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Determining the Optimal Biomass of Macrophytes during the Ecological Restoration Process of Eutrophic Shallow Lakes

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Abstract: Many studies have shown that macrophytes play a significant role in controlling eutrophication; however, only a few of these are based on macrophyte biomass. Based on the growth characteristic of macrophytes, we propose an approach for the assessment of the optimal biomass of macrophytes in the decay and growth periods in Lake Datong (a shallow lake), using a lake ecological model. The results showed that the pollution load of the lake should be reduced by 50% while conforming to the Environmental Quality Standards for Surface Water (EQSSW) Class III. In contrast, with an increase in the pollution load of 5%, the results indicate that the lake may deteriorate to a turbid state over the next few years. The macrophyte biomass should be harvested during the decay period, when 80% biomass is beneficial to the water quality of the eutrophic shallow lake. Based on macrophyte simulation from 2020–2024, the wet biomass of macrophytes should be controlled at 5.5 kg/m^2. The current macrophyte biomass in Lake Datong is four-fold higher than the simulated optimal biomass. This study provides a reference for the adequate ecological restoration of the lake and its subsequent maintenance, as well as scientific support for improving the comprehensive evaluation standard of healthy lakes and the theoretical basis of lake ecological restoration.

Keywords: shallow lake; macrophytes; optimal biomass; PCLake; Lake Datong; lake management

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1. Introduction

The restoration of macrophytes is an important link in the management and ecological restoration of eutrophic shallow lakes [1]. The success of long-term shallow lake restoration depends on the remediation of macrophytes [1,2]. Compared with deep-water lakes, shallow lakes usually have a higher ratio of the macrophyte growth area to the total lake surface area [1]. Macrophytes, as primary producers, are an important component of shallow lake ecosystems. They are one of the dominant factors affecting the structure of a lake ecosystem [3]. They occupy the key interface of lake ecosystems, greatly influencing water quality. They not only affect the composition and distribution of fish, plankton, and benthic animals in lakes, but can also eliminate waves and improve water quality [3–5]; they have an important impact on lake productivity and biogeochemical cycles [6]. In an aquatic ecosystem, macrophytes release allelochemicals into the water to inhibit phytoplankton growth [7–9]; directly absorb N and P from eutrophic water bodies for growth and reproduction [10–12]; remove nutrients from the water through the degradation and transformation of rhizosphere microorganisms [13–15]; and compete with phytoplankton for nutrients, light, and growth space, thus inhibiting phytoplankton growth [16–18]. The stable states in shallow lakes can be transformed from the turbid phytoplankton state to the clear macrophyte state [19–21], thus achieving water purification and water ecosystem restoration.

In the process of macrophyte restoration and maintenance in shallow lakes, the biomass of macrophytes is an important indicator affected by many factors. An excessive or insufficient biomass is detrimental to lake ecological restoration and water quality improvement. When the biomass is too high, macrophytes decay and decomposition can accelerate the swamping process, with consequent adverse effects on the ecosystem [22]. In summer, waters are characterized by macrophyte flourishment, resulting in a high level of photosynthesis, which leads to high CO_2 consumption in the water, causing the pH of the lake to rise suddenly and leading to subsequent fish mortality [22]. Conversely, if macrophytes are insufficient, the feeding needs of other aquatic animals cannot be met, and their nutritional competition and allelopathic effects on algae are not obvious; this leads to instability of the water ecosystem, reduced water self-purification ability, and erosion of the intensified littoral zone by wind waves [1]. Environmental problems caused by macrophytes in shallow lakes frequently occur, resulting in an increasing focus on the management of the macrophyte biomass. The development of a scientific evaluation method and analysis of the main influencing factors and mechanisms of macrophyte biomass are urgently required to provide a scientific basis for ecological restoration projects and subsequent ecosystem maintenance.

The identification of the target macrophyte biomass when ecologically restoring eutrophic shallow lakes usually includes the three following methods: the historical maximum method, maximum holding value of the lake, and food web model evaluation. However, these methods have certain drawbacks [22]. No current method can comprehensively determine the optimal macrophyte biomass of shallow lakes for ecological restoration. The PCLake model was developed by Dutch lake and marsh ecological modelers—that is, the Janse team. The model not only comprehensively considers the basic elements of a shallow lake ecosystem, but also has a wetland module for emergent macrophyte growth [23,24]. It is a widely used model in lake-water ecosystem research [23] and has been applied to climate change research [25,26], lake carbon input [27], biodiversity research [28,29], and watershed management [30]. It has also been used to amplify specific components of ecosystems (e.g., the effects of herbivores) [26], and in the management of surface water ecological restoration, because it can predict multiple environmental factors. PCLake has become an important tool for simulating the effects of various measures on the restoration and eutrophication control of shallow lakes [30].

The aims of this study are to (1) develop an optimal biomass assessment method for macrophytes in shallow lakes during growth and decline phases based on field investigations, indoor experiments, and the PCLake model; (2) evaluate the optimal macrophyte biomass in the growth and decay periods considering Lake Datong as the case study, and determine the macrophyte harvest time; and (3) provide a practical reference for the maintenance and management of macrophytes during the growth, harvest, and decay periods.

2. Materials and Methods

2.1. Study Area

The study area is Lake Datong, Hunan Province, China (Figure 1), which is the largest inland lake in Hunan Province [31]. In the early 1950s, the original area of Lake Datong was 313.4 km^2. After continuous reclamation, the lake surface gradually shrank, such that the current lake area is 82.67 km^2. The east-west and north-south diameters of Lake Datong are 15.75 and 13.70 km, respectively. The water level is 28.8 m, the average water depth is 2.58 m, and the maximum water depth is 2.94 m. The lake area has a humid monsoon climate from mid-subtropical to north subtropical, with an average annual temperature of 16.6 °C. The annual precipitation is 1237.7 mm, of which approximately 68% occurs during April to September. Datong Lake belongs to the Lake Dongting water system, and the water mainly relies on lake precipitation and surface runoff for replenishment. Three main channels are connected to Lake Datong: Daxin River, Laohe River (the intersection of Laosan and Saiyang Canals), and Wuqi Canal. The remaining ditches are connected to surrounding rivers and eventually lead to Lake Datong. The elevation of Lake Datong is lower than that of the surrounding areas, such that the water systems and ditches in the basin are connected; the lake area is thus a "sink" of non-point-source pollution. Relying on electric gates to control drainage, the hydrodynamic conditions of the lake are poor. Moreover, aquaculture activities have seriously degraded the water ecosystem of Datong Lake [32].

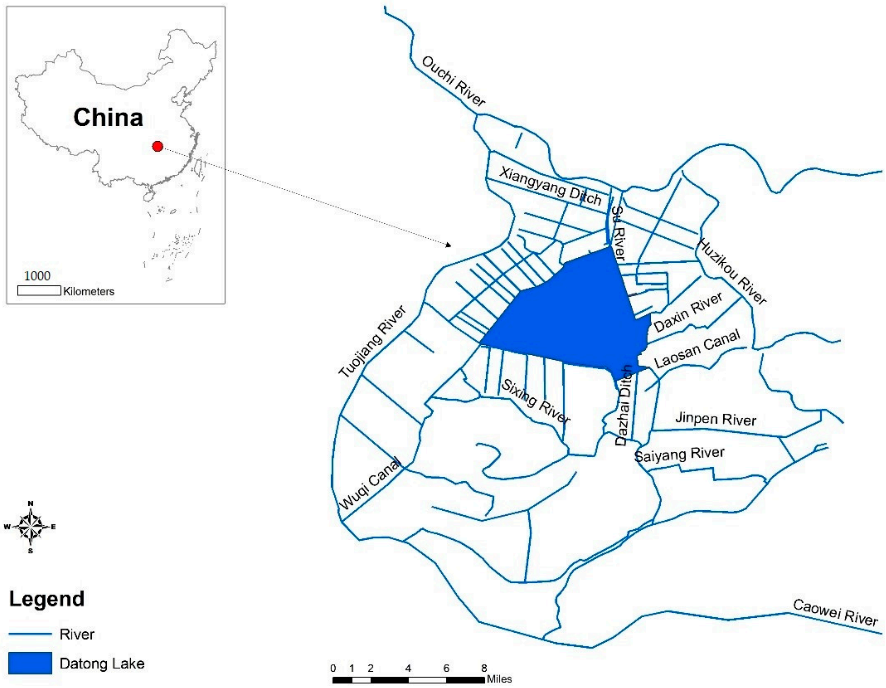


Figure 1. Location of the study area.

According to the Environmental Quality Standards for Surface Water (EQSSW) (Table 1), the water quality of Lake Datong was rated as inferior to Class V. The main pollutants that exceeded the standards were the total phosphorus (TP) and total nitrogen (TN). Water pollution is an important issue for the Ministry of Ecology and Environment of the People's Republic of China, and has become a key target of China's Water Pollution Control Action Plan. Comprehensive management was implemented at the end of 2017 when the local government launched the macrophyte restoration project of Lake Datong, which involved the planting of macrophytes and improvements to the water quality. By the end of December 2018, the macrophyte coverage of Lake Datong had reached 10–15%. In 2019, the local government continued to build on its previous achievements in terms of macrophyte planting and restoration. By the end of 2019, the macrophyte coverage of Lake Datong had been restored to 30%.

Table 1. Environmental Quality Standards for Surface Water (EQSSW) nutrient water quality standard of China (unit: mg/L). TN: total nitrogen; TP: total phosphorous.

Rank	Parameters	I	II	III	IV	V
1	NH_4^+-N	0.15	0.5	1	1.5	2
2	TN	0.2	0.5	1	1.5	2
3	TP	0.02	0.1	0.2	0.3	0.4
		(0.01/lake and reservoir)	(0.025/lake and reservoir)	(0.05/lake and reservoir)	(0.1/lake and reservoir)	(0.2/lake and reservoir)

2.2. Research Roadmap

Figure 2 shows the research roadmap for determining the optimal biomass of aquatic macrophytes in shallow lakes. This included the following steps:

(I) Basic data for the target lake were collected and investigated; values for important state variables in the PCLake model were selected.

(II) The optimal macrophyte biomass in shallow lakes at the initial stage of decline was determined via laboratory simulation. Based on field investigations, we determined the actual macrophyte biomass. We did not consider the various ecological effects caused by macrophyte biomass, only the factors affecting the habitat.

(III) The optimal biomass assessment of macrophytes in shallow lakes during the growth period was evaluated by the PCLake model. Here, we combined the PCLake model and indoor experiments to determine the appropriate biomass of macrophytes in the growth and early decline stages based on the following steps:

(i) Preliminary estimation of the optimal biomass range for the macrophyte growth period in shallow lakes using the PCLake model. When using the PCLake model to analyze the optimal macrophyte biomass, we employed water quality parameters as the final output value and the macrophyte biomass for a horizontal comparison. Corrections were performed after steps (ii) and (iii); therefore, the results in this section are only preliminary estimates of the optimal macrophyte biomass during the growth period.

(ii) Second estimation of the optimal macrophyte biomass in the shallow lake. We compared the initial estimate and the actual allowable macrophyte biomass under existing habitat conditions. If this reached the optimal biomass required under the water quality target, the existing habitat conditions could meet the requirements for macrophyte restoration under the water quality target. If the requirements were not met, environmental protection measures were taken to improve the habitat conditions, expand the macrophyte biomass, and then a second model estimation was performed. After the above improvements, the new parameters were re-input into the PCLake model for calculation, and the optimal biomass range for the second calculation period was obtained.

(iii) The optimal macrophyte biomass in shallow lakes at the initial stage of decline was determined via laboratory simulation.

(iv) Final determination of the optimal biomass for the growth period of macrophytes in the shallow lake's final optimal biomass, which is the growth period of the macrophytes in Lake Datong.

2.3. Data Collection

Meteorological data were obtained from the China Meteorological Data Network (http://data.cma.cn (accessed on 18 April 2020)). We selected the following meteorological data: annual average temperature, precipitation, and wind speed at Nanxian station, Yiyang City. Water quality data were collected from the center of the lake (national control point) and from rivers entering the lake from 2018 to 2019 (provided by the Ecological Environment Bureau of Yiyang City). Aquatic organisms data were based on a survey carried out in 2019 by our research group. To collect phytoplankton in the water, a one liter sample of the water was taken and 15 mL Lugol's solution was added. After sedimentation for 48 h, a concentrated liquid sample was collected and preserved with 5% formalin. To determine phytoplankton, 50 mL residue was collected after removing the supernatant [33,34]. For zooplankton determination, 20 L of the sampled water was collected using a No. 25 plankton net (pore size, 64 μm). The concentrated samples were placed in 50 mL bottles fixed in 4% formaldehyde solution and transported to the laboratory in plastic bottles [35]. Phytoplankton and zooplankton were counted in a 0.1 mL counting chamber (20 mm × 20 mm) using a microscope at a magnification of 400. Benthic organisms were collected using mud samplers, were washed over 0.5 mm screens and fixed in 75% ethanol solution, and transported to the laboratory in plastic bottles. The fish resource survey adopted separate collection points. This is the traditional fishing method using a gillnet and ground cage, where individuals survey the lake using fishing boats to count fish species. The molluscan resource survey was conducted using Peterson mud samplers. Macrophytes were collected using a self-made sampler. Water quality parameters and sediment TP were analyzed according to the Practical Manual of Environmental Monitoring Method Standards of China [36]. For all incoming or outgoing rivers, we recorded the river flow (using an acoustic Doppler flow meter; Link Quest ADCP; flow Quest 2000-AFA-BC, San Diego, CA, USA). These small river sampling sites are indicated by the yellow dots in Figure 3. For the model, we used the RAND function in Microsoft Excel to randomly assign the parameter value range.

2.4. Laboratory Experiment

We carried out indoor experiments to determine the impact of macrophytes on water quality. The experimental group assumed a certain percentage for the remaining macrophyte biomass after harvesting (for the macrophyte biomass calculation, if the biomass was set to 40%, the remaining biomass after harvesting would be 60%). We set up six different experimental groups (i.e., 0%, 20%, 40%, 60%, 80%, and 100%). As harvesting in the wild mainly removes only the stems and leaves of the macrophyte, the macrophyte roots were left in place in this study. Therefore, when adding biomass, roots of the same quality were placed at the mud-water interface of each test group, with three parallel samples in each group (Figure 4). The test was carried out from 25 December 2018 to 25 May 2019, for a period of 150 days. We collected water and sediment samples every 10 and 30 days, respectively, and recorded the changes in the morphology of each macrophyte during the decomposition process. The TN and TP concentrations were analyzed following the Practical Manual of Environmental Monitoring Method Standards of China [36].

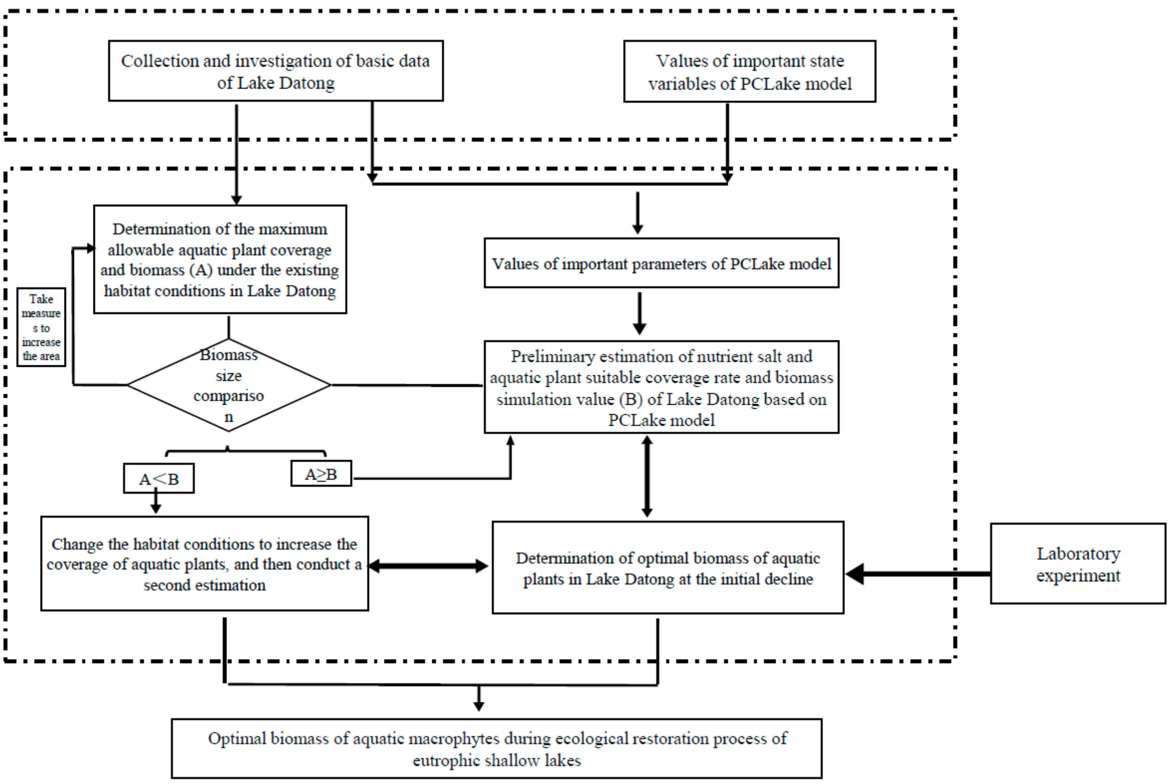


Figure 2. Roadmap of research.

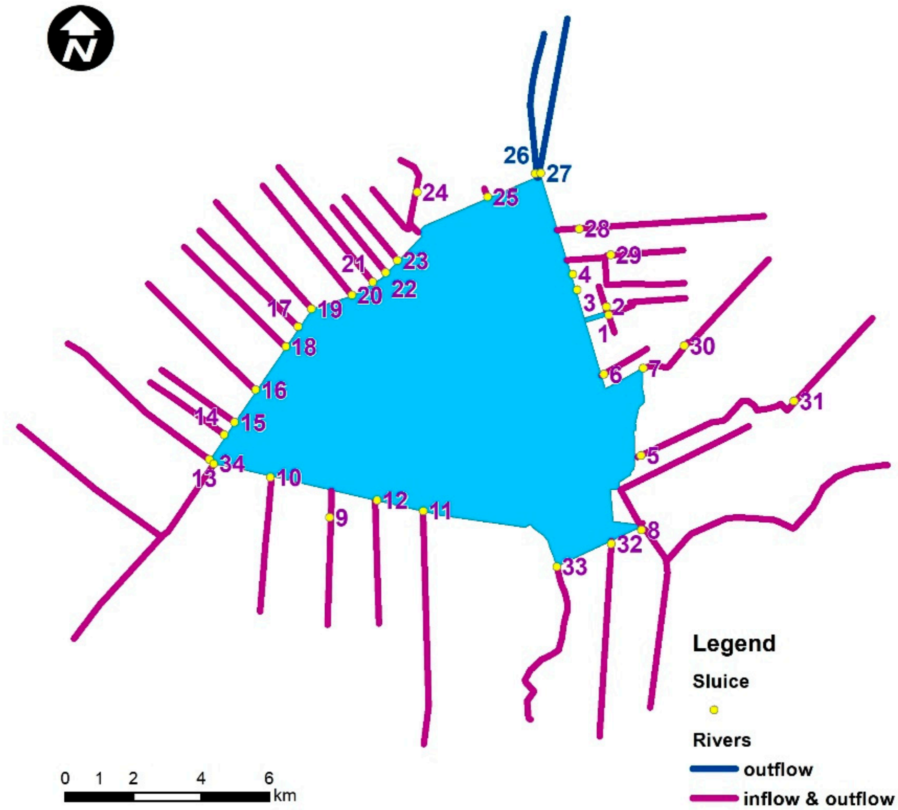


Figure 3. Map of the rivers entering (sampling sited denoted by yellow dots) Lake Datong (through electric gates), as well as the outflow (violet) and bidirectional flow (navy blue). The bidirectional flow of the river indicates that precipitation depends on the alternating in- and outflow of river water.

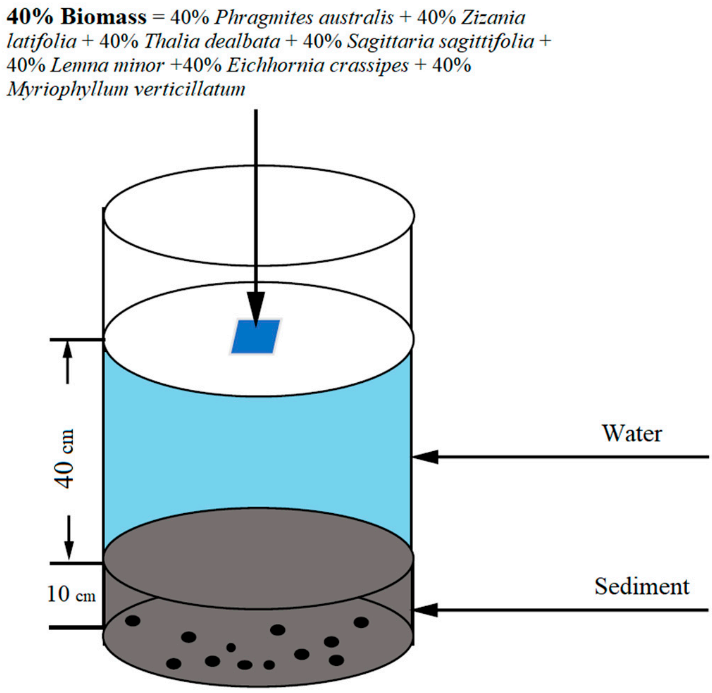


Figure 4. Amount of macrophytes used in the experiments (taking 40% biomass as an example).

2.5. PCLake Model

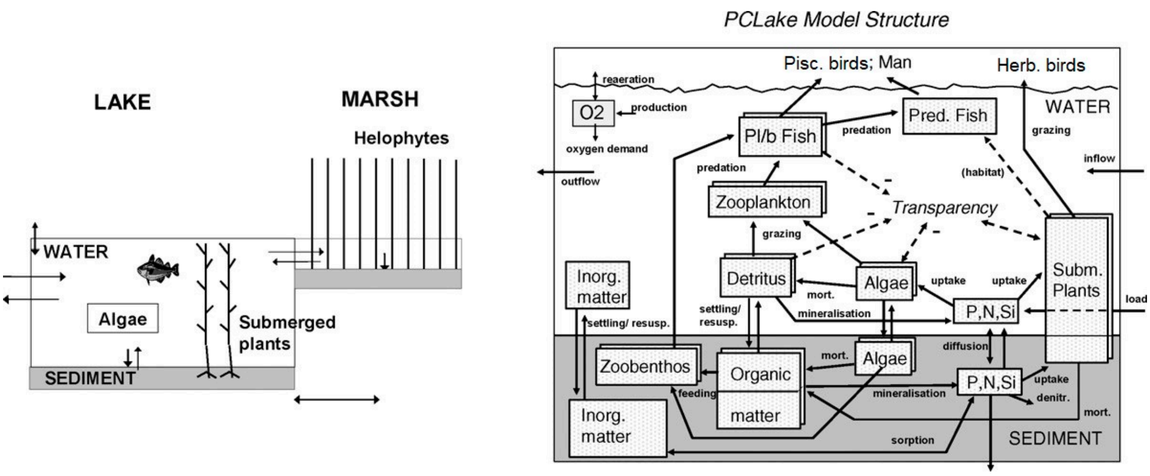
The PCLake model not only comprehensively simulates the basic elements of shallow lake aquatic ecosystems, but also contains a lakeside wetland module (Figure 5). This model is specifically designed for pollutant control in shallow lake water as well as steady-state transition prediction. The model does not consider horizontal or vertical changes in shallow lakes; rather, it assumes that these lakes are homogeneous and well-mixed (i.e., non-stratified). Therefore, the PCLake model is only applicable to shallow lakes [37]; it is more targeted and professional than other lake-water ecological models, especially for shallow lakes. The PCLake model has been calibrated and verified for 43 lakes across the Netherlands, Belgium, Ireland, and Poland [23]. PCLake comprises many coupled ordinary differential equations for mineralization, nitrification, denitrification, phosphorus absorption, nutrient exchange, and phytoplankton and debris sedimentation, among others.

Due to the responses of the lake conditions and models to different environmental conditions, there are variations in the number of sensitive parameters. In this study, we adjusted the PCLake model in accordance with the monitoring data by changing the state variable parameters of some models to fit the modeling purpose of evaluating the optimal biomass of Lake Datong. We considered the results of previous studies to determine the highly sensitive parameters in terms of the actual circumstances in the study area and focused on the parameters described below (Table 2). We expanded the normal version of the PCLake model to allow for random parameter value collection and execution. These modifications were implemented in the model described by Mooij et al. [30].

Table 2. Parameter calibration table. Chl-*a*: chlorophyll *a*; DOMW: Total organic matter dry weight; DW: Dry weight; TN: total nitrogen; TP: total phosphorus; Veg: vegetation. An X under sensitivity allocation denotes if the parameter was identified as sensitive for the given water quality variable according to the 90th percentile criteria. Sensitivity illustrates the summarized and ranked normalized sensitivity for each parameter across all water quality variables. **** and *** indicate high sensitivity.

ID	Parameter	Unit	Description	Sensitivity Allocation				Sensitivity
				Chl-*a*	TN	TP	Veg	
237	cDayWinVeg	-	End of growing season	X	X	X	X	***
354	cDCarrBent	-	Carrying capacity of zoobenthos	X	X	X	X	***
340	cFiltMax	L mg/(DM d)	Maximum filtering rate (when DOMW = 0)	X	X	X	X	****
304	cMuMaxBlue	d^{-1}	Maximum growth rate of bluegreens	X	X	X	X	***
229	cMuMaxVeg	d^{-1}	Maximum growth rate of vegetation at 20 °C	X	X	X	X	****
346	cPrefDet	-	Selection factor for detritus	X	X	X	X	***
230	cQ10PodVeg	-	Temperature quotient of production	X	X	X	X	***
234	cQ10RspVeg	-	Temperature quotient of respiration	X	X	X	X	***
370	cSigTmFish	°C	Temperature constant of fish (sigma in Gaussian curve)	X	X	X	X	***
353	cSigTmZoo	°C	Temperature constant of zooplankton (sigma in Gaussian curve)	X	X	X	X	****
171	cThetaMinS	-	Exponential temperature constant of sediment mineralization	X	X	X	X	****
167	cThetaMinW	-	Exponential temperature constant of mineralization in water	X	X	X	X	****
352	cTmOptZoo	°C	Optimum temperature of zooplankton	X	X	X	X	****
347	fDAssZoo	-	DW-assimilation efficiency of herb. zooplankton	X	X	X	X	****
218	fRotVegWin	g	Root fraction outside growing season	X	X	X	X	***
341	hFilt	mg DM/L	Half-saturated food concentration for filtering	X	X	X	X	****
231	hLRefVeg	W/m^2	Half-saturated light at 20 °C	X	X	X	X	***
380	kDAssFiAd	d^{-1}	Maximum assimilation rate of adult fish	X	X	X	X	***
231	kDRespVeg	d^{-1}	Dark respiration rate of vegetation	X	X	X	X	***

In addition, the model scenario provides important insights into key drivers and reveals possible changes in lakes in the future. Here, we designed five nutrient content scenarios (current load: monitor data in 2019; increase in current load by 5%; and reduce current load by 10%, 20%, and 50%). These are five simulation scenarios that were considered for investigating the influence of reductions in the nutrient load on the water quality and macrophyte biomass.



(**a**) (**b**)

Figure 5. Illustration of the PCLake model. (**a**) Diagram of the lake structure and (**b**) schematic model structure. Solid lines indicate material flow and dashed lines indicate a functional relationship. Negative and positive signs indicate decreased and increased transparency, respectively. The abbreviations are as follows: denitr., denitrification; Herb. birds, herbivorous birds; Inorg. matter, inorganic matter; mort., natural mortality; Pisc. birds, predatory birds; Pl/b Fish, Piscivorous fish and benthivorous fish; Pred. Fish, predatory fish; resusp., resuspension; and Subm. plants, submerged plants. Modified from Janse [23].

3. Results

3.1. Model Calibration and Verification

Calibrating a set of parameters is time-consuming and complex. The default value of each calibration parameter in the calibration parameter set was changed by ±20% to avoid the mutual interference of parameters. By running random parameter sets, the corresponding parameter value in the best-fitting zone was finally determined as the calibration parameter value, followed by the verification of the model calibration result. Figure 6 presents this result, which shows the measured water quality values and model simulation results. The predicted model value was similar to the actual measured value. Although certain differences existed, all errors were within acceptable limits. The measured TP value was similar to the simulated concentration value. Within its range, the trend varied only slightly, and the concentration difference was only 0.2 mg/L. The measured TN value was also similar to the simulated concentration value. In January and December, the concentration ranged from 0.10 to 0.14 mg/L, where the trend between the two datasets was similar. Certain differences occurred in the simulated and measured values of the NH_4^+-N concentration. However, the difference in the density was small. The curves showed similar trends, where the maximum concentrations were similar. Finally, the simulated Chl-*a* concentrations were similar to the measured values. Figure 6 shows the model validation results. Analog data were suitable as measurement data. The root mean square errors for Chl-*a*, TN, TP, and NH_4^+-N were 5.47, 0.47, 0.11, and 0.007 mg/L, respectively.

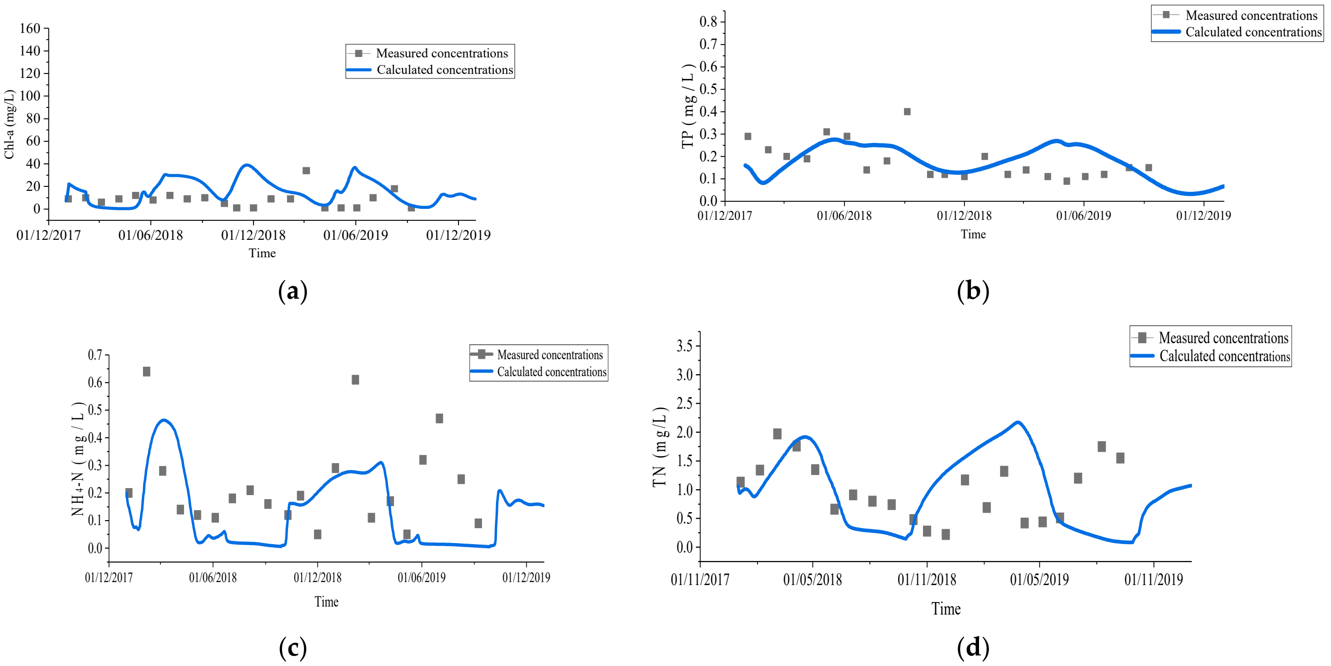
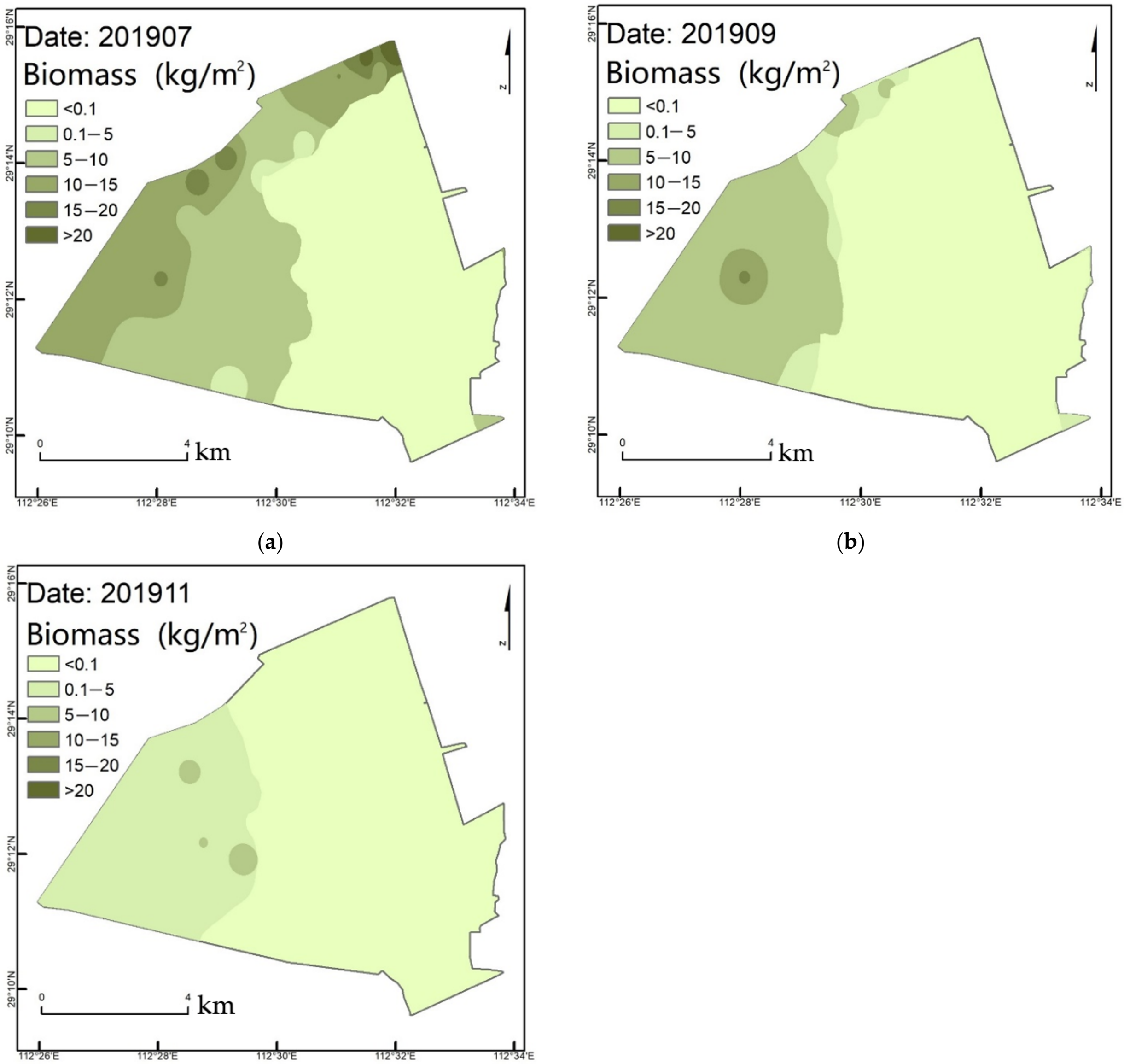


Figure 6. Calibration results for the simulated (blue lines) and measured (brown squares) values of the water quality parameters in Lake Datong: (**a**) chlorophyll *a* (Chl-*a*), (**b**) total phosphorus (TP), (**c**) ammonium nitrogen ($NH_4{}^+$-N), and (**d**) total nitrogen (TN).

However, in the second half of 2019, the data differed significantly. This significant difference in the data may have been caused by macrophyte decline and decomposition in the second half of 2019. The survey results in 2019 (Figure 7) demonstrated that macrophytes were mainly distributed in the western part of Lake Datong. In July, the macrophytes were distributed over an area of 39.67 km^2, which amounts to 48% of the total water surface area of Lake Datong. In September they were distributed over an area of 27.2 km^2 and they were spread over 23.99 km^2 in November, respectively amounting to 33% and 29% of the total water surface area of Lake Datong. The range of macrophyte distribution gradually decreased from July to November.

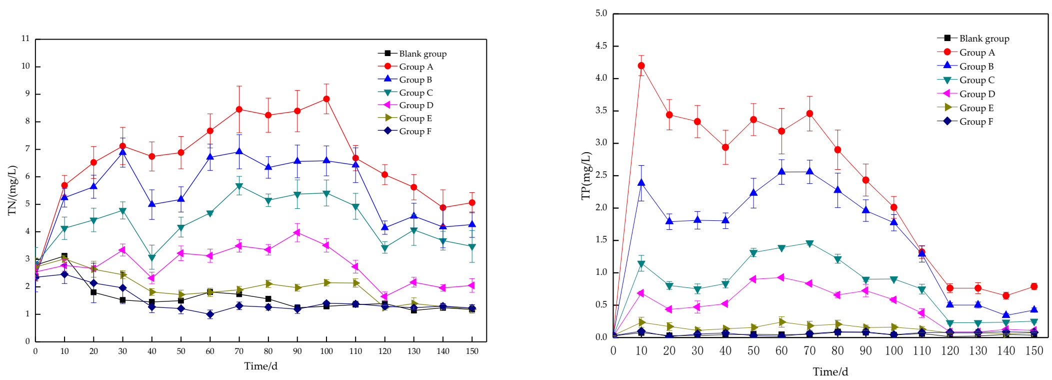
3.2. Optimal Biomass for Decay Period

Macrophyte decomposition releases nutrients into the water, altering their concentration in the water. Figure 8 shows changes in the nutrient concentrations in the water; ρ(TN) increased rapidly within 0–30 d in experimental groups A, B, C and D. In groups B, C, and D, ρ(TN) decreased rapidly compared with that in group A within 30–40 days, peaked at approximately 70 days, and slowly became stable after 100 days. The end states ρ(TN) of groups A, B, C, and D were (5.06 $\pm$ 0.37), (4.26 $\pm$ 0.46), (3.57 $\pm$ 0.58), and (2.05 $\pm$ 0.25) mg/L, respectively (Figure 9). Compared with the control group, experimental group E increased in the first 10 days of the initial experiment, gradually decreased within 10–40 days, and then slowly increased to approximately day 80 to reach its maximum. Group E was relatively stable and remained unchanged within 80–110 days. During this period, ρ(TN) was (2.09 $\pm$ 0.12) mg/L, which gradually decreased and stabilized after 110 days at 1.24 mg/L. Compared with the control group, the change in experiment group F was not notable in the middle of the experiment. It increased slowly within 90–120 days and then gradually decreased to stability; ρ(TN) was 1.27 mg/L.



(**a**) (**b**) (**c**)

Figure 7. Biomass distribution of the macrophytes throughout Lake Datong.



(**a**) (**b**)

Figure 8. Changes in the nutrient concentrations in water during the macrophyte decay period with time: (**a**) TN and (**b**) TP.

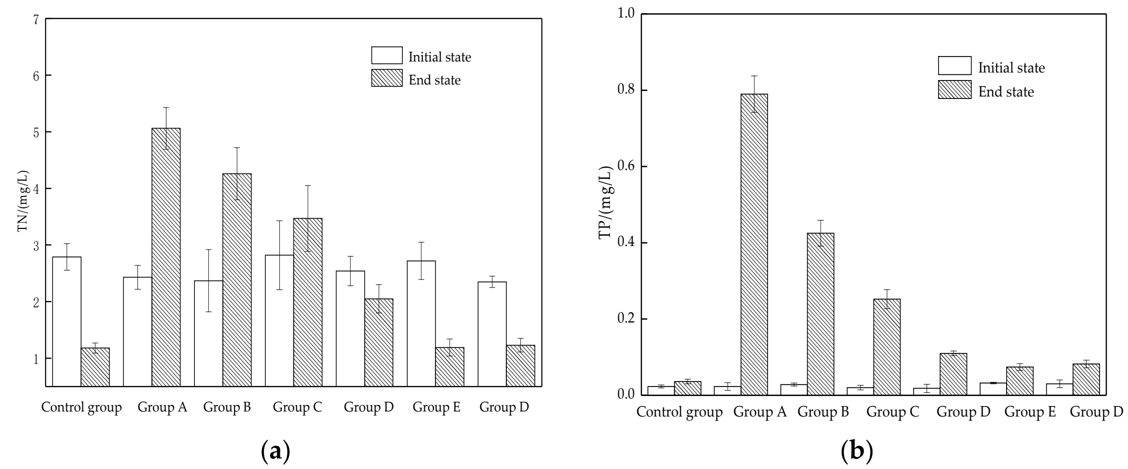


Figure 9. Changes in the nutrient concentrations in water at the initial and end state of the macrophyte decay period: (**a**) TN and (**b**) TP.

The changing trends of ρ(TP) in experimental groups A, B, C, D, and E were similar throughout the macrophyte decomposition process (Figure 8). ρ(TP) increased rapidly at the initial stage of the experiment, decreased to stability within 10–40 days, and increased to its peak again within 40–70 days. The peak ρ(TP) of each group was lower than that on day 10 in the initial stage of the experiment; the increase in the speed was slower and slowly decreased to stability after 70 days. At the end state of the experiment, the ρ(TP) values of groups A–E were (0.734 $\pm$ 0.08), (0.424 $\pm$ 0.083), (0.24 $\pm$ 0.013), (0.107 $\pm$ 0.019), and (0.067 $\pm$ 0.009) mg/L, respectively, representing respective increases of 32, 15, 10, 4.7, and 3 times compared with the values in the initial state (Figure 9). Compared with the control group, group F did not change significantly during the entire experimental period. ρ(TP) increased slightly, indicating that macrophyte roots also decomposed and had an impact on the water quality.

At the same time, as shown in Figure 9, 20% macrophyte biomass was found to be more beneficial to water purification in winter and spring than full harvesting. The optimal macrophyte biomass can inhibit the release of nutrients in the sediment and provide nutrients for macrophyte growth in the next growth phase.

3.3. Scenario Simulation

Using the PCLake model, we simulated 10%, 20%, and 50% reductions in the nutrient load, as well as a 5% increase in the nutrient load, and analyzed the impact of these measures on the water quality of Lake Datong. We also simulated the nutrient concentration changes in Lake Datong under different pollution load scenarios. Increasing the nutrient load in the lake significantly increased the TP, TN, NH_4^+-N, and Chl-*a* concentrations over time (Figure 10). This shows that Lake Datong was in an unstable state in 2019, requiring management to prevent water quality deterioration caused by an increase in the pollution load.

Reducing the nutrient load in Lake Datong by 10%, 20%, and 50% decreased the NH_4^+-N content by 45.42%, 55.52%, and 77.73%, respectively, over the next five years. The annual trend was consistent with that of the original input. The nutrient load increased sharply from the macrophyte decay period (autumn and winter) to the following spring, after which a slow decline occurred. Similarly, reducing the nutrient load by 10%, 20%, and 50% decreased the average TP content of the lake by 33.32%, 55.24%, and 81.11%; the macrophytes biomass by 36.55%, 37.27%, and 35.29%; the TN content by 36.72%, 51.05%, and 73.94%; and the Chl-*a* content by 38.87%, 53.12%, and 80.85%, respectively, over the next five years. Large differences in the TP, TN, NH_4^+-N, Chl-*a*, and macrophytes biomass existed only when the nutrient reduction rate was 10%; these differences were negligible when the reduction rate was 20% or 50%.

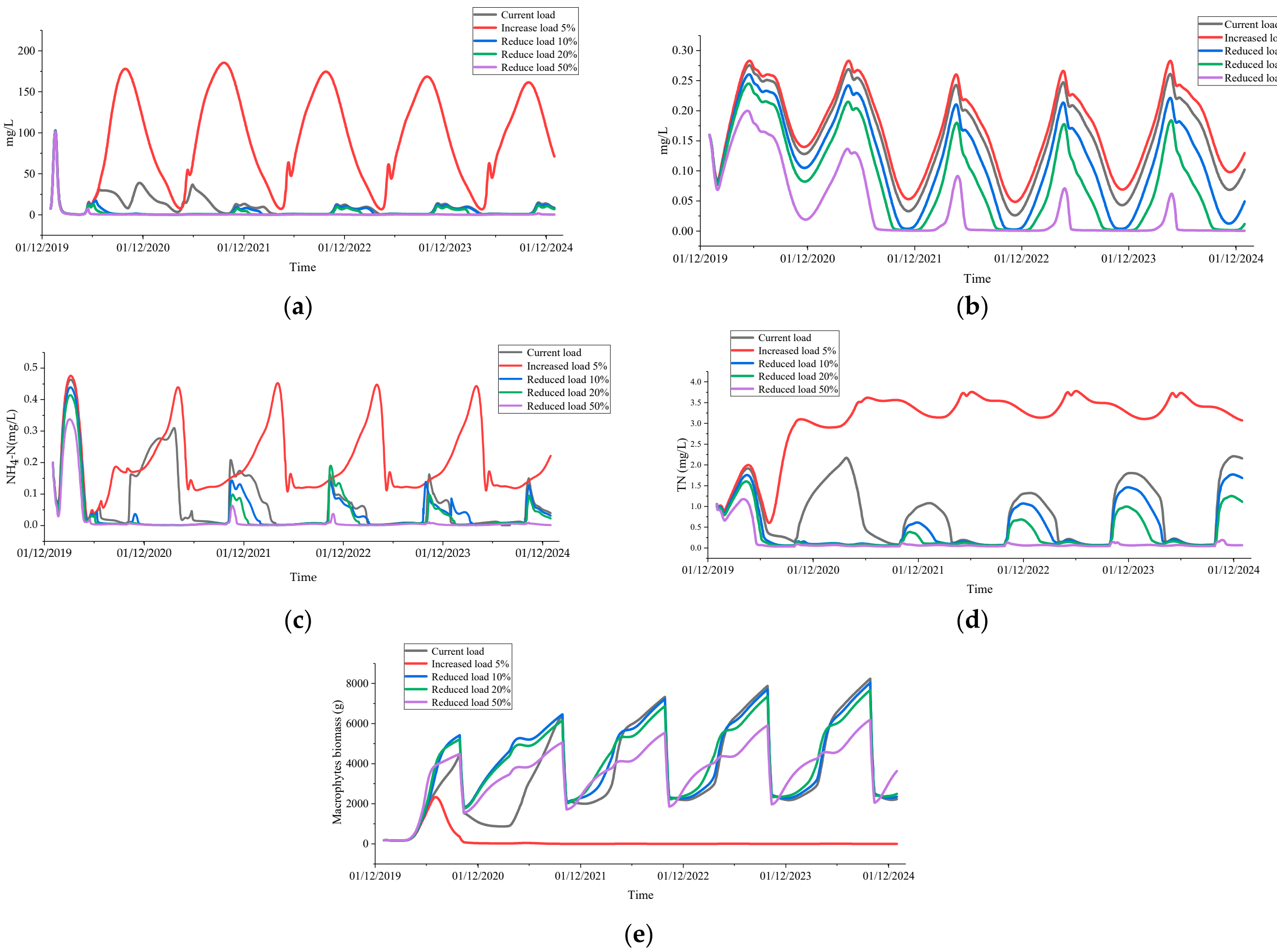


Figure 10. Simulations of decreasing and increasing nutrient loading in Lake Datong at the current load (brown lines), a 5% increased load (red lines), a 10% reduced load (blue lines), a 20% reduced load (green lines), and a 50% reduced load (purple lines) for the following factors: (**a**) chlorophyll *a* (Chl-*a*), (**b**) total phosphorus (TP), (**c**) ammonium nitrogen ($NH4^+$-N), (**d**) total nitrogen (TN), and (**e**) macrophytes biomass.

The simulation results showed that if the pollution load in Lake Datong was reduced by 20%, the TP content could reach <0.1 mg/L, satisfying EQSSW Class III. If the pollution load was reduced by 50%, the TP content could reach levels below 0.05 mg/L. The water quality met the EQSSW Class III only during the spring-summer transition, and so efforts to reduce the nutrient load in the lake should be concentrated during this period. To ensure that the EQSSW Class III standard can be maintained throughout the year, our simulations suggest that the optimal macrophyte biomass (wet weight) in summer is 5.5 kg/m^2.

4. Discussion

The PCLake model can be a useful tool to improve our understanding of the dynamic relationships among water quality, nutrients, and macrophytes. Here, we showed that the PCLake model could sufficiently predict the restoration and water quality of Lake Datong. Continual monitoring of the water level changes and full consideration of the spatial heterogeneity could significantly enhance the accuracy of the simulation. Therefore, through collaborations between modelers and field researchers, high-quality results can be obtained, which would enable lake managers to respond to changes in lake systems and environmental factors.

4.1. Modeling Process

Due to the non-linear and complex causal mechanisms of shallow lake-water ecosystems, simple models cannot accurately assess a system's response to changes in external conditions [38–40]. The PCLake model has a high prediction accuracy, can simulate complex aquatic ecosystems, and has developed into a comprehensive model of aquatic ecology. This model is suitable only for shallow lakes, and is more targeted and professional than other lake-water ecological models.

The PCLake model considers the abiotic and biological components of an aquatic ecosystem [23]. The abiotic components comprise the exchange of organic and inorganic substances between sediments and water, including precipitation, resuspension, adsorption, diffusion, and burial. The biological components include phytoplankton, benthic animals, herbivorous fish, and predatory fish. Phytoplankton and macrophytes are primary producers [23]. The model can also include a lakeside wetland module composed of another 42 state variables and 35 parameters [41]. It has a flexible structure, where each sub-module can be split, and it can be flexibly selected and used in combination with other applications in real-life scenarios. For example, Janse [23] combined the lake and lakeside wetland modules to simulate the impact that swamps have on lake restoration, revealing that the presence of lakeside wetlands can enhance restoration.

4.2. Nutrient Input

Pollutants can enter Lake Datong through three paths: (1) river flow into the lake, (2) wet and dry sedimentation, and (3) sediments or macrophytes. For the first path, field investigations have revealed that Lake Datong has a culvert gate control at its estuary to control flood storage, irrigation, shipping, and breeding. Authorities have constructed a total of 33 electric gates to control river flow into the lake. Except for rivers numbered 26 and 27 (violet), all gates (navy blue) are bidirectional, as shown in Figure 3. During high water withdrawal periods (e.g., during farmland irrigation), the water levels of the rivers flowing into Lake Datong are high. Therefore, the concentrations of pollutants entering the lake via the rivers differ periodically. For example, TN showed regular fluctuations, which correlated with the pollution load of the lake. When the pollution load peaked in March and September, the TN levels in Lake Datong also peaked, reflecting two periods of high water or withdrawal period for activities such as farmland irrigation. Consequently, the pollutants in Lake Datong varied significantly between the high- and low-water periods.

Pollution sources in the lake differ during summer and winter months; during the former, large amounts of pollutants from external sources enter the lake, while during the latter, pollution from the internal sources is predominant. A large amount of external pollution enters the lake during the summer period; the internal pollution source of the lake is therefore mainly active in the winter period. The TN and TP levels in Lake Datong were high from July to August 2019, which was a high water and withdrawal period for activities such as farmland irrigation, causing nitrogen and phosphorus to accumulate in the rivers that flow into the lake. Moreover, macrophytes growth was dense and the lake-water temperature was higher in summer, which accelerated the decomposition of macrophyte matter. The nutrients absorbed during macrophytes growth were thus released back into the lake, causing secondary pollution. This may also be the reason for the significant data diversity in the second half of 2019.

The distribution of macrophytes in Lake Datong is uneven, with that in the southwest being dense and that in the eastern bank being sparse. During periods of vigorous macrophyte growth, the area with no biomass was 40.33 km^2, while areas with biomass values of 5–10, 10–15, 15–20, and >20 kg/m^2 were 21.83, 14.64, 1.36, and 0.38 km^2, respectively (Figure 7). Model simulations showed that the maximum amount of macrophytes per unit of Lake Datong was more than four-fold the appropriate biomass (Figure 10e). If the macrophytes are not managed through harvesting, they can die and decompose, releasing the nutrients absorbed during macrophytes growth back into the lake, thereby becoming a new pollution source. Finally, *Chlidonias hybrida* is the most common bird species in Lake

Datong in summer, with a population of more than 30,000 birds. This species lives on the lake surface and its waste enters the water, decreasing the water quality.

In summary, Lake Datong is significantly affected by water exchange from farming ponds and agricultural tailwater. The pollution load of the lake varies greatly throughout the year, where pollutants are discharged into it over short periods (spring and summer), rendering its ecosystem vulnerable to deterioration.

4.3. Macrophytes Biomass Management

Macrophytes are important primary producers in an aquatic ecosystem. They provide a nutrition basis and a habitat for other aquatic animals, and serve as a foundation for the development of a complex aquatic ecosystem. In the early stage of ecosystem restoration, macrophytes, as pioneer species, can accelerate the succession of the ecosystem and maintain its biodiversity and stability. However, based on our simulations, the unit macrophytes biomass of Lake Datong was the maximum value investigated, which exceeded the optimal biomass by more than four-fold. According to the simulation experiment for the nutrient release process, the concentrations of TN, TP, NH_4^+-N, and NO_3-N in the overlying water increased rapidly to a maximum within 0–30 days after the death of the macrophytes. Therefore, harvesting should be conducted after the withering or slow growing period of macrophytes to avoid secondary pollution caused by the decomposition of macrophytes. The harvest rate of macrophytes should be 80%. To reduce the biomass of submerged macrophytes, management strategies can be established to reduce the energy flow and nutrient cycle in the Lake Datong ecosystem.

5. Conclusions

The PCLake model could accurately simulate the dynamic changes in nutrients in Lake Datong under scenarios with different levels of nutrient loads. Increasing the nutrient load in the lake increased the TP, TN, NH_4^+-N, and Chl-*a* concentrations in the water, which will continue to increase with time. Current management strategies in the lake basin should be improved to prevent the further deterioration of the water quality of Lake Datong. Based on macrophyte simulations from 2020 to 2024, the biomass value (wet weight) of macrophytes should be controlled at 5.5 kg/m^2. The current macrophytes biomass in Lake Datong is four times higher than the simulated optimum biomass. During the decline period, macrophytes should be harvested at a rate of 80%. Moreover, when macrophyte biomass becomes excessive, macrophytes decay, causing the release of nutrients into the water and adding to the water pollution load. Thus, this situation should be avoided when aiming to maintain water quality.

These results are invaluable to shallow lake managers and local stakeholders, and can be used to support management, planning, and strategic decisions regarding similar shallow lakes globally. When managing eutrophic shallow lakes, we should consider taking steps to regulate the levels of pollutants entering the lake. Furthermore, the impact of the nutrients released during macrophyte decomposition on the lake buffer system should be considered in order to improve the ecological restoration of shallow lakes.

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