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Research papers

Pollutants removal efficiency assessment of constructed subsurface flow wetlands in lakes with numerical models

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ABSTRACT

Ecological remediation with subsurface flow wetland is one of the most widely used methods for pollution abatement. Assessment on its implementation efficiency is necessary but difficult. To evaluate the pollutant removal effect of constructed subsurface flow wetlands, a wetland growth model coupling with a hydrodynamic water quality model has been put forward. The coupled model has been used to assess the impact of constructed subsurface flow wetlands on a polluted lake in Hubei Province, China. Four pieces of constructed subsurface flow wetlands composed of Reed and Smooth cordgrass with total area of 38.9 thousand square meters for pollutant removal have been designed for the lake. Results showed that reductions of chemical oxygen demand (COD), total phosphorus (TP) and total nitrogen (TN) were 246.38, 28.14 and 3.29 tons/year, respectively. Compared with the different pollutants, the removal efficiency of subsurface flow wetlands on TN (49%) is bigger than TP (34%), but less than COD (60%). Furthermore, the higher water temperature, smaller flow velocity and bigger water depth will improve the pollutants removal performance of subsurface flow wetlands.

1. Introduction

Controlling water pollution and restoring the water environment have become national strategic activities in many countries. Ecological remediation is a significant method of environmental governance (Sun et al., 2017). Subsurface flow wetland is the most widely used in water ecological restoration (Ranieri et al., 2011). A subsurface flow wetland is a kind of aerobic wetland, which always contains free water surface, submerged plants, and floating plants. The treatment of sewage by constructed wetland is the comprehensive result of the physical, chemical and biological processes among plants, substrate and internal microorganisms, including precipitation, filtration, oxidation, degradation and adsorption (Wu et al., 2018). Experimental researches have been done to assess pollutant removal performances of wetlands to wastewater, results of which showed that different kinds of wetlands have different removal efficiency to different pollutants (Hu et al., 2020; Saeed et al., 2018). However, wastewater removal efficiency of wetland is highly correlated with solar radiation intensity, temperature, nutrient availability and hydrodynamic condition (Huang et al., 2010). In different water, the performance of the same wetland system is completely different. Based on the previous experimental research, it is still indispensable to develop pre-assessment models for removal efficiency evaluation of wetland for wetland engineering design and construction plans. Nevertheless, as the complexity of pollutants-water-wetland system, it is still challenging to assess how much pollutants that subsurface flow wetland can remove, before the subsurface flow wetlands project is implemented.

Many methods, such as simple design models, first-order k-C* model, plant growth model and Monod-type equations, have been proposed to evaluate the efficiency of ecological remediation measures. Rules of thumb and regression equations are two typical kinds of simple design models. For example, the horizontal subsurface flow (SSF) constructed treatment wetlands assess equations are the fastest, but the roughest (Herrera-Melián et al., 2020; Kadlec, 1997). Several authors have studied regression equations of inlet and outlet pollutant concentrations of horizontal SSF constructed treatment wetlands (Boog et al., 2019; Griffin et al., 1999). However, due to neglecting many important factors of wetlands growth, these equations are always oversimplified and have great uncertainty (Rousseau et al., 2004; Wang et al., 2020). The plant growth model is based on the empirical relationship between plant

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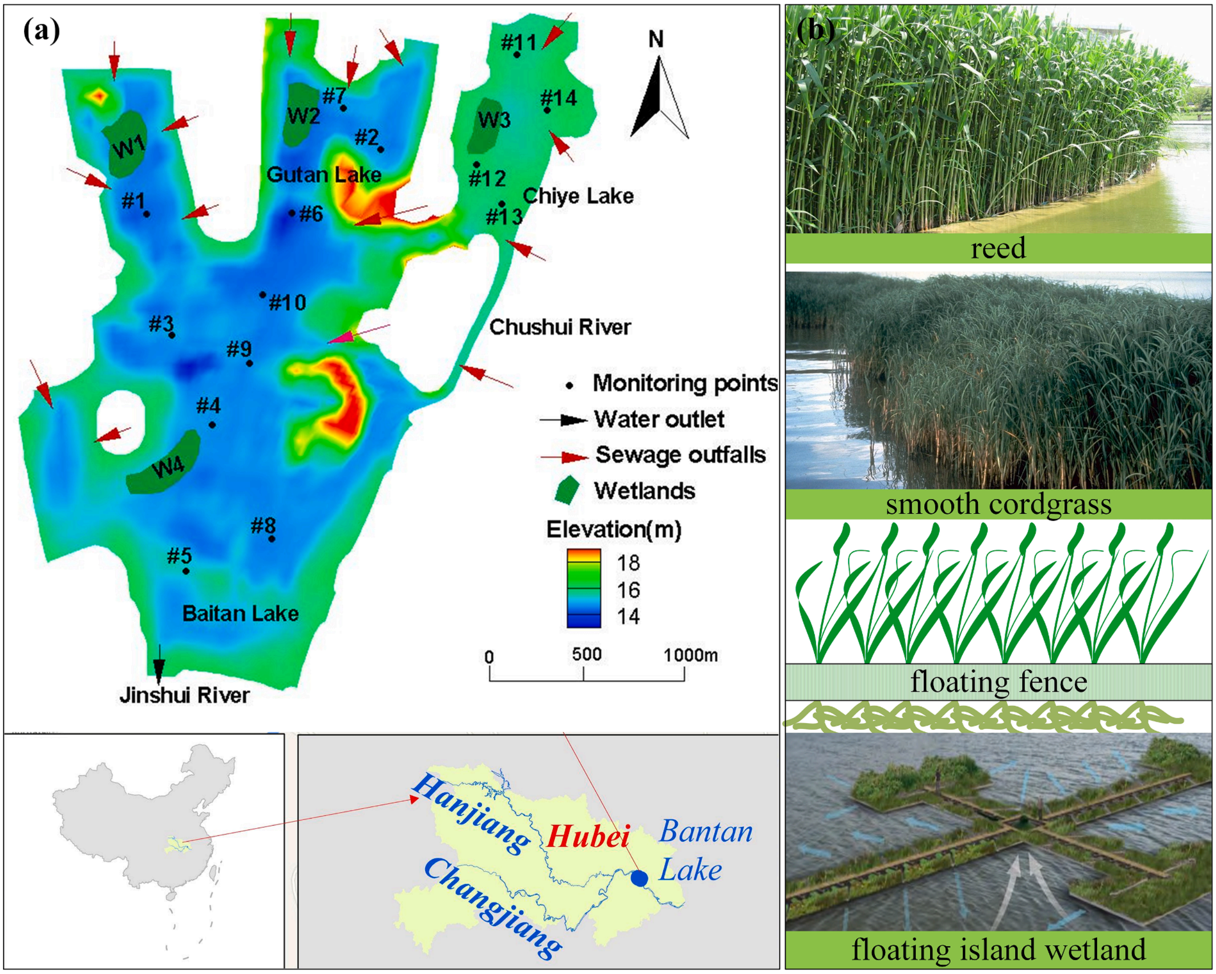

Fig. 1. Water quality measured points and subsurface flow wetlands of Baitan, Gutan and Chiye Lakes.

biomass and environmental conditions. Many researches have studied the relationship among plant growth, water temperature, nutrients and sunlight (Nxawe et al., 2010; Weerakoon et al., 2020). Monod-type equation is a kind of first-order models, in which the relatively low concentrations are used for representing first-order rate reactions instead of high concentrations used for zero-order rate reactions. Research has found that Monod-type model over performs a first-order model in simulation accuracy (A.I. et al., 2019; Mitchell and McNevin, 2001). Nevertheless, without considering the ecological process, these methods are simplified and based on assumptions, which cause errors in fitting with the complex operating conditions of subsurface flow wetlands (Saeed and Sun, 2011).

To describe the physical, chemical and biological processes of subsurface flow wetlands more completely, many mechanisms or processes based numerical models have been developed (Fioreze and Mancuso, 2019; Savickis et al., 2016; Smesrud et al., 2014). In these models, the typical transformation and degradation processes of carbon and nitrogen, the water and oxygen balances, as well as plant growth and decay processes are considered. Some of these processes have been developed in modules, for example, the multi-component reactive transport module CW2D (Langergraber, 2002), including 12 components (dissolved oxygen, organic matter, ammonium, nitrite, nitrate, nitrogen gas, inorganic phosphorus, as well as heterotrophic and two species of autotrophic micro-organisms) and 9 processes (hydrolysis, mineralization of organic matter, nitrification, denitrification, and a lysis process for the micro-organisms) (Langergraber et al., 2009). And numerical models describe the changing processes of a large number of components in detail (Sanchez-Ramos et al., 2019). Whereas, the extension and application of these numerical models are always difficult for their complex characters and abundant data requirements.

For the design of subsurface flow wetlands, the assessment tool should be precise and be applicable under the conditions of limited data. This study has provided a coupled method to evaluate the efficiency of pollutant reduction in constructed subsurface flow wetlands in a lake in China. It simplifies the numerical plant-growth model integrated with hydrodynamic and water quality model and will be appropriate in areas where data are limited. Therefore, the objectives of this study are: (a) to develop a hybrid water ecological model for the design of subsurface flow wetlands, and (b) to assess the pollutant reduction capacity of a practical constructed subsurface flow wetlands project.

2. Methods and materials

2.1. Study areas

The Baitanhu Lake (containing Baitan Lake (BT), Gutan Lake (GT) and Chiye Lake (CY) are located in Huanggang City, Hubei Province, China, as shown in Fig. 1. These three lakes are heavily polluted mainly by organic materials and nutrient sources, especially in the chemical oxygen demand (COD), total phosphorus (TP) and total nitrogen (TN). In recent years, the government has realized the importance of water environmental protection and increased investments in environmental improvement. A project, which is in accordance with the Huanggang Urban Master Plan (2011–2030) and the Baitan Lake Area Control Plan, has been set up to improve the water quality, within the 25.27 km^2 of the Baitan Lake planning area. In this project, constructed subsurface flow

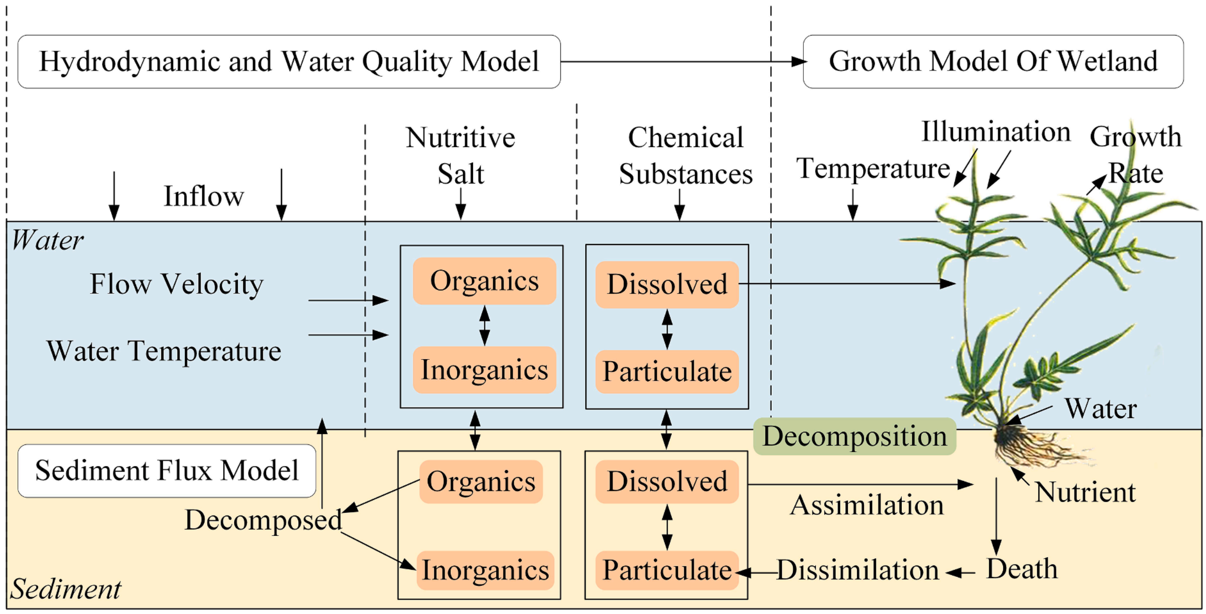

Fig. 2. The structure of the coupling model.

wetlands were designed for water quality improvement.

This project was designed in 2013, and four constructed wetlands (*W1, W2, W3, W4)* will be planted, as shown in Fig. 1(a). The W1, W2 subsurface flow wetlands will be constructed in the arm of Baitan Lake and Gutan Lake; the W3 subsurface flow wetland will be constructed in Chiye Lake, and the W4 subsurface flow wetland will be constructed in the south-east of a Baitan island. Fig. 1(b) shows a typical cross section of the subsurface flow wetland. The subsurface flow wetland will be created as a floating island wetland, which is a recent bio-engineering technology for improving water quality. Aquatic species are planted on a floating raft with their roots extending into the water column underneath the raft, thus able to absorb and remove nutrients such as nitrogen and phosphorus from the water. The common local species, such as Reed and Smooth cordgrass, have been selected to be planted in the subsurface flow wetland.

Up till now, only one wetland (W3) has been finished. Measured data in 2013 before and after planting of W3 planted have been used for model verification. The other three wetlands were used for pollutants removal efficiency assessment by numerical models.

2.2. Models developments

Water and subsurface flow wetlands coupled with bottom sediment compose an independent ecosystem. During the processes of growth, maturity, decline and death, subsurface flow wetlands not only assimilate nutriment from waters and sediments for primary production, but return nutrients to the environment after death (Pincam et al., 2020). Which is influenced by water hydrodynamic, water nutrient substance and other environmental factors. Considering these processes, a coupled model consisting of a hydrodynamic water quality model, a sediment model and a water ecological model has been developed, as shown in Fig. 2.

2.2.1. Hydrodynamic and water quality model

The hydrodynamic model and water quality model were based on a common two dimensional hydrodynamic and water quality lake model (Xu et al., 2020), including continuity equation (1), momentum equations in × and y directions (2, 3) , and diffusion control equations of nutrients (4):

$$\frac{\partial Z}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \tag{1}$$

$$\frac{\partial hu}{\partial t}+\frac{\partial huu}{\partial x}+\frac{\partial hvu}{\partial y}+gh\frac{\partial z}{\partial x}+\frac{gn^2h\sqrt{u^2+v^2}u}{h^{4/3}} = hfv+\frac{\rho_a f_w\left(w_x^2+w_y^2\right)w_x}{\rho_w}+\frac{\partial}{\partial x}\left(h\gamma_t\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\gamma_t\frac{\partial u}{\partial y}\right) \tag{2}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hvv}{\partial y}+gh\frac{\partial z}{\partial y}+\frac{gn^2h\sqrt{u^2+v^2}v}{h^{4/3}} = -hfu+\frac{\rho_a f_w\left(w_x^2+w_y^2\right)w_y}{\rho_w}+\frac{\partial}{\partial x}\left(h\gamma_t\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\gamma_t\frac{\partial v}{\partial y}\right) \tag{3}$$

$$\frac{\partial hC_i}{\partial t}+\frac{\partial huC_i}{\partial x}+\frac{\partial hvC_i}{\partial y}=\frac{\partial}{\partial x}\left(hK_x\frac{\partial C_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(hK_y\frac{\partial C_i}{\partial y}\right)-hk_dC_i+S_m-S_p \tag{4}$$

where, u and v are respectively the average velocity in x and y directions (m/s); z is water level (m); *h* is water depth (m); *f* is Coriolis coefficient, *f* = *2Ωsin(lat)*, and Ω is the Earth rotation angular frequency, while *lat* is latitude; γ_t is turbulent viscosity coefficient (m^2/s); ρ_a and ρ_w are air density and water density, respectively; f_w is wind stress coefficient; w_x and w_y are respectively wind speed in x and y directions; n is the roughness factor; C_t is the concentration of nutrients in the water (mg/L); K_x and K_y are nutrients diffusion coefficient in x and y directions (s/m^2), respectively; k_d is the degradation coefficient of nutrients (s^{-1}); S_m is nutrient load from lakebed sediments *(kg)*, and S_m can be calculated as:

$$S_m=\lambda(C-C_d) \tag{5}$$

where, λ is the nutrients release coefficient of sediment (mg/m^2·d); C and C_d are nutrient concentrations in the water and sediment, respectively; C is calculated by the water quality model; C_d is computed by the sediment flux model.

S_p represents the nutrient removed by subsurface flow wetlands through sediment, including plants absorbed by plants (S_{orb}) and consumed by the microorganisms attached to roots (S_{con}).

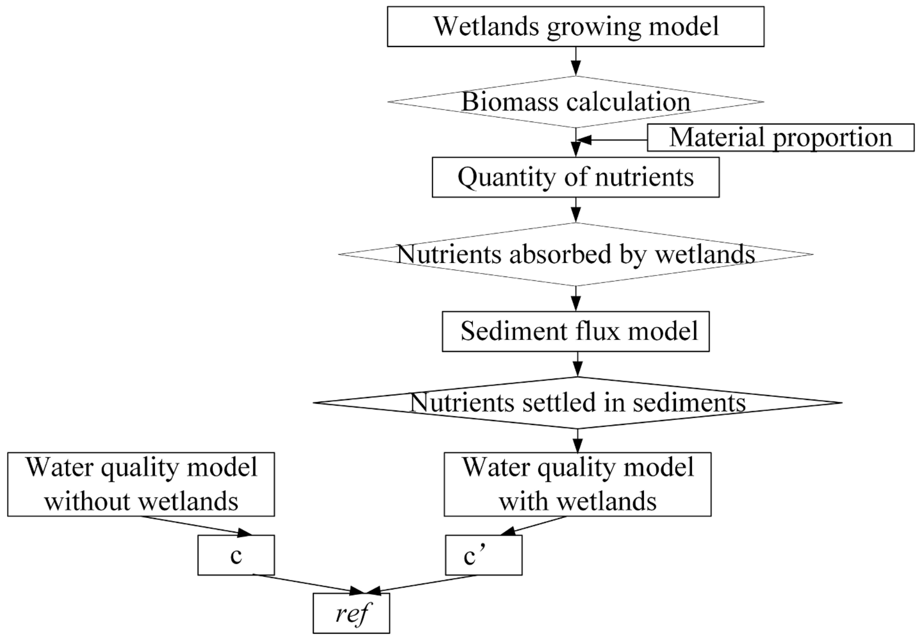

Fig. 3. Processes of nutrient removal efficiency evaluation with models.

$$S_p = S_{orb} + S_{con}$$
$$S_{con} = \lambda_s \left(\frac{S_{orb}}{t}\right) + \lambda_k k_d \tag{6}$$

S_{orb} can be calculated by biomass through a proportion of nutrients (C: N: P, Carbon, Nitrogen and Phosphorus) constituting the total biomass, while both λ_s and λ_k are the coefficient.

2.2.2. Sediment flux model

Nutrient concentration in sediment is affected by physical, chemical and biological processes, including diffusion, adsorption, mineralization, nitrification and denitrification, and plants absorption process (Ge et al., 2020; Zhang et al., 2014). The basic equation is as follows:

$$\frac{\partial(\theta + f\rho K_d)C_i^s}{\partial t} = \frac{\partial}{\partial t}\left(\theta D \frac{\partial C_i^s}{\partial z}\right) - \frac{\partial q C_i^s}{\partial t} - \varphi C_i^s + k\theta\rho S_{2i} \tag{7}$$
$$\varphi = k\theta\rho(1-f)K_d + \theta\lambda_1 + f\rho K_d \lambda_2$$

$$\frac{\partial S_{2i}}{\partial t} = k\theta[(1-f)K_d C_i^s - S_{2i}] - \lambda_3 S_{2i} \tag{8}$$

where, C_i^s is nutrients concentration in the aqueous phase of sediment (mg/L); θ is the percentage of saturated water content; $\rho$is sediment density; K_d is distribution coefficient of water and sediment; k is first order adsorption rate constant; D is dispersion coefficient; z is the depth of sediment; λ_1, $\lambda_2$and λ_3 are first order degradation rate coefficient in the aqueous phase, equilibrium adsorption phase and non-equilibrium adsorption phase, respectively; S_2 is the adsorbent concentration in non-equilibrium adsorption phase.

2.2.3. Growth model of wetlands

During the growth of subsurface flow wetlands, pollutants will be absorbed and reduced. Previous studies have reported that the growth of subsurface flow wetlands is influenced by water temperature, water and nutrients (Oliver et al., 2017; Steinman et al., 2014). In an ideal condition, plant growth can be regarded as a time change function of its maximum growth rate and environmental factors. A common function for subsurface flow wetlands growth is as follows (Hem, 1971):

$$\frac{dB}{dt} = G_{bmax}(t)G(T,t)G(NU,t)G(I,t)G(W,t)B \tag{9}$$

where, B is the biomass of subsurface flow wetlands (g/m^2); $G_{bmax}(t)$is the maximum growth rate for plants (g/m^2·d); $G(T,\ t)$is temperature limiting factor; $G(NU,t)$ is the nutrient limiting factor; $G(I,t)$is the illumination limiting factor; $G(W,t)$is the water limiting factor, related to water depth and flow velocity; t is the time of plants growing (d).

During realistic simulation (realistic temperature, nutrient and illumination), the detailed relationships between plant growth and environmental conditions depend on the plant species. Thus, equation (9) can be:

$$\frac{dB}{dt} = G_{bmax}(t)B \tag{10}$$

2.2.4. Model conditions

The boundary conditions and initial condition are as follows:

(1) Inflow boundary conditions:

$$\begin{aligned} Q &= Q_{in}(x,y,t) \\ C &= C_{in}(x,y,t) \end{aligned} \tag{11}$$

(2) Outflow boundary condition:

$$Q = Q_{out}(x,y,t) \tag{12}$$

(3) Initial condition:

$$\varphi = \varphi(x,y,0) \tag{13}$$

where, Q_{in} is the quantity of inflow (m^3/s); $x,\ y$ are respectively the locations of elements; t is the time; C is the pollutant concentration (mg/L); φ is indicators' initial values of modeling, including water level, pollutant concentration.

Equations will be solved by the finite control volume method with an upwind scheme.

2.2.5. Removal efficiency

To evaluate the nutrient remove efficiency of subsurface flow wet-

Table 1
Pollutant loads in stock and from external sources.

Lakes	Pollutants		
	COD	TP	TN
In stock (ton)	174.29	0.43	12.43
External pollutant loads (ton/year)	403.26	9.58	66.87
Total	577.55	9.51	79.3

lands, a removal efficiency (*ref*) index was set as follows:

$$ref = \frac{\sum_{i=1}^{m} c_{it} \times V_{it} - \sum_{i=1}^{m} c'_{it} \times V_{it}}{\sum_{i=1}^{m} c_{it} \times V_{it}} \tag{14}$$

where, t is the date; I is the number of grid cells in the two-dimensional model; V is the volume of the grid (L); c is the nutrient concentration without subsurface flow wetlands; c' is the nutrient concentration with subsurface flow wetlands.

The processes of calculating removal efficiency are shown in Fig. 3.

Firstly, the wetland growth model is used to simulate the total biomass of wetlands. According to the proportion of carbon, nitrogen and phosphorus in biomass, the nutrients absorbed by wetlands can be calculated. In this process, the botanical photosynthesis, respiration and nutrient absorption through the stem and leaf are ignored.

Secondly, assuming that nutrients in sediment are dynamically balanced, the nutrients absorbed by wetlands will be supplemented by water. With this assumption, the sediment flux model will be operated, which will get nutrients concentration in sediment for every grid.

Thirdly, the nutrient in water in two scenarios (with or without

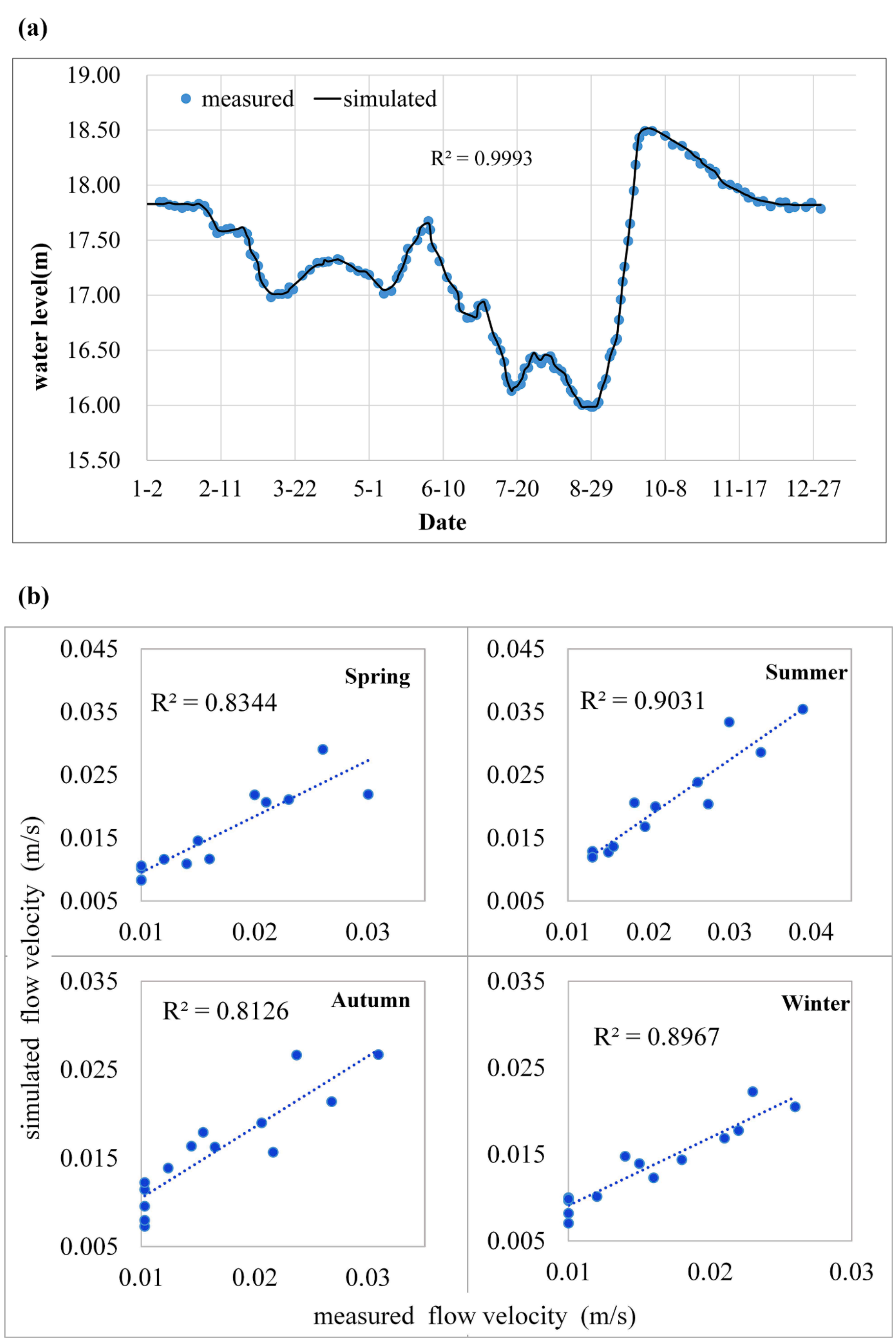

Fig. 4. Observation and simulation of average water level and flow velocity.

Table 2
Measured data at 14 measure sites on March 5, 2013.

Sites	COD (mg/L)	TP (mg/L)	TN (mg/L)
#1	27.10	0.0765	2.475
#2	28.20	0.0844	2.500
#3	26.58	0.0763	2.430
#4	29.04	0.0820	2.400
#5	25.46	0.0784	2.345
#6	26.91	0.0824	2.480
#7	28.76	0.0830	2.490
#8	24.08	0.0826	2.515
#9	27.15	0.0845	2.465
#10	26.32	0.0836	2.490
#11	26.85	0.0767	2.430
#12	27.23	0.0777	2.320
#13	26.54	0.0775	2.310
#14	27.65	0.0770	2.465

wetlands) will be simulated by the water quality model. Using equation (10), the total volume, the removal efficiency of different nutrients removed by wetlands in the whole lake and every grid in time series or within a specific time can be computed.

2.3. Model conditions setting

Two-dimensional regular grids have been used for model simulation with mesh size of 10–30 m. According to the current situation of water quality of lakes, COD, TN, and TP were set as three water quality indexes. Inflow from *Chushui River* and outflow from *Jinshui River* are the boundary conditions of two tributaries. In addition, two sluice gates have been set to control the inflow and outflow. Through field investigation and monitoring, we have obtained the loads of pollutants source, hydrological and water quality conditions of the lakes. Based on the survey data, there are almost 15 outfalls around the lakes (as shown in Fig. 3). Wastewater carrying pollutants from storm-water runoff, fish farming, agriculture and soil erosion enter into the lakes. The external pollution source loads are estimated as shown in Table 1. For shoreline protection, the non-points sources pollutants are gathered and entered into the lake through 15 sewage outfalls, with 403.26 tons per year (t/a) COD, 9.58 t/a TN and 66.87 t/a TP, which have been treated as lateral input conditions.

Pollutant loads from external pollutant sources are much larger than pollutants in stock, with COD of 403.26 tons, TN of 66.87 tons and TP of 5.77 tons every year.

The water level of the outlet (shown in Fig. 4, measured data) has been set as a boundary condition. Initial conditions of each grid were gained from the measured value of 14 measured sites in early spring by inverse distance weighted interpolation, as shown in Table 2.

For model calibration and validation, measured data at 9# and 12# from March 5, 2013 to the March 4, 2014 were used for model calibration. Data at #1, #6, #7, #9 and #13 (selection of measuring sites is random, which is evenly distributed in the three lakes) were set for model validation.

2.4. Scenarios of simulation

Two scenarios have been designed for the model simulation. The first one is the scenario without subsurface flow wetlands, while the second one is a comparable scenario with 4 subsurface flow wetlands. As shown in Fig. 3, there are 4 subsurface flow wetlands in three lakes, and sizes of subsurface flow wetlands *W1, W2, W3, W4* are 14,515 m^2, 9,211 m^2, 5,870 m^2 and 9,304 m^2, respectively. In these four wetlands, the Reed and Smooth cordgrass are both planted about 50 percent of the total. A full year period was set for simulation from March 5, 2013 (without wetlands) to March 4 of the next year (planned year with wetlands). In the wetland scenario, it is assumed that the water, temperature and light factors are all in an appropriate state, while plant growth is mainly

Table 3
The $G_{bmax}(t)$ of wetlands.

$G_{bmax}(t)$		$t(d)$
Reed	Smooth cordgrass	
1.011	1.011	$0 < t \leq 60$
1.022	1.007	$61 < t \leq 122$
0.999	1.007	$122 < t \leq 184$
0.983	0.993	$184 < t \leq 245$
0.963	0.973	$245 < t$

Table 4
the proportion of nutrients of wetlands.

Reed			Smooth cordgrass			$t(d)$
ΛN	ΛP	ΛC	ΛN	ΛP	ΛC	
0.0098	0.0018	0.4811	0.0149	0.0017	0.5927	$0 < t \leq 60$
0.0089	0.0021	0.4816	0.0112	0.0019	0.5927	$61 < t \leq 122$
0.0095	0.0006	0.4826	0.0090	0.0012	0.5927	$122 < t \leq 184$
0.0086	0.0004	0.4837	0.0057	0.0007	0.5927	$184 < t \leq 245$
0.0078	0.0004	0.4825	0.0054	0.0006	0.5927	$245 < t$

restricted by nutrients. Thus, the $G_{bmax}(t)$ is the main factor affecting the biomass of wetland. According to the pervious study, the $G_{bmax}(t)$ can be obtained from Table 3.

In the different growing period of wetlands, the proportion of nutrients is different, which can be gained from Table 4.

2.5. Parameters calibration and model validation

2.5.1. Sensitive parameters and value ranges

For the hydrodynamic model, the roughness coefficient is the deterministic parameter. Comparing measured flow velocity, water level and simulated results, the roughness coefficient of these three lakes is around 0.2 to 0.25.

For the water quality model, the degradation coefficient (K_d), nutrients diffusion coefficient (k_{xy}) and nutrient release rate (λ) from sediment in three lakes are calibrated, as shown in Table 5.

Parameters of the sediment flux model are calibrated with the same values in three lakes, as shown in Table 6. To simplify models, the λ_s and λ_k were set as 1.

2.5.2. Model calibration and validation

(1) Scenario without wetlands

Model calibration results of water level and flow velocity are shown in Fig. 4, and the calibration results of COD, TN and TP concentration without wetlands at 9# and 12# in 2013 are shown in Fig. 5.

As shown in Fig. 4, after parameters calibration, the simulated water level and measured water level match well, where the coefficient of the determinant (R^2) is over 0.99. In addition, it also indicates that the model can simulate the flow velocity characteristics of temporal and spatial variation, with R^2 bigger than 0.8 in four seasons.

The Fig. 5 shows that the measured data and simulated data of COD, TN and TP at locations 9# in the *Baitan* Lake and #12 in the *Chiye* Lake, which are also matching well. The relative errors range from −14% to 12%, and the errors of90% samples are between −10% and 10%.

(2) Scenario with wetlands

After wetland (W3) planted, the water quality concentration was simulated and the parameters were calibrated. The coefficient of the determinant (R^2) and relative error have been used for water quality model validation. Furthermore, results of measured data and simulated data in five sections (#1, #6, #7, #12 and #13) on March 29, May 17 and June 9 were shown in Fig. 6.

As shown in Fig. 6, the R^2 of COD, TP, TN are respectively 0.7618, 0.9221 and 0.9395; the relative errors of these three water quality indexes are 9%, 7.11% and 7.69, respectively. For many previous studies

Table 5
Parameters of water quality model.

Lakes	K_d (d^{-1})			k_{xy} (d^{-1})			λ (d^{-1})		
	COD	TP	TN	COD	TP	TN	COD	TP	TN
BT	0.558	2.566	1.166	0.135	0.198	0.156	1.903	1.745	2.177
GT	0.553	2.938	2.221	0.154	0.169	0.186	1.903	1.158	2.163
CY	0.855	2.989	2.254	0.198	0.172	0.146	0.881	1.176	2.193

Table 6
Parameters of sediment flux model.

Parameter name	Symbol	Value	Range
Percentage of saturated water content	β	0.5	[0,1]
Sediment density	ρ	1.2	[1,10]
Distribution coefficient of water and sediment	K_d	0.2	[0,1]
First order adsorption rate constant	K	0.75	[0.2,0.8]
Dispersion coefficient	D	0.11	[0.05,0.3]
First order degradation rate coefficient in aqueous phase	λ_1	0.8	[0,1]
Equilibrium adsorption phase	λ_2	0.4	[0,1]
Non-equilibrium adsorption phase	λ_3	0.4	[0,1]

about water quality models, that R^2 larger than 0.6 is can be judged as satisfactory (Masocha et al., 2018; Moriasi et al., 2007; Shi et al., 2011). Additionally, the relative errors of this model are all less than 10%in scenarios with or without wetlands, which present that the model used in this paper is reasonable for water quality and wetland simulation.

3. Results and discussion

3.1. Removal efficiency of wetlands to different pollutants

Comparing spatial distribution of COD\TP\TN on July 30 in these two different scenarios, results are shown in Fig. 7.

As shown in Fig. 7, in the scenario without wetlands, the concentration of pollutants is larger in the bays than that in the middle of lakes.

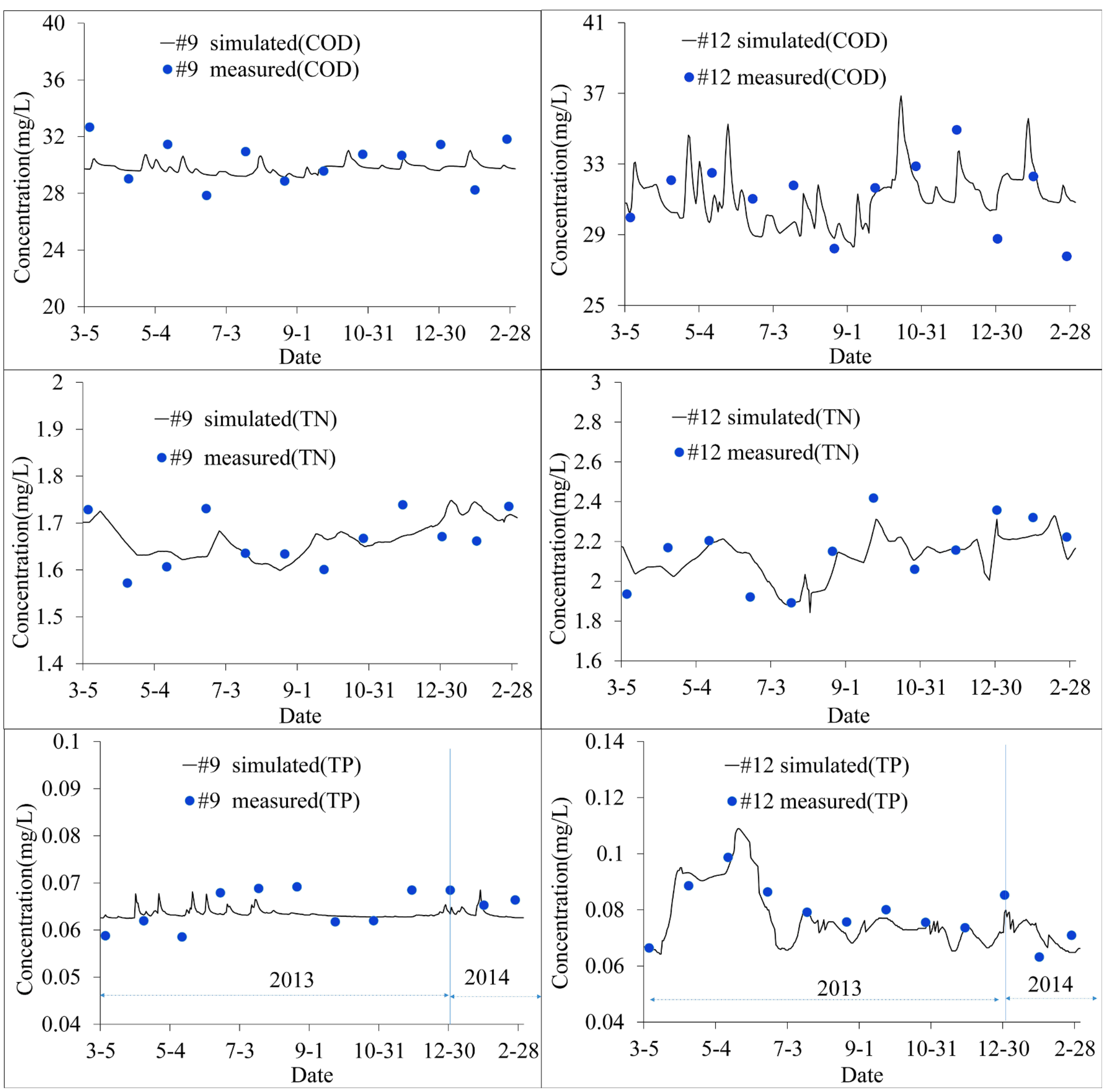

Fig. 5. Measured and simulated COD, TN and TP concentration at #9 and #12 without wetlands.

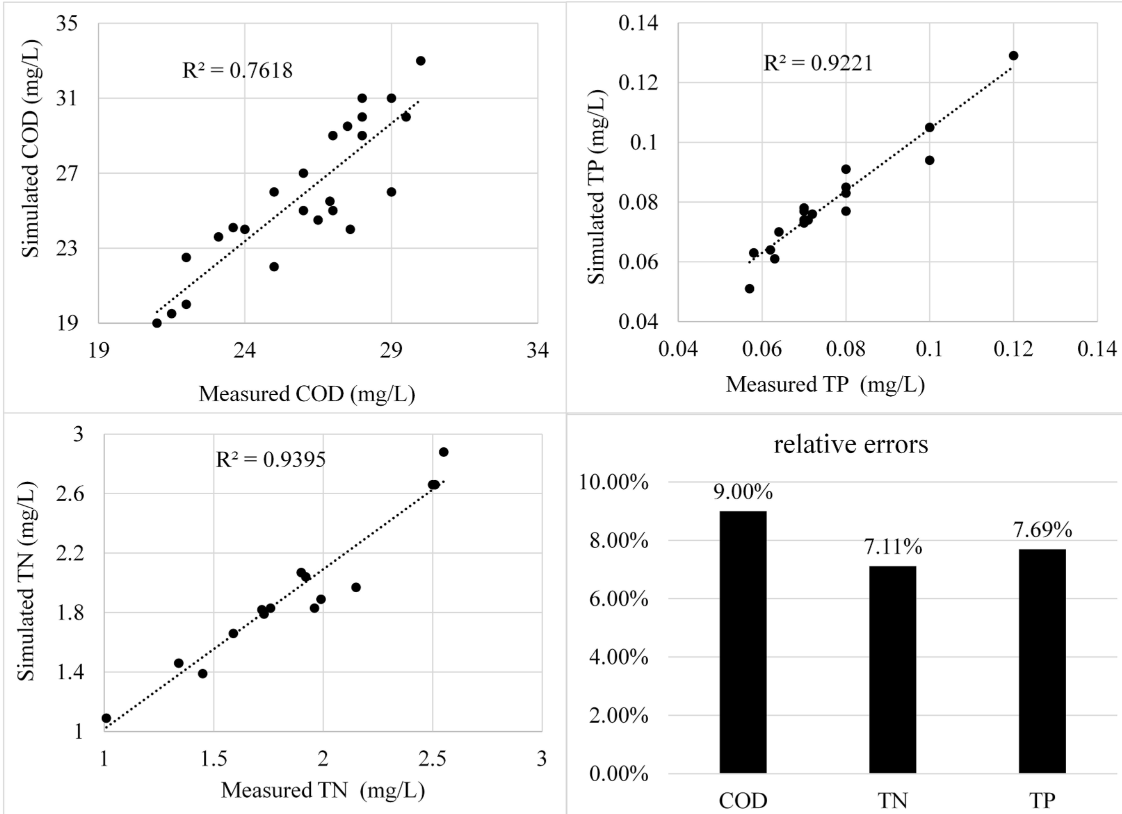

Fig. 6. The coefficient of determinant (R^2) and relative error of model validation.

Pollutants are usually discharged into the lake from sewage outfalls around the bays (Mu et al., 2013). Most outfalls are located in the bays of Gutan Lake and Chiye Lake. Because of this, water quality of the Gutan Lake and Chiye Lake is worse than that of the Baitan Lake. The results of the scenario without-project indicated that the water quality of COD and TN in Gutan Lake and Chiye Lake would deteriorate to some extent. Additionally, the pollutant concentration in areas around the sewage outfalls is the highest in the water.

According to the right portion of Fig. 7, the water quality is obviously improved after planting the subsurface flow wetlands. Especially the COD and TN are mostly removed by wetlands. Without wetlands, the concentration of COD in the Baitan Lake is almost over 20 mg/L, half of which is over 30 mg/L. However, with wetlands, the COD concentration drops below 20 mg/L. A large reduction of COD occurred along the bays in Gutan Lake and Chiye Lake. For TN, it has the same phenomenon as the COD. Whereas, the decrease of TP is not obvious, especially in the bays. It is indicated that the absorption of phosphorus by wetlands is relatively poor.

According to the simulation results, the quantity and efficiency of pollutant removal by wetlands were shown in Table 7. The impact of the wetlands is expected to lead to the annual reduction of COD 246.38 tons, TN 32.85 tons, and TP 3.29 tons.

The wetlands in lakes with a very good retention, storage and purification function have an active role in reduction of pollution load into the lakes, with removal rates to external pollutants loads COD 61%, TN 49% and TP 34%. Most of the COD input from external sources will be removed by wetlands. Which are similar to previous studies, displaying highest removal on COD, less on TN and the least on TP (Zhou et al., 2017; Zurita et al., 2009).

3.2. Removal efficiency of wetlands at different time periods

The pollutant concentration at #9 and #12 during one year from March 5 to March 4 in the next year is shown in Fig. 8. Without wetlands, in the center of Baitan Lake (#9), the concentration of COD is almost over 25 mg/L; TN is over 1.6 mg/L, and TP ranges from 0.06 to 0.07, which indicates a serious pollution. During the whole year, water quality concentration of COD\TN\TP at #9 tends to stay fairly flat. But with wetlands, the trends of COD and TN are dramatically changed, especially in June and early July. The concentration of COD at #9 on July 9 decrease to 15.8 mg/L from 29.3 mg/L, with over forty-five percent lower. On the other hand, water quality concentration fluctuates at #12 due to the external pollutant input. As the main pollutant source of the lake is non-point sources, a lot of pollutants will be washed into the lake by initial rain during the early rainy season from early May to mid-June (Grand-Clement et al., 2013). After that until August, the temperature and rainfall are gradually increasing, but pollutants reduce, which makes pollution be generally diluted by runoff around the lake. This is why the water quality concentration of COD\TN\TP is lowest at #12 during the period from June to August. During this period, with wetland, the pollutants of COD and TN will be largely removed at #12. Nevertheless, compared with COD and TN, the reduction of TP concentration is very small. The temporal distribution of pollutant concentration means that, with wetlands, comparatively, there will be a larger drop of pollutants during the late spring, the whole summer on COD and TN, but a smaller drop on TP.

3.3. Factors influencing pollutants removing efficiency of wetlands

Water temperature, flow velocity, and water depth are the major impact factors to the nutrients absorbing ability of wetlands (Bai et al., 2017; Seybold et al., 2002; Wen et al., 2013). For different pollutants, the main impact factors are various.

3.3.1. Pollutants characteristic

Generally, the mechanism of wetlands removing pollutants is that

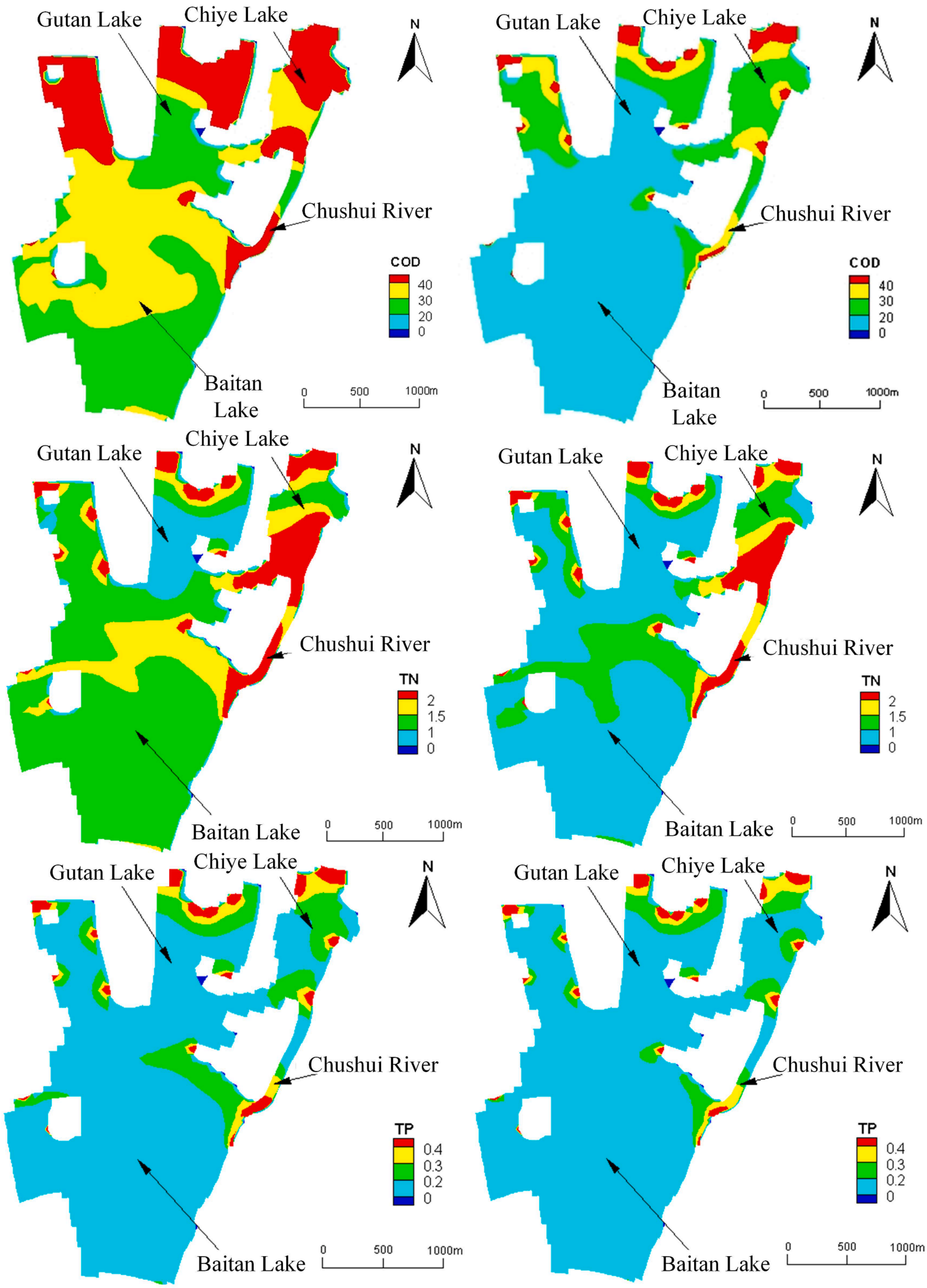

Fig. 7. Spatial distribution of COD \TN\TP on July 30 between scenarios without (left portion) and with (right portion) subsurface flow wetlands.

the plant roots, stems, leaves and root parts of the wetland matrix layer can intercept the suspended material in the polluted water and make it deposit to the base layer, during pollutants entering into the wetland. For wetlands, dissolved pollutants are more readily absorbed than particle pollutants. Most of the COD from the external sources are dissolved forms (Zeng et al., 2020), while phosphorus is constituted by dissolved and particulate phosphorus (Björkman et al., 2018). Most of the phosphorus is easily adsorbed by sediments and deposited at the bottom of the lake, which makes wetlands not disadvantageous to assimilate phosphorus (Ding et al., 2018; Zhou et al., 2005).

However, the average removal rate is less than the removal rate of 80%, 70% and 50% found by the researcher (Zurita et al., 2009), who

Table 7
Annual removal of water quality pollutants by wetlands.

Lakes	Remove quantity (ton/year)			Average removal rate (g/m^2.d)		
	COD	TP	TN	COD	TP	TN
CY	36.96	0.43	5.58	18.86	0.22	2.85
GT	61.6	0.76	8.87	18.32	0.23	2.64
BT	147.83	2.11	18.4	17	0.24	2.12
Total/Average	246.38	3.29	32.85	18.06	0.23	2.53

used a vertical subsurface flow constructed wetlands (VFCW) for domestic wastewater treatment. Especially the TP, only one-third of the TP can be cleaned. Besides, several studies discovered that the phosphorus removal in constructed wetland system is almost adsorbed by matrix, and only a small part of total phosphorus can be removed by plant absorption (Hussain et al., 2015; Kumar et al., 2011). Compared with the experimental studies, the matrix is not considered in this study, which may be the reason that removal efficiency of organics and nitrogen from wastewater is less.

3.3.2. Water temperature

Generally, plants have limited ability to directly purify pollutants of COD (only contributing 15%-19%) and TN (almost 20%-40%), while microorganisms in plant roots play a greater role in removing COD and TN (Vymazal, 2009). In this paper, the degradation of pollutants is set according to the plant growth, which is affected by water temperature. The correlation analysis between removal efficiency and water temperature is shown in Fig. 9.

In winter and early spring, the removal efficiency of the three pollutants was the lowest when the temperature was below 15℃. For example, the lowest removal rates of COD, TN and TP in this system were 24.24%, 33.0% and 20.7%, respectively. Researches indicated that the root activity of wetland and life activity of microorganism would decrease when temperature approach 10℃ (Gotor-Vila et al., 2017). Which made that the ability of wetlands and microorganism to remove pollutants was weak. With the temperature rising at the end of spring and reaching above 25 degrees in mid-to-late August, wetland activities were intensified. Meanwhile, the large roots of wetland provided favorable conditions for the reproduction of microorganisms, and then accelerated the pollutants removal speed of microorganisms (Saeed et al., 2018). In August, the removal efficiency of the three pollutants reached the maximum. For instance, the removal of COD will reach 93%, together with TN 63%, and TP 45%. When temperature drops in autumn, the removal efficiency of pollutants will decrease, and the trend

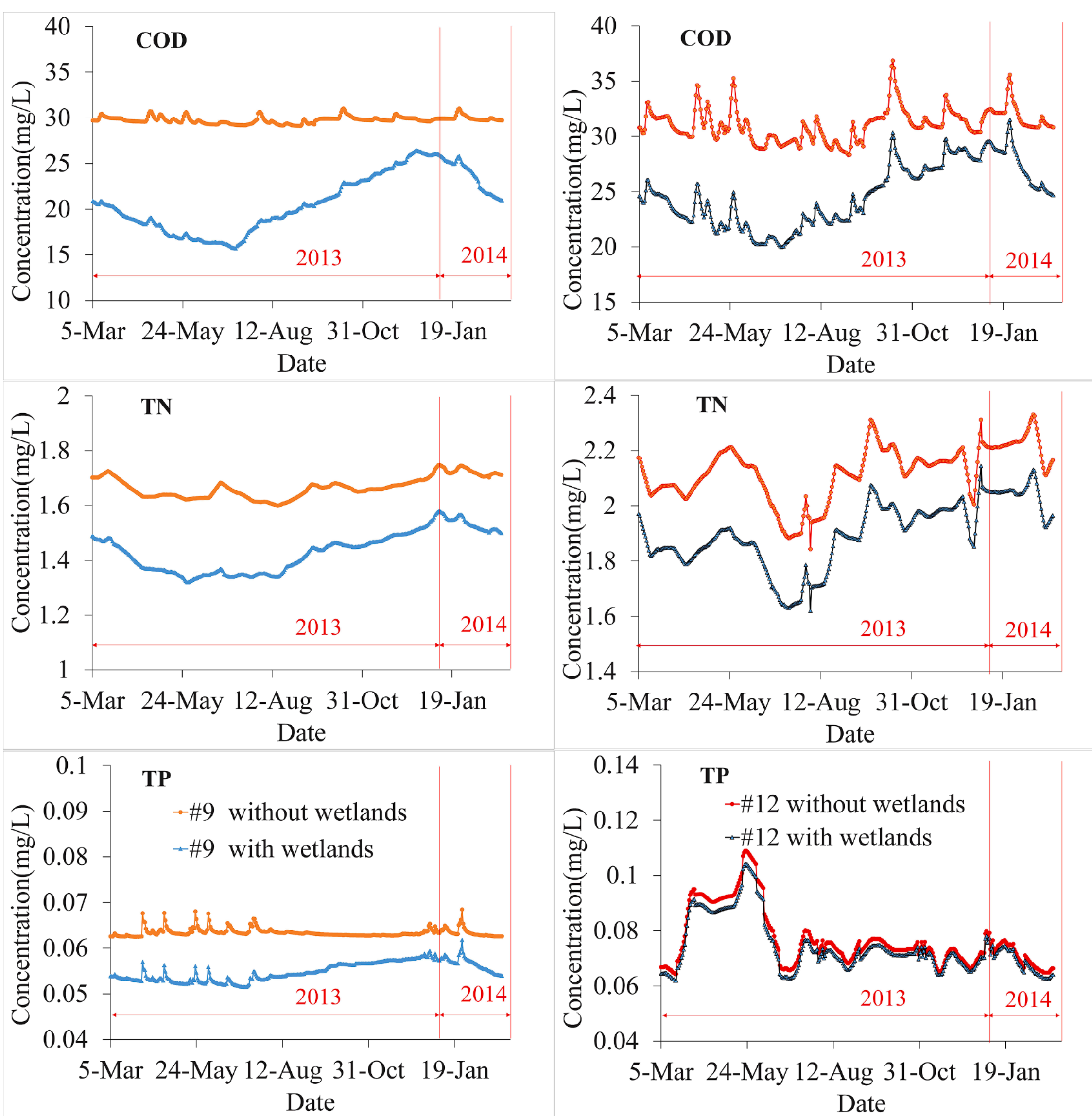

Fig. 8. Concentration of COD/TN/TP between scenarios before and after wetlands planted at point #9 and #12 during one year.

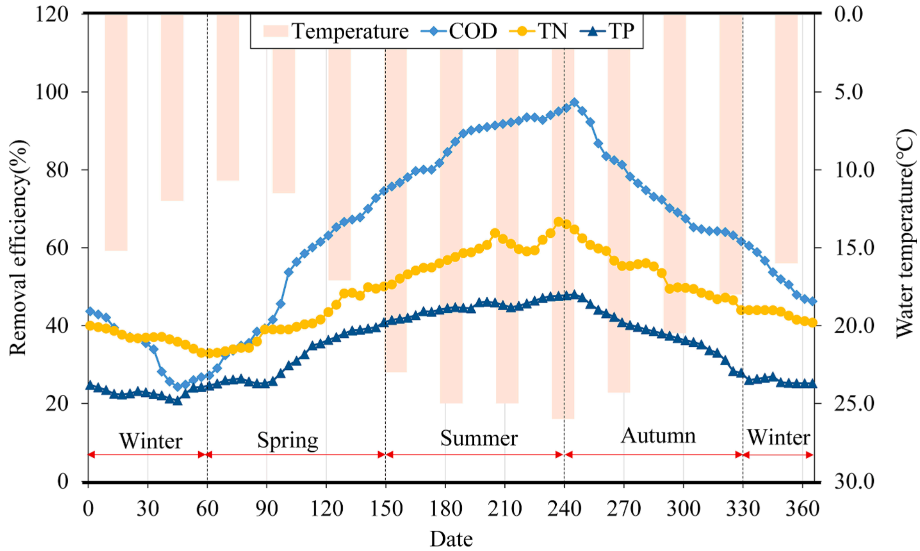

Fig. 9. Annual removal efficiency of wetlands to COD\TN\TP. Date 1 represents January 1st.

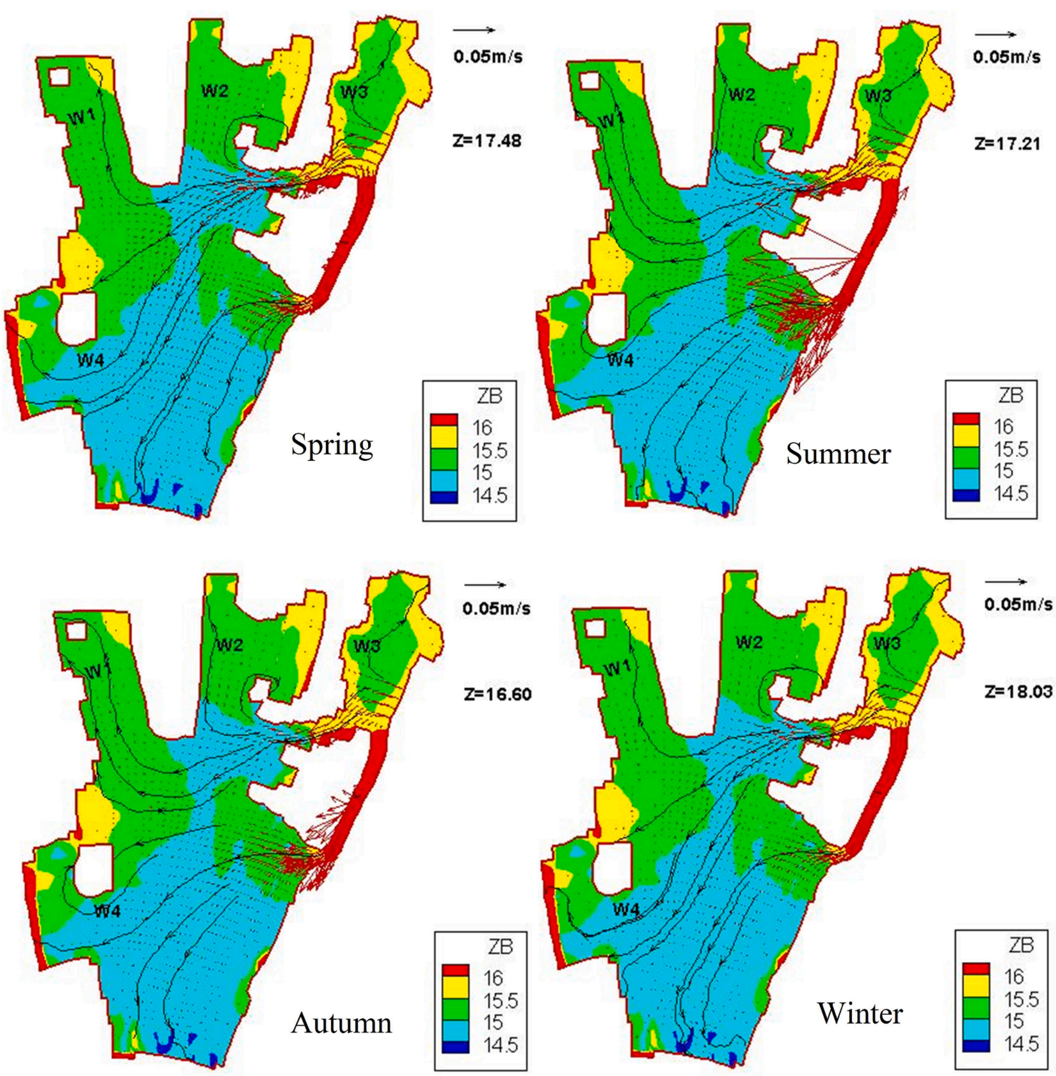

Fig. 10. Average flow velocity in four seasons. ZB is the bottom elevation. Z is the average water level.

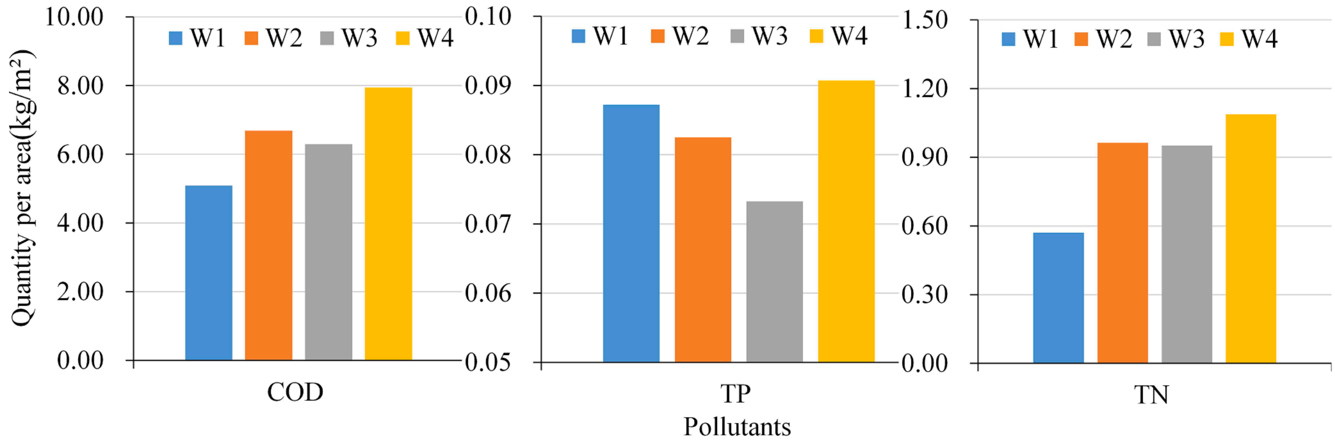

Fig. 11. Average annual pollutant removal quantity per area of wetlands.

will continue to decline until winter. This result is similar to many experimental analysis studies (Wu et al., 2018, 2017), suggesting that temperature has a significant impact on the removal efficiency of wetlands, and models in this paper can simulate this phenomenon.

3.3.3. Flow velocity and water depth

Flow velocity is an important impact factor for pollution degradation. Generally, higher flow velocity makes faster pollutant diffusion and degradation (Zhao et al., 2018). Flow velocity in the middle of lakes is higher than that in the bays. Fig. 10 shows the average flow velocity in lakes.

Water flow velocity will influence hydraulic load, which is an important parameter affecting the purifying effect of wetland (Damanik-Ambarita et al., 2016; Soini et al., 2002). As shown in Fig. 9, flow velocities around wetland areas in this lake are all below 0.005 m/s, which makes pollutants hard to diffuse. However, smaller hydraulic load will result in better removal efficiency (Andrade et al., 2013). On the whole, the flow velocity in the Chiye River is faster and brings pollutants from the Chiye River to Chiye Lake and Baitan Lake. Which leads to water quality in the Chiye Lake worse than that in the other two lakes. As shown in Fig. 9, there is an obvious moving trace of pollutants following water movement in the scenarios without subsurface flow wetlands. Average annual removal efficiency per area of COD\TN\TP is shown in Fig. 11.

Flow velocity in wetland W3 is higher than that in wetlands W2 and W4, which leads to lower quantity of average pollutants removal per area, and all other factors are similar. For example, the removal of quantity per area of COD, TP, TN is respectively 6.883 kg/m^2, 0.080 kg/m^2 and 1.039 kg/m^2 at wetland W3, which is less than W4 with 15.4%, 12.2 and 4.7%, respectively. Due to the lower flow velocity, the pollutants residence time increases correspondingly, then it is conducive to the absorption of plant roots and the decomposition of microorganisms (Zou et al., 2009). Especially, the components of TP, which are almost absorbed by sediment, will be easily taken away by the water flow. This leads to the removal of TP in W3 being the least.

Spatially, the water temperature, and flow velocity among wetlands W1, W2, W4 have little difference. However, the removal efficiency of W1 and W2 is less than that of W4. On the other hand, flow velocity in W1 is less than that in W3, but the removal of COD and TN is still less. That is to say, the flow velocity is not the significant factor that makes the difference of removal among the wetlands. Moreover, previous studies indicated that water depth is a key factor in pollutant removal of wetland (Cameron et al., 2003; Xu et al., 2016). Water depth of these four wetlands is different (in Fig. 10-summer). Water depth of W1 is almost one meter smaller than that of W4, and 0.5 m less than that of W3. The result shows that the average quantity per area of annual pollutant removal in W1 is 35.9% and 47.5% less than W4 on COD and TN, respectively. As for diffluent COD and TN, the increase of water depth increased the contact area and contact time between each component of wetlands and pollutants, so the removal rate of COD and TN increased with the increase of water depth. Since there is little difference in different wetland areas, the positive effect of increasing water depth on removal rate is greater than the negative effect of decreasing flow velocity.

4. Conclusion

Ecological remediation methods, especially the subsurface flow wetlands, are have been widely used for water pollution control. It is necessary to evaluate the efficiency of wetlands in reducing water pollutants. According to the growing characteristics of aquatic plant and nutrient migration theory in the plant-sediment–water interface, a numerical model combined with hydrodynamic water quality model, sediment flux model and wetlands growth model has been developed. Besides, an algorithm of wetlands pollutants removal efficiency based on this model was put forward. These methods were used to evaluate the capacity of subsurface flow wetlands (including the Reed and Smooth cordgrass) to reduce pollutants in a polluted lake. The accuracy of models used in the lake is acceptable. Spatial and temporal distribution of pollutants with or without subsurface flow wetlands were analyzed. Results showed that, with four wetlands, annual reductions are COD 246.38 tons, TN 32.85 tons and TP 3.29 tons with the reduced rate of external pollutant loads for COD 61%, TN 49%, and TP 34%. Wetlands can purify COD and TN significantly, but TP faintly. Additionally, water temperature greatly influences the pollutant removal performances of wetlands with a positive relationship. In August, when the water temperature reaches the highest, the removal rate will reach higher with COD 93% TN 63%, and TP. 45%. This is higher than that in the winter with COD 24.24%, TN 33.0% and TP 20.7%, when the water temperature is below 15℃. Flow velocity and water depth also had some effect on the removal efficiency.

Models developed in this paper are suitable for areas with limited data, which makes the extensive use of these models can be obtained. While in different growth periods, wetland has different pollutant removal capacity. The adsorption capacity of wetlands is not only influenced by DO, PH, varieties of wetlands, but also by flow velocity, water depth and other factors, except water temperature. These topics will be studied in further research.

CRediT authorship contribution statement

Yonggui Wang: Writing - original draft, Writing - review & editing. **Qiang Li:** Writing - review & editing, Visualization. **Wanshun Zhang:** Supervision, Methodology. **Shaofei Wang:** Supervision, Methodology.

Hong Peng: Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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