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Ecological Management Model for Macrophyte Phytoplankton Mixed Type Eutrophication, Lake Gucheng*

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Abstract: *Lake Gucheng is located in the southeast of Nanjing, with an area of 24.3 km^2, an average depth of 2 meters. The macrophytes of the lake were used to be abundant and their biomass was about 4.96 mg·m^{-2}. The annual average contents of total phosphorus (TP), total nitrogen (TN), PO^{3-}-P, COD_{Mn} and BOD_5 0.03, 1.31, 0.005, 3.61 and 1.46 mg·L^{-1}, respectively. Thus, the water quality of this lake is quite well. Recently, the water quality in part of the lake became worse because of some unreasonable exploitation and utilization of bioresources. The interactions between phytoplankton (N_1), macrophyte (N_2), fish (N_3), crab (N_4) were studied here. The macrophyte has great influences on both phytoplanktons, fish and crab, controlling the water quality and maintaining the fishery productivity. On the other hand, the phytoplankton, fish and crab also influence the macrophyte. It is key method of ecological management to maintain the macrophyte by fishery culture. Therefore, a modified Lotka- Volterra model has been established to estimate the interaction between N_1, N_2, N_3, N_4 and the influences of some water environmental parameters on these aquatic organism, environmental and economic effect. The main model consists four compartmental models and four submodels, involved 12 external variables, 8 state variables, 19 universal constants and 11 parameters. The values of most parameters were found from our experiments and calibrated by the model and actually measured data. The model has been validated by comparison the computed and experimental data of phytoplankton and macrophyte. The theoretical outputs showed a good agreement with the measured data. This model predicated that if the standing crop of fish and crab was higher than 2.65 g·m^{-2} during springtime in this lake, macrophytes would not grow, chlorophyll a content would arrive 34.8 mg·m^{-3} and the water quality would decrease. If the macrophyte grow well, the maximum fishery productivity would be about 1 600 t. In this case, the annually averaged phytoplankton chlorophyll a content should be 3.69 mg·m^{-3}, which is lower than the criterion (10 mg·m^{-3}) for eutrophic state. From 1991 to 1996, Lake Gucheng was managed with this model, its water quality maintain quite well, chlorophyll a content decreased from 3.51 (1991) to 1.89 mg·m^{-3} (1994). Meanwhile, the fishery productivity increased and the economic effect heightened year by year.*

Keywords: *Biosource, Eutrophication, Ecological model, Ecological Management, Environmental and economic effect, Lake Gucheng*

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The pollutants, from human production activities, deteriorate the water quality of lakes. However, a lake with health ecosystem can purify some pollutants. Unfortunately, improper development and utilization of lake resources may result in ecological degeneration and decreasing lake self-purification capacity. Therefore, it is important to manage lake with ecological method, especially to those lakes their ecosystems have not been deteriorated.

The Lake Gucheng is located in the southeast of Nanjing, with an area of 24.3 km^2, and the average depth of 2 meters. There are lush submerged macrophytes. The annual average biomass of submerged macrophyte is about 4.96 $kg \cdot m^{-2}$. Its dominants are *Potamogeton malainus, Potamogeton crispus and Vallisneria spiralis.* The annual average biomass of phytoplankton (Chlorophyll: Chla) is about 2.71 $mg \cdot m^{-3}$ and its dominants are *Scenedesmus* and *Dinobryon*. The annual average contents of total phosphorus (TP), total nitrogen (TN), PO_4^{3-}-P, COD_{Mn} and BOD_5 were 0.03, 1.31, 0.005, 3.61 and 1.46 $mg \cdot L^{-1}$, respectively. The water quality of this lake is quite well. However, recently, the water quality was worsen and the fish crop decreased year by year in part of the lake. These are mainly due to some unreasonable exploitation and utilization of bioresources, especially because of the degeneration of submerged macrophytes.

1. Conceptual Model

The environmental factors can effect strongly on individual species, population and community. On the other hand, individual species and population also have strong effects on not only the physical and chemical characteristics of environment (Jones *et al.* 1994, Jones and Lawton 1995), but also other individual species and population. In particular, certain plant and animal species have effects on resource availability that are disproportionately large in relation to their abundance or biomass in a food web (Hobbie 1992, Paster *et al.* 1993, and Vanni 1997). In the ecosystem of Lake Gucheng, the main populations and their relationship can be illustrated by figure 1.

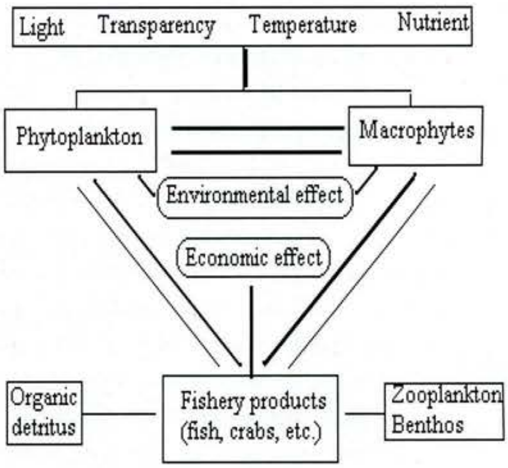

Fig. 1 The main populations and their relationship, Lake Gucheng

In the ecological system of Lake Gucheng, the aquatic macrophyte and phytoplankton (algae) maintain their co-existence by their competition (mainly their competition for light and nutrients). Macrophytes have advantage of competition for nutrient because they can get nutrients not only from water but also from the sediment. However, our experimental results demonstrated that aquatic macrophytes can absorb nutrients from water as the nutrient (mainly, phosphorus) is rich.

This behavior of aquatic macrophyte keeps the nutrients at a lower level and performs the function of "storage" and "drainage". On the other hand, as the nutrient concentration in water is low, macrophyte obtains its nutrients mainly from the sediment, and in this way it performs the function of a "pump". Therefore, the concentrations of the nutrients in water affect little on the growth of submerged macrophyte in the lake Gucheng. In our model, the affection of nutrients on aquatic plants can be ignored.

The result of AGP experiment showed that phosphorus is a dominant factor to control the growth of algae in this lake. Thus, in the model of algal growth, the chief nutrient that must be taken into consideration is dissolved phosphorus. In competition for light, macrophytes keep an absolute advantage because of their large bodies. Their tremendous shadow greatly reduce the amount of light radiating to water and even make algae living on water surface lack of light and lose its competitive ability. Besides, during the period of macrophyte growth, they continuously produce allopathic substance, which prevents algae from growing and developing. As a result, in the ecosystem of this lake, macrophytes can control the algal growth, retard the occurrence of "water bloom" and maintain the water quality in a good state. At the same time, they also provide fish and crabs with abundant bait and ideal living quarter simultaneously.

The competition among fish, crabs, macrophytes and algae dominates the dynamic of all those populations. Fish and crabs directly or indirectly use macrophytes and algae as bait. Excessive raising of herbivorous fish and crabs will destroy macrophyte population, which means that algae would develop extravagantly and "water bloom" would occur. Consequently the water quality become worse. In addition, over-development of macrophytes would obstruct the navigation and fishing. Especially during their non-growing period, the decay of great quantities of macrophytes would eventually effect water quality and speed up the aging course of the lake. It is very important to maintain the water quality and most possible economic output by making a balance between algae, macrophytes and fishery. The feasible method is controlling proper amount of macrophytes by raising proper fish and crabs, to control the amount of algae and maintain the good quality of water by proper amount of macrophytes. This is the main idea of our ecological management model and also the key point for realizing the sustainable development of lake environment and economics.

2. Mathematics Model

On the analyses of the conceptual model mentioned above, it is clear that in the ecological system of the lake Gucheng, the main biotic populations include two bait populations (macrophyte and algae) and one kind of predatory (fish and crabs). A kind of Volterra model (Chen Lan-sun, 1988) is chosen and amended as follows.

$$dN_1/dt = \gamma_1 N_1 (1 - N_1/K_1 - \alpha N_2/K_1 - \varepsilon N_3/K_1);$$
$$dN_2/dt = \gamma_2 N_2 (1 - N_2/K_2 - \beta N_1/K_2 - \delta N_3/K_2);$$
$$dN_3/dt = \gamma_3 N_3 (- N_3/K_3 + \sigma N_1/K_3 + \lambda N_2/K_3 + \omega B/K_3);$$

$dN_4/dt= \gamma_4 N_4(- N_4/K_4 + \nu N_1/K_4 + \psi N_2/K_4 + \rho B/K_4)$;

where γ_1, γ_2, γ_3 and γ_4 can be presented as follows.

$\gamma_1 = \gamma_{1max} f(T_1)[P/(K_{mp}+P)](1/K_e H) \cdot EXP\{[(-I_a/I_s)EXP(-K_e H)] - EXP(-I_a/I_s)\}$

$\gamma_2 = \gamma_{2max} f(T_1)(D/K_{ec})\ln\{[2+(I_m/I_k) \cdot EXP(-K_{es}Z)]/[2+(I_m/I_k)EXP(-K_{es}Z-K_{ec}h)]\}$

$\gamma_3 = \gamma_{3max} EXP[(-2.3) \cdot |(T-T_{opt})/15|] + \theta N_3 Sin[(t/180-0.5)\pi]$

$\gamma_4 = \gamma_{4max} EXP[(-3.1)|(T-T_{opt})/15|]$

The meanings of all symbols described above are shown in table 1.

3. Determination of constants and parameters

3.1 Determination of the maximal environmental capacity

(1) K_1: In the development and utilization of lake Gucheng, excessive utilization of macrophyte may raise fish crop. On the contrary, this will create an ideal growing environment for algae and lead the occurrence of eutrophication. To avoid the emergence of eutrophication and keep water quality in a good state, K_1 was set to 10.0 mg·m^{-3} according to the present condition of nutrients in this lake and the international standard of eutrophication.

(2) K_2: On the basis of the analysis above, K_2 was set to 7.0 kg·m^{-2} so as not to effect navigation and fishing, keep the environmental and economic effect in a sustainable development.

(3) K_3 and K_4: To utilize bait resources extensively and maintain proper amount of macrophyte, K_3 was set to 0.035 kg·m^{-2}, K_4 0.005 kg·m^{-2}, according to our experiments.

Table 1. Symbol's meaning in the model

N_1	algal biomass (Chla, mg · m^{-3})
N_2	macrophyte biomass (fresh weight, kg · m^{-2})
N_3	fishery crop (fresh weight, kg · m^{-2})
N_4	crab crop (fresh weight, kg · m^{-2})
α	Negative effect coefficient of algae to macrophyte
β	Negative effect coefficient of macrophyte to algae
ε	Predative effect coefficient of fish to algae
δ	Predative effect coefficient of fish to macrophyte
σ	Utilization rate coefficient of fish to algae
λ	Utilization rate coefficient of fish to macrophyte
ω	Utilization rate coefficient of fish to benthons and detritus
ν	Utilization rate coefficient of crab to algae
ψ	Utilization rate coefficient of crab to macrophyte
ρ	Utilization rate coefficient of crab to benthons and detritus
θ	Coefficient of reproduction and addition of fish
γ_1	Growth rate of algal population
γ_2	Growth rate of macrophyte population
γ_3	Growth rate of fish population
γ_4	Growth rate of crab population

γ_{1max}	Maximum growth rate of algal population
γ_{2max}	Maximum growth rate of macrophyte population
γ_{3max}	Maximum growth rate of fish population
γ_{4max}	Maximum growth rate of crab population
T_{1opt}	Optimum growth temperature of algae (℃)
T_{2opt}	Optimum growth temperature of macrophyte (℃)
T_{3opt}	Optimum growth temperature of fish (℃)
T_{4opt}	Optimum growth temperature of crab (℃)
T_{1max}	Temperature above T_{1opt} where algal growth rate is 10% of γ_{1max} (℃)
T_{2max}	Temperature above T_{2opt} where macrophyte growth rate is 10% of γ_{2max} (℃)
T_{1min}	Temperature below T_{1opt} where algal growth rate is 10% of γ_{1max} (℃)
T_{2min}	Temperature below T_{2opt} where macrophyte growth rate is 10% of γ_{2max} (℃)
K_{mp}	Constant for phosphorus uptake
I_s	Saturation light intensity for algal growth
I_k	half-optimal light intensity for macrophyte growth
K_1	Maximum carrying capacity of algae (Chla, $mg \cdot m^{-3}$)
K_2	Maximum carrying capacity of macrophyte (fresh weight, $kg \cdot m^{-2}$)
K_3	Maximum carrying capacity of fish (fresh weight, $kg \cdot m^{-2}$)
K_4	Maximum carrying capacity of crabs (fresh weight, $kg \cdot m^{-2}$)
B	Amount of detritus and benthon biomass (fresh weight, $kg \cdot m^{-2}$)
P	Dissolved inorganic phorphous ($mg \cdot L^{-1}$)
T	Temperature (℃)
D	mean day length (hours)
H	depth of water (m)
H	mean height of macrophyte (m)
Z	depth from water surface to macrophyte community tip (m)
I_a	the mean intensity of light ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
I_m	the maximum intensity of light ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
K_e	the coefficient of light extinction in the water (m^{-1})
K_{ec}	the coefficient of light extinction within macrophyte (m^{-1})
K_{es}	the coefficient of light extinction outside macrophyte (m^{-1})

Table 2. Values of model constants and parameters

Symbols	Values	Sources	Symbols	Values	Sources
α	1.690	Experiments, calibration	γ_{1max}	3.30	Jϕrgensen,1988
β	0.300	Experiments, calibration	γ_{2max}	0.126	Experiments, calibration
ε	80.0	Experiments, calibration	γ_{3max}	0.00025	Experiments, calibration
δ	100.0	Experiments, calibration	γ_{4max}	0.0002	Experiments, calibration
σ	0.01	Experiments, calibration	T_{1opt}	25.0	Experiments
λ	0.01	Experiments, calibration	T_{2opt}	25.0	Experiments
ω	0.005	Experiments, calibration	T_{3opt}	22.0	Experiments
ν	0.02	Experiments, calibration	T_{4opt}	26.0	Experiments
ψ	0.008	Experiments, calibration	T_{1max}	33.0	Experiments
ρ	0.03	Experiments, calibration	T_{2max}	33.0	Experiments
θ	0.00025	Experiments, calibration	T_{1min}	10.0	Experiments
I_s	850.0	Experiments	T_{2min}	10.0	Experiments
I_k	300.0	Experiments	K_{mp}	0.02	Jϕrgensen,1988

3.2 Determination of universal constants and parameters

The values of universal constants and parameters are shown in table 2. Most contents and parameters were determined experiments and calibrated by the model and observed data. Some are quoted from references.

4. Results

The simulated results are shown as follows (Fig. 1 and Fig. 2).

The model calculated values of the algal biomass (Chla) are relatively consistent with the actual measuring data in Lake Gucheng. The correlation coefficient is 0.9385 ($> \gamma_{(0.001,8)}$ 0.8721). The correlativity is remarkable. Error analysis shows only a little average error (+6.24%) for 12 groups of data, close to 0. It also shows that the model calculation is relatively consistent with actual data.

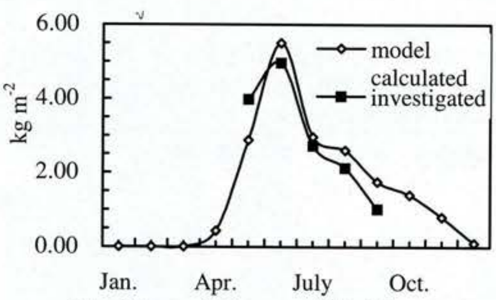

Fig. 2 Annual changes of the biomass of macrophyte, Lake Gucheng

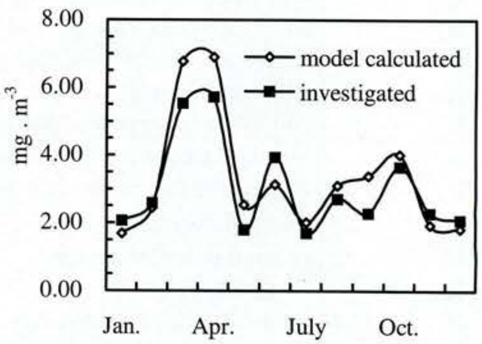

Fig. 3 Annual changes of Chla values, Lake Gucheng

The model-simulated values of macrophyte biomass are remarkably correspondent to the actual investigation data during macrophyte growth period (from May to September). The correlation coefficient is 0.8800 ($> \gamma_{(0.05,3)}$ 0.8783). Error analysis shows that the average error is 11.85 %.

These results also supported the model strongly. Therefore, our model is applicable.

5. Discussion and Conclusions

5.1 Ecological management is the key to realize the lake environment and economic sustainable development

The main problem of lake water environment is eutrophication. The algal over-reproduce is the mark of eutrophication. It is provided by a lot of practice that macrophytes can control algal growth. However, excessive growth of macrophyte may also result in some troubles. We have to use mower and other manpower to remove macrophytes. Now, we propose raising fish and crab to control macrophyte growth. This may not only reduce the troubles conducted from macrophyte, but also gain economic effect. In addition, this may save a lot of manpower and financial resource.

From 1991 to 1996, Lake Gucheng was managed with our ecological model. The annual average contents of total phosphorus (TP), total nitrogen (TN), PO^{3-}-P, COD_{Mn} and BOD_5 were 0.03, 1.31, 0.005, 3.61 and 1.46 $mg \cdot L^{-1}$, respectively. The algal biomass (Chla) decreased from 3.51 $mg \cdot m^{-3}$ (1991) to 1.89 $mg \cdot m^{-3}$ (1994). The water quality of this lake maintains quite well. Meanwhile, the fishery productivity increased and the economic effect heightened year by year. The practical results provided that the ecological management is the key point to realize the lake environmental and economic sustainable development.

5.2 Predication

In the coexistence system of fish and macrophyte, which of them grew excessively, the ecological equilibrium would be damaged. For example, when macrophytes begin to germinate in spring, if the standing crop of herbivorous fish is more than 2.65 $g \cdot m^{-2}$, macrophyte will not be able to germinate. As a result, algae will reproduce extensively and eutrophication will occur. Fish and crabs will lose an important resource of bait and a place of breading. Their growth rate will slow down. In addition, during the flood year, the water level of the lake heightens and the sand content in water is very high. The transparency decreases rapidly. Therefore, it is very difficult for macrophyte to obtain light to germinate and grow. Eventually, when the water level heightens suddenly, macrophytes may die in large-scale. In this case, we must cut down the standing crop of herbivorous and cultivate aquatic plant. According to our model predication, if macrophytes extinguished in this lake, the algal biomass (Chl*a*) would reach 34.8 $mg \cdot m^{-3}$ in April of next year.

If aquatic macrophytes grew excessively, dissolved dioxygen in water, especially in hypolimnion, would decrease. It is harmful to fish and crabs. Moreover, the dense macrophyte would directly retard navigation. It would also speed the process of lake aging.

According to the current biomass of macrophyte (4.96 $kg \cdot m^{-2}$), our model predicted a potential annual fishery productivity of about 1 600 t and an annual averaged phytoplankton chlorophyll content of 3.69 $mg \cdot m^{-3}$, which is lower than the criterion (10 $mg \cdot m^{-3}$) for eutrophic state. Guided by our ecological management model, the fishery productivity of Lake Gucheng increased year by year and its water quality maintain quite well.

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