Calculation of water environmental capacity and pollutant sharing rate with water diversion: a case study of Qinhuai River

Weiwei Song, Yong Pang, Yiping Li, Peng Zhang, Qing Xu and Xingqian Fu

ABSTRACT

With an overall consideration of hydrology, water quality and pollution sources, and the pollution source area, which affect the water quality, the Qinhuai River basin has been simplified as a control unit. Based on the establishment of the control unit water environmental model, the most unfavorable hydrological condition has been set up. The model comprehensively considers the effects of boundary water quality and the response relationship between the water quality of a cross-section and the general population. The allowable discharge of each generalization outfall can be calculated by the response relationship, and the chemical oxygen demand (COD), NH3-N, and total phosphorus (TP) water environment capacity of the control unit can be obtained. As shown in the results: in the near future (2017–2019) with 35% sewage interception and 30 m³/s water diversion; in the long term (after 2020) with 82% sewage interception, the water quality can reach the standard. Combined with the measured calculation, the paper also has made a quantitative analysis of the sharing rate of the main tributary and sewage pump station pollutant flux in the control unit and the whole basin within the administrative district.

Key words | administrative district, sharing rate, water diversion, water environment capacity, water quality standard

INTRODUCTION

The control unit is the primary control area for contaminants that ensures that the control section water quality is up to standard. When dividing the control unit, it is necessary to consider the hydrological situation and the distribution of pollution sources in the watershed and the administrative units. Pollutant sharing rate refers to the contribution rate of pollutants discharged into rivers by each administrative district. Prior to this, some scholars used a water environment mathematical model for calculation. Pang et al. (1998) established a water quality model of an artificial ecosystem to study the changes in water quality at the water intake under the conditions of changes in surface area, aquatic plant stocking density and water intake. Pang et al. (2005) calculated the amount of water entering the sea to the east of the Pearl River by an unsteady mathematical model in the river network area. Dong Guan River water quality basically reached the functional area water quality objectives (Pang et al. 2016a, 2016b). Wang et al. (2016a, 2016b) proposed a method of controlling the total cross-section pollutants as a control factor for water quality compliance. Based on the relevant test parameters and other related research results, Yang et al. (2016) simulated...
and analyzed the six scenarios of the study. The one-dimensional steady-state model was used to calculate the surface water quality of the Yellow River Diversion Project’s initial operation for water safety. Wang et al. (2016a, 2016b) established a mathematical model of the water environment based on MIKE11 on the inner Qinhuai River. Aiming at the present situation of the black body of the inner Qinhuai River water system, an optimal water diversion scheme under small, medium and heavy rainfall conditions was put forward. Based on the MIKE11 model, a mathematical model of the water environment of the Wangyu River network was built, with a study on the water quality reaching the standard under the condition of water discharge and roofing (Xu et al. 2016). According to the relevant references (Davies et al. 1992; Pigram 2000; Liu & Zheng 2002; Li et al. 2013), MIKE has been applied in many areas.

The purpose of this paper is: (1) analyze the present status of water quality in the Qinhuai River according to field investigation; (2) calculate the relationship between the water quality of the cross-section and the pollution control of the generalized outfall, as well as the allowable discharge of each generalization outfall of the control section; (3) calculate first the water environmental capacity of the Qinhuai River basin and the control unit both in the near future (2017–2019) and in the long term (after 2020); (4) calculate the pollutant flux (ammonia nitrogen, total phosphorus) in the administrative regions of the Qinhuai River basin; calculate first, as well as the sharing rate and average sharing rate of pollutants in the Qinhuai River basin.

**METHODOLOGY**

**Study area**

Qinhuai River, the Chinese lower reaches of the Yangtze River tributary, is the most important regional river in Nanjing. The Qinhuai River network consists of two sources, with two rivers merging into Qinhuai River in Jiangning District. Then the Qinhuai River arrives at Dongshan Bridge, dividing into two branch rivers (New Qinhuai River and Outer Qinhuai River) and then flowing into the Yangtze River. The total area of the basin is 2,659 km², with 1,708 km² in Nanjing (64%) and 951 km² in Zhenjiang Jurong (36%). Under normal circumstances (no diversion), Qinhuai River starts from south to north. In water diversion periods, the New Qinhuai River transfers water by sluice or pumping through the Outer Qinhuai back to the Yangtze River. In this paper, the river network surface water reaching standard quality is the main line, and the influence area of the three cross-sections is the Qinhuai River Basin based on the water quality standard of the JS-CS, TB-CS and QW-CS in the bifurcated river (Figure 1). A large amount of measured data proves that the upstream water quality of YB-CS has reached the standards, and the affected area is further simplified to obtain the study area (control unit, Figure 1). Qinhuai River basin pollution is serious, and the People’s Republic of China Ministry of Environmental Protection requires three sections (JS-CS, TB-CS, QW-CS) to reach the water quality standard.

**Data of hydrology and water quality field investigation**

During the period from August to December in 2016, simultaneous monitoring of hydrology and water quality was performed three times. The flow of the river was measured by a shipping ADCP (Acoustic Doppler Current Profiler). At the same time, we conducted water sampling at all monitoring sites. We used a 10-litre bucket to collect water samples at the 1/4, 1/2, and 3/4 river-width of the cross-section. The water sample depth was 0.5 m underwater. We filled the water samples in 500 ml volume Plexiglas bottles and dropped 15 drops of 98% concentrated sulfuric acid as a stabilizer in each water sample. The concentration of chemical oxygen demand (COD) was determined by the acid potassium permanganate method, the concentration of ammonia nitrogen was determined by the spectrophotometric method of nano-reagent, and the total phosphorus concentration was determined by ammonium molybdate spectrophotometry. For the first time of diversion, the average flow was 72 m³/s (3–7/08/2016). For the second time of diversion, the average flow was 40 m³/s (26–30/09/2016). For the third time, during a no-diversion period, the average up-flow was 38 m³/s (21/11–27/12/2016). The purpose of this study is to master the present status of water quality in the study area and the diversion ratio of the bifurcated river. It also aims to trace the pollutant source of the complex river network in the Qinhuai River. It will provide basic monitoring data for the water environment with
comprehensive restoration planning and verification of water quality with models. The three instances of simultaneous monitoring data are shown in Figure 1.

Establishment of a mathematical model of the water environment

In order to perform the simulation of water quality, we chose a convective diffusion model, and the water quality simulation calculation has to be established on the basis of a hydrodynamic model.

Hydrodynamic model

The governing equation for hydrodynamic calculations is the Saint-Venant equation describing the one-dimensional unsteady flow of the open channel, including the continuity equation and the momentum equation. It also
supplemented the floodplain and the lateral inflow (Wang et al. 2016c, 2017):

\[
\frac{\partial Q}{\partial x} + b \frac{\partial h}{\partial t} = q
\]

(1)

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{a Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + gQJ = 0
\]

where: \( Q \) is the flow rate; \( x \) is the spatial coordinate along the direction of the water flow; \( b \) is the storage width, indicating the total river width including the beach lands; \( h \) is the water level; \( t \) is the time coordinate; \( q \) is the side inflow, with the inflow being positive and the outflow being negative; \( \alpha \) is the momentum correction coefficient; \( A \) is the cross-sectional area of main channel; \( g \) is gravitational acceleration; \( C \) is the Chézy coefficient; and \( R \) is the hydraulic radius.

The hydrological conditions of the flow margin were calculated by a runoff convergence model from the rainfall and evaporation data, and the flow rate of the YB-CS was calculated to be 37 m³/s. The water level boundary for the Qinhuai River into the Yangtze River, JS-CS, was 5.4 m and the Outer Qinhuai River was 5.2 m.

**Convective diffusion model**

The distribution and concentration of pollutants in water are mainly based on their own degradation, together with the movement of water flow and the diffusion of pollutants. The governing equation of convection–diffusion models is a one-dimensional convection–diffusion equation (Hahladakis et al. 2013; Albanese et al. 2014; Wang et al. 2014; Cai et al. 2015; Carlin et al. 2015; Chen et al. 2015; Devkota & Fang 2015):

\[
\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x} \left( AD \frac{\partial C}{\partial x} \right) = -AKC + C_2q
\]

(2)

where: \( x \) is the spatial coordinate along the direction of the water flow; \( t \) is the time coordinate; \( Q \) is the flow rate; \( C \) is the material concentration; \( A \) is the cross-sectional area of the main channel; \( D \) is the longitudinal diffusion coefficient; \( K \) is the linear attenuation coefficient; \( C_2 \) is the source-collecting concentration; and \( q \) is the flow rate of the side-inflow.

The boundary condition of water quality was created by the results of field monitoring of hydrological and water quality. Concentrations of COD, ammonia nitrogen (NH₃-N) and total phosphorus (TP) are shown in Figure 1.

**RESULTS AND DISCUSSION**

**Control unit outfall generalization and response relationship construction**

The sewage outfall was found by satellite map and further generalized. Generalized outfall sewage into the river is from industry, urban life, rural life, farmland, livestock and poultry farming as well as runoff. Generalizing the tributaries and pumping stations along the river, the sewage in the densely populated areas, sewage plants, and industrial enterprises as outfalls, if the distance between the outfalls is short, they are combined into one. Dispersed sewage outlets that are far away and have low discharge can be generalized to non-point sources. The generalized outfalls and the control section of the control unit and the whole basin are shown in Figure 1.

The boundary condition of the tributaries and the water quality, and then the response relationship between the main stream and the control section water quality. The water quality in the tributary import functional area should reach the standard and the value of the water quality in the boundary should be taken for the measured data. The relationship between the control section and the generalized population response is constructed as follows.

Diversion period (Figure 1):

Qinhuai River: \( C_{\text{Dongshan bridge}} = C(C_{\text{Yangqiao bridge}}, W_1, W_2, W_3, \ldots, W_9, W_{\text{non-point source}}) \)
New Qinhuai River: \( C_{\text{Heding bridge}} = C(C_{\text{JS-CS}}, W_{10}, W_{11}, W_{12}, \ldots, W_{24}, W_{\text{non-point source}}) \) (5)

Outer Qinhuai River:

\( C_{\text{Qiqiao weng}} = C(C_{25}, C_{\text{Dongshan bridge}}, C_{\text{Heding bridge}}, W_{25}, W_{26}, W_{27}, \ldots, W_{32}, W_{\text{non-point source}}) \) (6)

No-diversion period (Figure 1):

Qinhuai River: \( C_{\text{Dongshan bridge}} = C(C_{\text{Yangqiao bridge}}, W_{1}, W_{2}, W_{3}, \ldots, W_{9}, W_{\text{non-point source}}) \) (7)

New Qinhuai River: \( C_{\text{Jiezhi sluice}} = C(C_{\text{Heding bridge}}, W_{10}, W_{11}, W_{12}, \ldots, W_{24}, W_{\text{non-point source}}) \) (8)

Outer Qinhuai River:

\( C_{\text{Qiqiao weng}} = C(C_{25}, C_{\text{Dongshan bridge}}, W_{25}, W_{26}, W_{27}, \ldots, W_{32}, W_{\text{non-point source}}) \) (9)

Model verification

After the model’s calculations, the model was verified. Based on the monitoring data, the parameters of the hydrodynamic model were verified by a trial-and-error method. Depending on the measured flow rate and water level data from each hydrology station and water level station, the roughness of each channel was calculated, which ranged between 0.025 and 0.032. It can be seen from the figure that the calculated values are in good agreement with the measured values (Figure 2(1)–(3)). Therefore, the hydrodynamic model can simulate the hydrological process of the Qinhuai River basin.

According to the pollutant sources and the characteristics of water pollution on the plains of the Qinhuai River basin, the main pollutants in the study area were living pollution and tertiary pollution, with the main water quality targets exceeded being NH\(_3\)-N and TP, which were selected as simulation objects of water quality. The degradation rate of NH\(_3\)-N was 0.05–0.07 d\(^{-1}\) and the degradation coefficient of TP was 0.05–0.08 d\(^{-1}\). Furthermore, the degradation rate of ammonia was calculated with the utilization of the monitoring data. The calculated value of the model is less than 30% compared with the measured value, and the result is suitable (Figure 2(4)–(7)). The model can be used to describe the water quality change process in the Qinhuai River basin.

**Schemes for reaching water quality standard**

Based on the numerical simulation, the water quality of the present situation is simulated. Based on the different reduction rates and different New Qinhuai River water diversion flows, the non-diversion conditions (seven schemes) and diversion conditions (six schemes) are simulated under a total of 13 schemes in Table 1.
According to the People’s Republic of China Ministry of Environmental Protection requirement, JS-CS, TB-CS and QW-CS water quality should all reach class IV. COD, NH$_3$-N, and TP concentrations (mg/L) of class IV should be $\leq$ 50, $\leq$ 1.5, $\leq$ 0.3. In the no-diversion period (Table 1), the pollutant concentrations are far higher than the standard values, and the water diversion is of more importance and significance (the bold parts of the table indicate the standard cannot be reached). Scheme 2–4 is an optional scheme for the diversion period with 35% pollutant reduction rate and 30 m$^3$/s water diversion discharge in the near future 2017–2019. Scheme 1–6 is an optional scheme for the no-diversion period with 80% pollutant reduction rate after 2020 without water diversion.

**Calculation of water environment capacity of the control unit**

According to the survey data of pollution sources, the hydrological water quality and field survey of the tributaries of Qinhuai River basin in 2016, using the response relationship between the constructed control section and the generalized outfalls, the reduction in control unit is calculated in the near-future and long-term water quality standards. According to the YB-CS water functional boundary conditions and the hydrological conditions, the water quality standard is reached, as well as the sum of the maximum allowable emissions of generalized outfalls (Figure 1) in the control unit, that is, the water environmental capacity. Scheme 2–4 corresponds to recent allowable emissions (2017–2019), and Scheme 1–6 corresponds to the long-term allowable emissions (after 2020) in Table 2.

**Pollutant flux-sharing rate across administrative districts**

Results of calculation (Webb et al. 1997; Barakat et al. 2011; Bresciani et al. 2013; Davis et al. 2015) of the pollutant flux and flux-sharing rate of 32 tributaries discharged into Qinhuai River are shown in Figure 3. From Figure 3(a), we can see the calculated flux and the sharing rate of the pollutants of the Qinhuai River basin in every administrative district. Emissions of pollutants in Jiangning District account for 2/3 of the control unit, with the largest sharing rate, followed by Yuhuatai District with 1/5. In consideration of the whole basin indirect impacts of Jurong City (Jurong River) and Lishui District (Lishui River), the sharing rate of pollutant flux is calculated (Equation 10) with the third-time measured data in Figure 3(b):

\[
\begin{align*}
W_j & = Q_i C_i \quad (i = 1, 2, 3 \ldots) \\
W_i & = \frac{W_j}{\sum W_j} \quad (j = 1, 2, 3 \ldots) \\
n & = \frac{1}{\sum n}
\end{align*}
\]

\[n = \text{sharing rate}; \quad W_j = \text{pollutant flux}; \quad Q_i = \text{flow}; \quad C_i = \text{concentration}; \quad i = \text{cross-section}; \quad j = \text{administrative district}.
\]
After comparing the pollutant sharing rate of the model-calculated and measured values in the administrative districts, it can be concluded that the sharing rate of the measured value is smaller than the model-calculated value in Jiangning District, because the outfalls of Jurong and Lishui were generalized into Jiangning in the model calculation. In contrast, the sharing rate of Qinhuai District increased, because the upper reaches of the QW-CS in the model calculation do not include consideration of pollutants in the downstream of the Outer Qinhuai River. Therefore, the measured and model-calculated flux and sharing rates basically correspond to each other, and the article methods and results are correct.

<table>
<thead>
<tr>
<th>Generalized outfall</th>
<th>Current emissions (t/a)</th>
<th>Recent allowable emissions (t/a)</th>
<th>Long-term allowable emissions (t/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD</td>
<td>NH3-N</td>
<td>TP</td>
</tr>
<tr>
<td>1</td>
<td>1,045</td>
<td>134</td>
<td>10.5</td>
</tr>
<tr>
<td>2</td>
<td>751</td>
<td>97</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>528</td>
<td>31</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>1,355</td>
<td>174</td>
<td>13.6</td>
</tr>
<tr>
<td>5</td>
<td>604</td>
<td>78</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>339</td>
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</tr>
<tr>
<td>8</td>
<td>530</td>
<td>68</td>
<td>5.3</td>
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<tr>
<td>9</td>
<td>972</td>
<td>125</td>
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<tr>
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<tr>
<td>12</td>
<td>762</td>
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<td>10.3</td>
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<tr>
<td>13</td>
<td>1,001</td>
<td>129</td>
<td>10</td>
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<td>2.3</td>
</tr>
<tr>
<td>32</td>
<td>207</td>
<td>27</td>
<td>2.1</td>
</tr>
<tr>
<td>Total</td>
<td>24,536</td>
<td>3,046</td>
<td>248.6</td>
</tr>
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</table>

| Reduction rate (%) | / | / | / | 0 | 35 | 34.5 | 0 | 80 | 80.5 |
CONCLUSION

Generalization of control unit outfall and construction of the response relationship between water quality and emissions, and the simulation of a water environment mathematical model can be used to calculate the water environmental capacity and pollutant sharing rate with an overall consideration of factors such as hydrology, water quality and pollution sources, and the pollution source area. Taking Qinhuai River basin as an example, in the near future (2017–2019), the water environmental capacities of COD, NH₃-N, and TP are 24,536 t/a, 2,132 t/a, and 173.7 t/a respectively with water diversion being 30 m³/s. In the long term (after 2020), the water environmental capacities...
of COD, NH₃-N, and TP are 24,536 t/a, 609 t/a, and 49.6 t/a respectively without water diversion. The paper has made a quantitative analysis of the sharing rate of the generalized outfalls' pollutant flux in the control unit and the whole basin within the administrative district. On the basis of the cross-sections' water quality reaching the standard quality, the sharing rates of different administrative districts are listed as follows: Qinhuaui District, the average sharing rate of NH₃-N is 12% and the average sharing rate of TP is 13%; Yuhuatai District, the average sharing rate of NH₃-N is 20% and the average sharing rate of TP is 15%; Jianye District, the average sharing rate of NH₃-N is 2%; Jiangning District, the average sharing rate of NH₂-N is 55% and the average sharing rate of TP is 53%; Lishui District, the average sharing rate of NH₃-N is 1% and the average sharing rate of TP is 2%; Jurong City, the average sharing rate of NH₂-N is 10% and the average sharing rate of TP is 17%. This paper provides a method for cross-section water quality to reach the water quality standard by pollutant interception and water diversion. It also provides a method for analyzing the sharing rate of pollutants in different administrative districts, which can be used as a legal basis for determining environmental pollution events. The calculation of the water environment capacity will serve as the basis for controlling the total amount of pollutants in the area.

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