In eutrophic lakes, algae are known to be sensitive to chlorine, but the impact of chlorine on the wider ecosystem has not been investigated. To quantitatively investigate the effects of chlorine on the urban lake ecosystem and analyze the changes in the aquatic ecosystem structure, a dynamic response model of aquatic species to chlorine was constructed based on the biomass density dynamics of aquatic species of submerged macrophytes, phytoplankton, zooplankton, periphyton, and benthos. The parameters were calibrated using data from the literature and two simulative experiments. The model was then validated using field data from an urban lake with a surface area of approximately 8000 m² located in the downtown area of Guangzhou, South China. The correlation coefficient (R), root mean square error-observations standard deviation ratio (RSR) and index of agreement (IOA) were used to evaluate the accuracy and reliability of the model and the results were consistent with the observations (0.446 R < 0.985, RSR < 0.7, IOA > 0.6). Comparisons between the simulated and observed trends confirmed the feasibility of using this model to investigate the dynamics of aquatic species under chlorine interference. The model can help managers apply a modest amount of chlorine to control eutrophication and provides scientific support for the management of urban lakes.

Lake eutrophication is recognized to have deleterious effects on aquatic ecosystems, environmental systems and economies worldwide. Eutrophication leads to harmful algal blooms and the formation of hypoxic environments due to high nutrient loads. Since the 1960s, many studies, techniques, and policies for eutrophication control have been proposed and developed. Reducing external nutrient sources and restoring normal ecological conditions are accepted as the main measures for controlling eutrophication. 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 be performed specifically, thus remains “rough and wild”, particularly for the problem of lake eutrophication. For example, the lack of reliable and quantitative interpretations of lake ecosystems has led to lake eutrophication dynamic that present a long duration and rebound effect. Therefore, quantitative models have been developed and are considered potential tools for eutrophication management. These models are used to simulate the dynamics of each component in the lake ecosystem, which are complicated and include self-regulation and feedback. 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. Lake models have been successfully developed in recent decades and expanded from monolayer, single ventricular components with zero dimensions to multi-level, multi-chamber components in three dimensions. Among these models, integrated models including AQUATOX, PAMOLARE, CAEDYM and WASP, have been established and applied in lake environment research and management. Despite the wide variety of available models, most focus on large lakes, whereas urban lakes, which play important and indispensable roles in urban water systems and microclimate regulation, receive much less attention. Urban lakes, which provide both
cultural and natural landscapes, act as important recreation sites and are closely related to citizens’ daily lives. Compared with lakes far away from cities, urban lakes are generally characterized as small, shallow and subject to frequent human impacts32. Urban lakes generate landscape heterogeneity and ecological diversity within a city. In addition, via the runoff, storage and infiltration of water, urban lakes can protect freshwater resources, control flooding, replenish groundwater and regulate the urban microclimate33. Despite their important functions in the urban ecosystem, urban lakes are easily affected or damaged by sewage discharge, storm runoff, and human activities34,35. Urban lake ecosystems are delicate and difficult to manage in a self-sustaining manner36. In recent years, urban lakes have increasingly suffered from a series of environmental problems, including the deterioration of water quality and, in particular, eutrophication events. For example, Lake Pamvotis in Ioannina, Greece, and Lake Kuminghu in Beijing, China, have experienced eutrophication problems at different levels29,30. To address eutrophication problems and prevent crashes in aquatic ecosystem balance, an important first step is to reveal the regulatory mechanisms of the lake ecosystem by constructing specific models.

Modeling studies of urban lakes are not being wide spread in the literature31. To date, most reports and discussions have concentrated on simulating hydrodynamics behaviors and water quality changes both physically and chemically but have not considered ecological processes32. Researchers have suggested establishing detailed models for shallow urban lakes to explore ecological heterogeneities and problems33. Lake ecosystems reflect the processes of exchanging material and energy with the atmosphere, water, sediment, and organisms. By now, most ecological models for lake ecosystems have focused on genera since the genera-specific model has many obvious merits, such as user-friendly, easy to calibrate and validate. However, many biological characteristics of species are unique. If the constructed model of aquatic populations is based on genera, the parameters might not be unique and stable, and possibly result in an insufficient understanding of the ecological functions of some important species14,34. Therefore, a species-specific model, that treats aquatic species as basic components and accurately simulates the dynamics of these species, is essential to complete and strengthen the urban lake management, and provide one more choice for studying.

Urban lake management should be based on a comprehensive understanding of the ecological dynamics of aquatic ecosystems35. The main tasks of lake management are to regulate the balance of the aquatic ecosystem and mitigate the impacts of external interferences36. Adding chlorine was proved to be an effective method to control the lake eutrophication, and thus has been applied for lake management37,38. Chlorine reacts with water to produce small molecules of hypochlorous acid. Hypochlorous acid spreads along the surface of the algal cell, penetrating the membrane and oxidizing intracellular protein, resulting in the inhibition of algae growth39. However, small molecules of hypochlorous acid, similar to chlorine, diffuse into plants and oxidize intracellular protein, eventually leading to the death of algae40. Therefore, a species-specific model, that treats aquatic species as basic components and accurately simulates the dynamics of these species, is essential to complete and strengthen the urban lake management, and provide one more choice for studying.

In this study, a dynamic model of a shallow urban lake was constructed based on the dynamics of primary aquatic species. The model considers individual aquatic species and chlorine interferences to simulate a shallow urban lake ecosystem. Under chlorine interference, the dynamics of several aquatic organisms and water quality were simulated with a specific model that integrates organism biomass dynamics, the ecological relationships between aquatic species, and phosphorus and chlorine in water. The model can help managers apply a modest amount of chlorine to control eutrophication and provides scientific support for the management of urban lakes. Furthermore, the structure and parameter values of this model can provide reference data for the study of urban lake models in the near areas.

Results
Calibration and validation. The calibrated parameters based on the results of the two experimental results or obtained from the literature are presented in Table 1. Model validation was performed using the monitored data from Lotus Lake.

The attenuation model of chlorine according to the results of experiment 1 is presented in Table 2. The R values ranged between 0.9130 and 0.9601, reflecting good agreement between the model and the observations. The results of the regression analysis is showed the linear relationship between C0 and K. A higher initial concentration of chlorine corresponded to slower attenuation. The root mean square error-observations standard deviation ratio (RSR) was 0.55, which indicated good performance.

Table 3 shows the results of the model evaluation for each component. The simulated values showed good qualitative agreement with the measurements based on the R, RSR and IOA measures. The R values ranged between 0.446 and 0.985. Except for the simulated biomass densities of M. lospuleuclart (Claus) and G. compressus (Hutton), the simulated values presented highly significant correlations with the measurements (p < 0.01). In addition, the RSR values for all of the components were less than 0.7 and were thus satisfactory. The values of IOA for all the components were greater than 0.6, reflecting consistency between the model and observations.

Simulation of TP in water and sediment. Figure 1 shows the total phosphorus concentrations according to the modeled data and the field data for lake water and sediment.

The TP in water presented a single peak (Fig. 1(a)) with a value of approximately 1.65 mg L⁻¹. Although differences were observed between the measurement and simulation values, the trends of TP concentration obtained from the model were generally in agreement with the observations. The increase in TP not only led to the outbreak of eutrophication but also resulted in an increase of TP in sediment (Fig. 1(b)) due to settling during this period.
Table 1. Model input parameters based on experiments or obtained from the literature, (the validation parameters are shown in brackets). a Vallisneria natans (Lour.) Hara; b Microcystis aeruginosa; c Aphanizomenon flos-aquae; d Euglena gracilis; e Melosira granulata (Ehr.) Ralfs; f Ulothrix tenerrima (Kütz.); g Oscillatoria chloris; h Synechococcus acus; i Brachionus plicatilis; j Diaphanosoma brachyurum (Lièvin); k Mesocyclops leuckarti (Claus); l Chironomidae larvae; m Pomacea canaliculata (Caenogastropoda, Ampullariidae); n Gyraulus compressus (Hütton). [e1] experiment 1; and [e2] experiment 2.

| Components                      | Correlation coefficient (R) | Root mean square error observations standard deviation ratio (RSR) | Index of agreement (IOA) |
|---------------------------------|-----------------------------|-------------------------------------------------------------------|-------------------------|
| V. natans (Lour.) Hara          | 0.985**                     | 0.09                                                              | 0.872                   |
| M. aeruginosa                   | 0.908**                     | 0.431                                                             | 0.951                   |
| A. flos-aquae                   | 0.885**                     | 0.697                                                             | 0.941                   |
| E. gracilis                     | 0.731**                     | 0.692                                                             | 0.838                   |
| M. granulata (Ehr.) Ralfs       | 0.931**                     | 0.479                                                             | 0.948                   |
| U.tenerrima (Kütz.) Kütz.       | 0.860**                     | 0.582                                                             | 0.893                   |
| O. chlorine                     | 0.933**                     | 0.004                                                             | 0.936                   |
| S.acus                          | 0.965**                     | 0.017                                                             | 0.976                   |
| B. plicatilis                   | 0.839**                     | 0.604                                                             | 0.998                   |
| D. brachyrum Lièvin             | 0.940**                     | 0.374                                                             | 0.967                   |
| M.leuckarti (Claus)             | 0.446*                      | 0.231                                                             | 0.668                   |
| Chironomidae larvae             | 0.902**                     | 0.591                                                             | 0.932                   |
| P.canaliculata(Caenogastropoda, Ampullariidae) | 0.820**   | 0.518                                                             | 0.848                   |
| G.compressus (Hütton)           | 0.763*                      | 0.496                                                             | 0.749                   |
| TP in water                     | 0.967**                     | 0.257                                                             | 0.898                   |
| TP in sediment                  | 0.875**                     | 0.607                                                             | 0.983                   |

Table 3. R, RSR, and IOA values indicating the agreement between the measured and simulated values. **Significant at p < 0.01, *significant at p < 0.05, 0 < RSR < 0.5 indicates very good performance, 0.5 < RSR < 0.6 indicates good performance, 0.6 < RSR < 0.7 indicates satisfactory performance, and 0.7 > RSR indicates unsatisfactory performance (6).
**V. natans (Lour.) Hara.** The simulated and observed biomass densities of *V. natans* (Lour.) Hara are shown in Fig. 2. A single peak was found for the biomass density of *V. natans* (Lour.) Hara. The simulated values were analogous to the observed values, with corresponding peaks in May. Although the simulated maximum values were larger than the observed values, the relative error was less than 15% (12.3%). The simulated results were reasonable. However, eutrophication began in the lake on May 10th, resulting in the decline of *V. natans* (Lour.) Hara biomass density. Both the observations and simulations followed decreasing trends after mid-June, when phytoplankton and periphyton appeared to be blooming (Figs 3 and 4). Subsequently, the biomass density of *V. natans* (Lour.) Hara continued to decrease, reaching a measured density of approximately 3000 g·m$^{-2}$ in September.

**Phytoplankton.** The main species of phytoplankton in the lake were *M. aeruginosa*, *A. flos-aquae*, *E. gracilis*, and *M. granulata* (Ehr.) Ralfs. The simulated and observed biomass densities of the four main species of phytoplankton are presented in Fig. 3.

Three peaks were found in the biomass density dynamics of *M. aeruginosa*, whereas only one peak was found for each of the remaining three species. The simulated and observed patterns of the densities of the four phytoplankton species presented similar trends. *M. aeruginosa* was clearly very sensitive to chlorine. Decreases in the biomass density of *M. aeruginosa* and *E. gracilis* were observed on May 8th, 19th, and 29th, June 4th, July 17th and August 4th and August 28th based on both the observations and simulations due to the intense inhibitory effects of chlorine. In addition, both the simulated and observed values for *A. flos-aquae* and *M. granulata* (Ehr.) Ralfs presented increasing trends after the application of chlorine on May 8th, 19th, and 29th and June 4th, reflecting a weak effect of chlorine on these species. The peaks in density for four species of phytoplankton presented distinct delays in the simulations relative to the observed values. Although the modeled values agreed well with the observations, the observed maximum values were smaller than the corresponding simulated values.

**Periphyton.** *O. chlorine*, *U. tenerrima* (Kütz.) Kütz, and *S. acus* were the dominant species of periphyton in the lake. Figure 4 shows the simulated and observed biomass density values for these three main species.

Unlike the biomass densities of phytoplankton, the biomass densities of periphyton displayed a single peak according to both observation and simulation. Although differences were observed between the observations and simulations, the trends and density values obtained from the model were generally consistent with the
observations. In addition, the simulated maximum biomass densities of each of the three species of periphyton agreed well with the observations; however, the observed duration of the *O. chlorine* bloom was shorter than the simulated duration, whereas the opposite pattern was observed for *U. tenerima* (Kütz.) Kütz. Among the three species, *U. tenerima* (Kütz.) Kütz. had the strongest restoration ability and exhibited an increasing trend after August 21st.

**Zooplankton and Benthos.** The main species of zooplankton in the lake were *B. plicatilis*, *M. leuckarti* (Claus) and *D. brachyurum* (Liévin). Chironomid larvae, *P. canaliculata* (*Caenogastropoda* and *Ampullariidae*) and *G. compressus* (Hütton) were the dominant species of benthos in the lake. The simulated and observed biomass density values of the three main species of each zooplankton and benthos are presented in Fig. 5.

Three peaks were observed in the biomass density of all three main species of zooplankton (Fig. 5(a)), with similar values observed between the simulations and observations. A decrease in the biomass density of each of the three species occurred when chlorine was applied on May 8th, 19th, and 29th, June 4th, July 17th, and August 4th and August 28th. The modeled peaks of *B. plicatilis* were obviously higher than the corresponding observed values, and this pattern was also observed in the other two zooplankton species, but the discrepancies were not obvious. Despite that, the relative error between the simulations and observations was relatively small. A single peak in the biomass density of each of the benthos species was observed (Fig. 5(b)). Although differences were observed between the measurements and simulations, the trends and values obtained from the model were generally in agreement with the observations. The modeled peaks for the Chironomid larvae and *G. compressus* (Hütton) were much higher than the observed peaks.

Overall, this study explored the responses of the aquatic species to chlorine interference with two initial concentrations, i.e. 0.045 and 0.188 mg/L. The results showed that, within this concentration range, chlorine has a remarkable inhibitory effect on the dominant species (*M. aeruginosa*), thus control eutrophication in the urban lake.

**Discussion**

The model developed in this study coupled dynamic modules of biomass density of the main aquatic species with environmental factors. 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. Marchi developed a model to simulate the seasonal dynamics of major components of Lake Chozas, when an invasive fish was introduced into the lake. Compared with the previous studies, the model developed in this study focused on species instead of genera. Addressing only the dynamics of a category of aquatic organisms, obviously, ignores the ecological functions of certain important species. 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 dynamic of species and to understand the mechanisms among aquatic species.
Therefore, the constructed model in this study is essential to help the manager to complete and strengthen the urban lake management.

In addition, using chlorine is an effective method to manage the lake eutrophication, hence it is necessary to comprehensively understand the ecological dynamics of aquatic ecosystems under chlorine interference in urban lake management. This model, using the exponential function to couple the chlorine interference and accurately simulating the responses of the species to chlorine interference, can help managers apply a modest amount of chlorine to control eutrophication and provides scientific support for the management of urban lakes.

The dynamic model presented in this study explained the radical changes observed in the shallow urban lake. Both the simulated and observed results showed that the algae with cystic structure and zooplankton were sensitive to chlorine, whereas the algae with filamentous structure and submerged macrophytes showed strong resistance to chlorine. The increase in TP in the water between June 12th and 22nd clearly promoted the growth of phytoplankton and periphyton, which resulted in the breakout of eutrophication. The results confirmed that abundant TP nutrients provided the foundation for the phytoplankton outbreak. However, the TP additions were necessary but not sufficient, as evidenced by the low TP concentrations between May 2nd and June 12th. However, the biomass of *A. flos-aquae* and *M. granulata* (Ehr.) Ralfs presented increasing trends in the measured experiment. The biomass densities of phytoplankton and periphyton species presented decreasing trends from July 12th to August 10th, resulting in a regime shift in the lake ecosystem from a turbid phase to a clean phase. During this period, the TP in water showed a decreasing trend (Fig. 1), thereby limiting the growth of phytoplankton and periphyton. Moreover, the intense interference of chlorine inhibited the growth of *M. aeruginosa*, which was an active species on July 17th and August 4th.

By comparing the trends and biomass density values of the main aquatic species under the chlorine interferences between the simulations and observations, we found that the modeled results were acceptable with certain discrepancies. Chlorine can decay in a few hours. The attenuation model of chlorine ran with a time interval of...
one hour. However, the daily amount of chlorine in water used as input in the model was calculated using the exponential equation to produce a daily average. Thus, the calculation method and the time interval of chlorine concentrations might have introduced errors into the simulations. In addition, the density peaks of the four species of phytoplankton presented distinct delays in the simulations relative to the observed patterns, which was likely because the simulations were run without considering the hydrodynamic effects. Studies have found that small-scale motion or low flow velocity were generally favorable for algal growth and aggregation in monoculture or mixed culture. Despite these discrepancies between the simulated and observed values, good agreement was observed for both the values and trends, and the model satisfactorily described the dynamics of aquatic species under chlorine interference. The structure and parameter values of this model can provide a reference for the study of urban lake models in the near area.

The model accurately simulated the dynamics of aquatic species with the chlorine interference in an urban lake. Differences between the observed and simulated values were inevitable because some important components of the ecosystem were ignored in the model, including fishes and bacteria species and hydrodynamic influences. In addition, because of the limitations of study time and location, the further validation of the model on different lakes and other seasons are recommended. Nonetheless, the model incorporated the main species in each class of aquatic organism that performed critical functions in the lake ecosystem and exhibited good performance. Therefore, this study provides strong support for the use of the model for urban lake eutrophication management.

Figure 5. Observed and simulated biomass density values of three main species of zooplankton and benthos in the lake (the arrows represent chlorine interference).
The only artificial intervention included in the system. Tables 5 and 6 show the different parameters and equations food chain, competition, predation, respiration, and mortality are the main processes in the model. Chlorine is considered the main components of the model. The phosphorus in water, as a linkage in the system, is directly related to plankton, zooplankton, periphyton, benthos, detritus and the total phosphorus in water and sediment are considered the main components of the model. The phosphorus in sediment; NH4, ammoniacal nitrogen in water; NO3, nitrate nitrogen; ON, organic nitrogen.

Materials and Methods

Dynamic model of biomass density. A simulation model for the lake is developed by coupling the biomass density dynamic modules of the main aquatic organisms and environmental factors. The model is developed using Stella software (version9.1.4). The system dynamics of the model presents a strong modeling environment and a simple operation mode48. The model structure is presented in Fig. 6. 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. Chlorine is the only artificial intervention included in the system. Tables 5 and 6 show the different parameters and equations in the model.

Primary producers. Submerged macrophytes, phytoplankton and periphyton are primary producers in the ecosystem and have similar ecological processes, including growth, death and respiration. The biomass density model of the submerged macrophytes, phytoplankton and periphyton is built based on the concepts of Marchi49 (equation 1). The model of phytoplankton also incorporates the settlement process and grazing process of zooplankton (equation 2). Growth is a function of temperature, phosphorus, light and population inhibition (equation 3). The growth of phytoplankton and periphyton also incorporates the inhibition of V. natans (Lour.) Hara growth (equation 4). Mortality is a function of temperature and chlorine (equation 5). Respiration loss is a function of temperature (equation 6). The grazing of zooplankton on phytoplankton is a function of temperature as well as phytoplankton and zooplankton populations (equation 7). The settling of phytoplankton is an exponential function and a function of the temperature and depth of the lake (equation 8). Key parameters for different species of primary producers are presented in Table 1.

Table 4. Models published in the literatures. 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; NH4, ammoniacal nitrogen in water; NO3, nitrate nitrogen; ON, organic nitrogen.
Consumers. The biomass density model of zooplankton and benthos is constructed based on the concepts established by Cerco. Zooplankton and benthos are the main consumers in the model. Grazing, death and respiration are recognized as the main processes (equation 9). The grazing of zooplankton is a function of the temperature, assimilation efficiency, ingestion rate and phytoplankton (see equation 7), whereas the grazing of benthos is a function of temperature, assimilation efficiency, ingestion rate and detritus (equation 10).

Detritus. Benthos grazing, decomposition and settling are recognized as the main processes for detritus (equation 13). The majority of the detritus originate from the mortality of biological components. The settling of detritus is a function of lake depth, the settling rate of detritus, the biomass density of detritus in water and temperature (equation 14). The decomposition of detritus is a function of temperature, the decomposition rate of detritus and the biomass density of detritus (equation 15).

Total phosphorus (TP) in water and sediment. The uptake of primary producers, diffusion from sediment, decomposition of detritus, and settling are recognized as the main processes underlying TP variations in water (equation 16). The settling of TP in water, phytoplankton, detritus, decomposition of benthos and diffusion are the main processes for TP in sediment (equation 17). Diffusion is a function of the TP concentration in water and sediment, the diffusion rate of phosphorus, the lake depth and the active layer of sediment (equation 18). The settling of TP in water is a function of the lake depth, the settling rate of phosphorus and the TP concentration in water (equation 19).

Parameter calibration. Calibration data are obtained from the literature and two experiments in the laboratory. Data on the ingestion rate, the assimilation efficiencies of zooplankton and benthos, and the respiratory cost for grazing by zooplankton are obtained from the literature. The inhibitory rate of chlorine on phytoplankton and zooplankton is obtained from the literature. The half saturation constants for phosphorus uptake from water (mg m$^{-3}$ day$^{-1}$) and the half saturation constant for solar radiance are obtained from the literature. The attenuation rate of chlorine and the inhibitory rate of chlorine to submerged macrophytes are obtained from the data from experiment 1. The daily maximum growth, mortality and respiration rates of aquatic species, and the attenuation coefficient caused by the self-population density, as well as the attenuation coefficients of phytoplankton and periphyton due to V. natans (Lour.) Hara, are obtained from data in experiment 2.

Experiment 1. To explore the inhibitory rates of chlorine to filamentous algae and submerged macrophytes, a co-culture experiment is performed with Spirogyra spp. and V. natans (Lour.) Hara at various initial concentrations of chlorine solution in the laboratory. The fresh weight of Spirogyra spp. and V. natans (Lour.) Hara is 10 g and 15 g, respectively, and the organisms are cultured in a container (18.0 $\times$ 12.0 $\times$ 6.5 cm) containing 750 mL....
of chlorine solution. The initial concentration of chlorine solution, obtained using sodium hypochlorite solution, is set to 100, 150, 200, 250 or 300 mg L\(^{-1}\). Each treatment has three replicates. The chlorophyll-a contents of *Spirogyra* spp. and *V. natans* (Lour.) Hara are measured at 24, 48, 72 and 96 h according to the acetone methods\(^{55}\). The concentration of chlorine is detected at 1, 2, 3, 6, 12, 18, 24, 48, 72 and 96 h according to standard methods\(^{56}\).

To understand the dependence between the initial concentration of chlorine solution (\(C_0\)) and attenuation rate (\(k\)), a regression analysis is used. In addition, the root mean square error-observations standard deviation ratio (RSR, equation 23) is used to evaluate the accuracy of the curve estimation in the regression analysis.

**Experiment 2.** To explore the model parameters of primary producers and consumers, the effects of submerged macrophytes and daphnia magna on lake eutrophication are investigated in the laboratory. White polyethylene

| Symbol | Description | Unit |
|--------|-------------|------|
| Ae     | Assimilation efficiency of zooplankton | day\(^{-1}\) |
| As     | Active layer of sediment | m |
| Biom(i) | Biomass density | |
| Biomphy | Biomass density of phytoplankton species |
| Biomsvm | Biomass density of *V. natans* (Lour.) Hara |
| Biomzoo | Biomass density of zooplankton species |
| Cc     | Concentration of chlorine | mg L\(^{-1}\) |
| D      | Depth of the lake | m |
| Dec    | Decomposition biomass rate of detritus | day\(^{-1}\) |
| Det    | Biomass density of detritus |
| Diff   | Diffusion of TP from the sediment |
| Dr     | Decomposition rate of detritus | day\(^{-1}\) |
| Drr    | Diffusion rate of phosphorus | day\(^{-1}\) |
| Grazing(i) | Biomass of the phytoplankton grazed upon by zooplankton |
| Grazing2 | Biomass density of detritus grazed upon by benthos |
| Growth(i) | Process of growth |
| I      | Species |
| Ib     | Ingestion rate of zooplankton | day\(^{-1}\) |
| Ik     | Half saturation constant for solar radiance | MJ m\(^{-2}\) day\(^{-1}\) |
| Ip     | Half saturation constant for phosphorus uptake from water | mg m\(^{-3}\) day\(^{-1}\) |
| Tk     | Temperature effect constant of species |
| Tkp    | Temperature effect constant for primary producers |
| Kcc    | Attenuation coefficients due to chlorine | day\(^{-1}\) |
| Kpz    | Half saturation constant of phytoplankton grazing for zooplankton |
| Maxg   | Maximum growth rates | day\(^{-1}\) |
| Maxm   | Maximum mortality rates | day\(^{-1}\) |
| Maxr   | Maximum respiration rates | day\(^{-1}\) |
| Mortality(i) | Process of mortality |
| Mortality1–5 | Mortality of *V. natans* (Lour.) Hara, phytoplankton, periphyton, zooplankton and benthos |
| Pw     | Total phosphorus concentration in water | mg L\(^{-1}\) |
| Ps     | Total phosphorus concentration in sediment | mg g\(^{-1}\) |
| Respiration(i) | Process of respiration |
| Rf     | Respiratory cost for grazing by zooplankton | day\(^{-1}\) |
| Settling1 | Settlement of phytoplankton |
| Settling2 | Settlement of detritus |
| Settling3 | Settlement of TP in water |
| Sr     | Solar radiance | MJ m\(^{-2}\) day\(^{-1}\) |
| Sk     | Attenuation coefficient due to self-population density | day\(^{-1}\) |
| Smk    | Attenuation coefficients due to *V. natans* (Lour.) Hara | day\(^{-1}\) |
| Ser    | Settling rate of phytoplankton | day\(^{-1}\) |
| Serd   | Settling rate of detritus | day\(^{-1}\) |
| Serp   | Settling rate of phosphorus in water | day\(^{-1}\) |
| T      | Temperature | °C |

**Table 5.** Summary of the symbols in the model.
Table 6. Summary of the equations in the model.

| Equations | Reference |
|----------|-----------|
| Biom(i) = growth(i) − mortality(i) − respiration(i) | (1) |
| Biom(i) = growth(i) − mortality(i) − settling(i) − grazing(i) | | (2) |
| Growth(i) = Maxg(i) × Biom(i) × \( \left( \frac{pw}{pw + ptr} \right)^n \) + Tk × (T − 20) × \( \exp \left( \frac{m}{m + d} \right) \) | | (3) |
| Growth(i) = Maxg(i) × Biom(i) × \( \left( \frac{pw}{pw + ptr} \right)^n \) + Tk × (T − 20) × \( \exp \left( \frac{m}{m + d} \right) \) | | (4) |
| Mortality(i) = Biom(i) × Maxm(i) × Tk × (T − 20) × \( \exp (kcc × cc + 1000) \) | | (5) |
| Respiration(i) = Tk × (T − 20) × Maxr(i) × Biom(i) | | (6) |
| Grazing(i) = Biom(i) × ae(i) × ib(i) × (Tk × (T − 20)) × \( 1 − rf \) × \( \frac{Biom(i) − 0.5}{Biom(i) + kpp(i)} \) | | (7) |
| Setting1 = \( \frac{settling1}{T^{1/2}} \) × Biom(i) | | (8) |
| Setting1 = \( \frac{settling2}{T^{1/2}} \) × det | | (9) |
| Setting2 = \( \frac{settling2}{T^{1/2}} \) × det | | (10) |
| Dec = detr × det × Tk × (T − 20) | | (11) |
| Pw = diff + dec − growth1 − growth2 − growth3 − settling3 | | (12) |
| Ps = settling1 × 0.002 + settling2 × 0.002 + settling3 + mortality5 × 0.0001 − diff | | (13) |
| Diff = dr × (ps − pw) × \( \frac{T}{T} \) | | (14) |
| Setting3 = \( \frac{diff}{T} \) × pw | | (15) |

barrels with a volume of 65 L and a bottom sediment layer of 8 cm are used as the experimental containers. Fifty liters of water with 0.2 mg L\(^{-1}\) TP is transferred into each container. Next, *Microcystis aeruginosa*, *Aphanizomenon flos-aquae*, and *Melosira granulata* (Ehr.) Ralfs a cell density of 3 × 10\(^{5}\) ind L\(^{-1}\) are transferred into each container to produce a micro-scale eutrophic shallow lake ecosystem. *M. aeruginosa*, *A. flos-aquae*, *M. granulata* (Ehr.) Ralfs and daphnia magna are obtained from the Institute of Hydrobiology, Chinese Academy Sciences, Wu Han, China. *Vallisneria natans* (Lour.) Hara is planted at a biomass density of 800 g m\(^{-2}\) to create one experimental group. The same density of *V. natans* (Lour.) Hara along with the large *Daphnia magna* are obtained from the Institute of Hydrobiology, Chinese Academy Sciences, Wu Han, China. The small and shallow lake with a surface area of approximately 8000 m\(^2\) and an average depth of 0.8 m. Guangzhou mainly has a classic marine subtropical monsoon climate, with an annual mean temperature of 21.5°C and
average rainfall of approximately 1736 mm. The submerged macrophyte, V. natans (Lour.) Hara is planted in January 2015 and covers the whole lake bottom by March 2015.

The study period of the field investigation is from March 15th to September 30th, 2015. The surface shape of the lake is rectangular and divided into four parts by two intersecting diagonals. Samples of water, phytoplankton, zooplankton and periphyton are collected weekly, and sediment, submerged macrophyte and benthos samples are collected monthly at five points: one point at the center of the lakes and four other points, each in the center of one of the four parts. All samples are held at 4°C in an insulating container and were taken back to the lab immediately.

Eutrophication in the lake appears repeatedly after May 10th, 2015. Exogenous pollutants are input into the lake on June 10th, resulting in an outbreak of eutrophication. To control eutrophication, 5000 g of calcium hypochlorite containing 30% chlorine (i.e. 0.188 mg/L chlorine), is applied to the lake on May 8th, 19th and 29th; June 4th; July 17th; and August 4th; and 1200 g of calcium hypochlorite containing 30% chlorine (i.e. 0.045 mg/L chlorine) is applied on August 28th. The daily concentration of chlorine in the water is calculated using the exponential equation and then averaged over one hour.

\[ C_i = C_0 \times \exp(k \times t) \]  
\[ C = \frac{1}{24} \times \sum_{i=1}^{24} C_i \]

where \( C_i \) is the concentration of chlorine at a specific time; \( C_0 \) is the initial concentration of chlorine, which was calculated from the applied amount of calcium hypochlorite that was applied; \( k \) is the attenuation rate; \( t \) is time (h); and \( C \) is the daily average concentration of chlorine.

The R, RSR and IOA values are calculated to assess the reliability and accuracy of the model. The RSR varies from 0 to a large positive value. A lower RSR indicates better simulation performance. The IOA is developed by Willmott60 and measures the degree of model simulation error in a range from 0 to 1. When this measure is close to 1, the measurement present high consistency. The detailed calculation formulas for R, RSR and IOA are shown in Equations 23, 24 and 25.

\[ R = \frac{\sum_{i=1}^{n}(y_i - \overline{y})(y_i' - \overline{y}')}{\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2 \sum_{i=1}^{n}(y_i' - \overline{y}'))} \]  
\[ RSR = \frac{\sqrt{\sum_{i=1}^{n}(y_i - y_i')^2}}{\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \]  
\[ IOA = 1 - \frac{\sum_{i=1}^{n}(y_i - y_i')^2}{\sum_{i=1}^{n}(y_i' - \overline{y}) + |y_i - \overline{y}|^2} \]

where \( y_i \) and \( y_i' \) are the observed and simulated values, respectively, and \( \overline{y} \) and \( \overline{y}' \) are their average values, respectively.

Data availability statement. The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author Contributions
Zhiqiang Yan, and Beicheng Xia designed the research. Zhiqiang Yan performed the experiments. Zhiqiang Yan, and Yafei Wang wrote the paper. Zhiqiang Yan, and Di Wu constructed the model.

Additional Information
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