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Regulation and Management of Lake Eutrophication in Urban Regions Based on the Improved Model-Yan-Model II

Z. Q. Yan[1], M. Y. Jiao[1], Y. F. Wang[1 **], and B. C. Xia[1 *]

[1] *School of Environmental Science and Engineering, Sun Yat-sen University, Guangzhou 510275, China*

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ABSTRACT. The construction of a model based on an analytic system and dynamic structure is an important technique in lake management. The Yan-Model conducts system simulations based on the dynamics of the main aquatic species but does not include filter-feeding fish and N elements, which have important effects on eutrophication. Based on the Yan-Model, modules for the filter-feeding fish *A. nobilis* and the N cycle were constructed and combined to form a new model, the Yan-Model II. After model calibration and validation, a scenario analysis was performed to simulate eutrophication regulation and external pollution impacts. The results show the following: (1) the simulated and measured values of the lake ecosystem were highly consistent (R > 0.9, RSR < 0.7); (2) an eutrophic lake could be effectively restored by planting *Vallisneria natans* (Lour.) Hara with low biomass density; (3) assuming that urban sewage drained into the lake, equal or more than 600 m^3 of urban sewage would lead to an increase in the Chl-a concentration to a level that exceeded the eutrophication threshold; and (4) an *Aristichthys nobilis* density of 50 g/m^3 had a strong ability to control phytoplankton growth. Using the improved model, this study successfully guided the ecological restoration of Dongshan Lake. This model can be used for lake management and sustainable development in urban ecosystems.

Keywords: eutrophication, management, urban lake, aquatic ecosystem, sustainable development

1. Introduction

Lake eutrophication is recognized to have deleterious effects on aquatic ecosystems and economies worldwide (Paerl et al., 2011). However, due to the lack of a reliable, quantitative understanding of the ecological interactions between the internal and external environments of lake ecosystems, current urban lakes management is difficult to perform (Kuo et al., 2008). At present, the management measures of urban lakes remain "rough and wild", which has led to a lake eutrophication dynamic that presents a long duration and rebound effect. Therefore, lake models are considered potential tools for eutrophication management (Willuweit and O'Sullivan, 2013). These models are used to simulate the dynamics of various variables in the lake ecosystem, which are complicated and include self-regulation and feedback (Jørgensen, 1986; Liu et al., 2015; Tang et al., 2016). Thus, lake models can contribute to a better understanding of the ecological mechanisms in lake ecosystems and provide effective technical support for managers to evaluate environmental problems, predict environmental benefits and analyze environmental risks (Jørgensen, 2010; Huang et al., 2015).

Lake models have been successfully developed in recent decades and expanded from monolayer, single ventricular components to multi-level, multi-chamber components, and from zero dimensions to three dimensions (Whitehead et al., 2014). According to complexity, the lake models are divided into hydrodynamic models, water quality models and ecological models. Based on the theory of hydrodynamics, a hydrodynamic model is constructed to simulate the characteristics of lake flow under different interference conditions and the distribution of different pollutants in the lake (Gong et al., 2016). Simons (1973) built a two-dimensional circulation model to study the winter circulation pattern of Lake Ontario and put forward a specific method to calculate the large-area lake circulation with a multilayer model, which established the foundation for the development of a hydrodynamic model. A lake water quality model is a method that uses a mathematical formula to describe the regular pattern of interactions among biology, physics and chemistry (Small et al., 2018). An ecological dynamics model is used to study the dynamics of various variables in the ecosystem and to describe the temporal and spatial changes of species composition and properties. Jørgensen et al. (1978) constructed an ecological model with the state variables of nutrients N, P, phytoplankton and zooplankton, which established a foundation for the simulation of lake eutrophication. Among these models, integrated models including AQUATOX (Zhang and Liu, 2014), PAMOLARE (Gurkan et al., 2006), CAEDYM (Trolle et al., 2008) and WASP (Yen et al., 2012) have been established and applied in lake environment research and management. More

[*] Corresponding author. Tel.: + 86 13570936999; fax: + 86 20 39332742.
E-mail address: xiabch@mail.sysu.edu.cn (B. C. Xia).
[**] Corresponding author. Tel.: + 86 18588646507; fax: + 86 20 39332742.
E-mail address: wangyf97@mail.sysu.edu.cn (Y. F. Wang).

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recently, most ecological models for lake ecosystems have focused on genera since the genera-specific model has many obvious merits, such as being user-friendly and easy to calibrate and validate (Arhonditsis and Brett, 2005; Mao et al., 2008). However, many biological characteristics of species are unique. If the constructed model of a biological population is based on only the specific genera, then the obtained parameter values might not be unique and stable, possibly resulting in an insufficient understanding of the ecological functions of some important species.

A dynamic model of the urban shallow lake ecosystem (Yan-Model) was constructed based on the characteristics of the lake and ecological relationships among aquatic species (Yan et al., 2018). The ecological relationships included the growth competition of the submerged macrophytes, phytoplankton and periphyton, the predation relationship between zooplankton and phytoplankton, and the predation relationship between benthos and detritus. However, the Yan-Model ignores the effects of nitrogen and filter-feeding fishes, which are phytoplankton predators. Nitrogen is an important contributor to eutrophication, and filter-feeding fishes are the major consumers of phytoplankton. Filter-feeding fishes have an immediate influence on eutrophication via direct predation, but regulating the fish population has been identified as a potential difficulty (Mueller et al., 2004; Wang et al., 2008). *Aristichthys nobilis* is a predator of both phytoplankton and zooplankton (VanMiddlesworth et al., 2017), so there is a two-way effect because zooplankton is also a controlling factor of phytoplankton. Moreover, *A. nobilis* populations are often overgrown, and the individuals are very large compared to phytoplankton individuals. Thus, the overgrowth of an *A. nobilis* population may strongly disturb the balance of a lake ecosystem. Guo et al. (2017) have attempted to simulate and regulate the dynamics of *A. nobilis* populations, but a satisfactory result has not been reached. It is very difficult to find a stable balance between controlling phytoplankton growth and destroying the balance of lake ecosystems (Sagehashi et al., 2000). Nitrogen cycling in lake ecosystems is directly related to the processes of biological metabolism (Horne and Viner, 1971; Schindler and Hecky, 2009), and Wu et al. (2017) quantitatively discussed the contributions of internal circulation and external input to eutrophication using a nitrogen mass balance model in Dianchi Lake. The results of this study indicated that the internal circulation mechanism inhibited sediment release and enhanced denitrification. Thus, this study focuses on improving the Yan-Model by combining a filter-feeding fish population dynamics model and nitrogen cycling model to form a new model, called the Yan-Model II. In addition, during the construction of ecosystem models, it is very important to understand the structure of the system and the mechanisms of the ecological processes. However, the complexity of some ecological processes makes it difficult to analyze the mechanisms, or the availability of the knowledge and information required to construct a mechanical model is inadequate. When a process is very clear, the input and output of the process could be considered the base for model establishment (Millie et al., 2012). In this study, a microcosm experiment of the biomanipulation of *A. nobilis* was carried out to obtain a large amount of data. Because the factors affecting the dynamics of the *A. nobilis* population are comprehensive, it was difficult to establish a mechanism model to simulate the *A. nobilis* population. However, the biomanipulation data supported the construction of an empirical model to describe the population dynamics of *A. nobilis*. The feeding and excretion processes of *A. nobilis* are considered in other modules.

Thus, the objective of this study was to improve the Yan-Model by combining a filter-feeding fish population dynamics model and a nitrogen cycling model to form a new model, called the Yan-Model II. A microcosm experiment of the biomanipulation of fish was carried out to support the construction of an empirical model for describing the population dynamics of

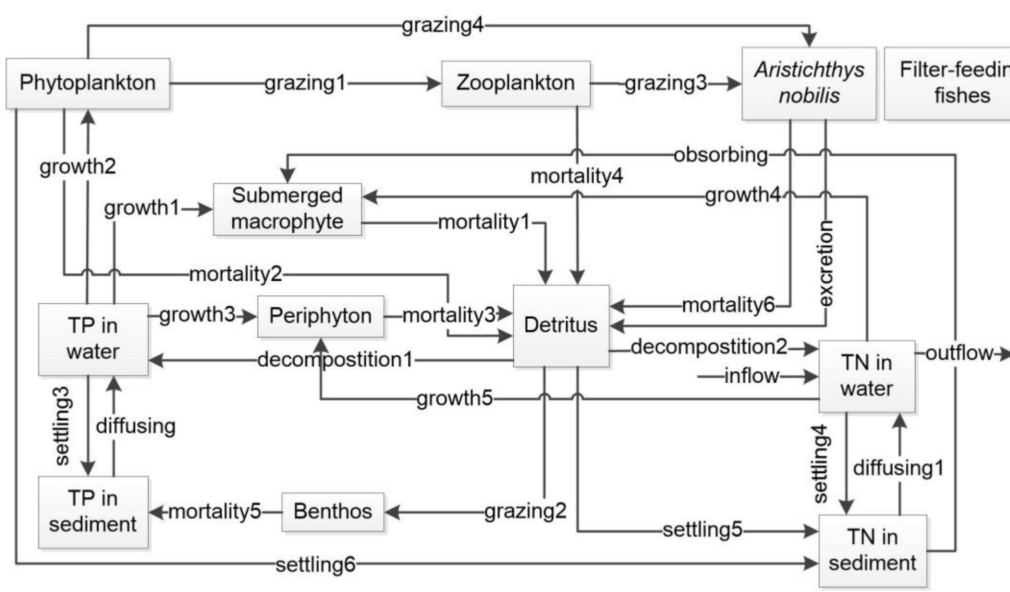

Figure 1. Conceptual diagram of the model (the arrows represent kinetic interactions among components).

filter-feeding fish. The data gained from another biomanipulation experiment and field measurement are used to calibrate and verify the parameters of the model. Specifically, the objective entails:

(1) Building an ecosystem model to improve the Yan-Model by combining a filter-feeding fish model and a nitrogen cycling model;
(2) By setting multiple scenarios, the most appropriate scheme for the control of eutrophication and remediation of lake ecosystems could be obtained according to simulations with different scenarios;
(3) Providing decision support for urban lake managers from multiple perspectives, such as sustainable development of urbanization, management of eutrophication of urban lakes, and aquatic ecosystem remediation (Huang and Chang, 2003).

2. Materials and Methods

The Yan-Model simulates the ecosystems of city lakes (Yan et al., 2018). *Vallisneria natans* (Lour.) Hara, phytoplankton, zooplankton, periphyton, benthos, detritus and the total phosphorus in water and sediment are considered the main components of the model. The phosphorus in water, as a linkage in the system, is directly related to the growth of submerged macrophytes, phytoplankton and periphyton and to the sediment of the lake. The food chain, competition, predation, respiration, and mortality are the main processes in the model. In this paper, the modules of the population dynamics of a filter-feeding fish, *A. nobilis*, and nitrogen cycling in the lake ecosystem were added and coupled with the Yan-model. The model structure is presented in Figure 1.

2.1. New Submodel

The Yan-Model II was based on the Yan-Model and included two additional submodels, the *A. nobilis* dynamics model and the nitrogen cycle model. The detailed parameters are listed in Table 1.

(1) *A. nobilis* dynamics model:

$$\frac{dbmfish}{dt} = predation - death - excretion \tag{2-1}$$

$$\begin{aligned}\frac{dpredation}{dt} = (&pr_1 * f'a(a, b, c, d, e, T) + \\ &pr_2 * f'b(a, b, c, d, e, T) + \\ &pr_3 * f'c(a, b, c, d, e, T) + \\ &pr_4 * f'e(a, b, c, d, e, T) * bmfish\end{aligned} \tag{2-2}$$

$$\frac{ddeath}{dt} = \max\ m * f'(T) * bmfish \tag{2-3}$$

$$\frac{dexcretion}{dt} = \max\ e * f^{'}(T) * bmfish \tag{2-4}$$

where *predation*, *death* and *excretion* are the growth, death and excretion processes of *A. nobilis*, respectively, pr_1, pr_2, pr_3 and pr_4 are the predation rates of *A. nobilis* on *M. aeruginosa*, *A. flos-aquae*, *M. granulata* (Ehr.) Ralfs and *D. brachyurum* (Liévin), respectively, and max *m* and max *e* are the maximum mortality and excretion rates of *A. nobilis*, respectively.

(2) Nitrogen dynamic process model:

$$\frac{dwn}{dt} = in + diff + dec - upt - set - out \tag{2-5}$$

where *wn*, *in*, *diff*, *dec*, *upt*, *set* and *out* represent the nitrogen concentration, external input, sediment release, debris decomposition, primary producer growth absorption, sedimentation and output, respectively:

$$\frac{din}{dt} = \frac{tin}{v} \tag{2-6}$$

where *tin* is the total amount of nitrogen input and *v* represents the volume of lake water:

$$\frac{ddiff}{dt} = difr * (sn - wn) * ac / d \tag{2-7}$$

where *difr* is diffusivity, *sn* is the content of N in sediment, *wn* is the content of N in water, *ac* is the depth of the sediment active layer, and *d* is the depth of the lake:

$$\frac{ddec}{dt} = decr * \det * 1.05^{T-20} * kpd \tag{2-8}$$

where *decr* is the maximum decomposition rate of debris and *kpd* is the concentration of nutrients in debris:

$$\frac{dup(i)}{dt} = gbbm(i) * kbbm(i) \tag{2-9}$$

where *gbbm*(*i*) denotes the growth of primary producers and *kbbm*(*i*) denotes the nutrient content of primary producers:

$$\frac{dset}{dt} = \frac{sr}{d} * B \tag{2-10}$$

where *sr* represents the sedimentation rate of nutrients:

$$\frac{dout}{dt} = to / v \tag{2-11}$$

This formula was used to represent the total nutrient output:

$$\frac{dsed}{dt} = set - diff - upt \tag{2-12}$$

Table 1. List of Parameter

Symbol	Description	Unit
a	Biomass density of *M. aeruginosa*	mg m^{-3}
ac	Depth of the sediment active layer	m
b	Biomass density of, *A. flos-aquae*	mg m^{-3}
bmfish	Biomass density of *A. nobilis*	g m^{-3}
bsm	Biomass of submerged macrophytes	kg m^{-2}
c	Biomass density of *M. granulata* (Ehr.) Ralfs	mg m^{-3}
d	Depth of the lake	m
death	Death processe of *A. nobilis*	
dec	Debris decomposition	day^{-1}
decr	Maximum decomposition rate of debris	day^{-1}
det	Biomass density of debris	mg m^{-3}
diff	Sediment release	
difr	Diffusivity	day^{-1}
e	Biomass density of *D. brachyurum* (Liévin)	mg m^{-3}
excretion	Excretion process of *A. nobilis*	
gsm	Maximum growth rate of submerged macrophytes	day^{-1}
gbbm	Growth of primary producers	day^{-1}
in	Total amount of nitrogen input	mg L^{-1}
ibzoo	Predatory rate of *A. nobilis* for zooplankton	day^{-1}
ibph	Predatory rate of *A. nobilis* on phytoplankton	day^{-1}
kbbm	Nutrient content of primary producers	mg g^{-1}
kpd	Concentration of nutrients in debris	mg g^{-1}
kpd	Concentration of nutrients in debris	mg g^{-1}
maxm	Maximum mortality rates of *A. nobilis*	day^{-1}
maxe	Maximum excretion rates of *A. nobilis*	day^{-1}
nkpsp	Half saturation constant for nitrogen absorption by *V. natans* (Lour.) Hara	day^{-1}
nkmi	Half saturation constant for nitrogen absorption by *M. aeruginosa*	day^{-1}
nka	Half saturation constant for nitrogen absorption by *A. flos-aquae*	day^{-1}
nkme	Half saturation constant for nitrogen absorption by *M. granulata* (Ehr.) Ralfs	day^{-1}
out	Output of nitrogen	
pr_1	Predation rates of A. nobilis on *M. aeruginosa*	day^{-1}
pr_2	Predation rates of A. nobilis on *A. flos-aquae*	day^{-1}
pr_3	Predation rates of A. nobilis on *M. granulata* (Ehr.) Ralfs	day^{-1}
pr_4	Predation rates of A. nobilis on *D. brachyurum* (Liévin)	day^{-1}
predation	Growth process of *A. nobilis*	
set	Sedimentation	
sn	Content of *N* in sediment	mg g^{-1}
sr	Sedimentation rate of nutrients	day^{-1}
T	Temperature	℃
upt	Nitrogen of primary producer growth absorption	
v	Volume of lake water	m^{-3}
wn	Nitrogen concentration in water	mg L^{-1}

$$\frac{dupt}{dt} = gsm * bsm * kbbm * 1.05^{T-20} \qquad (2\text{-}13)$$

where *gsm* denotes the maximum growth rate of submerged macrophytes and *bsm* denotes the biomass of submerged macrophytes.

2.2. Parameter Calibration

Calibration data are obtained from the literature and biomanipulation experiments in the laboratory. A white plastic bucket with a volume of 65 L (r: 0.17 m, h: 0.5 m) was used, and 8 cm of sediment was added with initial nitrogen and phosphorus concentrations of 5.3 and 0.87 mg/kg, respectively. Fifty liters of water with initial N and P concentrations of 1.5 and 0.2 mg L^{-1}, respectively, were transferred into each bucket. Next, *M. aeruginosa*, *A. flos-aquae*, and *M. granulata* (Ehr.) Ralfs at a cell density of 3×10^6 ind. L^{-1} were added to each bucket to produce a microcosm of a eutrophic shallow lake ecosystem. The *M. aeruginosa*, *A. flos-aquae*, *M. granulata* (Ehr.) Ralfs and *Daphnia magna* specimens were obtained from the Institute of Hydrobiology, Chinese Academy Sciences, Wuhan, China. *Vallisneria natans* (Lour.) Hara was planted at a biomass density of 800 g m^{-2} to create one experimental group. Four treatments and three replicates were set for an 80-day observation.

(1) *V. natans* (Lour.) Hara

(2) *V. natans* (Lour.) Hara + 100 ind./L *D. brachyurum* (Liévin)

(3) *V. natans* (Lour.) Hara + 40 g *A. nobilis*

(4) *V. natans* (Lour.) Hara + 100 ind./L *D. brachyurum* (Liévin) + 40 g *A. nobilis*

The daily concentrations of N and P in the water, the biomasses of phytoplankton and zooplankton, the concentrations of N and P in the sediment, and the biomasses of *V. natans* (Lour.) Hara and *A. nobilis* were monitored every 10 days.

2.3. Parameters and Sensitivity Analysis

The literature (DeAngelis et al., 1989; Sagehashi et al., 2000; Sagehashi et al., 2001; Amemiya et al., 2005; Amemiya et al., 2007; Wang et al., 2014) provided the parameters of the predation of *A. nobilis* on phytoplankton, the zooplankton predation rate, and the half-saturated constant of nitrogen absorption by phytoplankton. A sensitivity analysis for each parameter was carried out. The final value of each parameter was determined by using the results of the biomanipulation experiment and simulation.

Sensitivity analysis is a parameter-by-parameter simulation method for the evaluation of the sensitivity of a parameter. When a certain parameter is studied, median values are used for other parameters. The maximum and minimum values of the parameter are simulated, and the formula is as follows:

$$MRE = \left(\sum_{i=1}^{n}\left|\frac{P_{\max} - P_{\min}}{P_{\max}}\right|\right)/n \tag{2-14}$$

where *MRE* is the mean relative error, $P_{\max}$ and $P_{\min}$ are the modeled values when the variables are set to the maximum and minimum parameters, respectively, and n is time (d).

2.4. Model Verification and Accuracy Analysis

Based on the Yan-Model, ecological restoration engineering was carried out in Koi Lake in Guangzhou (longitude: 113°15'42"E, latitude: 23°7'54"N). The area of the lake is approximately 20,000 m^2. In this lake, the biomass densities of *M. aeruginosa*, *A. flos-aquae*, and *M. granulata* (Ehr.) Ralfs reached 6, 18 and 15 mg/m^3, respectively, and the N and P concentrations of water were 3.5 and 0.35 mg/L, respectively. The lake exhibited serious eutrophication before restoration. The restoration measures included all the elements of the model.

Five sampling sites were set to evaluate the restoration effect, and samples were taken weekly from July 15 to October 12, 2018, after eutrophication was controlled. The P and N concentrations in water and biomass densities of phytoplankton and submerged macrophytes were detected.

The observed and simulated states of the ecosystem were compared throughout the restoration process, and the correlation coefficient (R) (Setegn et al., 2008) and root mean square error-observation standard deviation ratio (RSR) (Moriasi et al., 2007) were applied as follows:

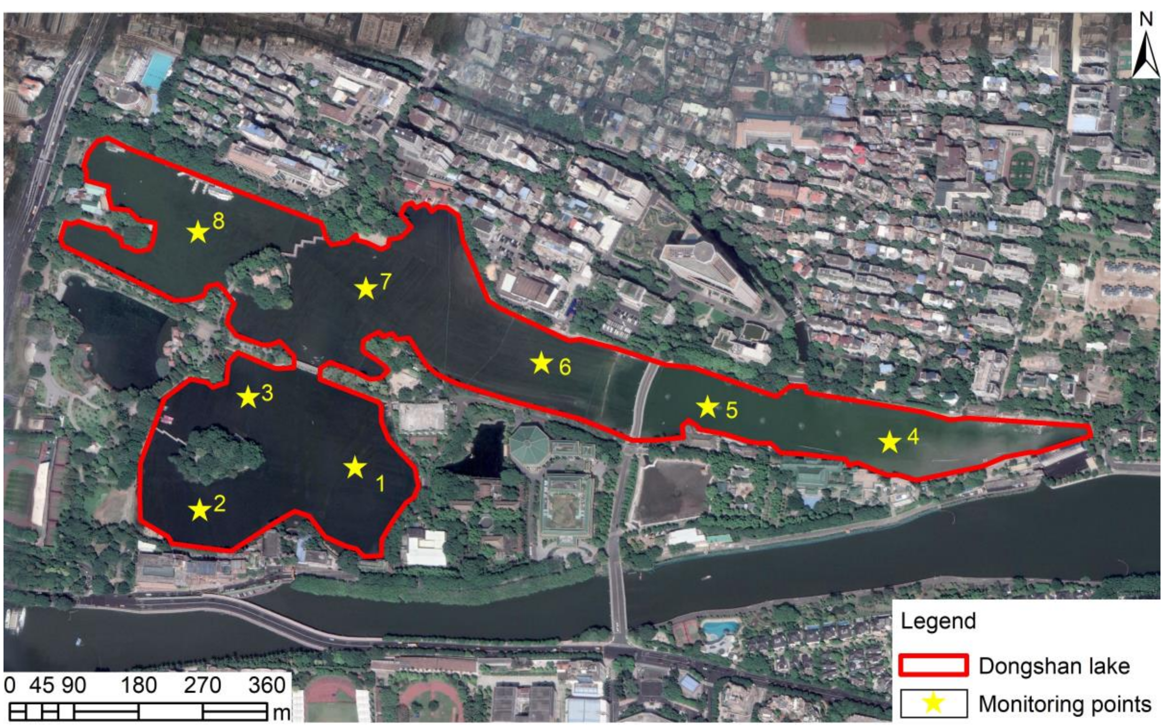

Figure 2. Location and surrounding enviroment of Dongshan Lake (Digits indicate the monitoring points).

$$R = \frac{\sum_{i=1}^{n}(y_i - \bar{y})(y_i' - \bar{y}')}{\sqrt{\sum_{i=1}^{n}(y_i' - \bar{y}')^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{2-15}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(y_i - \bar{y}_i')^2}}{\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{2-16}$$

where y_i and y_i' are observed and simulated values, and $\bar{y}$ and $\bar{y}'$ are the average of y_i and y_i', respectively.

2.5. Application of the Yan-Model II

2.5.1. Dongshan Lake

Dongshan Lake and Koi Lake are connected to the Pearl River. The lake has an area of approximately 32.5 hm^2 and a depth of 1.4 ~ 1.7 m. In this lake, the biomass densities of *M. aeruginosa*, *A. flos-aquae*, and *M. granulata* (Ehr.) Ralfs reached 6, 18 and 15 mg/m^3, respectively, and the N and P concentrations of water were 3.5 and 0.35 mg/L, respectively. Dongshan Lake receives urban nonpoint source pollution and has exhibited serious eutrophication for a long time. To restore the ecological environment of Dongshan Lake, the ecological restoration project was carried out in Guangzhou. The restoration project of Dongshan Lake was completed in March 2018. After the restoration project was completed, the water of Dongshan Lake was blocked from the Pearl River to form a closed urban lake ecosystem. However, on day 180, the typhoon Mangkhut brought much of the Pearl River water into the lake, which was a risk accident and caused serious pollution.

2.5.2. Model Simulation

The Yan-Model II was applied to perform eutrophication restoration. A Chl-a content of 11 mg/m^3 in urban lakes was set to indicate eutrophication. In this case, the biomass densities of *M. aeruginosa*, *A. flos-aquae*, and *M. granulata* (Ehr.) Ralfs reached 6, 18 and 15 mg/m^3, respectively, and the N and P concentrations of 3.5 and 0.35 mg/L, respectively, were considered eutrophication. The following two scenarios were set for the simulation.

(1) The N, P and Chl-a concentrations in the water were simulated and detected under different lake ecosystem constructions, *V. natans* (Lour.) Hara (0, 1800, 2400, and 3000 g/m^2) and *A. nobilis* (0, 20, 50, and 80 g/m^3) during 100 days of restoration. The conversion formulas for phytoplankton biomass and Chl-a were reviewed from the literature (Borics et al., 2000).

(2) Based on the low densities of *V. natans* (Lour.) Hara (1800 g/m^2) and *A. nobilis* (20 g/m^3), 200, 400, 600 and 800 m^3 of urban sewage with N and P concentrations of 15.0 and 4.0 mg/L, respectively, were assumed to be imported to the lake, and the dynamics of eutrophication were simulated.

2.5.3. Ecological Restoration Project of Dongshan Lake

Based on the prediction results of scenario simulation, the Yan-Model II was applied to guide the eutrophication restoration of Dongshan Lake. The *V. natans* (Lour.) Hara was planted at the most economical result of scenario simulation (1) in Dongshan Lake.

After the restoration project, serious pollution of the Pearl River appeared in the restoration area because of typhoon Mangkhut on day 180. Based on the prediction results of the scenario simulation, *A. nobilis* was introduced into Dongshan Lake to control the outbreak of eutrophication.

3. Results

3.1. Calibration and Validation

The calibrated parameters based on the results of the ex-

Table 2. List of Parameter Values

Parameter	Value	Literature Value	Unit	Reference
(*ibzoo*) Predatory rate of *A. nobilis* for zooplankton	28	7 ~ 34 (68.7%)	day^{-1}	DeAngelis et al., 1989; Amemiya et al., 2005, 2007
(*ibph*) Predatory rate of *A. nobilis* on phytoplankton	0.2	0.15 ~ 0.35 (68.1%)	day^{-1}	Sagehashi et al., 2000
(maxm) Maximum mortality rate of *A. nobilis*	0.5	0.5	day^{-1}	DeAngelis et al., 1989; Amemiya et al., 2005; Amemiya et al., 2007
(maxe) Maximum excretion rate of *A. nobilis*	0.7		day^{-1}	
(*nkpsp*) Half saturation constant for nitrogen absorption by *V. natans* (Lour.) Hara	0.13	0.1 ~ 0.19 (32.1%)	day^{-1}	Wang et al., 2014
(*nkmi*) Half saturation constant for nitrogen absorption by *M. aeruginosa*	0.4	0.006 ~ 4.32 (22.8%)	day^{-1}	Wang et al., 2014
(*nka*) Half saturation constant for nitrogen absorption by *A. flos-aquae*	0.6	0.006 ~ 4.32 (18.3%)	day^{-1}	Wang et al., 2014
(*nkme*) Half saturation constant for nitrogen absorption by *M. granulata* (Ehr.) Ralfs	0.011	0.006 ~ 4.32 (13.2%)	day^{-1}	Wang et al., 2014
Nitrogen deposition rate from the sediment	0.035		day^{-1}	
Nitrogen content of phytoplankton	0.06	0.05 ~ 0.078	day^{-1}	Drago et al., 2001
(*kbbm*) Nitrogen content of *V. natans* (Lour.) Hara	26.13	26.13	mg/g	Wang et al., 2014

perimental results or obtained from the literature are presented in Table 2. Model validation was performed using the monitored data from Koi Lake. The range of parameters in this case study are mainly derived from the literature (Table 2) (DeAngelis et al., 1989; Sagehashi et al., 2000; Sagehashi et al., 2001; Amemiya et al., 2005; Amemiya et al., 2007; Wang et al., 2014), and their precise values are determined by the results of the sensitivity analysis. The sensitivities of *A. nobilis* to zooplankton and phytoplankton were 68.7% (*ibzoo*) and 68.1% (*ibph*), respectively, and the half-saturation constant of nitrogen absorption ranged from 13.2 to 32.1%. The parameters of the model were calibrated by using the results of the biomanipulation experiment.

3.2. Simulation of the Model

The Yan-Model II was validated using in situ survey data from Koi Lake. The comparison between the simulated and observed values in the model is shown in Figure 3.

The simulation results showed that all variables exhibit strong consistency. The biomass densities of *V. natans* (Lour.) Hara decreased but then increased. The biomass densities of *A. nobilis* showed an increasing trend. The biomass densities of the three phytoplankton species were significantly different; two of the species exhibited a large peak, while *M. aeruginosa* did not exhibit a peak and only slowly decreased throughout the study period.

The N concentration in the water showed a strong fluctuation, and the observed and simulated results exhibited the same trends. The N contents in the sediment slightly decreased, and the observed and simulated results were very similar throughout the study period.

The total trends of the simulated and observed P concentrations in the water were consistent, although the simulated P concentration in the water had two obvious peaks in the early stage. The trends of the P content in the sediment were basically consistent with the trends of the P concentration in the water, and the trends of the simulated and observed results were consistent.

3.3. Accuracy Analysis

The results of the accuracy analysis are shown in Table 3. The R values are higher than 0.9 with $p < 0.01$, and all RSRs are smaller than 0.7. These findings indicate that all results are highly correlated and accurate.

3.4. Application of the Yan-Model II

3.4.1. Eutrophication Control and Management

The dynamic changes in the N, P and Chl-a concentrations in the water were simulated under different densities of *V. natans* (Lour.) Hara (0, 1800, 2400, 3000 g/m^2) and *A. nobilis* (0, 20, 50, 80 g/m^3) (Figure 4).

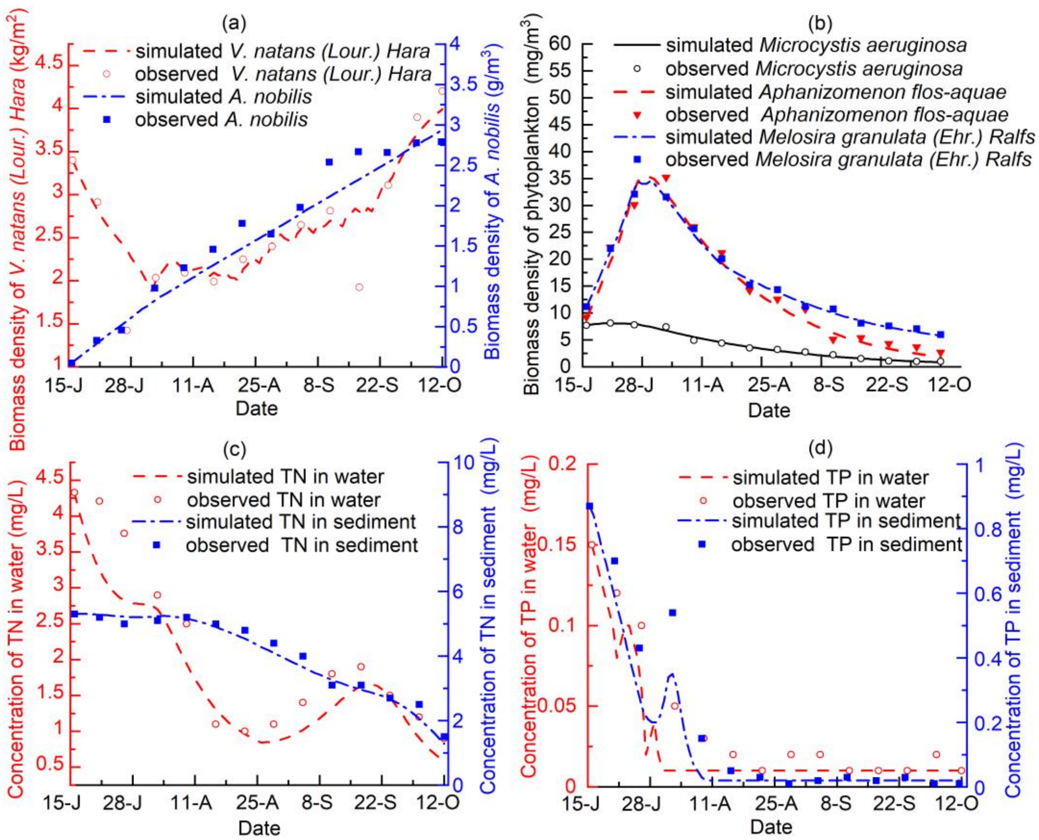

Figure 3. Comparison of the simulated and observed dynamics of variables of Koi Lake.

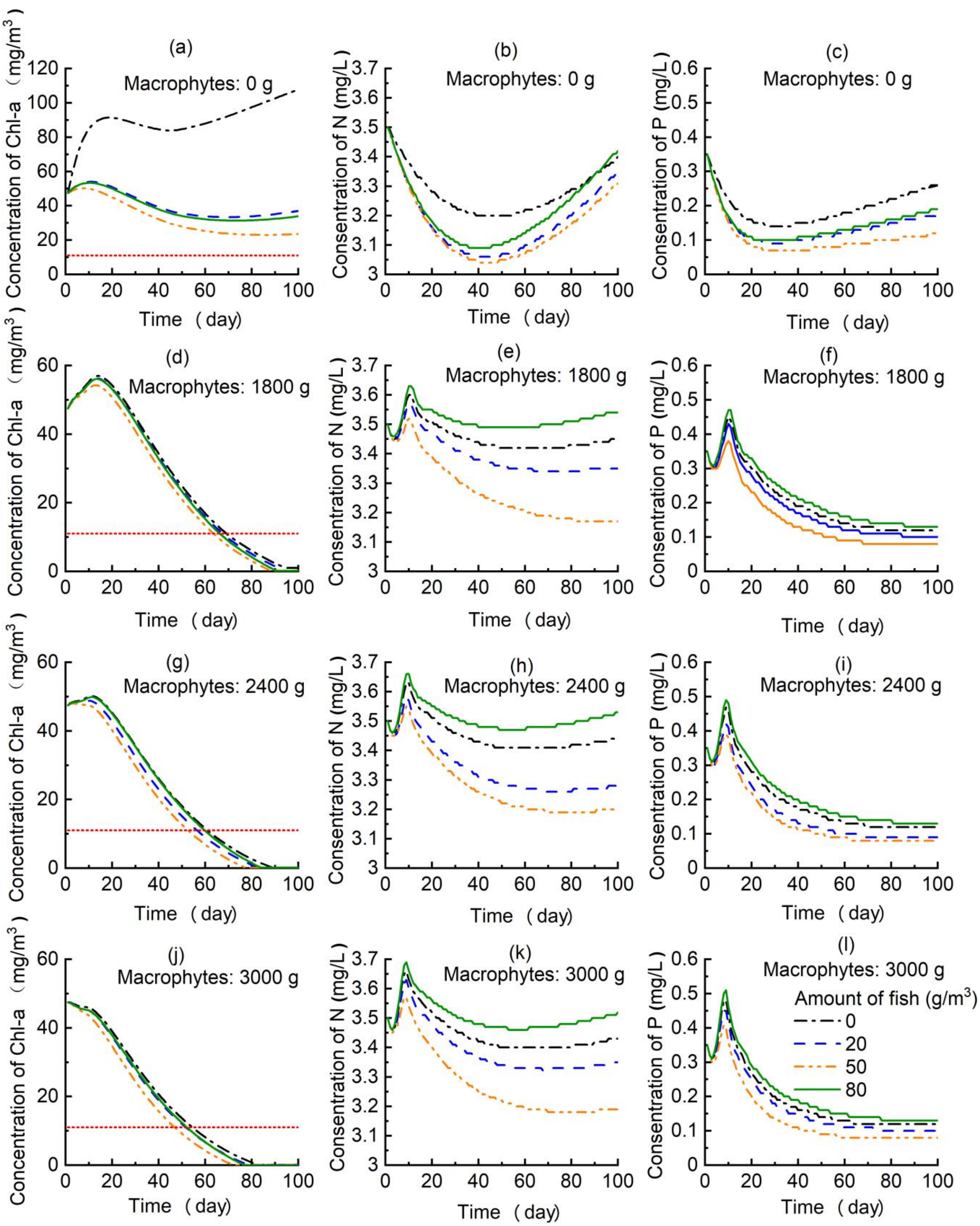

Figure 4. Dynamics of Chl-a, N and P concentrations in water of different treatments of *V. natans* (Lour.) Hara and *A. nobilis* (the red dot line represents the eutrophication threshold: 11 mg/m^3 of Chl-a).

Table 3. R and RSR of Accuracy Analysis for the Parameters of the Yan-Model II

Parameters	R	RSR
Phosphorus in water	0.942**	0.44
Phosphorus in sediment	0.976**	0.27
Nitrogen in water	0.965**	0.38
Nitrogen in sediment	0.991**	0.17
V. natans (Lour.) Hara	0.998**	0.66
M. aeruginosa	0.994**	0.11
A. flos-aquae	0.989**	0.16
M. granulata (Ehr.) Ralfs	0.997**	0.08
A. nobilis	0.985**	0.21

**significant at $p < 0.01$, * significant at $p < 0.05$, 0 < RSR < 0.5 indicates very good performance, 0.5 < RSR <0.6 indicates very good agreement, 0.6 < RSR < 0.7 indicates good agreement, and 0.7 > RSR indicates not good agreement.

As shown in Figure 4, the macrophyte *V. natans* (Lour.) Hara is the absolute factor controlling eutrophication, regardless of *A. nobilis* density. When macrophytes are absent, Chl-a is always above the threshold of eutrophication. *A. nobilis* can decrease the concentration of Chl-a, but eutrophication cannot be controlled when there are no macrophytes in the lake ecosystem. The biomass densities of *V. natans* (Lour.) Hara between 1800 and 3000 g/m^2 are not important for controlling eutrophication. A high density of macrophytes resulted in the Chl-a concentration reaching a level lower than the threshold of eutrophication by approximately one or two weeks earlier than occurred under a low density of macrophytes.

The concentration dynamics of N and P in the water were impacted by *V. natans* (Lour.) Hara. In the first 10 days, N and P decreased rapidly without macrophytes, but a small decrease followed an immediate increase in the N and P concentrations appeared for all macrophyte treatments. Then, the concentrations of N and P decreased at different rates for all macrophyte treatments. The maximum and minimum rates of decrease appeared in the 50 and 80 g/m^3 fish treatments. The rate of the decrease in the P concentration was greater than of the rate of the decrease in the N concentration. In the treatments without macrophytes, the concentrations of N and P increased again during days 40 ~ 45 day (N) and 20 ~ 25 (P).

The simulation results reveal that the macrophyte *V. natans* (Lour.) Hara is the core factor controlling eutrophication. The filter-feeding fish *A. nobilis* is an auxiliary factor regulating eutrophication and has little effect on reducing N and P concentrations.

3.4.2. Pollution Impact and Regulation

A general urban lake ecosystem restored with 1800 g/m^2 of *V. natans* (Lour.) Hara and 20 g/m^3 of *A. nobilis* was assumed to be polluted by urban sewage (N: 15.0 mg/L, P: 4.0 mg/L) at different dates and with different amounts of sewage. The responses of the ecosystem and eutrophication (concentration of Chl-a) are shown in Figure 5.

When the lake ecosystem was restored, and the Chl-a concentration was below the threshold of eutrophication, 200 and 400 m^3 of urban sewage could not cause eutrophication of the lake ecosystem. When the lake ecosystem was restored to a stable state with low Chl-a concentrations, 600 m^3 of urban sewage could not cause eutrophication of the lake ecosystem, but 800 m^3 of urban sewage could cause serious eutrophication. The results reveal that a healthy urban lake ecosystem could mitigate many pollutant inputs from outside of the lake, but the mitigation is limited.

Even if the total amount of sewage was divided into two or three parts, the amount of sewage dominated the impact. Figure 5 shows that the 3 × 200 and 2 × 400 m^3 sewage inputs had impact responses that were similar to those from the 600 and 800 m^3 sewage inputs to the lake ecosystem.

A general lake ecosystem has a buffer capacity for external pollution, but its capacity is relatively limited. The above simulated results showed that the capacity is related to the amount of pollutants and the state of the lake ecosystem.

3.4.3. Application to Urban Lake Restoration Management

The restoration of Dongshan Lake was completed in March 2018. The dynamics of *V. natans* (Lour.) Hara and the Chl-a, P and N concentrations in the water during the period of restoration are shown in Figure 6.

As shown in Figure 6, the concentrations of Chl-a, N and P in the water quickly decreased with the growth of *V. natans* (Lour.) Hara. On approximately day 80, the biomass density of macrophytes reached the highest level, and the concentrations of Chl-a, N and P decreased to the lowest levels on days 80, 140 and 60, respectively. The concentrations of Chl-a and P remained low for 100 to 120 days. On day 180, serious pollution appeared in the restoration area, and the concentrations of Chl-a, N and P greatly increased due to this disturbance, but the macrophyte density remained stable. The Chl-a, N and P concentrations took 100, 110 and 40 days, respectively, to return to the low levels that appeared before the disturbance. In the water, N exhibited great fluctuations while P remained stable. A serious disturbance can destroy the balance of aquatic ecosystems for as long as 100 days.

4. Discussion

4.1. Model Improvement

The modules of filter-feeding fish *A. nobilis* and N are newly included in the Yan-Model. This modification improves the application of this model system to lake ecosystems. This improvement has been tested to obtain better results via simulations.

The *A. nobilis* module was constructed by using a biomanipulation experiment. In this study, the experiment was not enough to establish a mechanism model, so an empirical model was constructed. The feeding and excretion procedures of the fish were coupled with other modules of the lake ecosystem model. Compared with the mechanism model, the empirical model has few parameters and improved flexibility. The mechanism model for *A. nobilis* has been established based on the

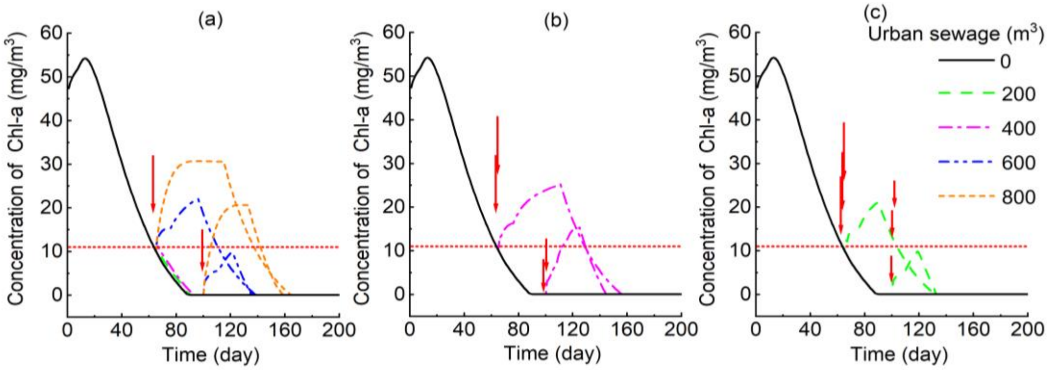

Figure 5. Dynamics of the Chl-a concentration in water under different pollution shocks (the red dot line represents the eutrophication threshold: 11 mg/m^3 of Chl-a).

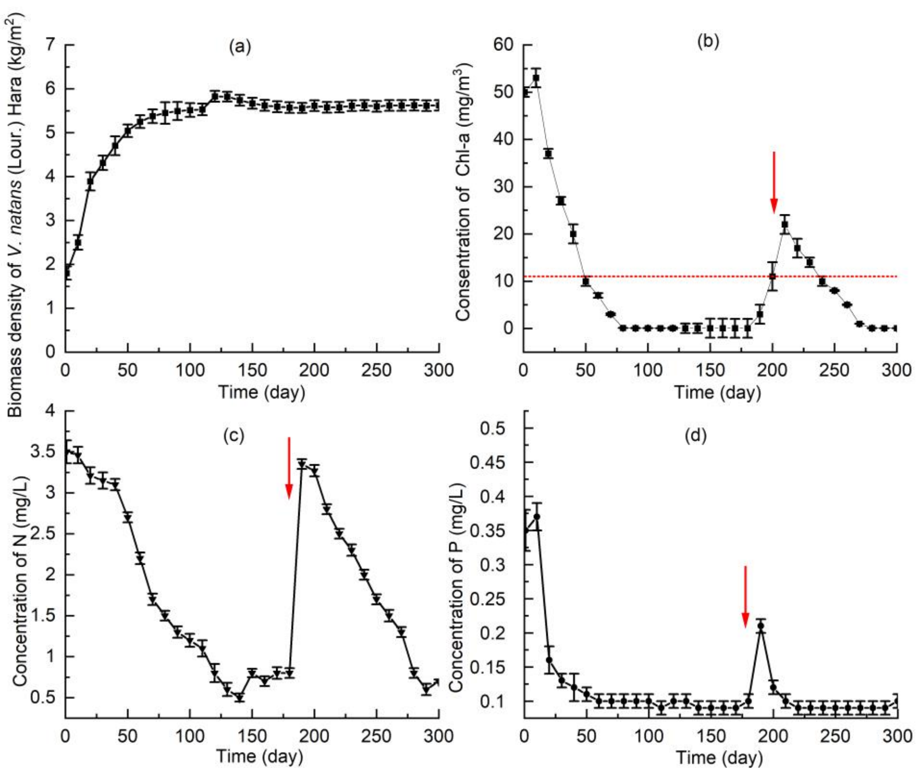

Figure 6. The results of the ecological restoration of Dongshan Lake in water (solid arrows indicate pollutant input; dotted arrow indicates *A. nobilis*; the red dot line represents the eutrophication threshold: 11 mg/m^3 of Chl-a).

Table 4. Models Published in the Literatures

Object	State Variables	Functions/Equations	Reference
Yuqiao Reservoir	Epi, Sm	7	Zhang et al., 2015
Chozas Lake	Phy, Zoo, TN, TP, Det, Psed, and Fish	30	Marchi et al., 2011
Chesapeake Bay	TP, TN, SS, DO, Zoo, ChlaSm, and Ben	7	Cerco and Meyers, 2000
Washington Lake	Phy, Zoo, OC, TN, TP, SiO_2, and DO	59	Arhonditsis and Brett, 2005
Taihu Lake	Phy, Zoo, TN, TP, Det, DOM, DO, Psed, Nsed, and Csed	19	Mao et al., 2008
Dianchi Lake	Chla, TN, TP, NH_4, NO_3, and ON	13	Wu et al., 2017

*Epi, epiphyton; Sm, submerged macrophytes; Phy, phytoplankton; Zoo, zooplankton; TN, total nitrogen in water; TP, total phosphorus in water; Det, detritus; Psed, total phosphorus in sediment; SS, suspended solid; DO, dissolved oxygen in water; Chla, chlorophyll-a; Ben, benthos; OC, organic carbon; DOM, dissolved organic matter; Nsed, total nitrogen in sediment; Csed, carbon in sediment; NH_4, ammoniacal nitrogen in water; NO_3, nitrate nitrogen; ON, organic nitrogen.

interactions between *A. nobilis* and the external environment. A differential equation was used to describe the dynamics of *A. nobilis* (Li et al., 2015), which contains a large number of state variables, driving variables and model parameters, including physiological and ecological characteristics and activities of *A. nobilis*. The application of the mechanism model of *A. nobilis* could require the real-time monitoring of the state variables of the model and the lake ecosystem (Niu et al., 2013). The application of the empirical model had some limitations. In this case study, the Yan-Model II, was successfully applied to predict the effect of ecological restoration on eutrophication in Dongshan Lake.

Table 4 lists the similar models from other studies. Most of these models focused on the dynamic simulation of nutrients and phytoplankton or chlorophyll-a. Compared with the previous studies, the model developed in this study focused on improving the Yan-Model by combining a filter-feeding fish population dynamics model and a nitrogen cycling model to form a new model (Yan-model II). The composition and interrelationship of the lake ecosystem in the new model include submerged macrophytes, phytoplankton, periphyton, zooplankton, benthos phosphorus dynamics modules, filter-feeding fish and a nitrogen cycling model, which present more detail than the previous studies. Therefore, this model can more abundantly reflect the real situation of the lake ecosystem.

Compared with the previous studies, the model developed in this study focused on species instead of genera. Although a simpler genera-specific model may be easier to use, calibrate and validate, a species-specific model based on the dynamics of primary aquatic species provides a tool for the researchers and managers who aim to explore the dynamics of species and to understand the mechanisms among aquatic species. Therefore, we believe that the constructed model in this study is essential to help the manager to complete and strengthen the urban lake management.

4.2. Explanation of Changes in the Lake

The dynamic model presented in this study explained the radical changes observed in the shallow urban lake. The observed results showed that the regulating effect of *A. nobilis* on phytoplankton was limited. The fish *A. nobilis* had a limited effect on the reduction of the growth of phytoplankton, but this effect decreased with time. Feeding and excretion of the fish are in the same system, and nitrogen and phosphorus are in cycling in the lake except little of them for fish growth. The control effect of *A. nobilis* on phytoplankton was greatly reduced due to excretion and their disturbance to lake sediment (Huser et al., 2016), and there was even a negative effect on phytoplankton growth (Yi et al., 2016; Williamson et al., 2018). Another factor is that cyanobacteria cannot be digested by *A. nobilis* (Domaizon and Devaux, 1999).

4.3. Response to External Pollution

A stable lake ecosystem should be able to bear some disturbance. In this study, different external pollution inputs were set to impact the ecosystem, and the simulation results revealed the disturbance limitations based on Yan-Model II. For the management of urban lake eutrophication, the threshold of lake eutrophication, 11 mg/m^3 of Chl-a, was set as the standard to maintain the water quality. The simulation results show that the ecosystem has different capacities to bear external pollution at different stages and discharge intensities. Important functions of the lake ecosystem model were to quantitatively describe the response of the lake ecosystem structure to different types of pollutant inputs (Tang et al., 2016) and understand the buffer capacities of lakes to pollution impacts and the ability to regulate for adverse environments (Liu et al., 2015). Here, the Yan-Model II was used to obtain those values. In this simulation analysis, the Yan-Model II considers only two main pollutants, nitrogen and phosphorus, and many other pollutant factors are ignored, such as particulate organic carbon (POC) in water (Carpenter et al., 2016; Lin et al., 2018), BOD and bioelements.

In Figure 5, the maximum external pollution that will allow the ecosystem to remain in a non-eutrophication state is 400 m^3 of urban sewage at the stage when the water quality of the lake is controlled to below the eutrophication threshold, while this level is 600 (600 or 200 × 3) m^3 at the stage where the lake water quality remains below the eutrophication threshold for a long time. Any amount of sewage more than the above two numbers will cause the eutrophication of the lake ecosystems. These two quantities are the limitations to bearing external pollution for maintaining the water quality below eutrophication under the respective conditions (concentration of pollutants and the stage of lake restoration). The model could be used to perform additional simulations, and more results could be obtained.

4.4. Application of the Model

Unlike large natural lakes, urban lakes are often located in urban areas with high population densities, domestic sewage and industrial sewage discharge (Wu et al., 2014), and urban lakes are often small with shallow and fragile ecosystems, so eutrophication is common (Waajen et al., 2016). However, more research on lake ecosystem simulations has been conducted on large natural lakes than small urban lakes. Although some studies have focused on shallow urban lakes, more studies have focused on hydrodynamics and eutrophication (Gong et al., 2016; Yang et al., 2017), and the simulation objects are often based on the genus and not the species level. The Yan-Model II systematically covers the composition of aquatic organisms at the species level and the structure of lake ecosystems and provides a scientific theoretical and practical reference for the ecological management of shallow urban lake ecosystems.

4.5. Accuracy and Completeness of the Model

By comparing the simulated and measured values of each variable of the Yan -Model II, the results simulated and observed in Dongshan Lake were in good agreement, and the relative coefficients and accuracy indicated very good performance at the 0.01 probability level. The analysis of the structure of the lake ecosystem indicates that the shortcomings due to the absence of microorganisms are obvious. The role of microorganisms in aquatic ecosystems is important, but its behavior is too complicated to reflect in a simulation model. In lake ecosystems, microorganisms play important roles in the energy flow, material cycle, and maintaining the metabolic process and relative stability of the lake ecosystems (Tsuji et al., 2006; Oie et al., 2007). Further model improvements will consider the functions of microorganisms and quantitative models even though these functions are rarely researched.

Hydrodynamic factors are a very important part of lake simulations, which have an important impact on the growth of aquatic organisms and the cycles of pollutants (Peters and Marrasé, 2000; Rahmani and Zarghami, 2015; Xia et al., 2015). However, hydrodynamics may not be important for urban lakes due to their small and shallow areas.

4.6. An Example of Sustainable Urban Management

Urban lakes are an important urban landscape and play an important role in regulating urban microclimates. However, urban lakes are disturbed by high-intensity human activities, resulting in high vulnerability and frequent eutrophication, which become obstacles to sustainable urban development (Chowdhury et al., 2016). Establishing lake ecosystem models to promote lake management has become an important means for sustainable urban development (Rusuli et al., 2015). As a part of sustainable municipal management, scientific decision-making based on lake ecosystem simulations could serve as a reference for other fields of the urban management of public affairs.

The model developed in this study could be used to simulate the ecological risk caused by various management measures and modify management measures by system response.

5. Conclusions

Based on the Yan-Model, the filter-feeding *A. nobilis* module and the N cycle module were added. The growth and ecological process of *A. nobilis* were determined via biomanipulation experiments, and an empirical model of *A. nobilis* growth dynamics was established. This empirical model was calibrated and validated with experimental data and could accurately and quantitatively simulate ecological processes. In this study, a simulation of eutrophication regulation and external pollution impacts was performed, and a decision-making method and procedure for sustainable urban management were developed. The application to guide ecological restoration of Dongshan Lake is an extension of the model, which further proves the theoretical and practical importance of the model and the ecosystem simulation model.

The simulated and measured results for the Dongshan Lake ecosystem by the Yan model II were highly consistent. The values of the correlation index R were significant for all state variables of the model. The main findings of this study are as follows:

(1) By simulating eutrophication management, eutrophic lakes could be effectively restored by planting *V. natans* (Lour.) Hara at a low biomass density. The filter-feeding fish, *A. nobilis*, could quickly inhibit the growth of phytoplankton, but the restoration of eutrophic lakes is difficult.

(2) *A. nobilis* at a density of 50 g/m^3 has a strong ability to regulate phytoplankton growth.

(3) By simulating external pollution impacts, a total of 600 m^3 of urban sewage is the maximum limit for sustainable lake ecosystem development.

(4) The Yan-Model II provided very good guidance for restoring eutrophication in Dongshan Lake, including the construction of aquatic ecosystems and sustainable management.

(5) This study is applicable to not only lake ecosystem management but also urban system sustainable management. The methods used to establish the ecosystem models and simulate the responses under different scenarios could serve as references for decision-making in similar fields, even urban systems. The Yan-Model II is an acceptable simulation model for urban lake ecosystems and is better than the Yan-Model.

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References

Amemiya, T., Enomoto, T., Rossberg, A.G., Takamura, N. and Itoh, K. (2005). Lake restoration in terms of ecological resilience: a numerical study of biomanipulations under bistable conditions. *Ecol. Soc.*, 10(2), 3. http://dx.doi.org/10.5751/ES-01357-100203

Amemiya, T., Enomoto, T., Rossberg, A.G., Yamamoto, T., Inamori, Y. and Itoh, K. (2007). Stability and dynamical behavior in a lake-model and implications for regime shifts in real lakes. *Ecol. Model.*, 206(1-2), 54-62. https://doi.org/10.1016/j.ecolmodel.2007.03.019

Arhonditsis, G.B. and Brett, M.T. (2005). Eutrophication model for Lake Washington (USA): Part I. Model description and sensitivity analysis. *Ecol. Model.*, 187(2-3), 140-178. https://doi.org/10.1016/j.ecolmodel.2005.01.040

Borics, G., Grigorszky, I., Szabó, S. and Padisák, J. (2000). Phytoplankton associations in a small hypertrophic fishpond in East Hungary during a change from bottom-up to top-down control. *Hydrobiologia*, 424(1-3). https://doi.org/79-90.10.1023/a:1003948827254

Carpenter, S.R., Cole, J.J., Pace, M.L. and Wilkinson, G.M. (2016). Response of plankton to nutrients, planktivory and terrestrial organic matter: a model analysis of whole-lake experiments. *Ecol. Lett.*, 19(3), 230-239. https://doi.org/10.1111/ele.12558

Cerco, C.F. and Meyers, M. (2000). Tributary Refinements to Chesapeake Bay Model. *J. Environ. Eng.*, 126(2):164-174. https://doi.org/10.1061/(asce)0733-9372(2000)126:2(164).

Chowdhury, G.W., Gallardo, B. and Aldridge, D.C. (2016). Development and testing of a biotic index to assess the ecological quality of lakes in Bangladesh. *Hydrobiologia*., 765(1), 55-69. https://doi.org/10.1007/s10750-015-2399-6

DeAngelis, D.L., Bartell, S.M. and Brenkert, A.L. (1989). Effects of nutrient recycling and food-chain length on resilience. *Am. Nat*., 134(5), 778-805. https://doi.org/10.2307/2462215

Domaizon, I. and Devaux, J. (1999). Experimental study of the impacts of silver carp on plankton communities of eutrophic villerest reservoir

(France). *Aquat. Ecol*., 33(2), 193-204. https://doi.org/10.1023/a:1009984713183

Drago, M., Cescon, B. and Iovenitti, L. (2001). A three-dimensional numerical model for eutrophication and pollutant transport. *Ecol. Model*., 145(1), 17-34. https://doi.org/10.1016/s0304-3800(01)00384-2

Gurkan, Z., Zhang, J. and Jørgensen, S.E. (2006). Development of a structurally dynamic model for forecasting the effects of restoration of Lake Fure, Denmark. *Ecol. Model*., 197, 89-102. https://doi.org/10.1016/j.ecolmodel.2006.03.006

Gong, R., Xu, L., Wang, D., Li, H. and Xu, J. (2016). Water quality modeling for a typical urban lake based on the EFDC model. *Environ. Model. Assess.*, 21(5), 643-655. https://doi.org/10.1007/s10666-016-9519-1

Guo, H.J., Chen, L.S. and Song, X.Y. (2017). A kind of non-traditional biomanipulation model with constant releasing fish. Math. Method. *Appl. Sci*., 40(13), 4727-4737. https://doi.org/10. 1002/mma.4340

Horne, A.J. and Viner, A.B. (1971). Nitrogen fixation and its significance in tropical Lake George, *Uganda. Nature*., 232(5310), 417-418. https://doi.org/10.1038/232417a0

Huang, G.H. and Chang, N.B. (2003). The Perspectives of Environmental Informatics and Systems Analysis. *J. Environ. Inform*., 1(1), 1-7. https://doi.org/10.3808/jei.200300001

Huang, L., Fang, H. and Reible, D. (2015). Mathematicalmodel for interactions and transport of phosphorus and sediment in the Three Gorges Reservoir. *Water Res.*, 85, 393-403. https://doi.org/10.1016/j.watres.2015.08.049

Huser, B.J., Futter, M., Lee, J.T. and Perniel, M. (2016). In-lake measures for phosphorus control: the most feasible and cost-effective solution for long-term management of water quality in urban lakes. *Water Res.*, 97, 142-152. https://doi.org/10.1016/j.watres.2015.07.036

Jørgensen, S.E. (1986). Structural dynamic model. *Ecol. Model*., 31, 1-9. https://doi.org/10.1016/0304-3800(86)90051-7

Jørgensen, S.E., Mejer, H. and Friis, M., (1978). Examination of a lake model. *Ecol. Model*., 4, 253-278. https://doi.org/10.1016/0304-3800(78)90010-8

Jørgensen, S.E. (2010). A review of recent developments in lake modelling. *Ecol. model.*, 221, 689-692. https://doi.org/10.1016/j.ecolmodel.2009.10.022

Kuo, J.T., Hsieh, P.H. and Jou, W.S. (2008). Lake eutrophication management modeling using dynamic programming. *J. Environ. Manage*., 88, 677-687. https://doi.org/10.1016/j.jenvman.2007.03.027

Liu, H., Benoit, G., Liu, T., Liu, Y. and Guo, H.C. (2015). An integrated system dynamics model developed for managing lake water quality at the watershed scale. *J. Environ. Manage*., 155, 11-23. https://doi.org/ 10.1016/j.jenvman.2015.02.046

Li, J.M., Huang, P., Zhao, Z.M. and Zhang, R.D. (2015). Ambiguous influences of omnivorous fish on trophic cascade and alternative states: Implications for biomanipulation from an ecological model. *Aquat. Ecosyst. Health*, 18(1), 105-113. https://doi.org/105-113.10.1080/14634988.2015.998895

Lin, C., Ma, R.H., Wu, Z.P., Xiong, J.F. and Min, M. (2018). Detection of the sensitive inflowing river indicators related to non-point source organic pollution: a case study of Taihu Lake. *J Environ Inform*., 32, 98-111. https://doi.org/10.3808/jei.201600343

Mao, J.Q., Chen, Q.W. and Chen, Y.C. (2008). Three-dimensional eutrophication model and application to Taihu Lake, China. *J. Environ. Sci*., 20, 278-284. https://doi.org/10.1016/s1001-0742(08)60044-3

Marchi, M., Jørgensen, S.E., Bécares, E., Corsi, I., Marchettini, N. and Bastianoni, S. (2011). Dynamic model of Lake Chozas (León, NW Spain)-Decrease in eco-exergy from clear to turbid phase due to introduction of exotic crayfish. *Ecol. Model.*, 222, 3002-3010. https://doi.org/10.1016/j.ecolmodel.2011.04.016

Moriasi, D.N., Arnold, G., Kuijk, M., Bingner, R., Harmel, R.D. and Veith, T. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE.*, 50, 885-900. http://dx.doi.org/10.13031/2013.23153

Millie, D.F., Weckman, G.R., Young II, W.A., Ivey, J.E., Carrick, H.J. and Fahnenstiel, G.L. (2012). Modeling microalgal abundance with artificial neural networks: demonstration of a heuristic 'Grey-Box' to deconvolve and quantify environmental influences. *Environ. Model. Softw*., 38, 27-39. https://doi.org/10.1016/j.envsoft.2012.04.009

Mueller, C.R., Eversole, A.G., Turker, H. and Brune, D.E. (2004). Effect of silver carp Hypophthalmichthys molitrix and freshwater mussel Elliptio complanata filtration on the phytoplankton community of partitioned aquaculture system units. *J. World Aquacult. Soc*., 35(3), 372-382. https://doi.org/10.1111/j.1749-7345.2004.tb00101.x

Niu, Z.G., Wang, X.J. and Chen, Y.X. (2013). Lake aquatic ecosystem models: A review. *Chinese J. Ecol.*, 32(1), 217-225. https://doi.org/10.13292/j.1000-4890.2013.0063

Oie, C.S., Albaugh, C.E. and Peyton, B.M. (2007). Benzoate and salicylate degradation by Halomonas campisalis, an alkaliphilic and moderately halophilic microorganism. *Water Res*., 41(6), 1235-1242. https://doi.org/10.1016/j.watres.2006.12.029

Paerl, H.W., Xu, H., Mccarthy, M.J., Zhu, G., Qin, B., Li, Y., Gardner. and Wayne, S. (2011). Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): the need for a dual nutrient (N & P) management strategy. *Water Res.*, 45(5), 1973-1983. https://doi.org/10.1016/j.watres.2010.09.018

Peters, F. and Marrasé, C. (2000). Effects of turbulence on plankton: an overview of experimental evidence and some theoretical considerations. *Mar. Ecol. Prog*., 205(3), 291-306. https://doi.org/10.3354/meps205291

Rahmani, M.A. and Zarghami, M. (2015). The use of statistical weather generator, hybrid data driven and system dynamics models for water resources management under climate change. *J. Environ. Inform*., 25(1), 23-35. https://doi.org/10.3808/jei.201400285

Rusuli, Y., Li, L., Ahmad, S. and Zhao, X. (2015). Dynamics model to simulate water and salt balance of Bosten Lake in Xinjiang, China. *Environ. Earth.*, 74(3), 2499-2510. https://doi.org/10.1007/ s12665-015-4257-2

Sagehashi, M., Sakoda, A. and Suzuki, M. (2000). A predictive model of long-term stability after biomanipulation of shallow lakes. *Water Res.*, 34(16), 4014-4028. https://doi.org/10.1016/s0043-1354(00)00165-2

Sagehashi, M., Sakoda, A. and Suzuki, M. (2001). A mathematical model of a shallow and eutrophic lake (the Keszthely Basin, Lake Balaton) and simulation of restorative manipulations. *Water Res*., 35(7), 1675-1686. https://doi.org/10.1016/S0043-1354(00)00435-8

Schindler, D.W. and Hecky, R.E. (2009). Eutrophication: more nitrogen data needed. *Science*, 324(5928), 721-722. https://doi.org/10.1126/science.324_721b

Setegn, S.G, Srinivasan, R. and Dargahi, B. (2008). Hydrological modelling in the Lake Tana Basin, Ethiopia Using SWAT Model. *Open Hydrol. J*., 2(1), 49-62. https://doi.org/10.2174/187437810080 2010049.

Simons T.J. (1973). *Development of three-dimensional numerical models of the Great Lakes*. Iwd Scientific, 12

Small, G.E., Niederluecke, E.Q., Shrestha, P., Janke, B.D. and Finlay, J.C. (2018). The effects of infiltration-based stormwater best management practices on the hydrology and phosphorus budget of a eutrophic urban lake. *Lake Reserv. Manage*., 35(1), 38-50. https://doi.org/10.1080/10402381.2018.1514549

Tang, C.Y., Li, Y.P. and Acharya, K. (2016). Modeling the effects of external nutrient reductions on algal blooms in hyper-eutrophic Lake Taihu, China. *Ecol. Eng*., 94, 164-173. https://doi.org/10.1016/j.ecoleng.2016.05.068

Trolle, D., Jørgensen, T.B. and Jeppesen, E. (2008). Predicting the effects of reduced external nitrogen loading on the nitrogen dynamics and ecological state of deep Lake Ravn, Denmark, using the DYRESM–CAEDYM model. *Limnologica. Ecol. Manage. Inland. Waters.*, 38, 220-232. https://doi.org/10.1016/j.limno.2008.05.009

Tsuji, K., Asakawa, M., Anzai, Y., Sumino, T. and Harada, K.I. (2006). Degradation of microcystins using immobilized microorganism isolated in an eutrophic lake. *Chemosphere*, 65(1), 117-124. https://

doi.org/10.1016/j.chemosphere.2006.02.018

VanMiddlesworth, T.D., McClelland, N.N., Sass, G.G., Casper, A.F., Spier, T.W. and Lemke, M.J. (2017). Fish community succession and biomanipulation to control two common aquatic ecosystem stressors during a large-scale floodplain lake restoration. *Hydrobiologia*, 804(1), 73-88. https://doi.org/10.1007/s10750-016-2696-8

Waajen, G.W., Van Bruggen, N.C., Pires, L.M.D., Lengkeek, W. and Lürling, M. (2016). Biomanipulation with quagga mussels (Dreissena rostriformis bugensis) to control harmful algal blooms in eutrophic urban ponds. *Ecol. Eng.*, 90, 141-150. https://doi.org/10.1016/j.ecoleng.2016.01.036

Wang, H.J., Liang, X.M., Jiang, P.H., Wang, J., Wu, S.K. and Wang, H.Z. (2008). TN: TP ratio and planktivorous fish do not affect nutrient - chlorophyll relationships in shallow lakes. *Freshwater Biol.*, 53(5), 935-944. https://doi.org/10.1111/j.1365-2427.2007.01950.x

Wang, Y.H., Jiang, Y.Z., Liao, W.H., Gao, P., Huang, X.M., Wang, H., Wang,H., Song, X.S. and Lei, X.H. (2014). 3-D hydro-environmental simulation of Miyun reservoir, Beijin. *J. Hydro-environ. Res.*, 8(4), 383-395. https://doi.org/10.1016/j.jher.2013.09.002

Whitehead, P.G., Jin, L., Crossman, J., Comber, S., Johnes, P.J., Daldorph, P., Flynn, N., Collins, A.L., Butterfield, D., Mistry, R., Bardon, R., Pope, L. and Willows, R. (2014). Distributed and dynamic modelling of hydrology, phosphorus and ecology in the Hampshire Avon and Blashford Lakes: Evaluating alternative strategies to meet WFD standards. *Sci. Total Environ.*, 481, 157-166. https://doi.org/10.1016/10.1016/j.scitotenv.2014.02.007

Willuweit, L. and O'Sullivan, J.J. (2013). A decision support tool for sustainable planning of urban water systems: Presenting the Dynamic Urban Water Simulation Model. *Water Res.*, 47, 7206-7220. https://doi.org/10.1016/j.scitotenv.2014.02.007

Williamson, T.J., Vanni, M.J., González, M.J., Renwick, W.H., Bremigan, M.T. and Conroy, J.D. (2018). The importance of nutrient supply by fish excretion and watershed streams to a eutrophic lake varies with temporal scale over 19 years. *Biogeochemistry*, 140(2), 233-253. https://doi.org/10.1007/s10533-018-0490-6

Wu, Q., Xia, X., Li, X. and Mou, X. (2014). Impacts of meteorological variations on urban lake water quality: a sensitivity analysis for 12 urban lakes with different trophic states. *Aquat. Sci.*, 76(3), 339-351. https://doi.org/10.1007/s00027-014-0339-6

Wu, Z., Liu, Y., Liang, Z.Y., Wu, S.F. and Guo, H.C. (2017). Internal cycling, not external loading, decides the nutrient limitation in eutrophic lake: A dynamic model with temporal Bayesian hierarchical inference. *Water Res.*, 116, 231-240. https://doi.org/10.1016/j.watres.2017.03.039

Xia, X.H., Wu, Q., Mou, X.L. and Lai, Y.J. (2015). Potential impacts of climate change on the water quality of different water bodies. *J. Environ. Inform.*, 25(2), 85-98. https://doi.org/10.3808/jei.201400263

Yang, L.K., Peng,S., Zhao, X.H. and Li, X. (2017). Development of a two-dimensional eutrophication model in an urban lake (China) and the application of uncertainty analysis. *Ecol. Model.*, 345, 63-74. https://doi.org/10.1016/j.ecolmodel.2016.11.014

Yan, Z.Q., Wang, Y.F., Wu, D. and Xia, B.C. (2018). Exploration of an urban lake management model to simulate chlorine interference based on the ecological relationships among aquatic species. *Sci. Rep-UK.*, 8(1), 8325-. https://doi.org/10.1038/s41598-018-26634-8

Yen, C.H., Chen, K.F., Sheu, Y.T., Lin, C.C. and Horng, J.J. (2012). Pollution source investigation and water quality management in the Carp Lake watershed, Taiwan. *CLEAN–Soil, Air, Water*, 40, 24-33. https://doi.org/10.1002/clen.201100152

Yi, C.L., Guo, L.G., Ni, L.Y., Yin, C.J., Wan, J. and Yuan, C.B. (2016). Biomanipulation in mesocosms using silver carp in two Chinese lakes with distinct trophic states. *Aquaculture*, 452, 233-238. https://doi.org/10.1016/j.aquaculture.2015.11.002

Zhang, C., Gao, X.P., Wang, L.L. and Chen, X.J, (2015). Modelling the role of epiphyton and water level for submerged macrophyte development with a modified submerged aquatic vegetation model in a shallow reservoir in China. *Ecol. Eng.*, 81, 123-132. https://doi.org/10.1016/j.ecoleng.2015.04.048

Zhang, L. and Liu, J. (2014). AQUATOX coupled foodweb model for ecosystem risk assessment of polybrominated diphenyl ethers (PBDEs) in lake ecosystems. *Environ. Pollut.*, 191, 80-92. https://doi.org/10.1016/j.envpol.2014.04.013