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ECOLOGICAL MODEL (N-P) FOR SHALLOW LAKES. STUDY CASE: STIUCII LAKE

Gabriela Elena DUMITRAN[1], Liana Ioana VUȚA[2]

Existența la nivel mondial a unui procentului de mare de lacuri cu probleme de eutrofizare, face necesară existența unui instrument de prognoză a calității acestor ecosisteme. Lucrarea de față propune un model bistrat (nutriet-fitoplancton), care descrie comportarea biochimică a unui lac natural eutrof de talie mică. Modelul 1D propus permite estimarea concentrației de nutrienți şi biomasă algală şi evidențierea efectului limitant al nutrienților asupra ratei de creştere alge. Acest model este calibrat şi validat pentru lacul Ştiucii.

Global existence of a large percentage of lakes with eutrophication problems, demands a predictive tool for the quality of these ecosystems. This paper proposes an ecological model (nutrient-phytoplankton) that describes the biochemical behavior of a small natural lake eutrophic. The 1D model developed allows the estimation of nutrients concentration and algae biomass and nutrient limited evidence on algal growth rate. This model is a two layer model type which is calibrated and validated for Ştiucii Lake.

Keywords: ecological model, shallow lake, nutrient, eutrophication

1. Introduction

Although Romania is a signatory to the Ramsar Convention, the only studies related to wetlands are on Danube Delta. Furthermore, the necessity of complex ecological studies on wetlands is becoming more and more important, since the country is trying to develop a sustainable society.

Between permanent wetlands, marshes or oligotrophic swamps have an important economic, scientific and aesthetic importance. Such ecosystems are well represented in the drainage basin of the Somesul Mic, most of them in natural conditions while others under the human influence.

This study present the qualitative analysis of such an ecosystem, based on ecological modeling.

The first step has been to develop a 1D vertical model of the main turnover

[1] Lecturer, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: dumitran@hydrop.pub.ro
[2] Lecturer, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: l_vuta@yahoo.com

processes in the reservoir because water stratification has been reported as one of the favorable environmental factors to cyanobacteria dominance [1]. The second step consists in the introduction of the processes driving nutrients dynamics in the lake.

The need for prediction water quality has arisen largely as a result of increased eutrophication of lakes throughout the world [2]. The most common modeling approach is exemplified by the development and application of the steady state, input-output models. In this case, nutrient concentrations are calculated from net inputs and phytoplankton biomass used a correlation with the limiting nutrient, most often phosphorus, but the light, biological interactions and internal loading of nutrients are not considered [3]. A second approach, often referred to as ecological water quality modeling, specifically addresses many of the biological and chemical factors that are absent in the simple input-output models. In such models the physical processes of transport and turnover within the water body have been oversimplified, with the assumption of two compartment vertical systems [4]. The purpose of the present work is to present an ecological water quality model from a second category which is use to analyze the comportment of a shallow lake (Stiucii Lake).

2. Model description

Great variety exists among biochemical models, even if fundamental concepts are similar for most of them [5]. The presented ecological model simulates the evolution of three state variables: phytoplankton, soluble and insoluble phosphorus as nutrients for each vertical compartment system (epilimnion and hipolimnion). Thus, at each time step the values of water quality variables in the domain are given.

The two layer models for studying eutrophication phenomenon in lakes consider the interactions nutrients – trophic chain and are capable to illustrate very accurate the functioning of aquatic ecosystems [6]. The model presented in this paper is dealing only with the biochemical part of the process.

In this sense, a very significant biological phenomenon, with multiple effects onto water quality is the algae bloom. This is due to the basin eutrophication and to the temporary rise (sometimes of large proportions) of planktonic algae role in the entire ecosystem. The thermal stratification of water and the penetration of light are the main factors that determine the dynamics of the vertical distribution of phytoplankton. The general tendency of the vertical distribution of the total amount of phytoplankton is a gradual decrease from surface to the bottom of the basin [7]. The temporal variation of the amount of living algae from the phytoplankton has maximum values during the hot period of the year (June-October).

The numerical model presented is one dimensional and allows predicting the evolution of nutrients concentration and algae biomass for a lacustrian ecosystem and the limiting effects of the nutrients onto the algae growth rate. The physical model considers a lake, with a given geometry, polluted by punctual and disperses sources. A detailed approach is used for the transformation processes of the nutrients in the lake. For the Stiucii Lake, the representative nutrient is phosphorous and the two distinctive fractions of this element (soluble and insoluble) have been considered. So, the model state-variables are the soluble phosphorous (P_s), insoluble phosphorous (P_i) and the algae biomass (A), all of them being in a very strong interdependency.

Since the lake presents thermal stratification - direct stratification during summer and indirect stratification during winter – the water body can be represented by two layers – epilimnion and hypolimnion – each of them having homogenous properties and a very small variation of temperature gradient [8]. The two layers are separated by thermocline (fig. 1), which is a barrier of limited thickness but with a very important thermal gradient, which greatly reduces the vertical mix [9].

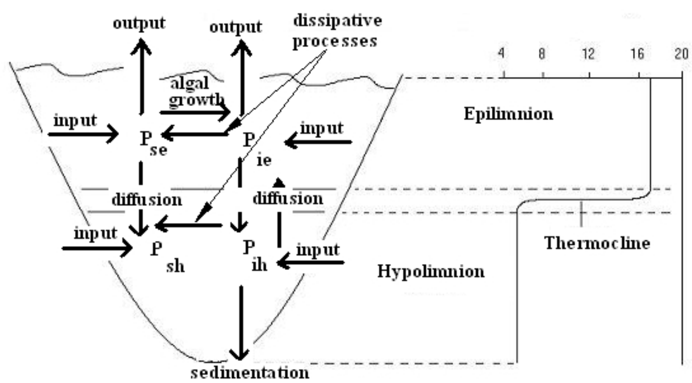


Fig. 1. The considered processes into a model and the temperature profile for the summer direct stratification in lakes.

Thus, for the studied water body are considered:

- pollutants input, represented by mass flow of the two phosphorus fractions, divided for the two water column layers;
- phosphorus elimination from the epilimnion;
- the transfer between the two layers, due to an intense diffusion during the two turnover periods (spring and autumn) and a limited one during winter/summer [10];
- sedimentation of insoluble phosphorous, which occur in both layers, but with different values according to the season [11];

- phytoplankton soluble nutrient intake, which is converted - by assimilation - to particulate phosphorus embedded in the algae mass. This processes is supposed to appear only in the epilimnion, where the temperature and light conditions endorse the photosynthesis activity especially during the hot season;
- insoluble phosphorus transformation in assimilable form by dissipative processes (respiration, excretion, mortality, decomposition) [12].

The physical model is mathematically transposed by balance equation of algae mass (A), soluble phosphorus in epilimnion (P_{se}), soluble phosphorus in hypolimnion (P_{sh}), insoluble phosphorus in epilimnion (P_{ie}) and insoluble phosphorus in hypolimnion (P_{ih}), [8, 13]:

$$\frac{\partial A}{\partial t} = [k_c(T,P,I) - k_{ra}(T) - \frac{v_a \cdot A_t}{V_e}]A\,, \tag{1}$$

$$V_e \frac{\partial P_{se}}{\partial t} = W_{se} - Q \cdot P_{se} + v_t \cdot A_t \cdot (P_{sh} - P_{se}) + k_{te} \cdot V_e \cdot P_{ie} - \\ - \left[U_P \cdot f_P \cdot f_{IP} + k_{ra} \cdot \left(P_{ie} - P_{ie\min}\right)\right] \cdot A\,, \tag{2}$$

$$V_e \frac{\partial P_{ie}}{\partial t} = W_{ie} - Q \cdot P_{ie} + v_t \cdot A_t \cdot (P_{ih} - P_{ie}) - k_{te} \cdot P_{ie} - v_e \cdot A_t . P_{ie} + \\ + (U_P \cdot f_P \cdot f_{IP} - k_{ra} \cdot P_{ie}) \cdot A\,, \tag{3}$$

$$V_h \frac{\partial P_{sh}}{\partial t} = W_{sh} + v_t \cdot A_t \cdot (P_{se} - P_{sh}) + k_{th} \cdot V_h \cdot P_{ih}\,, \tag{4}$$

$$V_h \frac{\partial P_{ih}}{\partial t} = W_{ih} + v_t \cdot A_t \cdot (P_{ie} - P_{ih}) - k_{th} \cdot V_h \cdot P_{ih} + v_e \cdot A_t \cdot P_{ie} - v_h \cdot A_t \cdot P_{ih}\,. \tag{5}$$

with

$$\alpha_0 = \frac{I_a}{I_{opt}} \cdot e^{-k_e \cdot h_e};\ \alpha_1 = \frac{I_a}{I_{opt}} \cdot e^{-k_e \cdot h_h};\quad f_P = \frac{P_{se}}{P_{se} + k_{SP}},\quad f_{IP} = \frac{P_{ie\max} - P_{ie}}{P_{ie\max} - P_{ie\min}}$$

$$k_c(T,P,I) = k_{\max} \cdot 1{,}066^{(T-20)} \cdot \min\left(f_P, \frac{2.718 \cdot f}{k_e \cdot H} \cdot \left(e^{-\alpha_1} - e^{-\alpha_0}\right), f_{IP}\right);$$

$$f = \frac{1}{\pi}\cos^{-1}\left[\tan\left(\pm\frac{\pi L}{180}\right)\cdot\tan\left(-23{,}45\frac{\pi}{180}\sin\left(\frac{2\pi(284+Nd)}{365}\right)\right)\right];$$

$$k_{ra} = 1{,}08^{(T-20)}; \quad I_a \cong 0.64 \cdot I;$$

Table 1

List of symbols

Symbol	
k_c	rate coefficient for phytoplankton growth $k_c(T, I, P)$
T	water temperature
I and I_{opt}	light intensity and optimal light intensity for phytoplankton growth
k_{ra}	rate coefficient for phytoplankton loss by mortality, respiration and excretion $k_r(T)$
v_a, v_e and v_h	sedimentation rate of phytoplankton and insoluble phosphorus in epilimnion and hipolimnion layers
A_t	thermocline surface
V_e and V_h	epilimnion and hipolimnion volumes
W_{se}, W_{ie}, W_{sh} and W_{ie}	contribution of both phosphorus forms in epilimnion and hipolimnion layers
Q	transit flow
v_t	rate coefficient for transfer by the thermocline layer
k_{te} and k_{th}	coefficient of phosphorus transformation from insoluble in soluble form
U_P	maximum rate of phosphorus uptake
f_P and f_{IP}	the influence of insoluble and soluble phosphorus on the growth of phytoplankton
$P_{ie\,min}$ and $P_{ie\,max}$	minimum and maximum internal phosphorus concentration
h_e, h_h and H	epilimnion, hipolimnion and total depth of lake
k_e	light extinction coefficient
k_{SP}	half saturation constant for external phosphorus uptake
N_d	number of days since the beginning of the year
L	latitude in degrees – positive for Northern Hemisphere
k_{max}	maximum phytoplankton growth rate

3. The Stiucii Lake and the available data for this study

In Apuseni Mountains, more than half of Romanian swamps are found, due to the favorable geological substrate (rich in siliceous rocks), low annual medium temperatures (1-6ºC), heavy rainfall (annual medium values of 800 - 1000 mm) and essentials conditions for appearance and development of sphagnum.

In this area, two large regions of swamps are delimited. The most important one is Molhasul Mare from Izbuc (also known like Swamp Lakes), recognized as natural reservation. It is found on the right side of Izbuc valley, which is a Somesul Cald tributary, at an altitude of about 1000m, has an oval shape and a surface of approximately 8 ha. In this swam, 21 small lakes have been identified. The deepest one is Stiucii Lake, formed as a result of tectonic phenomenon.

The Stiucii Lake is situated on Bontului Valey, at an altitude of about 274.5 m, has an area of 57.35 ha, a medium depth of 3.123 m and the maximum one of 6.8 m. The lake is surrender by emergent vegetation and the bottom of the lake is covered by submerged higher plants, up to 2-3 m depth. During the summer, the lake presents direct thermal stratification. The thermal stratification (fig. 2a) of water and the penetration of light are the main factors that determine the dynamics of the vertical distribution of phytoplankton. The temporal variation of the amount of living algae from the phytoplankton has maximum values during the hot period of the year (June-October) (fig. 2c). The phytoplanktonic biomass and nitrogen and the total phosphorus values place the lake into eutrophic - hypeutrophic category [14].

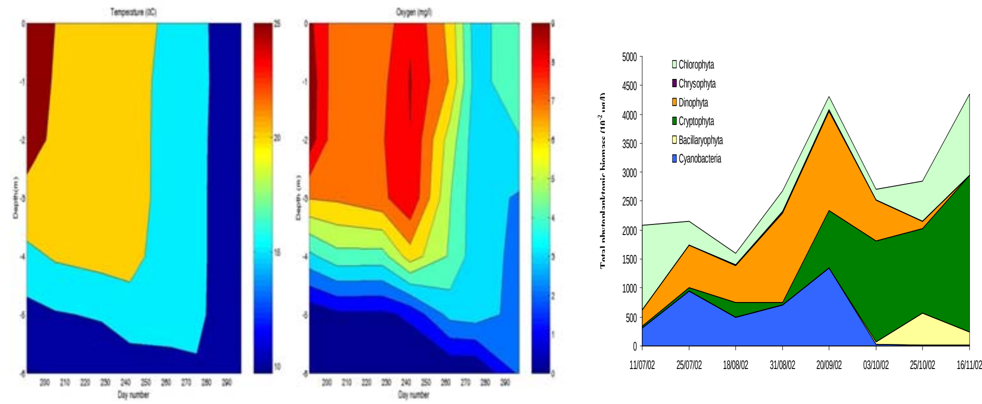


Fig. 2. Experimental values of (a) water temperature, (b) disolved oxigen and (c) phytoplankton biomass for the principals algal species in the Stiucii Lake.

The seasonal dynamics is according to the algae group succession in eutrophic natural lakes in the temperate area, characterized by a diatom spring pick followed by a decline in the hot period and then a regrowth in the autumn. The vertical distribution of phytoplankton biomass in the Stiucii Lake is influenced by the thermal stratification, which starts in June. The epilimnion is located up to 3 m depth while the termoclin has a limited thick. Thus, the phytoplankton from the two layers of the lake is different both by the biomass and by component species (fig. 3).

The general tendency of the vertical distribution of the total amount of phytoplankton is a gradual decrease from surface to the bottom of the basin. Vertical distribution of phytoplankton in Stiucii Lake is typical for moderate productive lakes, with stable summer stratification. Usually, the higher nutrients concentration is exploited by the deep communities. Thus, the presence of cyanobacteria and photosynthetic bacteria in these layers is the result of their ability to photosynthesis in low oxygen concentration and even in anoxic environments. Also, these organisms are tolerant to the presence of hydrogen sulfide in deep areas of the ecosystem and perform diurnal migration which leads to a smaller rapture by herbivorous zooplankton.

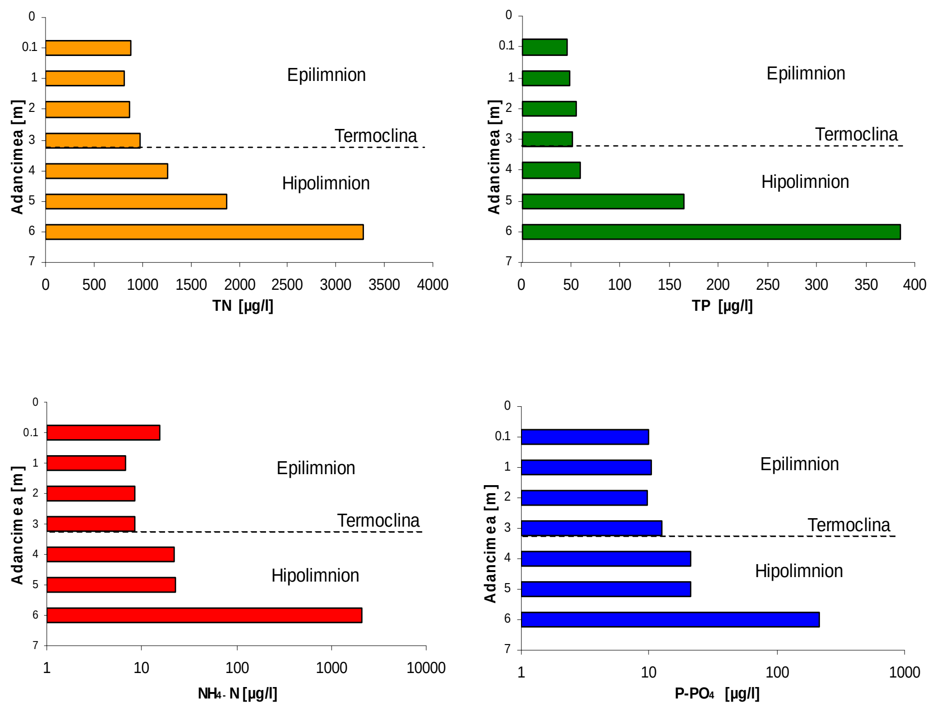


Fig. 3. Vertical distribution of a) ammoniacal nitrogen (N-NH_4), b) soluble reactive phosphorous (P-PO_4), total nitrogen (TN) and total phosphorous (TP) in Stiucii Lake in 27.07.2002.

3. Model calibration and validation

Based on the presented model, the computation of nutrients and algal biomass distributions and is done for a stratified lake and assuming that the water temperature T is variable. The model was calibrated with data from 2001 and 2002 in the Stiucii Lake. The calibration of the eutrophication model was realized by fine tuning of the model parameters within their observed literature ranges [15 - 17]. The kinetic coefficients and value used in model are presented in the Table 2. The validation of model was made for 130 days in 2002 summer, from July until November.

Table I1

The kinetics coefficients and value used in the model

Parameter	Units	Literature range [10, 11]	Assigned value
k_{max}	day^{-1}	0.7 – 2.2	1.25
$k_{sp\ P}$	$mg \cdot m^{-3}$	1 – 25	2
k_e	m^{-1}	0.01 – 0.03	0.2
I_{opt}	W/m^2	40-85	45
$P_{ie\ min}$	mgP/mgChl	0.1 – 0.5	0.85
$P_{ie\ max}$	mgP/mgChl	0.95 – 3.0	1.3
U_P	mgP/mgChl*day	0.14 – 1.0	0.3
$v_{a,}$	m/day	0 – 0.5	0.2
v_t	m/day	0.05 - 20	1.5 - winter season 0.0744 - summer season 15 - fall and spring turnover
k_{te}	day^{-1}	0.001 -0.1	0.005 - fall / spring turnover and winter season 0.068 - summer season
k_{th}	day^{-1}	0.003 – 0.07	0.005
v_e şi v_h	day^{-1}	0.05 – 0.6	0.103

Fig. 4 presents the results of phosphorous forms variations in the two layers considered. For the termoclin transfer coefficient instantaneous variation from a season to another have been admitted, which is reflected in the abrupt variation of graphics at season change. Thus, the values used for the coefficient were high for cold period and fully mixed water body conditions and small for hot season.

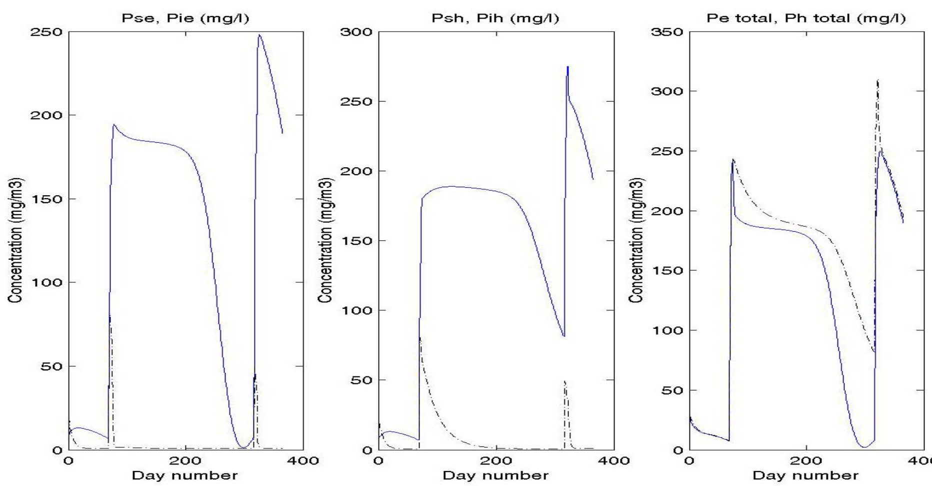
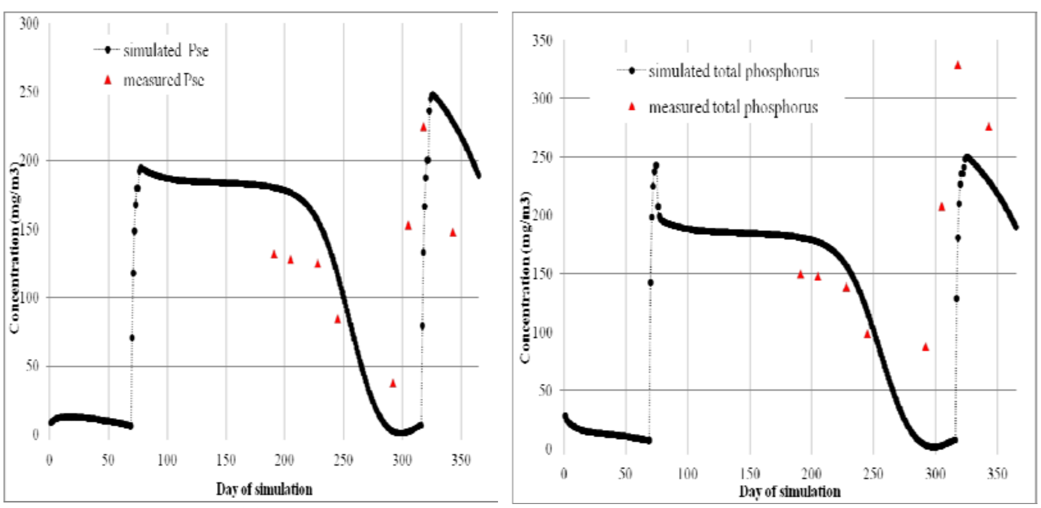


Fig. 4. Numerical spatial distribution of soluble and insoluble phosphorus in (a) epilimnion (b) hipolimnion and (c) total phosphorus for booth layer in the Stiucii Lake.

In fig. 4.(c) can be noticed that the level of total phosphorous in the hypolimnion is more stable then in the epilimnion. This is a consequence of the strong assimilation of the soluble phosphorous by plants during the hot season. Thus, the phosphorous pass into the particulate form and the insoluble fraction is increasing. The diminishing of photosynthetic processes at hypolimnion level is the reason of small variation over time of the two phosphorous forms. During the hot season, direct thermal stratification appears, the substance exchanges between the two layers are limited and, due to decomposition of insoluble phosphorous in hypolimnion, the soluble form concentration grow.

4. Discussion

The model reproduces temporal distribution of concentration of water quality constituents such as soluble phosphorus, total phosphorus and phytoplankton biomass. The comparison between simulated and observed values for Stiucii Lake is shown in Fig. 5 and 6. It can be seen that the model provides reasonable results for phytoplankton biomass, soluble reactive phosphorus and total phosphorus. The nutrients concentration is in indirect correlation with the algal production. Due to algae bloom, the nutrients concentration starts to decrease, and, when the phytoplankton peak is reach, the decomposition processes, along with the resuspension ones, generate a growth of the phosphorous concentration.



(a) (b)

Fig. 5. Measured and simulated (a) soluble phosphorus in epilimnion layer and (b) TP - total phosphorus for a one year period (2002).

During summer, the phytoplanktonic biomass is relatively low with a slight rise at the end of the period (Fig. 6) and is the result of a drop in available nutrients. The nutrients rich area, at the hypolimnion level, is practically isolated from the rest of the water body by thermocline.

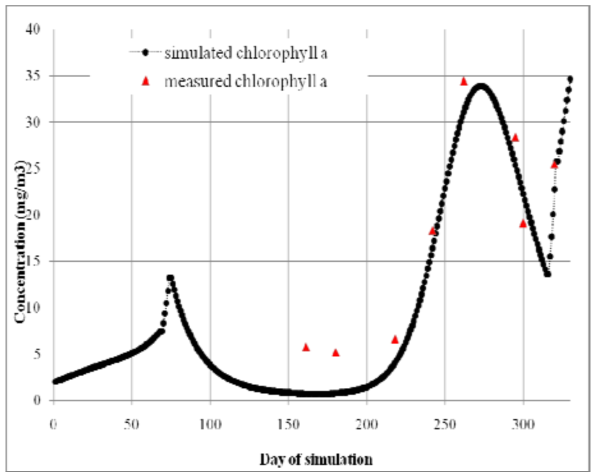


Fig. 6. Measured and simulated chlorophyll for one year period (2002).

In August and September, phytoplankton production is relatively constant, with a slight drop at the end of the period. This constant level of primary production in summer is the result of the available nutrients decrease. High value of TN:TP suggest that the phytoplankton is limited by phosphorous. Even if the phosphate is not entirely depleted, its low concentration shows this limiting tendency. However, the production has not declined very much which is probably due to the presence of a reserve of nitrogen. Although production is relatively high, phytoplankton biomass in epilimnion is low, as a result of nutrient limitation, loss by sedimentation and herbivorous zooplankton pressure. During September, the biomass increase for the same level of production. This shows that biomass losses by sedimentation are compensated by water turnover. Biomass accumulation is also a result of low density of herbivorous zooplankton and availability of important nutrients in the hypolimnion due to termoclin descent.

The autumn period is marked by fluctuation in phytoplankton biomass, thus in late September a maximum is reached followed by a slight decrease and then a continuous increase until November. Those fluctuations are due mainly to water masses circulation, a typical phenomenon for this time of year. The acute cooling registered in early September led to partial circulation of water masses. One of the consequences is the import of nutrients from the hypolimnion area, which can be observed in rising of some nutrients concentration. Further reduction in temperature causes complete turnover of water masses, a phenomenon that will characterize the period from October to November. The autumn turnover lead to apparition of algae communities adapted to more stable condition. This transition phase is marked by a slight decrease in phytoplankton biomass. Thus, dynoflagellates and cyanobacteria will be in continuous regress, being dependent on higher temperatures. Cryptophyceae, better adapted to cold weather and low light intensity, dominates the phytoplankton biomass. Beside them, chlorophyceae follow an ascending phase of biomass. Towards end of October, diatoms present a maximum of biomass.

Due to strong growth especially of diatoms, the nutrients (especially soluble phosphorus) are gradually depleted which can be seen in the decrease of production.

6. Conclusions

An ecological model was configured for the Stiucii Lake from Romania. The model was calibrated and validated with data from 2001 and 2002 in the analyzed lake. The food web structure of the model makes it possible to relate alternative managerial scenarios and associated nutrient loadings with compositional shifts in the plankton community.

The model reproduces spatial and temporal concentration distribution of water quality constituents such as differed forms of phosphorus and phytoplankton biomass. The calibrated models were used to evaluate the lake restoration possibilities and to improve the water quality from a eutrophic condition to oligotrophic condition in the Stiucii Lake.

The comparison between calculated results and field data are reasonably consistent. The values of the kinetic coefficients obtained from model calibration and validation analyses are consistent with the values reported in the literature.

Analyzing the recorded data and the numerical results allow to appreciate that the eutrophication phenomenon is related to large amount of phosphorus.

Successful protection of Stiucii Lake from non-point external loading may appear to be difficult, especially when drainage area greatly exceeds lake area and there are many sources of potential soil and nutrient loss. Nevertheless, there are several methods with great potential to significantly lower non-point loading of silt and nutrients. These methods all require work in the drainage area itself, meaning that lake manager often have to become land managers and terrestrial ecologists as well.

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