Nutrient’s response to water transfer in an urban river-network

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ABSTRACT

Through water transfer, the hydrodynamic conditions of the river network can be improved, and the biochemical degradation of pollutants can be promoted, but at the same time, the endogenous release may be intensified. It is therefore possible to subdivide the response of nutrient content to water transfer into three components. (a) Direct Impact (DI) of dilution through water diversion, (b) Indirect Impact (II) by sediments release, and (c) Self Impact (SI) of nutrient degradation and attenuation of nutrients. By combining field investigation, laboratory experiment, and numerical simulation, the contribution weight of DI, II, and SI to the change of nutrient concentration was quantitatively analyzed. The results show that: (1) In the upper reaches of the river network, II plays a leading role in the weight is more than 75%, increasing the amount of water diversion would increase the nutrient content; (2) SI plays a leading role in the tributary of the central part of the river network, the weight is more than 60%, and when the auxiliary pumping station is opened, the weight of II is less than 1%. (3) In the southeast of the river network, the nutrient release rate is sensitive to the change of hydrodynamics, and the weight of II is more than 90%. The results of this study can provide a reference for the formulation of a comprehensive hydrodynamic water quality management control scheme in the urban river network.

Key words: individual impact, numerical model, nutrient content, urban river-network, water transfer

HIGHLIGHTS

• Water transfer imposes direct and indirect impacts on nutrient concentration.
• The response of nutrient to water transfer can be divided into three components.
• The dilution weight of the downstream section is higher than that of the upstream section.
• The control of endogenous pollution in Liangxi River and southeastern rivers is the key to improve the water quality of river network.

1. INTRODUCTION

Using hydraulic structures such as pumps, sluices, and dams to transfer and distribute water and enhance the carrying capacity of the regional water environment are important measures to improve the water quality of rivers and lakes (Zhang et al. 2018; Daga et al. 2020). In the flat delta area of large rivers, under the action of estuarine sedimentation, it is easy to form a plain river network with dense rivers and crisscross channels under the action of estuarine sedimentation (Gu et al. 2018). In the region, the drop along the river course is small, the hydraulic driving condition is limited, and the flow is slow (Gan et al. 2012). Under natural conditions, material transport and diffusion is slow, coupled with the increase of pollutants into the river caused by urbanization, the phenomenon of water eutrophication induced by high nutrient load occurs from time to time (Deng et al. 2018). Excessive nutrient concentrations can weaken the ecological function of water bodies and reduce the diversity of structure that poses a serious threat to human health (Carpenter & Lathrop 2008; Taylor et al. 2014). Increasing the water diversion of the plain river network can improve the hydrodynamic conditions of the river and increase the content of dissolved oxygen in the water, which is beneficial to the degradation of pollutants by microorganisms, but at the same time, high flow velocity would increase the cutting effect of water flow on the riverbed. Aggravate the release of nutrients from sediment into overlying water (Schindler 2006; Graham et al. 2016; Leon et al. 2017; Shakibaeinia et al. 2017), the water quality deteriorated further. Therefore, it is of great significance to
quantitatively analyze the variation of nutrient load in different regions of the river network under different water transfer schemes.

The water quality-hydrodynamics response mechanism is affected by many factors. Decomposing the mechanism and quantifying the weight of various components is helpful to determine the water dispatching threshold and plan the dispatching scheme as a whole. Tang et al. (2014) studied the migration and diffusion law of pollution components in the middle route of the South-to-North Water transfer Project developed a water quality guarantee scheme accordingly; Jijian Chen et al., Chao Zhou et al. (Chen et al. 2013; Chao et al. 2014) used a mathematical model to analyze the mechanisms of flow movement and pollutant transport and diffusion under different regulation modes and combined with the interpolation method to obtain the calculation formula for controlling the transport of pollution clouds. Zhang et al. (2001) studied the behavior of phosphorus release and adsorption at the water-sediment interface of Taihu Lake by using the simulated disturbance environment constructed by constant temperature oscillator, the results show that there is a strong release of phosphate under high disturbance; Wang et al. (2015) Through the experiment, the relationship between the rate of TP release rate and disturbance intensity was obtained, and it was found that there was a peak value in the increase of TP concentration; Pauer et al. (Pauer & Auer 2000) showed that disturbance increased the dissolved oxygen content in water, coupled with the upward movement of high nitrogen concentration during sediment initiation, which promoted the nitrification at the sediment-water interface. However, most of these studies focus on the analysis of a single way or the conclusion of the integrity of the research region, while few people pay attention to the separation of water diversion effects. For the densely populated urban plain river network, the formulation of water quality improvement plan needs to be further refined. maximize the effect of water quality improvement brought by water transfer.

Therefore, this paper takes the eastern lakeside river network of Meiliang Bay of Taihu Lake as an example to study the following three aspects: (1) A hydrodynamic water quality coupling mathematical model considering pollutant degradation and transport is constructed and calibrated and verified; (2) A vertical release experiment of in-situ sediment in indoor flume is carried out. The coupling curve of nutrient factor release rate and bed shear stress is obtained, and the contribution value of sediment release in the actual environment is calculated. (3) The response mechanism weights of the flood, dry season TN, and TP concentrations in the character section of the river network to water diversion are analyzed, and the respective contributions of DI, II, nd SI in the water environment under different hydrodynamic conditions are obtained. The research method proposed in this paper evaluates the influence degree and comprehensive effect of water transfer on the positive effect of nutrient dilution and degradation and the negative effect of the endogenous release of pollutants in rivers with different characteristics and quantifies the contribution weight of each part. The results address the question of how many pollutants will be released while promoting the transport and degradation of nutrients in the river, which provides a basis for determining the best hydraulic control threshold, optimizing the dispatching scheme, and taking comprehensive river control measures. If the DI weight of the river is high, the quality of diverted water should be considered and clean water sources should be introduced. When the II weight of the river is high, measures such as river bed desilting or adding pollutant release inhibitor (Fukushima et al. 2018) should be taken before water diversion to control the endogenous release; when the river SI weight is high, some chemical and biological treatment measures can be taken.

### 2. MATERIALS AND METHODS

#### 2.1. Research area

The study area is the lakeside river network in Lihu New City, Binhu District, Wuxi City(31°31'24"–31°32'33"N, 120°16'17"–120°20'26"E), Wuxi City has a humid monsoon climate in the northern subtropics, with abundant rainfall, with an annual average temperature of 15.6 °C and an average annual rainfall of 1,112.3 mm. It has a resident population of 6.57 million in 2018 and the annual regional gross domestic product (GDP) is 1.1439 trillion yuan. Binhu District is rich in water resources, economically developed, with more than 70 large and small rivers, with a network density of 2.05 km/km², and a water surface rate of 6.91%. The annual average water level is 3.06 m, and the ground elevation is between 3.5 m and 6.2 m (Wusong base). It belongs to a typical plain urban river network (Figure 1). The river network extends from the Liangxi River in the north to Caowang River in the south, Li Lake in the west, and the Beijing-Hangzhou Grand Canal in the east. The upstream reaches of Taihu Lake is the third-largest freshwater lake in China, with a surface area of 2,338.1 km². It covers an area of
33.7 km² (Wang et al. 2016). The contents of N and P in Taihu Lake are high, especially in summer (July-September). The enrichment of cyanobacteria bloom is more serious (Ma et al. 2015). Under the action of the seasonal dominant wind, the bloom cyanobacteria in Taihu Lake drifted and converged to Meiliang Lake and diverted water from the Liangxi River to the river network through the pumping station, which caused great pressure on the water environment of the river network.

Under natural conditions, the hydrodynamic conditions in the river network area are weak, reciprocating flow, canal water backflow and other phenomena occur from time to time, and human activities limit the self-purification function of the water body. To supplement water sources and meet the needs of water exchange, the local government has set up 11 water diversion pumping stations of different sizes in the river network, in which Taihu Lake water introduced by Meiliang pumping Station and Daxuan pumping Station is the main water source of the river network, and the diversion flow and operation are shown in Figure 1, followed by natural injection of Li Lake to realize river-lake linkage. At the same time, the Lihu New Town area where the river network belongs is densely populated, human activities are frequent, and some sewage is discharged directly, so sluices and dams are set up to intercept water and control pollution to reduce the impact of production and domestic water discharge on the overall water environment of the river network. While these hydraulic structures play a role, they also have a certain impact on the structure and connectivity of the water system. 70% of the rivers have a long-term flow velocity of less than 0.01 m/s, the transport and diffusion of pollutants are slow and difficult to be consumed through degradation, as a result, it settles and accumulates in the sediments. The comprehensive

Figure 1 | (a) and (d) are photos of Liangxi River outlet sluice and Meiliang pumping station taken during field monitoring, respectively. (b) and (c) are the location of the research area, Binhu river network. (e) Satellite images of the study area from Google Earth (including the sampling sites of water quality and sediment, the location and size of the auxiliary pumping station and the selected research section). (f) The average daily flow of Meiliang pumping Station and Daxuan pumping Station in 2018 has the law of alternating and complementary operation. (g) Temperature and precipitation of research area in 2018.
nutrient value of the Binhu river network in 2017 is 57.3, which is in a state of mild eutrophication (Li & Qin 2012; He et al. 2020).

At present, the local government takes measures such as water diversion to release pollution, in-situ treatment, ecological floating island, flow control and pollution interception, sediment dredging and so on to deal with the problems of river eutrophication and algae proliferation. Among them, water quantity regulation can speed up water exchange, promote the degradation and attenuation of pollution factors, and gradually restore the ability of water self-purification, which is a normal method to solve the problem of water quality in a plain river network. Therefore, the quantitative analysis of the hydrodynamic water quality response mechanism can establish the basis for determining the comprehensive treatment methods adopted in different regions (Wang et al. 2019).

2.2. Data acquisition and process

According to the previous study of river distribution and water system structure in the study area, the river network is divided into four regions: Liangxi River, internal tributaries of the river network, Mali River and the southeast of the river network. A total of 103 water quality and 26 sediment sampling sites (Figure 1) were selected to carry out four surveys and monitoring of hydrology and water quality, sediments and algae in March, August, September and November 2018. The velocity of 1/4, 1/2 and 3/4 quartiles of the cross-section was measured by LB70-1C rotary cup current meter, and the water depth was measured synchronously by portable ultrasonic sounder. The sediment samples on the river bottom and the overlying water at the mud sample points were collected by a stainless steel sampler, and the overlying water was stored in a sealed polyethylene bucket. All the samples were stored away from light at 4 °C and brought back to the laboratory. Some of the deposited samples were centrifuged (3,500 r/min, 30 min) to obtain interstitial water, while others were used for indoor sediment release experiments in an extended annular flume. The contents of water quality factors in situ water samples, sediment interstitial water and experimental water samples were determined. The content of TN was determined by alkaline potassium persulfate digestion and ultraviolet spectrophotometry (GB/T 11894-1989); TP was determined by alkaline potassium persulfate digestion and molybdenum-antimony anti-color spectrophotometry (wavelength 700 nm) (GB/T 11893-1989).

Based on the field monitoring results, the local water quality standard Surface Water Environmental quality Standard was used to evaluate the water quality of the monitoring section in flood and dry season. During the flood season, the content of TN in the river network is generally high and serious, with an average concentration of 4.6 mg/L and a maximum concentration of 43.47 mg/L. Among the monitored sections, only three sections are up to the standard, with an over-standard rate of 95.7%, an average over-standard multiple of 2.67, and a maximum of 42.4 times. The average concentration of TP is 0.5 mg/L, the over-standard rate is 47.15%, the average over-standard rate is 1.15 times, the highest over-standard multiple is 50.7 times, and the over-standard rate of TP in Liangxi River is 40%. During the dry season, the average TN concentration of the river network exceeded the standard rate of 4.1 mg/L, by 89.3%, with an average exceeding the standard of 3.22 times, and the TN content of the most serious section exceeding the standard was 31.62 mg/L. The average concentration of TP in the river network is 0.51 mg/L, higher than the average concentration, accounting for 21.3%, the highest concentration of 8.59 mg, the over-standard rate of TP is 40.7%, the highest is 27 times, and the over-standard rate of TP in the monitoring section of Liangxi River is 80%. On the whole, there is little difference in the overall nutrient content of the river network in different water periods, but there are obvious differences in the nutrient concentration of rivers in different regions. For example, the contents of TN and TP in rivers in the southeast of the river network are 4–5 times higher than those in other areas of the river network.

2.3. Experimental design

2.3.1. Impact of disturbance on nutrient release

The adsorption and release of pollutants by sediment is in dynamic equilibrium (Han et al. 2020). Colloids and sediment particles have extensive micro-interfaces in natural water bodies, which form the basis of their coupling with pollutants and as pollutant carriers. The nutrients entering the water body are adsorbed on the surface of the particles and deposited into the sediment, and on the one hand, the driving force caused by the concentration gradient of the sediment-water interface is released from the interstitial water to the overlying water, on the other hand, due to the re-suspension of the sediment caused by the change of hydrodynamic conditions, the attached pollutants spread to the water body, increasing the pollution load of the overlying water body. The hydrodynamics of the plain river network has a significant response to the regulation of water volume, and
the critical velocity of sediment swirling driven by bed shear stress and the pollutant release rate depends on the sediment viscosity and the content of pollutants in the sediment. Therefore, the in-situ sediments and overlying water of typical sections were collected, and the vertical sediment release experiments under different hydrodynamic conditions were carried out in the laboratory by using an annular flume made of PVC plates. The migration and transformation law of target factors at sediment-water interface was obtained.

There are great differences in the physical morphology of the river in the study area, besides, the impact of human activities on the river has a strong regional, resulting in differences in the enrichment degree of pollutants in river sediments and the viscosity of sediment. The runner driven by an external motor is used to realize different levels of disturbance at the rotational speed of 0–500 r/min. The flow velocity change caused by water dispatching is simulated, and the relationship between bed shear stress and TN and TP release rate is obtained. After coupling with the hydrodynamic model, the water quality change under each dispatching scheme is predicted, and the action mechanism of water transfer on nutrient concentration is studied quantitatively. The response mechanism of nutrient load to hydraulic regulation under complex hydrodynamic conditions of plain river network is revealed.

2.3.2. Experimental equipment and scheme design

The annular flume device (Figure 2) consists of a straight road and a bend, with an overall perimeter of 10 m, a width of 0.3 m and a height of 0.45 m. The radius of the inner ring of the bending part is 0.65 m and the radius of the outer ring is 0.95 m. The total length of the two sections of the straight road is 5 m. A disc runner connected to the motor is set at 0.3 m on one side of the straight road to realizing hydraulic drive and is equipped with a speed regulating meter with a measuring range of 0–1,500 r/min. The mud area is set up on the other side of the straight road, and the water velocity is measured by Acoustic Doppler Velocimetry (ADV) at 0.05 m above the mud sample. The measured position can better characterize the average velocity in the trough under different disturbances (Li et al. 2016). A baffle parallel to the flume is set at the bend in front of the mud area, which weakens the deflection force of the water flow out of the bend and ensures that the shear stress on the bed surface is in the same direction as the ADV velocity measurement. The turbidity of the water body is measured between the baffle and the mud through a portable turbidimeter. When the turbidity tends to be stable, the concentration of TN and TP is sampled at the bend behind the mud area, and the disturbance level is improved synchronously.

Samples were laid for each section at a height of 0.05 m, a width of 0.3 m and a length of 1.5 m. The samples were statically compacted after being evenly paved and then slowly injected into the 0.2 m water depth after 12 hours. Seven disturbance levels are set at 0, 25, 50, 100, 200, 300, and 500 r/ min. For each disturbance level when the turbidity was stable, three parallel water quality samples were taken and 0.45 μm was used to filter the sediment particles to prevent re-absorption and the mean value was expressed as the nutrient concentration.

![Figure 2](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.182/898007/ws2021182.pdf)
The nutrient release rate under different interference intensity can be calculated by the following formula:

\[
R = V(C_n - C_0)/(A \cdot t)
\]  
(1)

where: \(R\) is nutrient release rate, mg m\(^{-2}\) d\(^{-1}\); \(V\) is the volume of overlying water in the annular flume, L; \(C_n\) is the concentration of nutrients in the \(n^{th}\) sample, mg/L; \(C_0\) is initial concentration, mg/L; \(A\) is mud bed surface area, m\(^2\); \(t\) is release time, d.

The flowing movement on the bed surface is described by bed shear stress, and the relationship between nutrient release rate and hydrodynamic conditions is established. Combined with the field measured velocity and calculated velocity of the cross-section, the sediment release amount under each dispatching scheme is obtained. The formula for calculating the shear stress on the bed surface is as follows:

\[
\begin{align*}
\tau_c &= \rho \cdot \mu_c^2 \\
\mu_c &= \frac{1}{R} \ln \frac{y}{K_c} + B_s
\end{align*}
\]

(2)

where: \(\tau_c\) is the critical shear stress at the bed surface, N/m\(^2\); \(\rho\) is water density; \(\mu_c\) is friction velocity; \(\mu_c\) is the average velocity of the cross-section, m/s; \(K\) is Kaman constant; \(y\) is the velocity at the \(y(m)\) height above the river bed, consistent with the sampled water depth (0.5 m below the surface of the water); \(k_s\) is the physical roughness of the sediment, because it is difficult to measure, according to the study of Qin, Li, etc. (Boqiang et al. 2003; Li et al. 2017), the value is 0.0002 m; \(B_s\) is the dimensionless function describing the flow characters near the bed surface.

2.4. Mathemetic model

2.4.1. Governing equation and numerical solution

The continuous data of hydrodynamics and water quality in the study area can be obtained by the method of numerical simulation, and the design scheme can be predicted and simulated. We have established a model coupled with flow, temperature, precipitation, sediment and aquatic ecology to simulate the migration and transformation of nutrients in water. The difference scheme of the hydrodynamic module is the Abbott-Ionescu six-point central implicit scheme, and the numerical calculation is carried out by the pursuit method, the discrete formation of nutrients in water. The difference scheme of the hydrodynamic module is the Abbott-Ionescu six-point central implicit scheme, and the numerical calculation is carried out by the pursuit method, the discrete formation of nutrients in water. The formula for calculating the shear stress on the bed surface is as follows:

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\[\begin{align*}
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} &= q \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\alpha Q^2}{A} \right) - gA \frac{\partial h}{\partial x} + gA \frac{Q}{k_s} &= 0
\end{align*} \]

(3)

where: \(t\) and \(x\) are the time and space coordinates of the calculation point; \(A\) is the cross-sectional area of water, m\(^2\); \(Q\) is the cross-sectional flow, m\(^3\)/s; \(h\) is the water level, m; \(q\) is the side inflow flow, m\(^3\)/s; \(K\) is flow modulus, m\(^3\)/s; \(\alpha\) is the vertical velocity distribution coefficient; \(g\) is the acceleration of gravity, m/s\(^2\).

Based on the hydrodynamic module, the water quality module simulates the diffusion and transport process of soluble matter and suspended matter in water by convection-diffusion equation, and is coupled with hydrodynamic module and convection-diffusion module at the same time. It can accurately describe the turbulent diffusion process of pollutants in water under a large concentration gradient, and simulate the Spatio-temporal transport of pollution factors. (Thompson et al. 2004). Input conventional parameters including degradation coefficient, temperature coefficient, settlement coefficient and so on, combined with water quality monitoring data to calculate the water quality in the region.

\[\frac{\partial(C)}{\partial t} + \frac{\partial(\mu AC)}{\partial x} = \frac{\partial}{\partial x} \left( ADX \frac{\partial C}{\partial x} \right) - AKC - (R(C_b - C) + \omega C) + AS(C) \]

(4)

where: \(t\) and \(x\) are the time and space coordinates of the calculation point, respectively; \(C\) is the average concentration of pollutants in the cross-section, mg/L; \(A\) is the cross-sectional area, m\(^2\); \(DX\) is the longitudinal dispersion coefficient.
of pollutants; \( K \) is the degradation coefficient of the simulated substance, \( d^{-1} \); \( C_b \) is the concentration of pollutants in sediment interstitial water, mg/L; \( R \) is the release rate of nutrients, mg/m²d\(^{-1}\); \( w_c \) is the comprehensive settling velocity of pollutants under disturbance; \( S(C) \) is the source term of pollutant emission.

2018 is selected as the simulation period, and generalization is carried out based on river network channel connectivity and actual water transport and storage capacity. There are 66 rivers in the model, with a total length of 62.11 km, including 49 boundaries and 11 hydraulic structures. The calculated water level points and discharge points are 546. The calculated water points are located at the cross-section of the river, and the calculated discharge points are between the calculated water points (Ahmed 2010). There are 48 inflow boundaries, which are located in the upper reaches of Liangxi River and along the banks of Lihu Lake, and one outflow boundary, which is located in The Beijing-Hangzhou Grand Canal. The data of river bottom elevation, cross-section shape, topography, water level and gate pump dispatching come from Binhu District Water Conservancy Bureau and Binhu District Environmental Protection Bureau. The boundary flow data are provided by Wuxi Hydrology Bureau, in which the daily average flow is used for the main inflow boundary of the river network, the monthly average discharge is used for the rest of the inflow boundary, and the water level boundary is selected for the outflow boundary. The hydraulic structure consists of two diversion pumping stations, each of which adopts the mode of alternating and complementary operation, diverting water together from Meiliang Bay of Taihu Lake, and merging into Binhu river network at the sluice gate of Liangxi River. The annual average flow of the two pumping stations is 23 m³/s. 9 auxiliary pumping stations are mainly used for the improvement of hydrodynamic conditions of tributaries and flood control and drainage. The location and scale of pumping stations are shown in Figure 1.

### 2.4.2. Numerical simulation experiment

Using the validated numerical model of river network water environment coupled with sediment release, ten typical sections are selected in the Binhu river network, including 2 in Liangxi River, 1 in Mali River, 3 in the southeast of river network including Caowang River, and 4 in internal tributaries of river network (Figure 1). Based on the actual operation of the river network in 2018, we change the water diversion of pumping stations and the opening and closing of auxiliary pumping stations. Four kinds of water quantity control schemes (Table 1) are designed, including the actual situation, focusing on the effect of the design scheme in the improvement of hydrodynamics and water quality. Simulate the flow, flow velocity and nutrient content of the cross-section under the corresponding scheme, and further calculate the contribution of II, DI and SI to the change of nutrient content underwater dispatching, and carry on the weight analysis.

We determined the contribution of II by controlling the nutrient release coefficient of sediments. When the three action pathways are fully considered, the nutrient release rate of scheme A, B, C, and D is a function of bed shear stress, and the concentration calculation result is expressed as \( C_{1x} \). When excluding the effect of II on the concentration of nutrient factors, the nutrient release rate of scheme B, C, and D is the fixed value based on the hydrodynamic simulation results of scheme A, which is expressed as \( C_{2x} \). The contribution of DI can be calculated by the dilution mixing model of the river to calculate the dilution effect of the water body from the upstream river to the research section; SI is related to many factors, such as flow rate, dissolved oxygen, and so on, and we regard it as a part other than the action of DI and II. The concrete calculation is carried out by formula (5):

\[
\begin{align*}
C_{\text{IIx}} &= C_{1x} - C_{2x} \\
C_{\text{DIx}} &= (C_{1x}Q_{1x} + C_{1A}Q_{1A})/(Q_{1x} + Q_{1A}) - C_{1A} \\
C_{\text{SIx}} &= C_{1x} - C_{1A} - C_{\text{IIx}} - C_{\text{DIx}}
\end{align*}
\]

(5)

### Table 1

| Scheme | Basic flow | Flow change | Auxiliary pumping station |
|--------|------------|-------------|--------------------------|
| A      | Measured flow | /           | Off                      |
| B      | Measured flow | + 20%     | Off                      |
| C      | Measured flow | /           | On                       |
| D      | Measured flow | + 20%     | On                       |
where: $C_{Dlx}$, $C_{Ilx}$, $C_{Slx}$ represent the contribution of DI, II, and SI to the change of nutrient factor concentration in scheme x, and x is scheme B, C, and D, respectively; $C_{1x}$, $C_{2x}$ represent the concentration calculation results of the twice model, respectively; $C_{1A}$, $Q_{1A}$ represent the calculated values of factor concentration and flow of scheme A of the study section, respectively; $C_{1Lx}$, $Q_{1Lx}$ represent the calculated values of nutrient factor concentration and flow from the upstream of the study section to the nearest cross-section scheme x, respectively. After obtaining the contribution value of each component, the influence weight of each part can be quantified by the following formula:

$$
g_{Dlx} = \frac{|C_{Dlx}|}{(|C_{Dlx}| + |C_{Ilx}| + |C_{Slx}|)}
$$

$$
g_{Ilx} = \frac{|C_{Ilx}|}{(|C_{Dlx}| + |C_{Ilx}| + |C_{Slx}|)}
$$

$$
g_{Slx} = \frac{|C_{Slx}|}{(|C_{Dlx}| + |C_{Ilx}| + |C_{Slx}|)}
$$

where: $g_{Dlx}$, $g_{Ilx}$, $g_{Slx}$ are the contribution weights of DI, II, and SI under scheme x, respectively. and the corresponding $C_{Dlx}$, $C_{Ilx}$, $C_{Slx}$ are the contribution values of each pathway to the change of nutrient concentration under the corresponding scheme.

### 3. RESULTS AND DISCUSSION

#### 3.1. Effect of disturbance on nutrient release from sediments

The flow velocity of the water body increases with the increase of the disturbance level, which enhances the shear effect of the sediment-overlying water interface. Under its action, the sediment rotates gradually and is suspended in the water body, so the TN and TP in the interstitial water are released into the water body. The release rates of TN and TP in the sediments of each section also changed significantly, from the adsorption of nutrients to the release of nutrients at rest. The release rates of most sections increased at first and then decreased with the increase of shear stress, and the release intensity of S5, S7, and S8 increased continuously. When the disturbance level is maximum, the turbidity increases significantly, and the turbidity at 500 r/min is 3–5 times higher than that at 300 r/min. The adsorption and release of nutrients in most sections tend to be dynamic equilibrium (Figure 3). During the experiment, the spin of sediment is roughly divided into three processes. When the disturbance level is lower than 200 r/min, the bed shear stress is less than 0.0005 N/m² and the maximum turbidity is 4.7 NTU. In
this state, the rotation of sediment is not obvious, only a few particles slide on the bed, and the movement is random, and the effect on nutrients changes from adsorption to release in this process. The TN release intensity of S9 was the highest at this stage, which was 6,449 mg/(m²·d), The maximum TP release intensity was 3,145 mg/(m²·d) for S2. When the disturbance exceeds 300 r/min, the average flow rate is 0.4 m/s, the bed shear stress is 0.0008 N/m², the turbidity increases by 1–2 times, and S2 up to 10.3 NTU. Under this condition, the path formed by the movement of particles can be seen with the naked eye, and the bed surface becomes uneven. There is fog on the inside of the pit, and occasionally a large mud mass roll. At this time, the release rate of nutrients is close to the peak, and the increasing rate slows down. The maximum release rate of TN is S9 up to 8,712 mg/(m²·d), the TP releases intensity of S6 was 2,119 mg/(m²·d). When the disturbance level reaches 500 r/min, the water body is turbid, mud masses continue to turn up around the sediment, some fall off in lumps, and the mud samples tend to collapse, with a flow velocity of 0.53 m/s, a bed shear stress of 0.0018 N/m² and maximum turbidity of 48.4 NTU. The adsorption and release of TN and TP from S1, S2, and S6 sections with low nutrient content in the sediment are close to dynamic equilibrium. The rest of the sections are still in a high release state. The river where S8 is located is affected by human pollution, and a load of nutrient factors is high in the sediment. The release rates of TN and TP, which are 15,104 mg/(m²·d) and 2,166 mg/(m²·d), respectively are the highest at the maximum disturbance level. The entire experimental process accords with the basic law of sediment movement, and the bed shear stress simulated by the disturbance level can also be well applied to the actual hydrodynamic conditions of the river network.

3.2. Model calibration and validation/ model performance

Combined with the hydrological data of the lakeside river network in 2018 and the field monitoring data, the hydrodynamic water quality model is calibrated, and the trial and error method is adopted to debug, select and verify the parameters (Figure 4). In order to calibrate the average monthly velocity, the hydrodynamic module selects the river channel where the study section is located from January to June to calibrate the average monthly velocity, which is verified by the data from July to December. The results show that the river roughness can be divided into two types according to the water surface width. when the maximum water surface width is greater than or equal to 30 m, the roughness is between 0.021 and 0.025, and when less than 30 m, the roughness is between 0.03 and 0.035. At this time, the average relative error between the calculated value and the measured value of each channel velocity of the river network is 3.8%–6.2%.

The module on water selects the measured data of flood and dry season data for calibration and verification respectively. Based on the study of river pollutant degradation coefficient by Feng (Feng et al. 2016) and Zhang (Zhang et al. 2015), the diffusion coefficient and degradation coefficient of TN and TP are determined by a trial algorithm. It is found that when the diffusion coefficient takes 10 m²/s, TN and TP degradation coefficient as 0.79 d –¹ and 0.2 d –¹ respectively, the average relative error is 16.2% and 19.7% respectively, which can meet the requirement that the average relative error between the calculated value of the model and the measured value is less than 20%. The verification results show that the model meets the accuracy of water quality simulation of Binhu river network.

3.3. Effect of water transfer on pollutant dilution

The effect of water transfer and pollution release is related to the amount of water diversion and the concentration of source water and background water quality. through the upper boundary water transfer pumping station and internal auxiliary pumping station of the river network, the flow of the river and cross-section can be changed, and the increased water transfer can be diverted and lost continuously in the river network. Finally, there are differences in the increase of water quantity in different rivers. Figure 4 is the change and proportion of flow and concentration of TN and TP of each section under the three dispatching schemes (Scheme B, C, and D) based on the actual scheme A during the flood and dry season. when the water transfer of the upper reaches of the river network is increased by 20%, the flow of Liangxi River tributaries S3 and S4 increases by more than 20%. The average flow of S4 in flood season increased from 0.23 m³/s to 0.313 m³/s, an increase of 36.29%. S1 and S2, the mainstream of Liangxi River, are located in the main channel of water transfer, and their discharge increments are increased by 3.93 m³/s and 4.19 m³/s, respectively; in the southeast of the river network, S8, S9 and S10 are longer from the diversion pumping station, and there are multiple open boundaries in the area flowing through Lihu Lake, so the flow response is not significant, increases by 0.01%, 0.07%, and 0.11% respectively in the flood season, while the average discharge of S8 and S9 decreases slightly in the dry season. The flow of S5, S6
and S7 in the middle tributaries of the river network and Mali River increased by 6.72% to 15.42%. Based on the comparison of the simulation results of schemes C, D, and A, the auxiliary pumping station of the river network mainly controls the water volume of the tributaries in the middle of the river network. Under the direct action of the auxiliary pumping station, the S3–S7 flow decreases, the decrease of S7 is small (1.04%), while of S3–S6 is larger and the flow direction of S3, S4, and S6 changes, in which the flow of S3 decreases from 1.17 m³/s before pumping station to 0.36 m³/s, and the flow reduction is the largest. S6 traffic decreased the most, by 97.47% (from 0.82 m³/s to 0.02 m³/s). Under the indirect action of the auxiliary pumping station, the flow of S1 and S2 in the mainstream of Liangxi River increased by 7.32% and 1.12% respectively, and the cross-sectional flow in the southeastern region fluctuated only slightly. In the case of the operation of the auxiliary pumping station, when the water transfer of the river network increases by 20%, the flow of S3–S7 remains unchanged due to the control of the pumping station, and the flow of S1 and S2 increases by 27.36% and 16.99% respectively under the comprehensive action, and the effect of the diversion pumping station and the auxiliary pumping station on the rest of the section is limited. In the dry season, the flow rate of S4 decreases under the action of the auxiliary pumping station, which is because the actual flow in the dry season is lower than that in the flood season, and the flow direction changes under the action of the pumping station, but the flow rate changes little. Under each scheme, the flow of S8 increases in the flood season and decreases in the dry season, but the range of change is less than 0.1%, which is caused by the fluctuation of its normal water quantity.

Based on the calculation results, when scheme B increased the water diversion by 20%, the water quality of S2 was improved, TN decreases 0.038 mg/L in the dry season (1.72%), TP decreases by 0.002 mg/L (1.69%),
Secondly, the TN of S7 decreased 0.022 mg/L (0.6%) and TP decreased 0.001 mg/L (0.5%) in flood season, the improvement of cross-section factor in the main river is greater than that in tributary section. In the flood season, the of TN and TP content in S6 decreased by 0.276% and 0.28% respectively, and 1.09% and 1.03% in the dry season. The improvement was quite different because the background values of factor concentrations were different in different water periods. In the section where the increase of water diversion led to an increase in water quality concentration, the factor concentration of S3, S4, and S5 in the tributaries increased greatly, especially in the dry season, the TN concentration increased by 1.34%, 1.47%, and 2.89%, respectively. content factors of S8, S9, and S10 are all decreased, but the decrease was not more than 0.01%, and there was no substantial impact of water dilution. After the auxiliary pumping stations are added in scheme C and D, the factor concentration of the river directly regulated by it decreases significantly, and the water quality of the diversion pumping station is no longer affected by the change of water quantity. In scheme C, when the auxiliary pumping station is opened and the water diversion is constant, the concentration of TN and TP in S3–S6 decreases in different water periods, and the decrease in the dry season is greater than that in the flood season. For example, in S4, the concentration of TN decreased by 19.35% in flood season, and by 20.01% in TP, and 25.33% and 23.34% in the dry season, respectively. The indirect effect of the auxiliary pumping station will slightly increase the concentration of nutritional factors in other sections. The TN concentration in S1 and S2 during the flood season increased by 0.015% and 0.359% respectively compared with that before the opening of the auxiliary pumping station. The TP concentration of S7 increased by 0.304% in the flood season, and the concentration of S8, S9, and S10 factors changed little after the opening of the auxiliary pumping station. Scheme D opened the auxiliary pumping station while increasing the water diversion, and more than 70% of the cross-section factor concentration was improved, in which, the tributary S3–S6 was not affected by the diversion water under the control of the auxiliary pumping station, S2, S9, S10 could dilute some pollutants under the comprehensive action, and the water quality of S8 increased slightly under each scheme, and the increase of TN concentration in the dry season was the largest (0.051%).

Figure 5 | The response of nutrient dilution (DI) in different regional sections to water transfer.
3.4. Effect of water transfer on nutrient release intensity of sediment

The release intensity of TN and TP in sediment mainly depends on the shear stress on the bed surface and the concentration difference between sediment interstitial water and overlying water. The physical and chemical properties of sediments in different rivers are quite different after long-term accumulation. Based on the indoor release tests carried out on the study section, the relationship between release rate and shear stress of different sections is determined, thus the release amount of nutrients under different hydrodynamic conditions is determined. The variation of the flow velocity of schemes B, C, and D relative to scheme A in flood and the dry season is shown in Figure 6. During the flood season, the flow velocity of S1–S7 under scheme B has increased, S1, which has the most increase in flow rate, is closest to the diversion pumping station, while the flow rate of S4 has increased from 0.019 m/s to 0.026 m/s, with the largest increase (35.7%). The flow rate of S8–S10 decreased slightly, with an average decrease of 0.41%. In scheme C, only the flow velocity of S1 and S2 increased, the velocity of other sections decreased, and the S3–S6 velocity decreased significantly, with an average decrease of 112.5%, in which the flow rate of S5 decreased to 0.001 m/s, the flow was almost static, the decrease of S3 was the largest (156.6%), and the change of S8–S10 velocity was not significant (less than 0.07%). In scheme D, the flow velocity of S1 and S2 is enhanced by the increase of flow and the auxiliary pumping station. Due to the control of the auxiliary pumping station, the flow velocity of S3–S6 is no longer affected by the change of water diversion, and the flow rate of S7–S10 decreases by 0.2% to 0.8%. In the dry season, the change of flow velocity under different schemes except S7 is similar to that in the flood season. In the dry season, schemes B, C, and D of S7 can improve their hydrodynamic conditions by 11.3%, 5.6%, and 5.2%, respectively. Therefore, the effect of hydraulic regulation on the adsorption and release of nutrients in river sediments in different regions of the river network is that only increases the amount of water diversion can improve the hydrodynamic conditions of the river where S1–S7 is located, thus increasing the release of nutrients. Without increasing the flow, only the auxiliary pumping station was opened, the TN and TP released from the sediment of S1 and S2 increased, the flow velocity of S3–S6 decreased significantly, the concentration of sediment adsorbed TN and TP, decreased, and the S3–S6 after the opening of the pumping station was no longer affected by the change of water diversion from the river network, so the opening of the auxiliary pumping stations are helpful to control the endogenous release of the responding river. When the auxiliary pumping stations are opened, the water diversion capacity is increased, the flow velocity of S1 and S2 is increased, and the nutrient release of sediment is increased. The endogenous release of S7 decreased slightly under schemes C and D in flood season but increased in other cases. There is little change in S8–S10.

3.5. Effect of water transfer on self-degradation of pollutants

The improvement of hydrodynamic conditions caused by hydraulic regulation can increase the content of dissolved oxygen in water, promote the degradation and transformation of nutrients by microorganisms, drive the rotation of particles, and provide more activation sites (Richey et al. 1985) and so on. The effect of hydraulic
control in flood and dry season on the degradation of TN and TP in each section is shown in Figure 6. Based on the flood season simulation results, the degradation effects of scheme B on TN and TP were quite different in sections. The nutrient concentrations of S1, S3, S4, S5 and S8 are increased, while the degradation decreased. The TN content of S3 increased from 1.18 mg/L to 1.22 mg/L, TP from 0.108 mg/L to 0.11 mg/L, and S8 increased slightly, and TN and TP increased by 0.04% and 0.08%, respectively. The nutrient concentration in other sections decreased, and the degradation was enhanced. The TN and TP degradation of S2 was the most, which was 2.94% and 2.14%, respectively. In scheme C, the TN and TP degradation of S3–S5 increased, and the maximum increase of TN and TP degradation was 52.3% and 54.2%, respectively. The TN degradation of S7 increased slightly (0.28%), TP degradation decreased (0.61%), and S8–S10 degradation changed to zero. It is difficult for auxiliary pumping stations to play a role in the degradation and dilution of pollutants in the southeast of the river network. In scheme D, the improvement of TN and TP degradation in most sections was improved, only the TN concentration of S1 and S8 increased, and the TP concentration of S1, S7, S8 and S10 increased. The degradation of TN and TP of S3–S6 under the action of the pumping station was not affected by the change of water diversion. During the operation of the auxiliary pumping station in the dry season, the TN and TP degradation of S3–S6 increased by 10% compared with the flood season, while the TN degradation of S8–S10 decreased by 0.2% to 0.5%, indicating that the promoting effect of the auxiliary pumping station on the degradation of tributaries in the river network in the dry season was stronger than that in the flood season, and inhibited the biochemical degradation in the southeast of the river network.

3.6. Nutrient response to water transfer

After calculation, the contribution degree of DI, II, and SI in the process of nutrient concentration change caused by water diversion is obtained (Figure 7), to refine the best water quality improvement measures that should be taken in different regions. On the whole, the contribution of DI to increase the diversion volume of the river network is less than 36.87%. Both the weight of score II and SI are more than 90%. This is because in the water

![Figure 7](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.182/898007/ws2021182.pdf)
diversion scheme of B and D, the amount of water is increased based on the original water diversion without changing the quality of water diversion, and the reduction of pollutants in the process of water body from the diversion pumping station to the target section is the basic condition for DI to play a role, such as S1, which is closest to the diversion pumping station. The time from the pumping station to the cross-section is short, and the role of II and SI is limited. The nutritional factor content of the newly added water in the cross-section is not significantly different from the background value of the receiving water body. Under the dilution effect, the contribution of DI to TN and TP is 8.6% and 4.5%, respectively. For the section far away from the diversion pumping station, such as S7, II and SI play a full role before reaching the fault, so that the diversion water quality has a more significant change, and the highest contribution of DI to TN and TP is 32.63% and 33.05%, respectively. At the same time, water diversion is continuously diverted in the river network, and the limited amount of water reaching S9 and S10 sections at the distal end of the river network is the reason for its low contribution to DI. The area where the flood of the river network is most affected by DI is the central and eastern region, such as the length of the water flow to S8 is far, and there are more main rivers and fewer tributaries along with the river network, which is conducive to dilution.

Specifically, the concentration of TN and TP of S1 in the upper reaches of Liangxi River increased under different schemes, and the contribution degree of the three pathways was II > SI > DI. The weight of II is 75.77% to 99.12%, under the same scheme, the dry season is larger than the flood season, in the same water period is C + D > B, which means that water diversion can have an effect on S1 within a short time after entering the river network, with less water loss, significant improvement of hydrodynamics, and little difference between the water quality and the actual scheme, so the sediment release has become the main factor for the increase of S1 nutrient content. Compared with S1, the II weight of S2 in the lower reaches of Liangxi River decreased, SI and DI increased. In flood and dry season, the SI and DI of TN and TP in scheme B and D were beneficial to the reduction of its content, and the nutrients of sediment were released in the design scheme, this is because the diversion was partially diverted before reaching S2, and the increase of bed shear stress was less than S1. At the same time, the TN in diversion went through biochemical degradation and diffusion in the middle and upper reaches of Liangxi River. The concentration decreased, so the weight of DI increased, and the maximum decrease of TN content was scheme B in the dry season, when the weights of II, SI, and DI were 30.05%, 45.51%, and 24.42%, respectively. Under the comprehensive action, the TP content of each scheme of S2 increased, and the contribution value of dilution and degradation was difficult to make up for the release of sediments. For example, the sediment release, degradation, and dilution of scheme D increased during the flood season, and the values of II, SI, and DI were 91.85%, 5.3%, and 2.85% respectively, and the release amount was much higher than that of dilution and degradation.

In the S3–S6 of the tributaries of the river network, when the auxiliary pumping station is opened by scheme C and D, the input water and flow velocity are controlled, and the decrease of flow velocity is beneficial to reduce the release of sediment and the consumption of nutrients by stable biochemical reactions of microorganisms. The pumping station also controls the input of nutrients and reduces the exogenous input, so the effects of the three pathways are beneficial to the reduction of TN and TP concentration in flood and dry seasons, and the weight of SI is the largest. In scheme C, the weights of DI, II, and SI of TN concentration of S6 in flood season were 2.34%, 2.78%, and 94.88%, respectively. When scheme B does not open the auxiliary pumping station, only increasing the amount of water diversion is not conducive to the reduction of nutrients in the tributary section. For example, the three effects of S3–S5 in scheme B will increase the concentration of TN and TP, in which the TN weights of II, SI, and DI of S5 in flood season are 2.15%, 63.7%, and 31.16% respectively, and the weights of the dry season are 0.81%, 64.58%, and 36.6%, respectively.

The concentration of TN and TP of S7 located in the middle of Mali River decreased under scheme B, while the concentration of TN and TP increased in flood and dry season in scheme C and D. Compared with other sections, S7 is indirectly affected by the pumping station and has a longer distance from the diversion pumping station, so the hydraulic regulation is more complex. The weight of TN and TP is SI > DI > II, and the weight of SI is between 58.8% and 66.46%. The DI is between 30.9% and 33.05%, and the weight of II is small (0.49%–10.3%).

The S8–S10 are located at the lower boundary of the river network, which is far away from the diversion pumping stations. After the increased water is continuously diverted, the improvement effect on the hydrodynamic water quality in this area is not significant. And secondly, the regulation and control effect of the auxiliary pumping station on this area is also limited. From the small changes of TN and TP concentration in this area under
different schemes, it was found that the nutrient concentration of S8 increased in flood and dry season, while that of S9 and S10 decreased under all schemes in flood season. In the dry season, except for the increase of TN concentration in scheme C, the others also decreased slightly. SI plays a leading role in the change of nutrient concentration in S8, with a weight of 60%–70%. II plays a leading role in the change of nutrient concentration in S10, and the weight is kept above 90%. The weight of the three pathways of S9 in scheme B and D is II > SI > DI, while in scheme C is SI > II > DI, this is because increasing 20% water diversion will have a certain disturbance effect on S9 sediment. Based on the indoor experiment on the nutrient release rate of S9 sediment (Figure 3), the shear stress produced by the flow velocity under the corresponding scheme exceeds the shear stress corresponding to the peak nutrient release rate in this section. Therefore, the flow velocity of scheme B and D was higher than that of scheme A, but the nutrient release intensity was lower than that of the initial scheme.

4. CONCLUSION

The change of hydrodynamic conditions caused by water transfer of urban plain river-network has an important influence on the content of nutrients in rivers, but little attention has been paid to the influence weight of various ways. This paper compares and analyzes the three action ways of II, DI, and SI caused by the change of hydrodynamics in different regions of the river network, and quantifies the contribution of each way to the concentration of nutrient factors, which can provide a theoretical basis for the formulation of dispatching scheme and hydrodynamic regulation threshold based on the improvement of water quality in the river network area. On the whole, the Binhui river network, as a channel for the discharge of lake water with high nutrient content into the Beijing-Hangzhou Grand Canal under the target of reducing the total amount of pollutants in Meiliang Bay, the DI contribution caused by hydraulic regulation is not more than 37%, while II and SI are more than 90% sometimes. Therefore, it is difficult to improve the water quality of the river network by diluting pollutants. This mainly depends on increasing water diversion to speed up the flow of water and promote the diffusion and degradation of nutrients. But at the same time, it will also lead to the release of nutrients in the sediment, so we need to make a quantitative analysis of the contribution of different pathways in different regions. Specifically, for the rivers in the southeast of the river network, the interaction between the water quantity and hydrodynamic conditions and the river network is not enough, and the response of the nutrient load to the designed regulation schemes is weak. For the rivers to the west of the Mali River, simply increasing the amount of water diversion can promote the biochemical degradation of TN and TP, but it is not enough to make up for the sediment release and the carrying capacity in the diversion water caused by the acceleration of water flow, so it is disadvantageous to the nutrient content of the river near the water diversion pumping stations of the river network. With the movement of water flow, after a period of transport and degradation, it can improve the water quality of medium and long-distance rivers. By simply opening the auxiliary pumping station, the velocity and flow rate of the tributaries are reduced, the external input and endogenous release of pollutants are controlled, and the water quality is improved, but this indirectly increases the pollution load of the mainstream. For example, the pollutant input and sediment release of Liangxi River have increased under the action of auxiliary pumping stations. Through increasing the amount of water diversion and the joint regulation of auxiliary pumping stations, the nutrient concentration in other sections of the river network has been improved except that the upper reaches of Liangxi River is impacted by water flow, which leads to the release of a large number of nutrients in the sediment and the increase of nutrient content.

Therefore, we suggest that floodgates should be set up in the upper reaches of Liangxi River to control the flow rate or carry out dredging to reduce the release of pollutants caused by flow disturbance, and pump stations should be set up in the southeast to realize the linkage with the river network, the elevation of regional water level and the flow rate is conducive to the degradation of pollutants (Gao et al. 2017). At that time, the joint regulation and control mode of increasing the water diversion of Meiliang and Daxuan pumping stations and opening the auxiliary pumps of the river network will be adopted, and the nutrient content of the regional water body will be generally improved. In the next step, we plan to set up more water diversion schemes and auxiliary pumping station operation schemes, and couple the eutrophication mathematical model to study the hydraulic regulation threshold under the target of more water quality improvement, so that the water environment of the lakeside river network can be significantly improved. It provides a reference for the formulation of hydraulic regulation and control scheme of an urban river network.
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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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