)}{\partial x} + \frac{\partial \mathbf{g}(q)}{\partial y} = \mathbf{b}(q)
\]

(5)

where \( \mathbf{q} \) is the vector of the conserved physical quantities; \( \mathbf{f}(q) \) and \( \mathbf{g}(q) \) are the flux vectors in \( x \) and \( y \) directions, and \( \mathbf{b}(q) \) is the source-sink vector.

\[
\begin{aligned}
\mathbf{f}(q) &= (h, hu, hv, hC, hS, hN, hP, hC_{chl-a})^T \\
\mathbf{g}(q) &= (hv, huv, hvS, hvN, hvP, hvC_{chl-a})^T
\end{aligned}
\]

The equations were solved by the finite volume method on an unstructured grid and the flux vector splitting scheme was used to calculate the normal fluxes of the variables across the interfaces between elements. Detailed calculation steps were documented in the references (Hu & Tan 1995; Ding et al. 2006).

Calculation schemes

Influenced by the hydrological condition variation of outer rivers, Poyang Lake is markedly characterized by high frequency water currents, which results in the fluctuations of environmental characters, and generates an uneven spatial distribution of water transparency. Here, the three typical current structures in Poyang Lake were determined for environmental characters, and generates an uneven spatial distribution of water transparency. Here, the three typical current structures in Poyang Lake were determined for evaluation. Gravity-style current is the most popular flow status in the lake, under which the water current is basically driven by gravity and the upper five rivers flow into Poyang Lake while the lake water flows out to the downstream Yangtze River. In case of the second Jacking-style current, the upstream rivers normally flow into the lake. But the higher water level of downstream Yangtze River prevents the outflow from the lake, and the lake water in the connecting region between the lake and the Yangtze River is kept at a relatively stable status, which to some extent reduces the water currents in the main lake. The third Backflow-style current is always observed with the continually increasing water level of Yangtze River. When the Yangtze River level is above that in the lake,
water will flow back to Poyang Lake from the Yangtze River, and in this situation, the inflow from the upstream five rivers is always remarkably decreased. The Gravity-style current is always equipped with a stronger disturbance in the main lake with the average velocity being 0.85 m/s, while that under Jacking and Backflow-style current, are respectively reduced to 0.25 m/s and 0.18 m/s. In case of the Backflow-style current, a strong contrary current can be observed in the connecting region between the lake and the Yangtze River. Figure 3 has shown the three water currents in a normal-water year.

RESULTS

Field relationships between water transparency and environmental factors

Based on the long-term field investigated data, the relationships between water transparency and the environmental factors in Poyang Lake were shown in Figure 4. The principles that water transparency responses to SS can be separated into three easily distinguished sections. When SS concentration was lower than 50 mg·L⁻¹, water transparency could reach 80 cm to 100 cm. As SS was increased between 60 mg·L⁻¹ and 90 mg·L⁻¹, the water transparency fluctuated approximately from 35 cm to 62 cm, and no distinct relationship was detected. Nevertheless, after the SS concentration was continually enhanced to 90 mg·L⁻¹–150 mg·L⁻¹, the transparency was markedly reduced to 12 cm–25 cm. Overall, a negative correlation between SS and water transparency can be observed. The impacts of Chl-a on water transparency can also be divided into three districts. With the concentration being less than 3.5 mg·m⁻³, water transparency was basically maintained above the level of 50 cm. After it was increased between 3.5 mg·m⁻³ and 8.0 mg·m⁻³, water transparency was declined to about 45 cm, and it did not show obvious departure from the mean level in this range. A marked drop of water transparency can be detected when the Chl-a concentration was higher than 8.0 mg·m⁻³, and the mean level was approximately 30 cm under this situation. The field data could indicate that water transparency in Poyang Lake displayed a stepwise reduction trend with COD increase. When COD concentration was lower than 5.0 mg·L⁻¹, the water transparency could be generally kept from 40 cm to 80 cm. However, with the concentration being increased above 8.0 mg·L⁻¹, the transparency was cut down to 20 cm–30 cm, evidently. Relative to the above factors, the water transparency in Poyang Lake showed no obvious correlation with TN and TP. Based on the studied data, TN and TP concentration respectively ranged from 0.18 mg·L⁻¹ to 4.28 mg·L⁻¹ and from 0.009 mg·L⁻¹ to 0.18 mg·L⁻¹, while the water transparency randomly fluctuated between 10 cm and 100 cm. This phenomenon could suggest that TN and TP are not the dominant driving factors for water transparency, but they may indirectly affect water transparency by adjusting the nutrient conditions for algae growth. All the investigated values of pH were basically maintained within 6.5 to 8.5, and the water transparency data exhibited a free departure from each other. No distinct correlation was observed between pH and water transparency in Poyang Lake.

Figure 3 | Sketch of the typical three current structures in Poyang Lake.
Water transparency driving function

The correlation coefficients between water transparency and the factors were calculated to establish the driving function of water transparency in Poyang Lake, which was shown in Table 1. It demonstrated that water transparency in Poyang Lake was in significant negative relevance with SS and the correlation coefficient was 0.628. Chl-a and COD did not play the evident role as well as SS, but the relationships were still at a relatively higher level and the coefficients were respectively 0.326 and 0.358. Correlation coefficients between water transparency and TN, TP, and pH were characterized at lower levels, of which the values were separately 0.126, 0.105 and 0.023. Referring to the results, we generalized the dominant driving factors on water transparency in Poyang Lake to SS, Chl-a and COD. To reflect the integrated impacts, the multiple regression driving equation for transparency was established by SPSS software.

| Correlation coefficients between water transparency and the environment factors |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|                 | SD               | SS               | COD              | Chl-a            | TN               | TP               | pH               |
| SD              | 1                | -0.628<sup>a</sup> | -0.358<sup>b</sup> | -0.326<sup>b</sup> | -0.126           | -0.105           | -0.023           |
| SS              |                   | 1                | -0.036           | 0.207            | 0.122            | 0.103            | 0.082            |
| COD             |                  |                | 1                |                  | 0.158            | 0.181            | 0.087            |
| Chl-a           |                  |                |                  | 1                | 0.462<sup>b</sup> | 0.615<sup>a</sup> | 0.229<sup>b</sup> |
| TN              |                  |                |                  |                  | 1               |                  |                  |
| TP              |                  |                |                  |                  |                 | 1               |                  |
| pH              |                  |                |                  |                  |                 |                 | 1               |

<sup>a</sup>Indicates significance level of 1%.
<sup>b</sup>Indicates significance level of 5%.
according to the measured data, which was shown as follows:

\[
SD = 21.54/SS + 0.385/COD - 0.209Chl-a \\
- 0.059(R = 0.855, \; P < 0.001)
\]  
(7)

where SD is water transparency, m; SS is the suspended sediment concentration, mg·L⁻¹; COD is the concentration of chemical oxygen demand; Chl-a is the concentration of chlorophyll-a. R is the relevance level; P is the significance level.

Model calibration and verification

The model was calibrated against the sequent field measured data at eight points from January to September in 2012. Simulation area includes the downstream Yangtze River, the upstream five rivers, and the Poyang Lake. With Gambit software, the lake was divided into 6,239 quadrilateral elements and 7,533 nodes according to the terrain characteristics. The mean element size was 700 × 700 m. The inflowing boundaries were the upstream five rivers, and the downstream Yangtze River was set as the outflow boundary. The boundary data including water level, water quality, SS and Chl-a concentration were determined according to the measured data gained from the Yangtze River Hydrology Bureau and Jiangxi Province Hydrology Bureau. The roughness coefficients were arranged between 0.01 to 0.035 and the wind drag coefficient was determined with \(1.0 \times 10^{-3}\). The sediment diffusion coefficients in x and y directions were respectively 0.1 m²·s⁻¹ and 1.0 m²·s⁻¹, and the horizontal eddy viscosity coefficient was \(0.5 \times 10^2\) cm²·s⁻¹. In the lake area, the north wind was detected with a dominant frequency and the average wind speed of \(3.01\) m·s⁻¹ at 10 m above the water surface was taken for calculation. During simulation, the outer solar radiation was considered the same to shield the influence of light intensity on water transparency. The time step was taken as 0.1 s to maintain the stability and precision for simulation. The results showed that the calculated data could agree well with the measured value, and the relative errors were basically between 10% and 18% (Figure 5). Considering the inevitable discrepancy between the numerical model and actual conditions, the observation error of field investigated results, and the frequently fluctuated environmental factors in Poyang Lake, the above deviation were acceptable to conduct numerical simulations in Poyang Lake. The relative error was basically in line with the prior evidences of Wang et al. (2014) and Wang et al. (2016). The model is capable of reflecting the dynamic processes of water transparency in Poyang Lake.

DISCUSSION

Based on the calculated results, the water transparency distributions in Poyang Lake under different current structures were shown in Figure 6. In general, water transparency in Poyang Lake was unevenly distributed, and the currents have an evident consequence for the transparency fluctuation covering the lake.

(1) Under gravity-style current, the average water transparency in the south lake was about 61.3 cm, but in the inlet area of Fu River south branch the transparency was observed at lower level of 18.5 cm for high SS concentration. The middle of the southernmost lake was characterized by the best water transparency of 72 cm to 75 cm because it is located in the coccygeal end region of the lake and the water disturbance was notably reduced. The same case was detected in the area located to the north of Xiu River, where the transparency could reach 71.5 cm. Since the Gan River south branch, Fu River west branch and Xin River were integrated in the joint area of south lake and middle lake, water transparency here was lower than that in other districts of the south lake, for the strong water current enhanced sediment suspension, of which the average level was 42.5 cm. For the expanded flow section in the middle lake, the weakened water current cut down the water sediment carrying capacity and strengthened the deposition processes, which played an accelerating role in transparency improvement. But the step-down water velocity also contributed to algae growth reducing the water transparency. The average level ranged from 63 cm to 68 cm. The north lake, where the flow section was narrow and the current intensity was apparently increased, was directly connected to the Yangtze River and the water transparency was approximately 59.5 cm. In the joint area of the north and middle lake, the transparency was evidently reduced to 40.3 cm because the flow section was changed here and the stable current from the middle lake was intensified rapidly, which resulted in a high volume of SS.

(2) In terms of the Jacking-style current, the north lake and the Yangtze River were basically characterized with the same water level. Due to the reduced water disturbance, the water transparency was improved generally than
that under the Gravity-style. For example, water transparency in the south lake was increased to 65.8 cm, increased by 7.35% than that under Gravity-style. The most distinct transparency improvement was observed in the joint area of the south lake and middle lake with the average value rising by 54.1% to 65.5 cm. Since water in the middle lake could not be easily transported out to the Yangtze River, the sediment
deposition process was enhanced and the water transparency went up between 65 cm and 72 cm. Due to the jacking impacts, an obvious dividing line could be detected in the middle lake. The transparency in the north area of the line was about 3 to 5 cm less than that in the south. The reasons for this might be generalized to the following two points: firstly, the south of the dividing line was the main lake, where the sediment carrying capacity was reduced and the water environment carrying capacity was adequate, both the lower sediment concentration and better water quality contribute to transparency improvement. Secondly, directly connected to the Yangtze River, the north lake was to some extent affected by the external water quantity with higher SS concentration, which reduced the water transparency.

(3) Under the situation of backflow-style current, the higher Yangtze River level resulted in a strong back flow from the river to the lake. The water transparency in the north lake was remarkably reduced than that in the former two conditions. Take the inlet areas of Xiu River and Gan River north branch, for example. The transparencies in this region under the flow structures of Gravity-style and Jacking-style were respectively 60.2 cm and 71.5 cm. Nevertheless, due to influence of the water volume from the Yangtze River, the transparency here was evidently reduced to 48.5 cm in the backflow-style situation, separately decreased by 19.4% and 32.2% than that in other two schemes. Water transparency in the south lake under backflow-style current was close to that under Gravity-style, whereas the values in the middle lake was, to an obvious extent, reduced than that under Gravity-style and Jacking-style. In the inlet area of Rao River under the previous two conditions, the water transparencies were respectively 63 cm and 70 cm, but in the Backflow-style current it dropped to 58 cm.

Water transparency in Poyang Lake varied remarkably under different flow conditions. The Backflow-style current structure was characterized by the lowest water transparency, and in the Jacking-style situation the water transparency basically reach the best level. Some regions located in the coccygeal end of the lake were detected with a steady water transparency because the water currents in these area were relatively independent and less influenced by the outer flow.

CONCLUSION

Unlike an isolated lake, river-connected lakes are always featured with frequently fluctuated environmental characters and more complicated water transparency changing mechanisms. In the present work, we selected Poyang Lake, the largest and most typical river-connected lake in China, to conduct a case study. Based on long-term field
investigated data, the relationships between water transparency and some environment factors were analyzed and the dominant items of SS, Chl-a and COD were determined to establish a driving function for water transparency in the Lake. The function was incorporated to develop a coupled model and the most typical three water structures, Gravity-style, Jacking-style, and Backflow-style current, were selected for numerical study. The results showed that the water transparency in Poyang Lake markedly varied with the current status. Water transparency under the Backflow-style current was detected at the lowest level, whereas the Jacking-style was characterized by the best water transparency. Due to the independent flow, the transparency in some coccycgeal end area of the lake was basically kept at a stable level. This work will provide an important guidance for water quality protection and ecological restoration in Poyang Lake and, hopefully, encourage large-scale and long-term water transparency research on river-connected lakes. However, there are several uncertainties that may need further exploration. First, at the present work, the driving factors for water transparency were generalized to the three items, SS, Chl-a and COD, but in field conditions, the factors are not limited to this. It would be better to negotiate more water quality parameters, such as temperature, metal ions and the biomass of submerged aquatic plants, to give a more accurate simulation. Furthermore, water transparency is an important ecological index, yet there are some other detailed indices for water quality to represent it as a single index, such as the ‘Effluent Quality Index’ (Rathnayake & Tanyimboh 2012, 2015; Rathnayake 2015). In the future, more efforts should be made to investigate the relationships between these water quality indices, as well as the in-depth driving mechanism for a single index.

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