Biomanipulation in shallow, eutrophic lakes: A numerical model with an application to Lake Bleiswijkse Zoom, The Netherlands

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Abstract; The prediction of temporal variations of biota following biomanipulation measures in lakes is of paramount importance in view of water quality management. The temporal variations of phytoplankton biomass as chlorophyll-a and transparency as secchi depths measurements are studied in the Lake Bleiswijkse Zoom, The Netherlands with a comprehensive biological model. In the formulation of the biological model, phytoplankton as several species, zooplankton, detritus, planktivorous and benthivorous fish and piscivorous fish are considered to be the major contributing biota for the food web manipulation. The biological model enumerates the species compositions at a given time taking biological, physical and meteorological processes in to account. Reduction of almost all planktivorous fish and 85% of benthivorous fish results in increase in transparency, decrease in algal biomass and decrease in resuspended inorganic matters leading to an environmental sound lake ecosystem. The model also provides useful insights in to positive and negative interrelationships among biota in the ecosystem. In other words, from the biomanipulation point of view, poor understanding of interactions among biota and hence, uncertainties of their accurate predictions may lead to controversial evidences.

Keywords; Biomanipulation, phytoplankton, zooplankton, detritus, planktivorous and benthivorous fish, piscivorous fish, transparency and macrophytes

1. Introduction

Lake restoration has long been considered to be primarily a matter of chemistry and engineering. Clearly, in-lake techniques to lower nutrient concentration or to remove sediments or rooted plants can be effective in improving lake tropic state following diversion of silt and nutrients. These approaches, however, usually ignore the biological interactions of the lake ecosystem which cause low water transparency and high internal nutrient release etc. Shapiro *et al.* (1975) and Shapiro (1978) suggested the term *biomanipulation* to include lake improvement methods that alter the food web to favor grazing on algae by zooplankton, or that eliminate fish species which recycle nutrients. (See fig. 1 & 2)

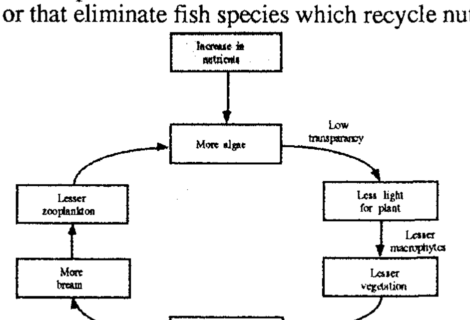

Fig.1 Schematic diagram of eutrophication due to increase in nutrients

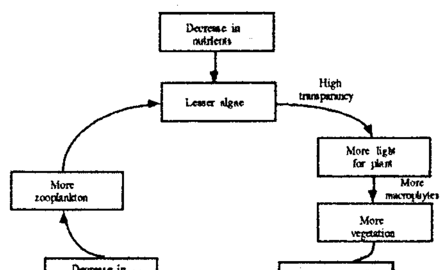

Fig.2 Schematic diagram of restoration by biomanipulation

Eutrophication of shallow lakes has led to an abundance in algal biomass, disappearance of most of the macrophytes and disturbance of the food chain. As eutrophication increases, piscivorous fish density falls sharply whereas planktivorous and benthivorous fish densities grow rapidly causing more resuspension of nutrients. This causes the eutrophication

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grow rapidly causing more resuspension of nutrients. This causes the eutrophication becomes intense. Eutrophication problems are, therefore, necessary to be combated in order to restore the water quality. This can be done with the reduction of nutrient levels. But it seems that the reduction of nutrient level does not merely solve the problem due to the present structure of the food chain. Hence, the manipulation of food chain is of paramount importance in combating the eutrophication problems. In other words, reduction of planktivorous and benthivorous fish such as roach*(Rutilus rutilus)* , rudd*(Scardinius erythrophythalmus)*, bream*(Abrama brama)*, carp*(Cyprinus carpio)* and introduction of piscivorous fish such as perch *(Percafluviatilis)*, pike*(Esox lucius)*, pike perch*(Stizostedion lucioperca)*, eel*(Anguilla anguilla)*, cat fish*(Silurus glanis)* are considered to be prerequisites for the restoration of water quality by the method of biomanipulation.

2. Need for mathematical modeling of biomanipulation

Yet, there are some uncertainties in the restoration of water quality by biomanipulation in terms of time period. For short term period of about two to five years, biomanipulation has been reported to have worked fairly well, but for long term restoration, it has worked only for some lakes. To analyze this phenomenon experimentally it becomes time consuming and very laborious process. Monitoring of all changes in biota is also a necessity. Moreover, it is too costly to carry out monitoring at length. Mathematical modeling may help to overcome this problem to a certain extent. Application of biomanipulation to deep lakes to achieve restoration of water quality is another uncertainty. This is another aspect to which the modeling can be applied. All interrelationships and interactions among biota are yet not documented in the literature, hence, certain simple interactions are assumed in developing this model. For example seasonal variations of pike perch density and bream density are not well documented in the literature. Hence, annual average values for some coefficients of the growth rates are adopted in the model. An accurate prediction of changes and the resistance to change of biota are not yet possible with mathematical modeling, but the average trend can be predicted fairly well. Furthermore, mathematical modeling enables to change the characteristics of trophic states such as oligotrophic, eutrophic and hypertrophic and then to analyze the eutrophication problem comprehensively. In the management point of view, modeling of eutrophication can be considered as a low-cost device compared to other methods.

3. State equations

The following governing equations are considered in the model. In this model state variables are phytoplankton comprising of fourteen separate types, zooplankton, detritus, planktivorous and benthivorous fish (Bream) and finally piscivorous fish (Pike perch).

$$\frac{dPy_i}{dt} = (Pg_i - M_i - R_i - G_i)Py_i \tag{1}$$

$$\frac{dZ}{dt} = (G_Z - R_Z - M_Z)Z \tag{2}$$

$$\frac{dD}{dt} = \sum (q.a_r M_i.Py_i) - u.D - s.D \tag{3}$$

$$\frac{dB}{dt} = ib + G_B.B - cb.B^2 - Pr_{max}.Fr.Pi \tag{4}$$

$$\frac{dPi}{dt} = ip + G_{Pi}.Pi - mp.Pi - cp.Pi^2 \tag{5}$$

where Py is phytoplankton concentration (mg/m^3); Pg is the gross growth rate of phytoplankton (per day); M is the natural mortality except grazing by zooplankton (per day),

day); i represents each phytoplankton type; Z is the zooplankton concentration (mg/m^2); G_Z is the growth rate of zooplankton (per day); R_Z is the respiration rate (per day); M_Z is the natural mortality including grazing by planktivorous and benthivorous fish (per day); D is the detritus concentration due to dead phytoplankton cells (mg P/m^3); q is the nutrient fraction which becomes detritus when a phytoplankter dies; a_i is the fraction of nutrient per unit of phytoplankton type; u is the mineralization rate constant of detritus (per day); s is the sedimentation rate constant (per day); B is the bream density (g/m^2); ib is the immigration rate of bream (g/m^2.day); G_B is the growth rate of bream (per day); cb is the intraspecific competition constant for bream (per m^2 g day); pr_{max} is the maximum predation rate of pike perch (per day); Fr is the functional response of pike perch; Pi is the pike perch density (g/m^2); ip is the immigration rate of pike perch (g/m^2 day); G_{Pi} is the growth rate of pike perch (per day); mp is the natural mortality rate of pike perch (per day); cp is the intraspecific competition constant for pike perch (per m^2 g day).

4. Transparency

Transparency is an important physical characteristic in terms of water quality. Secchi depth is normally used to predict the transparency. Before biomanipulation is applied to the lake, secchi depth is too low due to the high algal biomass and high inorganic resuspended matters. But after biomanipulation it becomes high due to less algal biomass and less inorganic suspended matters. Meijer (1990) suggests an equation for the reciprocal of the secchi depth with the concentration of chlorophyll-a, detritus and inorganic suspended solids as follows.

$$\frac{1}{SD} = 0.234 + 0.064\,In + 0.013\,Chl + 0.061\,Det \tag{6}$$

where In is the inorganic suspended solids (mg/l); Chl is the chlorophll-a concentration (μ g/l); Det is the detritus generated due to dead phytoplankton cells (mg/l)

5. Experimental area

This model is applied to the shallow and eutrophic lake Bleiswijkse Zoom, Netherlands. In 1987, the lake was devided into two compartments, the Galgje having an area of 3.1 ha (referred to as treated area) and the Zeeltje having an area of 11.3 ha (referred to as control area) by a wooden dam. In one compartment (i.e. treated area), 85% of the fish was removed and pike perch (piscivorous fish) were introduced while the other compartment (i.e. control area) was kept as a reference.

Lake Bleiswijkse Zoom is a narrow lake of length 2km and area14.4ha. in the west of The Netherlands.(fig.3) It was built in 1972 for recreational purposes. The average depth is about 1.1m. The major type of sediment of the lake is clay. A water inlet connects the lake with the eutrophic river Rotte, though in 1987 no water was let in. The loss of water by evaporation is compensated by precipitation and by some seepage from river Rotte. During 1980-1987 the lake was characterized by high phosphorus concentrations of about 0.4mg P/l, resulting in summer average chlorophyll-a concentrations of 80-200μ g/l and a secchi depth of 0.2m. (Meijer *et. al.*, 1989) During this period, Macrophytes were absent and densities of both bream and carp are high.

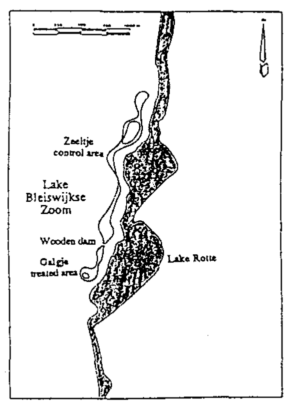

Fig. 3. Morphology of Lake Bleiswijkse Zoom

6. Results and discussion

Fourth order Runge Kutta method was used in this model in order to solve simultaneous differential equations representing state equations. A time step of one day was adopted for the entire computational period and the computational period started from mid April to end of November, 1987. Phytoplankton biomass and transparency in terms of chlorophyll-a and secchi depth measurements were compared with the measured values in Lake Bleiswijkse Zoom, The Netherlands, both in control area and treated area respectively. Temperature, total phosphorus and inorganic suspended matters both in control area and treated area in the Lake Bleiswijkse Zoom were measured as shown in fig. 4, 5 and 6 respectively.

The biomanipulation caused to decrease the chlorophyll-a concentrations in the treated area to 0-10μ g/l, whereas in the control area the chlorophyll-a concentrations varied between 10 and 150 μ g/l.(Fig.7) During the period of May to June simulated biomass differed from measured values considerably. This difference was caused by the types of nutrients considered in the model. In the model, average total nitrogen concentration of 2.5mg/l was assumed throughout the. entire computational period. Usually, during spring nitrogen limited phytoplankton species are predominant rather than phosphorus limited species. The algal biomass of the Lake Bleiswijkse Zoom mainly consisted of greens and blue greens. It is clear that with the application of biomanipulation measures the summer peak value of about 120μ g/l drastically reduced to a value less than 10μ g/l.

For the zooplankton densities, in treated area, the initial density was assumed to be 300mg/l whereas in control area it was assumed as 100mg/l. (Fig.8) In both cases it was seen that the zooplankton densities dropped sharply causing lesser predation on algae. The decrease in zooplankton standing stock was mainly due to high grazing pressure by planktivorous fish such as bream and white bream and the food limitation caused by lesser algal growth. The main species of zooplankton dominated in the Lake Bleiswijkse Zoom was large-bodied *Daphnia hyalina* of mean length 0.9mm. (Meijer *et. al.*, 1989)

In April 1987, 2000kg fish were removed from the treated area by scine- and electro-fishing. This comprised of most bream and white bream of 1200kg, and carp of 550kg. After removal of fish at least 45kg/ha. of bream and white bream (44kg/ha. larger than 16cm) and 59kg/ha. of carp were left in the treated area. (Meijer *et.al.*, 1989)

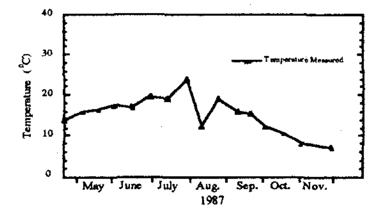

Fig.4 Temperature distribution in Lake Bleiswijkse Zoom in 1987

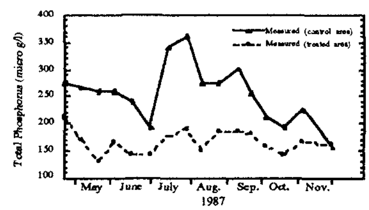

Fig.5 Total Phosphorus concentration in Lake Bleiswijkse Zoom in 1987

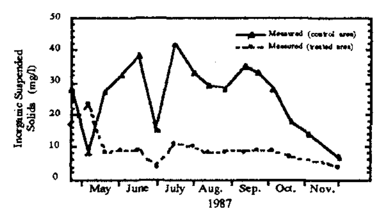

Fig.6 Inorganic suspended solids in Lake Bleiswijkse Zoom in 1987

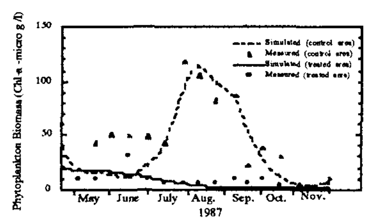

Fig.7 Chlorophyll-a concentration in Lake Bleiswijkse Zoom in 1987

Hence almost all of the planktivorous fish and about 85% of the benthivorous fish were removed from the treated area. In the model, initial value of bream density was kept as 500kg/ha. and 100kg/ha. both in control and treated areas respectively. (Fig.9) It is documented in the literature that for a successful restoration by biomanipulation the initial bream density should usually be less than 150kg/ha. (Hosper,1986) It was also seen that as time elapsed, bream density did not change drastically due to homeostasis imposed by the shear abundance of bream standing stock and the high growth rates even at high nutrient levels. As a result eutrophication becomes more intense leaving lesser zooplankton densities. High resuspension due to benthivorous fish like carp also caused high algal biomass in the control area. Hence, reduction of planktivorous and benthivorous fish is considered to be a prerequisite for a successful biomanipulation work. Once the biomanipulation measures worked, no drastic increase in bream density was found due to high predation pressure by pike perch density. This was observed only with respect to short term period of one year to five years. Since there are some controversial evidences documented in the literature simulations of long term periods with this model are yet an uncertainty.

In May and July Small pike perch in total 800 individuals of 3.0cm long were introduced in the treated area to control bream and carp. (Meijer *et. al.*,1989) Unlike the bream density pike perch population becomes minimal in the control area. Initially pike perch density in control area was kept at 1.5kg/ha. while in treated area it was kept at 4.5kg/ha. respectively. (Fig.10) It is also clear that an addition of piscivorous fish like pike perch is also a necessary for a successful restoration by the method of biomanipulation.

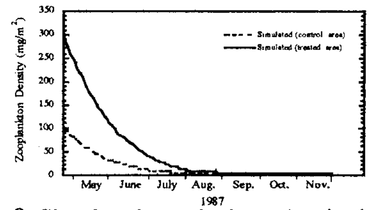

Fig.8 Simulated zooplankton density in Lake Bleiswijkse Zoom in 1987

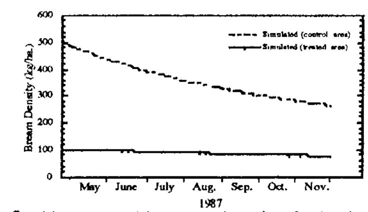

Fig.9 Simulated bream density in Lake Bleiswijkse Zoom in 1987

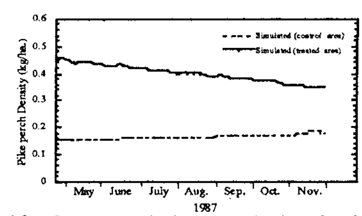

Fig.10 Simulated pike perch density in Lake Bleiswijkse Zoom in 1987

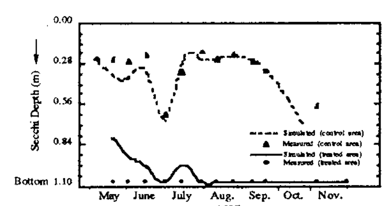

Fig.11 Transparency in Lake Bleiswijkse Zoom in 1987

After removal of fish secchi depth in the treated area increased to 1.1m (i.e. the bottom of the lake) and in control area the secchi depth remained rather low value of about 0.25m. (Fig.11) The simulated secchi depth vales were quite agreeable with measured value except at the beginning. At the beginning simulated secchi depth values were low than actual because of the high simulated algal biomass. From August onwards even the simulated secchi depth values were higher than the depth of the lake.

7. Conclusions

Both the experimental and model simulations show that a removal of planktivorous and benthivorous fish at least 85% and an introduction of piscivorous fish are necessary to improve water quality in Lake Bleiswijkse Zoom, The Netherlands. The biomanipulation measures seem to work in Lake Bleiswijkse Zoom resulting in low algal biomass and an increase of water transparency. Removal of large benthivorous fish led to a rapid decrease in the sediment resuspension causing decrease of inorganic suspended material. From July to November factors except zooplankton grazing were responsible for the high transparency in the lake. It is evident that this is related to high abundance of macrophytes which have high uptake of nitrogen. (Wetzel,1975) In addition, there are evidences for the limitations of the algal growth by macrophytes. Laboratory studies showed that some species of macrophytes *Chara sp.* limit the algal growth by means of allelopathy. (Wium Anderson *et. al.*, 1982; Anthoni *et. al.*,1980) Hence, modeling of macrophytes is considered to be a further improvement in this model.

With these results it can be concluded that the biomanipulation process can be modeled to a certain accuracy. No precise simulation is possible unless the uncertainties of interrelationships among biota of the lake ecosystem are clearly understood. The poor understanding of accurate seasonal variations among some species (For e.g. pike perch, bream etc.) also causes lesser accuracy in the predicted results.

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References

Anthoni, U., C. Cristophersen, J. Ogardo Mmadsen, Wium-Andersen, 1980. Biologically active sulphur compounds from from the green alga *Chara Globularis*, Phytochemistry,19:1228-1229

Carpenter, Stephen, R, David, M. Lodge, 1986. Effects of submerged macrophytes on ecosystem processes. Aquat Bot., 3/4: 341-370.

Hosper, S. H, 1989. Biomanipulation, new perspectives for restoration of shallow eutrophic lakes in The Netherlands. Hydrobiol. Bull. 23:5-10.

Hosper, S. H, Meijer, M. L, 1993. Biomanipulation, will it work for your lake? A simple test for the assessment of chances for clean water, following drastic fish-stock reduction in shallow, eutrophic lakes, Ecological engineering. 2:63-72.

Los, F. J, 1991. Mathematical Simulation of algae blooms by the model bloom 2, Version 2, documentation report, Delft Hydraulics.

Meijer, M. L, A. J. P. Ratt, R.W. Doef, 1989. Restoration by biomanipulation of Lake Bleiswijkse Zoom (The Nethelands) : First Results, Hydrobiol. Bll. 23. 49-57.

Meijer, M. L.,M. W. De Haan, A.W. Breukelaar, H. Buiteveld, 1990. Is reduction of the benthivorous fish an important cause of high transparancy following biomanipulation in shollow lakes? Hydrobiologia 200/201:303-315.

Phillips, G. L, Eminson, D. F, Moss, B, 1978. A mechanism to account for macrophytes decline in progressively eutrophicated fresh waters. Aquat.Bot.,4:103-126.

Scheffer M.,1989. Alternative stable states in eutrophic, shallow freshwater systems: A minimal model, Hydrobiol. Bull. 23, 73-83

Shapiro, J, La Marra, V Lynch, M, 1975. Biomanipulation An ecosystem approach to lake restoration. In P.L. Brezonik and J. L. Fox, eds, Water quality Management through Biological Control, Gainesville, FL: Department of Environmental Engineering Science, Uni. Florida, 85-96.

Shapiro, J, 1978. The need for more biology in lake restoration, In lake restoration, EPA-440/5-79-001,161-167.

Wetzel, R.G.,1975. Limnoloy. W. B. Saunders Company, Philadelphia.

Wium-Anderson,S., U. Anthoni, C. Cristophersen, and G. Houen,1982. Allelopathic effects on phytoplankton by substances isolated from aquatic macrophytes (Chrales). Oikos, 39: 187-190