Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.26362

206 (2020) 34–43
December

Effects of water transfer on improving water quality in Huancheng River, Chaohu City, China

Feng Deng[a,*], Zhongkai Liu[b], Lu Zhang[c], Xiaopeng Hu[d], Qiwen Guan[e]

School of Environmental Science and Engineering, Nanjing Tech University, Nanjing, Jiangsu 210000, China, Tel. +86 13851488840; Fax: +86 (25)58139652; email: dengf99@126.com (F. Deng), Tel. +86 13813850139; Fax: +86 (25)58139652; email: 459710700@qq.com (Z.K. Liu), Tel. +86 19850079336; Fax: +86 (25)58139652; email: 1397381362@qq.com (L. Zhang), Tel. +86 18305196767; Fax: +86 (25)58139652; email: 358911387@qq.com (X.P. Hu), 5 Tel. +86 13512512424; Fax: +86 (25)58139652; email: lzkzyc001@outlook.com (Q.W. Guan)

Received 2 January 2020; Accepted 18 July 2020

A B S T R A C T

Urban river pollution is an urgent environmental problem in China at present and water transfer has been proven to be a cost-effective method to resolve the issue. In this study, the effects of water transfer on improving water quality in Huancheng River, Chaohu City were investigated. The initial test indicated that water transfer could enhance the aeration while decreasing total phosphorus and chemical oxygen demand (COD_{cr}); however, a significant difference in the improvement effect was observed between two sections. Subsequently, the water flow was increased, which led to an enhanced improvement effect with a smaller difference observed between the two sections. Furthermore, a total pollutant control model was constructed with COD_{cr} as the index. The deviation between the simulation results and experimental data was in the range of 2%–20%. The results indicate an average COD_{cr} of below 28.99 mg/L under a water flow of above 1.67 m^3/s. The experimental and simulation results of this research provide managers with guidance to optimize water transfer plans.

Keywords: Huancheng River; Water transfer; Water quality improvement; Pollutant control model

1. Introduction

At present, over 80% of urban rivers in China are facing serious pollution problems, leading to degraded quality of the surrounding environment and posing threat to residents' health [1]. Water transfer has been applied as an auxiliary measure to continuously improve the regional water environment [2,3]. Compared with other aeration technologies, water transfer is one of the most cost-effective methods and improves water quality via multiple effects: (1) it helps enhance the water flow and wash out fine particles [4], thereby, dilute the pollutants [5]; (2) water transfer boosts water displacement, inducing contaminants to flow downstream [6,7]; and (3) water transfer enhances water aeration, inhibiting the emission of phosphorus and promoting microbial degradation [2,8,9]. Therefore, water transfer has many functions (e.g., aeration, flushing and dilution) for water body restoration [10,11]. While meeting the demand for water volume, this technology enables significant improvement of water quality (1 to 2 grades) in many sections [12]. The balance between economic and environmental benefits can be maintained by rationally selecting the water source, route and scale [4,13–17]. However, improving the water environment by water transfer has not been thoroughly studied. For practical application, it is important to study the ecological impact of water transfer on urban river restoration.

* Corresponding author.

The key to enhancing the effect of water transfer is to control the hydrodynamics of the target river by designing and optimizing the water transfer plan [16,18–20]. With a proper transfer scheme, the water quality can be effectively improved [17,21]. In the study carried out in Suzhou City, the water quality was improved to a higher grade under optimized operation, with a maximum pollutant reduction rate of 49.7% [22].

In actual engineering practice, the hydraulic model of river flow is often generalized into a one-dimensional unsteady flow model [23]. Due to its simplicity in calculations, the Muskingum method is usually used as a lumped river calculus method in actual practice. Moreover, the least-squares method can be applied to derive the parameters, reducing the calculation complexity and improving the accuracy [24,25].

In this study, the Huancheng River in Chaohu City was taken as the research object, and the effects of water transfer on water quality improvement were analyzed in two tests. On basis of the first test, the water transfer scheme was optimized. Moreover, a total pollutant control model was established and its accuracy was verified. Finally, a specific optimization plan was proposed.

2. Materials and methods

2.1. Investigation of the water quality status in Huancheng River

In this study, two background water quality surveys and two field water transfer experiments were conducted from October to November 2013. Fig. 1 illustrates the water system distribution in Chaohu City, and the distribution of

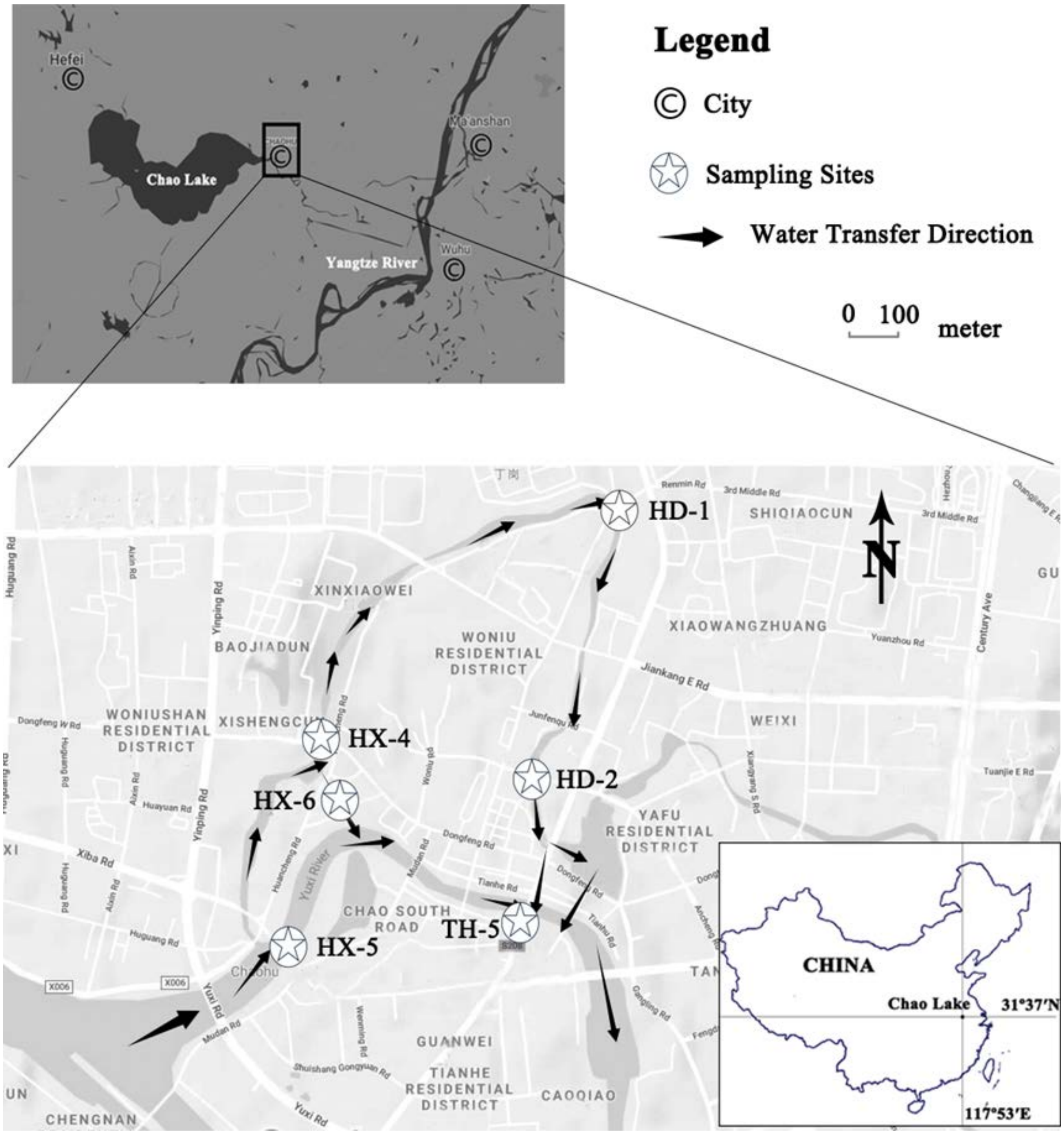

Fig. 1. Location of Chaohu Lake (a), the diagram of Chaohu Lake Basin (b), and the schematic diagram of the tests (c). *Notes*: dark areas represent waters and light areas represent land.

the surrounding water system and specific data of each section are presented in Table 1. The water quality monitoring sites are listed in Table 2. Huancheng River was divided into the East and West Ring City River with HD-1 as the interchange. On this basis, HD-1, HD-2 and TH-5 belonged to the East Ring City River System, while HX-4~6 were in the West Ring City River System.

2.2. Water transfer plan and sampling method

On November 28th, the initial water transfer test was carried out, in which Chaohu Lake was used as the source water. The sluice was drained from 10:00 to 15:00 before opening the Xi'an Bridge Gate to guide the water from Chaohu Lake into Huancheng River. Water sample collection and water level measurements were carried out simultaneously during the test.

On December 10th, two flood-control pumps were added in the HD-1 section for the second test. The downstream flood control pumps were started at 1 pm, and the water samples were collected simultaneously. Meanwhile, the water level and real-time flow rate at each sampling point were measured. The water transfer plan applied in the research is illustrated in Fig. 1.

There are three sampling processes: (1) A survey was conducted to acquire background water quality data of the surrounding water system. All the 23 sampling sites involved in the survey were listed in Table 3. (2) For real-time monitoring, six monitoring sites were selected (Table 2). On the day of the test, the first and second samples were collected at 9:50 and 11:00, respectively, before water transfer. Upon commencement of the test, the water was sampled with an interval of 1 h until 16:00. (3) After the test, sampling was conducted at the six sites every day for several days to verify whether the water quality was improved by water transfer.

Samples were taken from the centers of the monitoring sites, at a depth of 5cm below the river surface with a plexiglass sampler. Each sample was divided into two 500 mL bottles, with one being acidified to keep pH ≤ 2. According to the analysis of the background water quality, dissolved oxygen (DO), total phosphorus (TP) and chemical oxygen demand (COD_{cr}) were chosen as the monitoring indices in this study. The analysis projects and monitoring methods are shown in Table 4. Finally, a total of 227 water samples were obtained from the trial.

2.3. Analysis of water quality improvement effect

The spatial and temporal changes of water quality were analyzed with the real-time water quality data, and the factors affecting the water quality improvement effect were summarized.

2.4. Total pollutant control model design

The total volume of water transfer and its distribution in the tests were calculated and the reduction effects of dilution on various pollution indicators were analyzed. With COD_{cr} as the index, a one-dimensional water quality model was established. Moreover, the accuracy of the model was verified by combining the Muskingum flow algorithm. As a result, an optimized water transfer plan was proposed.

Table 1
Sections of Huancheng River

Section	River section description	Length (m)	Upstream section area (m^2)	Downstream section area (m^2)
S-1	Xiba Bridge – West Palace Bridge	745	6.33	80.84
S-2	Xishenggong Bridge – Renmin Road Bridge	1,800	80.84	11.43
S-3	Dividing the Tianhe River section at Xiangba Street	230	6.51	6.51
S-4	Renmin Road Bridge – Unity Road Bridge	1,200	11.43	19.40
S-5	Unity Road Bridge to the ear wash pool	314	19.41	–

Table 2
Locations of water quality monitoring sites

Point	Water system	Remarks	Normal water level (m)
HX-4	West Ring City River – Dongfeng West Road (Xishenggong Road and Bridge)	West Ring City River	6.56
HX-5	West Ring City River – Xiba Bridge (Xi'an Bridge Gate)	Water transfer starting point	6.56
HX-6	West Ring City River – Xiangba Street Bridge	Diverted to Tianhe	6.56
HD-1	East Ring City River – Renmin Road Bridge	East and West Ring Road Interchange	6.56
HD-2	Washing ear pool – Chaohu Middle Road Bridge	East Ring City River into Tianhe culvert (near the ear wash pool junction)	6.56
TH-5	Tianhe – East side of Guanyu Bridge	Tianhe confluence after water transfer	6.56

Table 3
Water sampling sites in the background water quality survey

Section	Number of sampling sites	Sampling location (site code)
Xipie Ditch	3	Xipie Ditch near 7410 Factory Gate Bridge (HX-10) Xipie Ditch Bridge near Zhuanchi River Diversion Office (HX-1) Xipie Ditch – Huguang Road Bridge (HX-11)
Caigang Pumping Station	2	Caigang Pumping Station Sump (HX-21) First bridge downstream of the outlet of Caigang Pumping Station (HX-2)
Shuangqiao River	2	Xipie Ditch to Shuangqiao River Bridge (SQ-1) Shuangqiao River – Hubin Road (SQ-2)
West Ring City River	3	West Ring City River – Dongfeng West Road (HX-4) West Ring City River – Xiba Bridge (HX-5) West Ring City River – Xiangba Street Bridge (HX-6)
East Ring City River	2	East Ring City River – Tuanjie Road bridge (HD-3) East Ring City River – Renmin Road Bridge (HD-1)
Ear Washing Pool	2	Washing ear pool – Chaohu Middle Road Bridge (HD-2) Washing ear pool – Tuanjie Road bridge (XE-2)
Lujia River	2	Lujia River – Dongtang Road Bridge (XL-1) Lujia River – Tuanjie Road bridge (XL-2)
Century Avenue Ditch	2	Century Avenue Ditch – Chaohu First Middle School (ZG-1) Century Avenue Ditch – Changjiang East Road (ZG-2)
Tianhe River	3	Tianhe – Yuxi Road Bridge (TH-1) Tianhe – Peony Road Bridge (TH-2) Tianhe – East side of Guanyu Bridge (TH-5)
Yuxi River	2	Yuxi River – Yuxi Road Bridge (YX-1) Yuxi River – the north of Yuxi Road (YX-2)

Table 4
Water sample analysis projects and monitoring methods

Number	Analysis project	Analytical method	Guideline
1	DO	Electrochemical analysis	HJ506-2009
2	COD_{cr}	Potassium dichromate method	GB/T11914-89
3	TP	Ammonium molybdate spectrophotometry	GB11893-89
4	Velocity	Cup-type current-meter	SL58-93
5	Depth	Sounding vertical	SL58-93

3. Results and discussion

3.1. Background water quality survey

Table 5 lists the background water quality data of Huancheng River. It is obvious that the water quality in the West Ring City River is better than that in the east counterpart. This is associated with the local hydrological conditions, that is, the channel of the East Ring City River is relatively narrow and many sections have been artificially reconstructed. At the Renmin Road monitoring site, the natural water channel has been transformed into a culvert, which blocks the East Ring City River and affects its fluidity. Therefore, in terms of background water quality, there is a significant difference between the East and West Ring City Rivers.

Table 5
Background data of Huancheng River

Section	DO (mg/L)	TP (mg/L)	COD_{cr} (mg/L)
East Ring City River	1.9–6.5	1.5–2.17	45–56.7
West Ring City River	6.4–8	0.1–0.2	21–28.3

3.2. Analysis of water quality improvement effect

3.2.1. Dissolved oxygen

The variations of DO at each monitoring site in the two tests are illustrated in Fig. 2. In the initial test, the aeration effect was significant in the sections of the East Ring City

Table 6
Real-time flow of Huancheng River

	10:00	11:00	12:00	13:00	14:00	15:00	16:00
HX-5	0	5.11	4.97	4.86	4.34	4.48	4.48
HX-6	0	2.8	3.28	3.36	3.84	4.06	4.06
HD-1	0	1.67	1.34	1.65	1.23	0.979	1.1
HD-2	0	0.023	0	0.289	0.053	0.256	0.168
TH-5	0.00	0.00	0.00	1.19	2.25	1.87	1.87

River. The DO concentration in the HD-1 section even increased by 87.64%. In contrast, the aeration effect was not as significant in the other two sections of the East Ring City River. As shown by the water system diagram (Fig. 1), the channel of the East Ring City River (especially from HD-1 to downstream) is narrow, blocking the water flow and leading to poor aeration at downstream.

In the second test, as expected, starting the pumps at HD-1 led to aeration enhancement at each monitoring site. The increment of DO reached 64.68% at HD-1. Moreover, the DO concentrations were also improved in the HD-2 and TH-5 sections (Fig. 2), which indicates that water flow is an important factor determining the effect of water transfer. However, the improvement effect at HD-1 was still much better than that in the other two sections, further confirming that the narrow channel restricted the aeration effect of water transfer in the East Ring City River.

3.2.2. Total phosphorus

Fig. 3 shows the removal of TP by water transfer in the two tests. In the initial test, due to water displacement and diffusion induced by water transfer, the TP concentration in the West Ring City River (HX-4~6) changed to around 0.1 mg/L. Specifically, the TP concentrations at HX-5 and HX-4 rose from 0.031 and 0.066 mg/L to 0.095 and 0.125 mg/L, respectively. Conversely, the TP concentration at HX-6 fell from 0.138 to 0.104 mg/L. As for the East Ring City River, the TP concentration at HD-1 fell by 40.48% from 1.68 to 1.00 mg/L. However, at the other two sites (HD-2 and TH-5), the TP concentrations did not change obviously, which was attributed to the narrow channel restricting the improvement effect of water transfer.

In the second test, after starting the pumps, the TP at HD-2 fell by 15%. This again proves that water fluidity has a great influence on the improvement effect of water transfer.

The real-time variations of TP at all the six monitoring sites are presented in Fig. 4. The sections in the West Ring City River have better background water quality. The curves of TP variation in the corresponding monitoring sites (HX-4~6) present a peak shape and fluctuate greatly. In contrast, the TP variation curves at sites (HD-1, HD-2 and TH-5) in the East Ring City River were valley-shaped, that is, falling first followed by rising, with significant fluctuation. In fact, the effect of water transfer on TP is two-sided: (1) The hydraulic shock stirs the river sediment to release phosphorus-containing pollutants, leading to increased TP concentration in the overlying water [26,27]; (2) meanwhile, conversely, the aeration effect of water transfer tends to inhibit the release of the pollutants. As a result, the TP concentration may not decrease after water transfer, but the strengthening of the scouring effect and the reduction of phosphorus-containing pollutants in the sediments could be achieved. Consequently, the adsorption capacity and tolerance of the river towards phosphorus-containing pollutants will be increased.

Interestingly, the curves at the three sites in the West Ring City River and HD-1 reached a peak at different time points, and the TP concentrations at upstream sites peaked later than those downstream. It was because the previous water transfer had rushed sediments at sites upstream and the sediments upstream were more resistant to scouring. Similarly, TH-5 locates in the Tianhe River and has better water fluidity. Therefore, the TP concentration at TH-5 peaked earlier than that at HD-2.

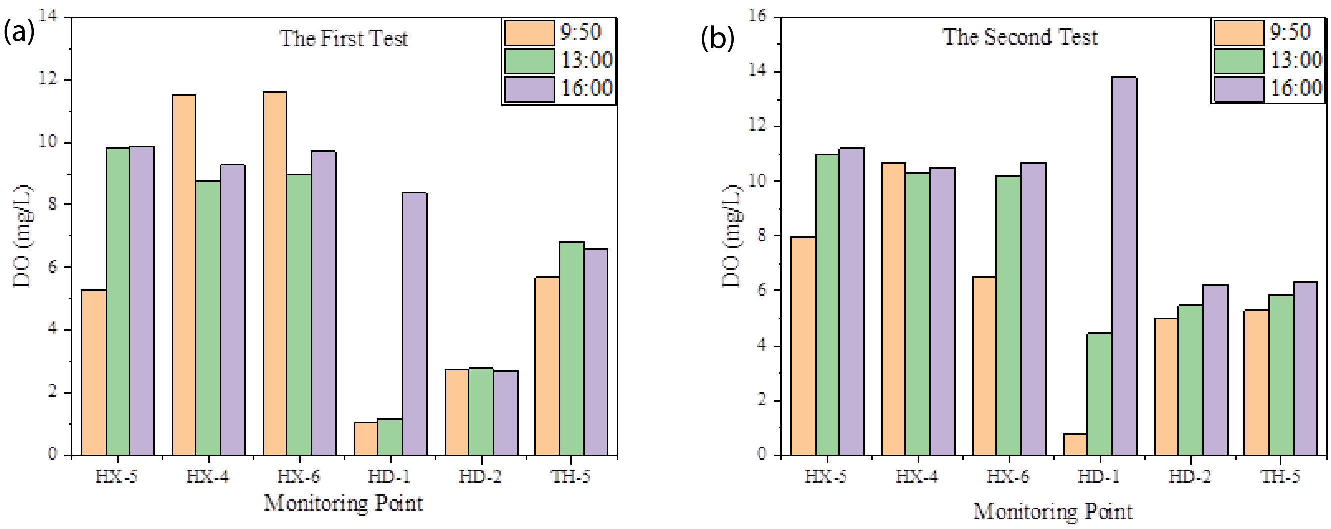

Fig. 2. Variations of DO in the two tests (a) first test and (b) second test.

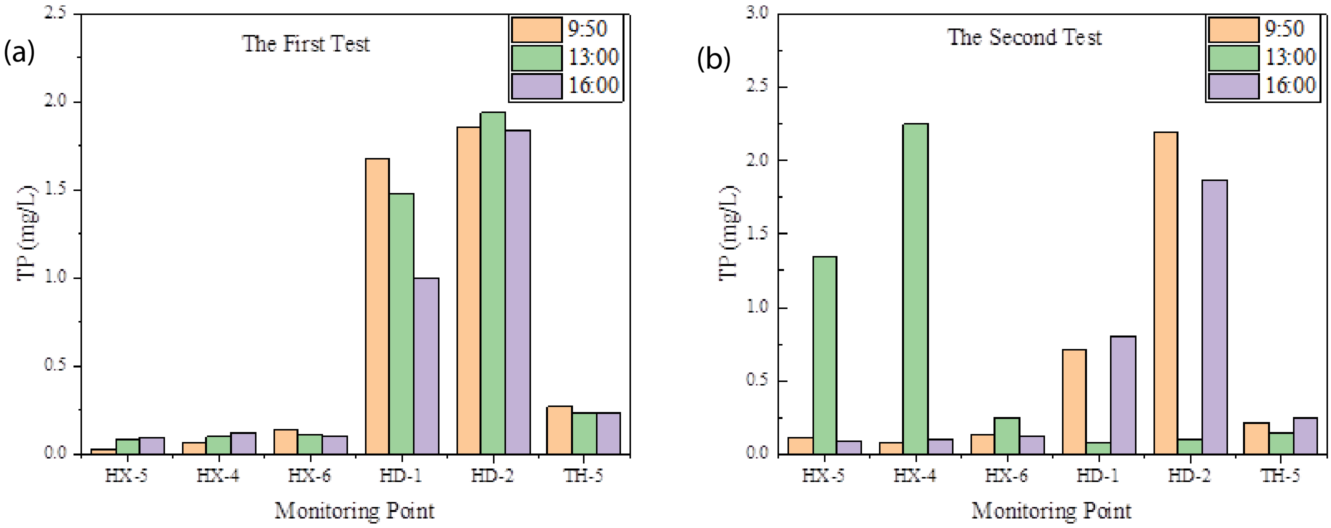

Fig. 3. Variations of TP in the two tests (a) first test and (b) second test.

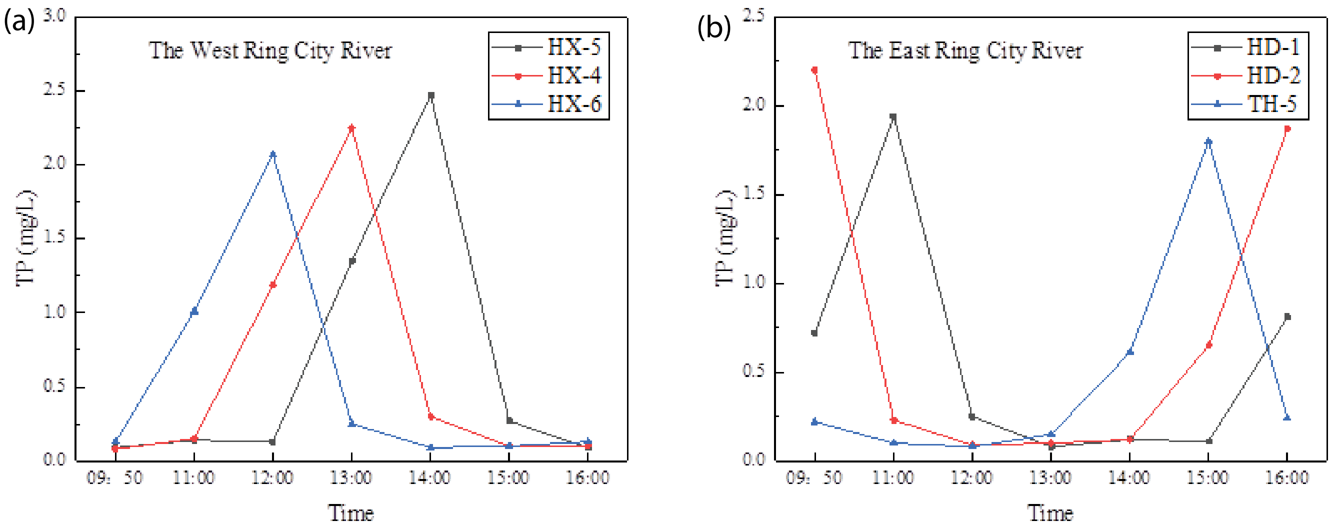

Fig. 4. Real-time variations of TP in the second test (a) West Ring City River and (b) East Ring City River.

3.2.3. Chemical oxygen demand (COD_{cr})

As shown in Fig. 5, the most significant decrease of COD_{cr} (18.65%) was observed at HX-6 in the initial test. The average concentration of COD_{cr} in the West Ring City River decreased, whereas the opposite trend was observed for that in the East Ring City River. The increased COD_{cr} concentration in the East Ring City River resulted from the narrow channel from HD-1 to TH-5 and the associated poor water fluidity and aeration effect of water transfer. After starting the pumps in the second test, the COD_{cr} concentration dropped in all the sections with an average decrease of 13%. It suggests that enhancing water fluidity optimizes the aeration effect and promotes COD_{cr} removal. As indicated by the real-time COD_{cr} curves in the second test (Fig. 6), the COD_{cr} concentration at each site showed an overall downward trend. Thus, upon considering the economic conditions, the water transfer duration can be appropriately selected to enhance the improvement effect.

3.3. Total pollutant control design

3.3.1. Dilution effect

The reduction of pollutants by water transfer mainly depends on the dilution effect [6]. The average TP and COD_{cr} concentrations in the source water were 0.81 and 18.83 mg/L, respectively. The real-time flow rates at each site are listed in Table 6. HX-5 is the starting point of Huancheng River and the short circuit to Tianhe is from HX-6 to TH-5. The volume of short-circuit water accounted for 75.25% of the total project, which seriously affected the water transfer effect in 4/5 of the sections.

The calculated average TP and COD_{cr} concentrations in each section of Huancheng River before water transfer are listed in Table 7.

According to Eqs. (1) and (2), the dilution capacity and final pollutant concentrations can be calculated.

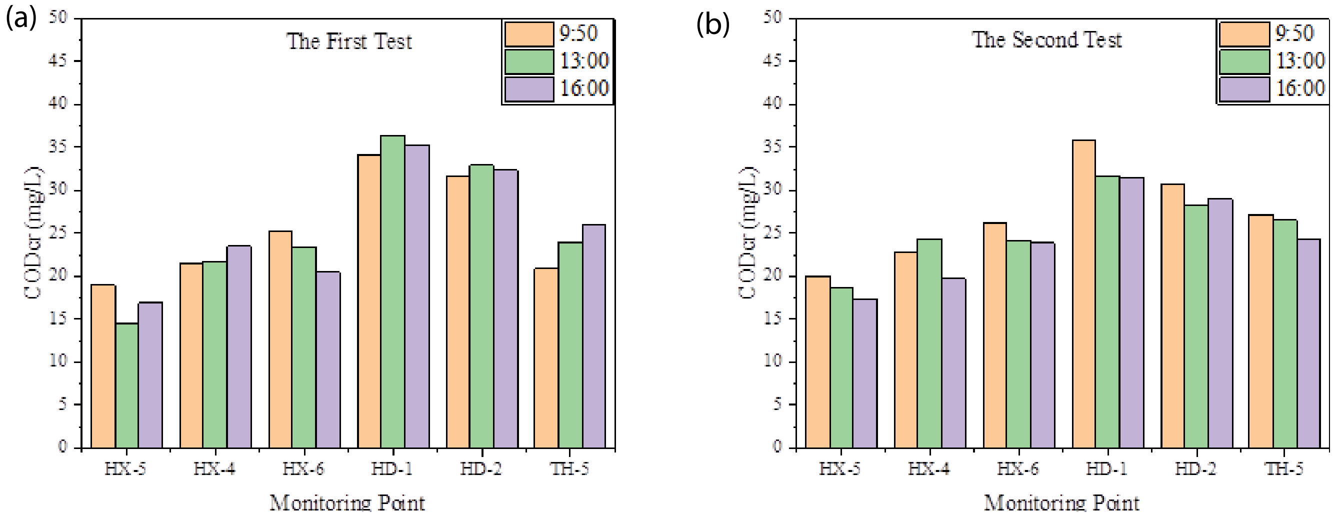

Fig. 5. Variations of COD_{cr} in the two tests (a) first test and (b) second test.

Table 7
Calculation of average concentrations in Huancheng River before water transfer

Section	Volume (m³)	TP (mg/L)	COD_{cr} (mg/L)
S-1	60,225.8	0.108	20.0
S-2	83,043	0.083	22.9
S-3	1,497	0.134	26.2
S-4	18,504	0.717	35.9
S-5	6,091.6	2.20	30.8
Entirety	169,361.4	0.24	23.60

$$Q_0\rho_0 + Q_1\rho_1 - Q_2\rho_2 - Q_3\rho_3 = Q\rho \quad (1)$$

$$Q_0 + Q_1 - Q_2 - Q_3 = Q \quad (2)$$

where Q_0 is the volume of Huancheng River before the test; Q_1 is the volume of inflow water; Q_2 is the volume of short-circuit water; Q_3 is the volume of river outflow; Q is the total volume of Huancheng River after water transfer; ρ_0 is the background concentration of the pollutant; ρ_1 is the concentration of the pollutant in the source water; ρ_2 is the concentration of the pollutant in the short-circuit water; ρ_3 is the concentration of the pollutant in the outflow; ρ is the final concentration in Huancheng River.

Considering the dilution effect only, after water transfer, the TP concentration in Huancheng River rose by 20.80% to 0.29 mg/L, whereas the COD_{cr} concentration fell by 14.84% to 20.55 mg/L.

3.3.2. Model simulation and verification

COD_{cr} was selected as the index for model construction. The pollutant load of each section was first estimated by Eq. (3).

$$\text{River section pollutant load} = \rho \times L \times \sum_{i=0}^{i=n} \frac{d \times \left(h_i + h_{i+1}\right)}{2} \quad (3)$$

where ρ is the pollutant concentration determined at the monitoring site; L is the length of the river section; d is the distance between the vertical lines; h is the measured depth; n is the number of verticals.

As the aspect ratio of Huancheng River is minor, the one-dimensional water quality model is applicable in this case [18,19]. Neglecting the diffusion effect, the analytical solution of the river steady-state one-dimensional water quality model was built as Eq. (4).

$$C = C_0 \exp\left(-KT\right) \quad (4)$$

where C is the concentration of the pollutant, mg/L; K is the degradation coefficient of the pollutant; T is time; and C_0 is the background concentration of the pollutant, mg/L;

As the attenuation of COD_{cr} in natural waters follows the first-order kinetic equation [28,29], a balance equation for the total amount of pollutants can be established as Eq. (5).

$$L = L_0 \cdot e^{-Kt} + L_1 + t\left(\rho_1 Q_1 - \rho_2 Q_2\right) \quad (5)$$

where L is the real-time pollutant load of the section; L_0 is the total background COD_{cr} in the section; K is the comprehensive degradation coefficient of the pollutant; T is time.

Assuming that the daily COD_{cr} input load in each section is constant, then $L_1 = T \times l$. The daily variation of COD_{cr} was calculated in the study. The least-squares method was applied to fit the balance equation parameters and the degradation coefficients of COD_{cr} (Table 8). It was found that although the R^2 values of the S-3 and S-5 sections were relatively low, the overall degree of fitting was good. Therefore, sections S-1 and S-4 that are located in the East and West Ring City Rivers, respectively, are selected for model verification (Fig. 7).

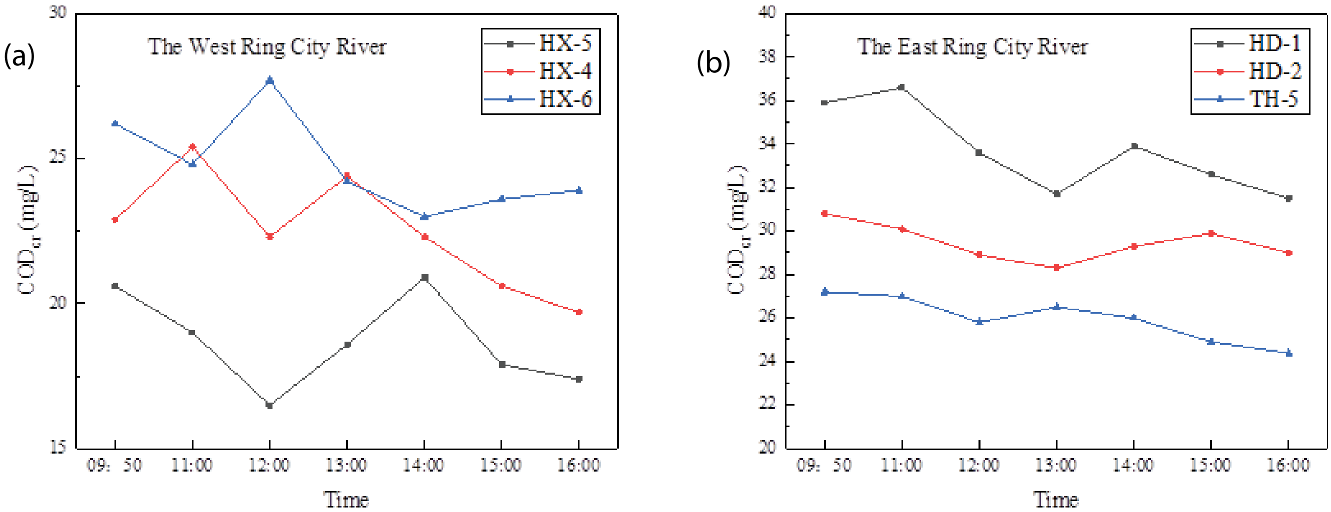

Fig. 6. Real-time variations of COD_{cr} in the second test (a) West Ring City River and (b) East Ring City River.

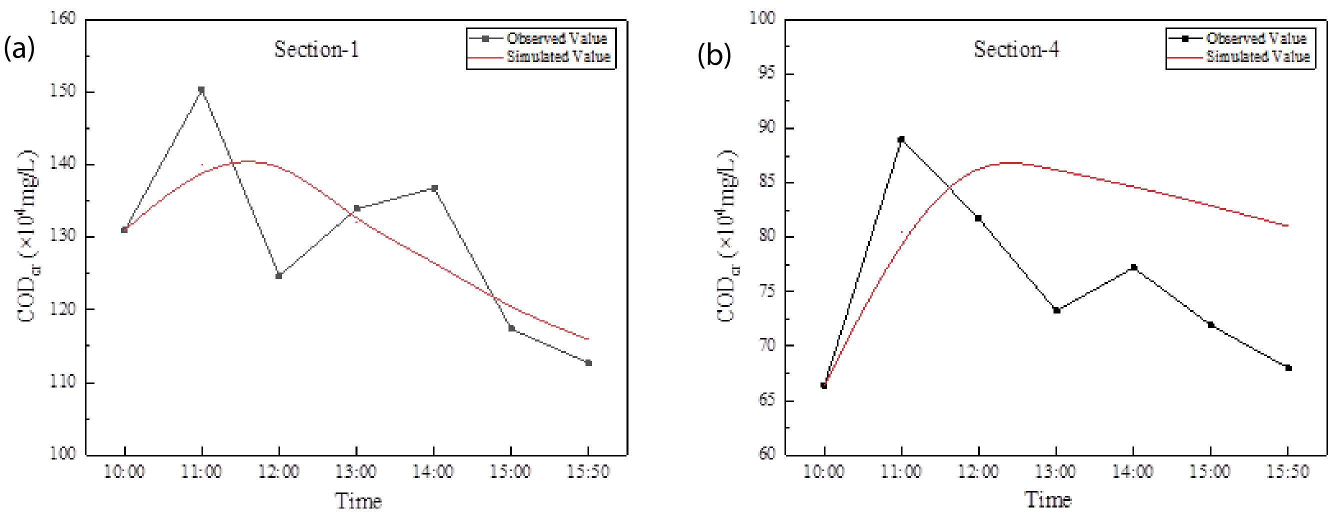

Fig. 7. Verification of total COD_{cr} balance equations in (a) section-1 and (b) section-4.

According to the results, the deviations between the simulation results and the experimental data were 2%–15% and 8%–20% in S-1 and S-4, respectively. It indicates that the accuracy of the model was relatively good and it is feasible for designing a water transfer scheme.

3.3.3. Water transfer target and optimization plan

The water quality and the improvement effect of water transfer gradually declined from the starting point of Xiba Bridge to downstream. As the S-4 section accounts for 4/5 of the total length of the East Ring City River, the S-4 section was chosen as the control object for simulation.

The expected target concentration of COD_{cr} in the S-4 section was set as 30 mg/L, that is, Grade IV of local surface water standard (GB3838–2002). Water that fulfills this grade can be used as general industrial water and non-direct recreational water. According to Eq. (5), the final formula was built as Eq. (6).

$$L = L_0 \cdot e^{-0.0053t} + 36,438.4 \cdot t + \left(\rho_1 Q_1 - \rho_2 Q_2\right)t \quad (6)$$

Based on the measured L_0 of 664,293.6 g, the total COD_{cr} in the S-4 section was calculated to be 555,120 g. If the water transfer time is set as the test time (5 h), the target reduction for water displacement and dilution is 109,818 g.

Combining the Muskingum method, the relationship between the total storage flow and the storage flow in the S-4 section is shown in Fig. 8.

The calculation equation of the S-4 section is derived as Eq. (7).

$$Q_{down2} = -0.56 \cdot Q_{up2} + 0.84 \cdot Q_{up1} + 0.28 \cdot Q_{down1} \quad (7)$$

In the study, the value of ρ_1 was set to 25 mg/L, the higher COD_{cr} concentrations were in the upper reaches of the S-4 section. Then, the value of ρ_2 was set to 30 mg/L. On this basis, under a water flow of 1.67 m^3/s at HD-1, the average

Table 8
Numerical simulation of total COD_{cr} in sections

Section	$L = L_0 \cdot e^{-kt} + l \cdot t + (\rho_1 Q_1 - \rho_2 Q_2)t$	R^2
S-1	$L = L_0 \cdot e^{-0.035t} + 803,277.4 \cdot t + (\rho_1 Q_1 - \rho_2 Q_2)t$	0.8594
S-2	$L = L_0 \cdot e^{-0.0073t} + 73,766 \cdot t + (\rho_1 Q_1 - \rho_2 Q_2)t$	0.9681
S-3	$L = L_0 \cdot e^{-0.0012t} + 1,048.5 \cdot t + (\rho_1 Q_1 - \rho_2 Q_2)t$	0.5864
S-4	$L = L_0 \cdot e^{-0.0053t} + 36,438 \cdot 4 \cdot t + (\rho_1 Q_1 - \rho_2 Q_2)t$	0.8425
S-5	$L = L_0 \cdot e^{-0.011t} + 10,106 \cdot 8 \cdot t + (\rho_1 Q_1 - \rho_2 Q_2)t$	0.6885

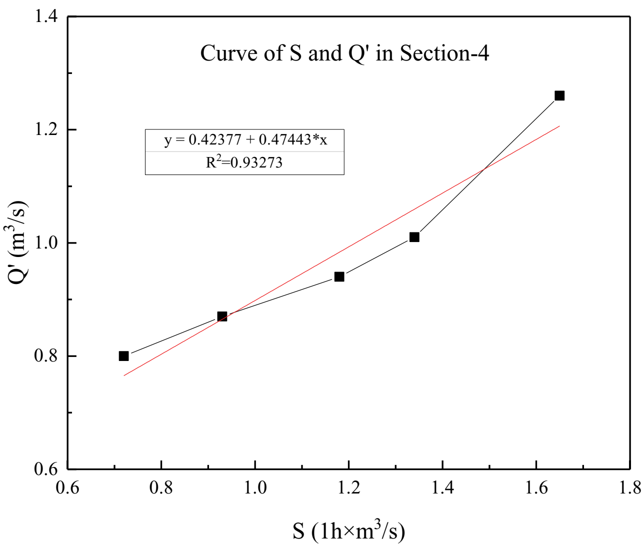

Fig. 8. Relationship between total storage flow and storage flow in the section-4.

COD_{cr} in the S-4 section was calculated to be 28.99 mg/L which is lower than the Grade IV of surface water standard. Considering the migration of pollutants with water, the value will be even lower.

4. Conclusion

In the first stage of the study, the river fluidity was identified as the key factor affecting the improvement effect of water transfer. After starting the pumps at HD-1, the DO concentration in the river increased by up to 64.68%, whereas the TP and COD concentrations decreased by 15% and 13%, respectively. The TP concentration rose in several sites as the scouring effect of water transfer led to the release of phosphorus-containing substances from sediments. However, the dredging of sediments helps enhance river restoration.

In the second stage of the research, a one-dimensional steady-state model was applied as the basis to establish a pollutant control model. The accuracy of the model was verified by combining the Muskingum method. The deviations between the simulation results and the actual measured values in the S-1 and S-4 sections were between 2% and 20%, implying a relatively good accuracy of the model. Finally, the simulation calculation suggests that satisfactory results can be achieved by controlling the flow at HD-1 via setting parameters such as the opening degree of the water control valve, the opening and closing of the water pump, and the speed of the water pump. For example, controlling the flow at HD-1 above 1.67 m^3/s enables an average COD_{cr} concentration of below 28.69 mg/L in the S-4 section.

Based on the research findings, the water supply optimization suggestions are as follows:

- Add a sluice at the Xiba Bridge (HX-6 point) to artificially control the water flow direction.
- Turn on the water pump at the downstream of the Xi'an Bridge Gate and East Ring City River to improve the water flow effect.
- Repair the cross-section of the Renmin Road Bridge (HD-1) to improve the vertical connectivity of the water body.

Acknowledgment

This work was financially supported by the Major Science and Technology Program for Water Pollution Control and Treatment (Nos: 2017ZX07202-01-003-002).

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