Working Paper

SIMULATION AND ANALYSIS OF PHOSPHORUS TRANSFORMATION AND PHYTOPLANKTON DYNAMICS IN RELATION TO THE EUTROPHICATION OF LAKE BALATON

A.V. Leonov

May 1980
WP-80-88

International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria

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PREFACE

One of the principal themes of the Task on Environmental Quality Control and Management in IIASA's Resources and Environment Area is a case study of eutrophication management for Lake Balaton, Hungary. The case study is a collaborative project involving a number of scientists from several Hungarian institutions and IIASA. This paper, originally prepared for the Second ISEM Conference on the State-of-the-Art in Ecological Modelling (Liege, Belgium, April, 1980), is a further contribution to the Lake Balaton case study. It describes a mathematical model of phosphorus transformation processes and phytoplankton growth in the lake. As such, the model presented here is one of three models currently being developed for the analysis of data characterizing recent variations of water quality within the lake. Results are reported for a comparison of the performance of the model with observations recorded for 1977.

SUMMARY

A mathematical model of phosphorus transformations has been applied to a real set of physical, biological, chemical observation data in Lake Balaton. The model includes dissolved oxygen and five phosphorus forms in water environments: phytoplankton phosphorus, bacterial phosphorus, dissolved inorganic phosphorus, dissolved organic phosphorus, and unliving particulate phosphorus, and also three phosphorus forms in interstitial water: inorganic, organic, and particulate phosphorus fractions.

The purpose of this report was to present the best possible calibration between existing observation data from 1977 and model output. This is one of the important steps that must be performed before application of the model for prediction and management purposes.

Hypothesis about three populations of phytoplankton give a model output that agreed reasonably well with the observation data for total P, dissolved P, dissolved organic and inorganic phosphorus, particulate organic phosphorus, and phytoplankton chlorophyll "a" in all basins simultaneously. This provides indirect evidences that the model considered is a reasonable representation of a complex ecological process in phosphorus transformation and phytoplankton dynamics in Lake Balaton.

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BACKGROUND

Lake Balaton is a large shallow lake in Central Europe. It is situated in the west part of Hungary. Surface area of the lake is about 600 km^2. The lake is 75 km long and 8 km wide. The average depth is about 3 m. and only in a small portion of the lake, divided by the peninsula of Tihany, the depths of the lake reach 11-12 m. Lake Balaton receives drainage from a catchment area almost ten times bigger than the water body itself, i.e., 5,775 km^2 (van Straten, et. al., 1979).

The river Zala is the major tributary to Lake Balaton and enters the water body at its southwestern part. It receives mainly agricultural runoff and some domestic and industrial disposals from a total catchment area of the river Zala watershed, 2,622 km^2. Significant nutrient loading to Lake Balaton results from the Zala River contributions because this river gives about 50-75% of the total inflow (Csaki et. al., 1978; van Straten, et. al., 1979). Other important tributaries enter the lake in its central part. The water outflow of Lake Balaton is regulated by a special gate at the northeastern end of the lake.

Lake Balaton is a typical example of a water body with changeable eutrophic conditions in different parts of the lake. The eutrophication of Lake Balaton is attributed to phosphorus and in a smaller degree to nitrogen loadings of the Zala River water flow discharge. The Zala River enters Lake Balaton in the shallow Keszthely Bay and the effect of the river is felt not only within the bay itself, but also in the next basin of Lake Balaton, i.e., Szigliget. In the last two basins, Szemes and Siófok, the effect of the Zala River may be considered quite low. The resultant situation is the decreasing eutrophic conditions from southwestern to northeastern ends of the lake.

During the last years, the water body eutrophication as an actual limnological problem became a subject of many special studies with the help of mathematical models of different degrees of complexity. The main purpose of these studies to quantify impacts and assess alternative control strategies in terms of biogenic element balances in various water bodies.

The special project named "The Lake Balaton Case Study" was initiated at the International Institute for Applied Systems Analysis in 1978. The general objectives of the project are development and application of improved ecological models with special reference to understanding and management of eutrophication processes in Lake Balaton. At the first step of study the main attention was given to the construction of phosphorus models since phosphorus is a key element of Lake Balaton eutrophication.

Comparatively simple phosphorus models used for the study of eutrophication take into account a limited number of phosphorus forms, usually total phosphorus or just two phosphorus fractions, particulate and dissolved phosphorus. Models with a limited number of phosphorus forms have been applied for studying less eutrophic water when sediments do not exert a significant influence on phosphorus cycling in water environment (Lung, et. al., 1976).

However, a much better understanding of the relationship between phosphorus input to a lake and phosphorus transformation processes in the aquatic-ecological system may be attained with the help of models constructed on the basis of synthesis of biological and chemical models. This type of models include several phosphorus forms, chemical as well as biological. Using this type of model it is possible to explain the dynamics of phosphorus in microorganism cells and concentration changes of each of the chemical forms of phosphorus present in the water and also the rates of phosphorus interchange between various forms including biological and chemical. This type of model is very useful for studying complex processes in conjunction with eutrophication such as phosphorus releases from sediment to overlying water, phosphorus loading from a watershed, phosphorus regeneration by microorganisms and others. An importnat stage in understanding the water body eutrophication is to quantify the rates of these processes and establish interaction which plays a significant role in phosphorus transformations. It is a complex problem setting which the model described in this report is specifically addressed.

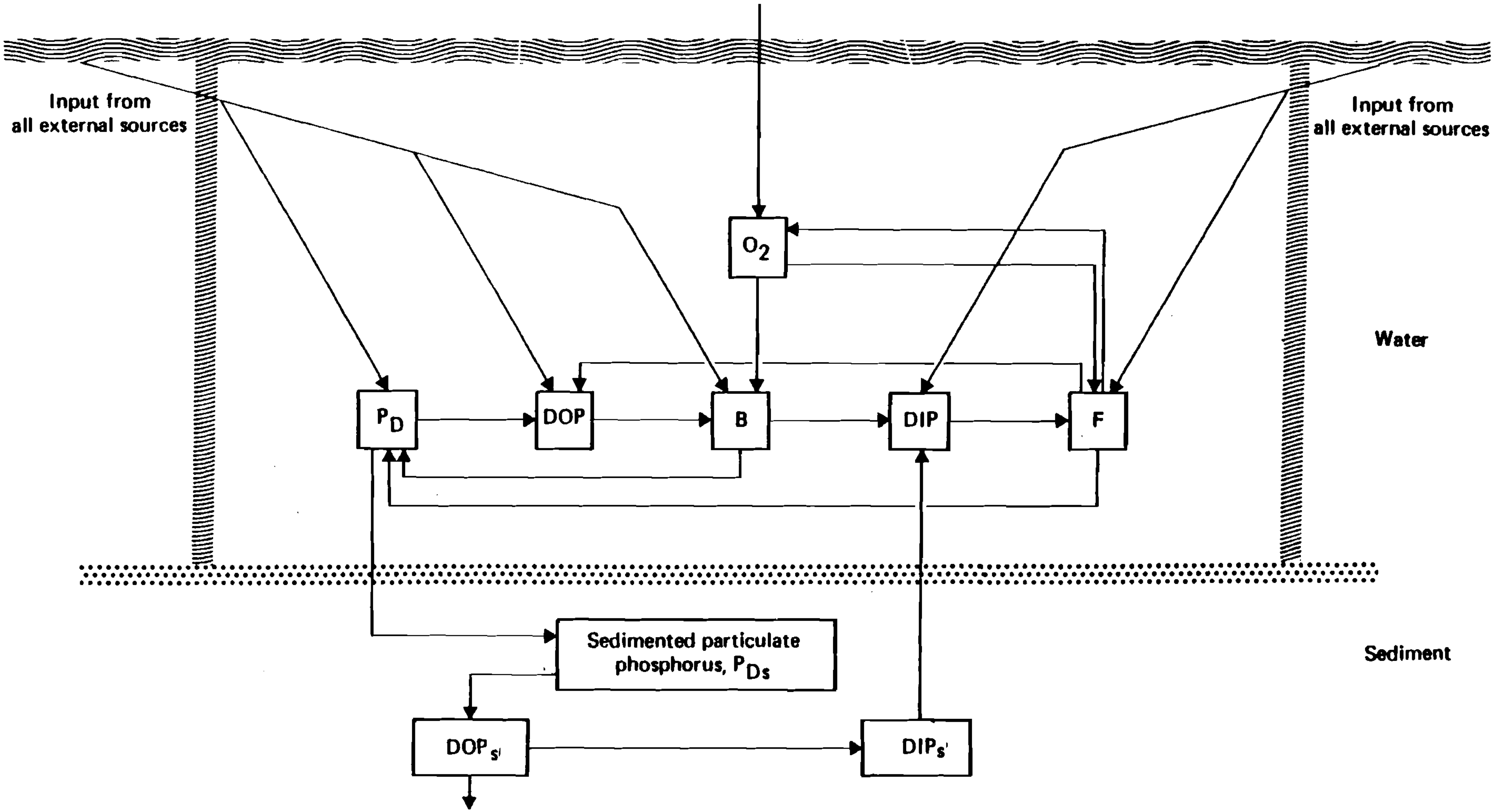
MODEL DESCRIPTION

The phosphorus transformation processes that develop in water environments depend on the interactions between biological and chemical phosphorus compounds. These interactions determine the transport of phosphorus from one form to another and, in one's turn, they are defined by kinetics of growth, mortality and total metabolism of microorganisms and nutrient recycling as a whole.

The structure of the phosphorus transformation and oxygen cycle model is shown in Figure 1. The next model compartments considered for a water environment are dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP), phytoplankton phosphorus (F), bacterial phosphorus (B), nonliving particulate phosphorus (P_D), and dissolved oxygen (O_2). Because the sediment-water interactions are a very important factor in the aquasystem of Lake Balaton that regulate the nutrient content and enrichment of water body by DIP, the model includes phosphorus forms in sediment, namely dissolved inorganic phosphorus (DIP_s), dissolved organic phosphorus (DOP_s), and nonliving particulate phosphorus (P_{Ds}) in interstitial water sediment.

Phytoplankton growth kinetics is a function of water temperature, incident solar radiation, and nutrient concentration, specifically DIP. Bacterial growth kinetics is a function of water temperature and DOP

Figure 1. Diagram of compartments of phosphorus transformation and oxygen cycle model.



concentration. These microorganisms also uptake oxygen in respiration processes. The nutrients which are results of microorganism activity, recycle from unliving particulate and soluble organic phosphorus forms to inorganic phosphorus. The kinetics of recycle processes are temperature dependent. The model takes into account the inputs of phosphorus forms from watershed areas and the loss of unliving particulate phosphorus by sedimentation. The dissolved oxygen is the result of phytoplankton production and reaeration that is considered to be a temperature-dependent process.

The model is constructed on the basis of mass conservation principles for each model compartments which are given by a set of coupled ordinary differential equations. All mass balance equations of the model considered are presented in Table 1.

Magnitudes of the rate constants for the kinetic terms in the mass balance equations are obtained by calibration of the model using a set of data observations which include: total phosphorus, total dissolved phosphorus, orthophosphate phosphorus, particulate inorganic phosphorus, and phytoplankton chlorophyll"a". Concentration of other phosphorus compounds important in the study and simulation of phosphorus transformations were received from these measured phosphorus quantities by difference calculations. These are dissolved organic phosphorus, particulate phophorus, and particulate organic phosphorus. In the first instance of model application the rate constants were chosen so that the model can reproduce the observed behavior of phosphorus compounds and phytoplankton in the most polluted area of Lake Balaton in 1977 (Leonov, 1980a). It was a preliminary test of a phosphorus model. In this report results of model application for simultaneous modeling phosphorus transformation in different basins of Lake Balaton in 1977 are presented.

SEGMENTATION OF LAKE BALATON

The phosphorus model built for Lake Balaton is applied in simultaneous simulation of phosphorus compounds and phytoplankton dynamics in various basins of the water body. Subdivision of Lake Balaton basins is shown in Figure 2. The structure reflects the four characteristic basins in the lake: I - Keszthely Bay, II - Szigliget Basin, III - Szemes Basin, and IV - Siófok Basin.

Each basin within the lake is reproduced in the model as a completely mixed system similar stirred tank reactor. Because the lake

Table 1. Mass balance equations for phosphorus transformation model of Lake Balaton.

Constituent	Symbol	Equations
Phytoplankton-P, mg P/l	F	$\frac{dF}{dt} = \underbrace{(UP_F - L_F - M_F)F}_{\textit{net growth}} + \underbrace{(Q_{in}/V) \cdot F^0}_{\textit{input by water flow}}$ $- \underbrace{(Q_{out}/V) \cdot F}_{\textit{output by water flow}} ,$ where $UP_F = \frac{K_1 \cdot R_{TF} \cdot R_{IF}}{1 + \frac{F}{\beta \cdot DIP}} ,$ $L_F = r_F \cdot UP_F ,$ $r_F = \frac{\frac{a_1}{a_2} \cdot UP_F}{\frac{1}{a_2} + UP_F} + (1 - \frac{a_1}{a_2}) ,$ $M_F = \frac{v_1 \cdot F}{UP_F} .$
Bacterial-phosphorus, mg P/l	B	$\frac{dB}{dt} = \underbrace{(UP_B - L_B - M_B) \cdot B}_{\textit{net growth}} + \underbrace{(Q_{in}/V) \cdot B^0}_{\textit{input by water flow}}$

Constituent	Symbol	Equations
		$- \underbrace{(Q_{out}/V) \cdot B}_{\text{output by water flow}}$
		where
		$UP_B = \dfrac{K_2 \cdot R_{TB}}{1 + \dfrac{B}{DOP}}$,
		$L_B = r_B \cdot UP_B$,
		$r_B = \dfrac{\dfrac{a_3}{a_4} \cdot UP_B}{\dfrac{1}{a_4} + UP_B} + (1 - \dfrac{a_3}{a_4})$,
		$M_B = v_2 + \dfrac{v_3 \cdot B}{UP_B}$.
Dissolved inorganic phosphorus, mg P/l	DIP	$\dfrac{dDIP}{dt} = \underbrace{L_B \cdot B}_{\text{bacterial excretion}} - \underbrace{UP_F \cdot F}_{\text{phytoplankton uptake}} + \underbrace{CZ_3}_{\text{external input}}$
		$+ \underbrace{s_2 \cdot DIP_s}_{\text{sediment release}} + \underbrace{(Q_{pr}/V) \cdot DIP_r}_{\text{input with rain water}} + \underbrace{(Q_{in}/V) \cdot DIP^0}_{\text{input by water flow}}$

Constituent	Symbol	Equations
		$\underset{\text{output by water flow}}{- (Q_{out}/V) \cdot DIP}$.
Dissolved organic phosphorus, mg P/1	DOP	$\frac{dDOP}{dt} = \underset{\text{detritus decay}}{K_3 \cdot P_D} + \underset{\text{phytoplankton excretion}}{L_F \cdot F} - \underset{\text{bacterial uptake}}{UP_B \cdot B} + \underset{\text{external input}}{CZ_4}$ $+ \underset{\text{input with rain water}}{(Q_{pr}/V) \cdot DOP_r} + \underset{\text{input by water flow}}{(Q_{in}/V) \cdot DOP^0} - \underset{\text{output by water flow}}{(Q_{out}/V) \cdot DOP}$.
Unliving particulate phosphorus, mg P/1	P_D	$\frac{dP_D}{dt} = \underset{\text{phytonplankton mortality}}{M_F \cdot F} + \underset{\text{bacterial mortality}}{M_B \cdot B} - \underset{\text{decay}}{K_3 \cdot P_D} - \underset{\text{sedimentation}}{s_1 \cdot P_D}$ $+ \underset{\text{external input}}{CZ_5} + \underset{\text{input by water flow}}{(Q_{in}/V) \cdot P_D^0} - \underset{\text{output by water flow}}{(Q_{out}/V) \cdot P_D}$.
Dissolved oxygen, mg O_2/1	O_2	$\frac{dO_2}{dt} = \underset{\text{photosynthesis}}{g_1 \cdot UP_f \cdot F} - \underset{\text{reaeration}}{K_4(O_2 - O_2^{sat})} - \underset{\text{bacterial respiration}}{h_1 \cdot L_B \cdot B}$ $- \underset{\text{phytoplankton respiration}}{h_2 \cdot L_F \cdot F} + \underset{\text{input by water flow}}{(Q_{in}/V) \cdot O_2^0} - \underset{\text{output by water flow}}{(Q_{out}/V) \cdot O_2}$.

Constituent	Symbol	Equations
Unliving particulate phosphorus in sediment, mg P/l	P_{Ds}	$\frac{dP_{Ds}}{dt} = \underbrace{s_1 \cdot P_D}_{\textit{sedimentation}} - \underbrace{s_3 \cdot P_{Ds}}_{\textit{decay}} .$
Dissolved organic phosphorus in sediment, mg P/l	DOP_s	$\frac{dDOP_s}{dt} = \underbrace{s_3 \cdot P_{DS}}_{\textit{oxidation}} - \underbrace{s_4 \cdot DOP_s}_{\textit{decay}} - \underbrace{CZ_6}_{\textit{conservation in sediment}} .$
Dissolved inorganic phosphorus in sediment, mg P/l	DIP_s	$\frac{dDIP_s}{dt} = \underbrace{s_4 \cdot DOP_s}_{\textit{organic P oxidation}} - \underbrace{s_2 \cdot DIP_s}_{\textit{sediment release}} .$

Temperature dependent parameters:

Constituent	Symbol	Equations
Temperature reduction factor for phytoplankton uptake rate (undimensional)	R_{TF}	$R_{TF} = w_s \cdot \max\left[0, \frac{T_{cr} - T}{T_{cr} - T_{opt}} \exp\left(1 - \frac{T_{cr} - T}{T_{cr} - T_{opt}}\right)\right]$

where

w_s is the height of function peak changed in range 0-1 ;

$\left.\begin{array}{l} T_{cr} \\ T_{opt} \end{array}\right\}$ are critical and optimal temperatures for certain phytoplankton groups ;

Constiuent	Symbol	Equations
		$w_s = 0.45$, $T_{cr} = 11.5^0C$, $T_{opt} = 8.5^0C$ } for winter-spring phytoplankton group $w_s = 1.0$, $T_{cr} = 29^0C$, $T_{opt} = 26^0C$ } for summer phytoplankton group
		$R_{TF} = 0.2 + \frac{0.022(e^{0.21T} - 1)}{1 + 0.028\ e^{0.21T}}$ } for autumn phytoplankton group .
Temperature reduction factor for bacterial uptake rate (undimensional)	R_{TB}	$R_{TB} = 0.3 + \frac{3.68 \cdot 10^{-3}(e^{0.403T} - 1)}{1 + 5.25 \cdot 10^{-3}e^{0.403T}}$.
Decompostion rate of nonliving particulate-P to DOP (day^{-1})	K_3	$K_3 = \frac{1.2 \cdot 10^{-4}(e^{0.351T} - 1)}{1 + 3 \cdot 10^{-4}e^{0.351T}}$.
Reaeration rate (day^{-1})	K_4	$K_{4(T)} = K_{4(20^0)} \cdot 1.05^{(T-20)}$.
Saturation oxygen level (mg O_2/l)	$O_2^{s\ t}$	$O_2^{sat} = 14.61996 - 0.4042 \cdot T + 0.00842 \cdot T^2 - 0.00009 \cdot T^3$.
Oxidation rate of P_{Ds} to DOP_s (day^{-1})	s_3	$s_{3(T)} = s_{3(20^0)} \cdot 1.05^{(T-20)}$,

where

T is water temperature in ^0C.

Constituent	Symbol	Equations
Light function for phytoplankton:		
Light reduction factor for phytoplankton uptake rate (undimensional)	R_{IF}	$R_{IF} = \frac{e}{K_e \cdot h}[\exp(-rx) - \exp(-rl)]$, where $rx = \frac{I}{I_{opt}}[\exp(-K_e \cdot h)]$ (h = 0.5 m) ; $rl = \frac{I}{I_{opt}}$ ($I_{opt} = 350$ cal/cm^2-day) .
Daily course of light intensity (cal/cm^2-day)	I	$I = I_{max} \cdot h[1 + \cos\frac{2\pi(t_{now} - t_{peak})}{f}]$, where t_{now} is current time of day in hours; t_{peak} is time of maximum light intensity (12 o'clock); f is photoperiod in hours.
Maximum light intensity (cal/cm^2-day)	I_{max}	$I_{max} = 2 \cdot I_{av}/f$,

Constituents	Symbol	Equations
		where
		I_{av} is mean daily light intensity ,
Light extinction coefficient (m^{-1})	K_e	$K_e = K_a + K_b \cdot \mu gChl"a"/l$.

The following are terms not earlier defined:

K_1 and K_2 are maximum uptake rates of nutrients by phytoplankton and bacteria, respectively, (day^{-1}) ;

s_1 is sedimentation rate (day^{-1}) ;

s_2 is release rate of DIP from sediment (day^{-1}) ;

a_1 and a_2 are coefficients that define efficiency of DOP excretion by phytoplankton (day) ;

a_3 and a_4 are coefficients that define efficiency of DIP excretion by bacteria (day) ;

v_1 and v_3 are coefficients that regulate the phytoplankton and bacterial mortality, respectively, as a function of their biomass and nutrient content $[(mg\ P/l)^{-1} \cdot day^{-2}]$;

v_2 is rate of natural mortality of bacteria (day^{-1}) ;

Constituents	Symbol	Equations

UP_F and UP_B are specific uptake rates of nutrients by phytoplankton and bacteria (day^{-1}) ;

L_F and L_B are specific excretion rates of nutrients by phytoplankton and bacteria (day^{-1}) ;

M_F and M_B are specific mortality rates of phytoplankton and bacteria (day^{-1}) ;

Q_{in}, Q_{out}, and Q_{pr} are input, output flow rates and precipitation rate, respectively, (all m^3/day) ;

DIP_r and DOP_r are concentrations of DIP and DOP in rain water (mg P/l) ;

CZ_3, CZ_4, and CZ_5 are direct loading rates of DIP, DOP, and P_D from all external sources (all mg P/l-day) ;

CZ_6 is conservation rate of DOP in sediment (mg P/l-day) ;

g_1 is regulator of photosynthesis rate by daily course of radiation:

$$g_1 = \begin{cases} g_2 \text{ for light hours of day} \\ 0 \text{ for night hours of day} \end{cases} ;$$

h_1 and h_2 are stoichiometric coefficients ;

F^0, B^0, $P_D{}^0$, DIP^0, DOP^0, and $O_2{}^0$ are concentrations of model compartments in a former basin (all mg/l) .

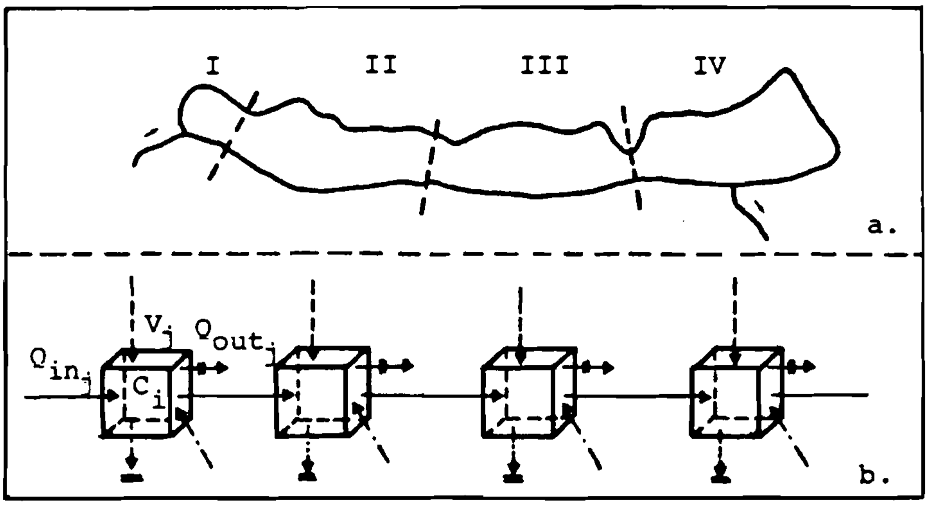


Figure 2. Subdivision of Lake Balaton by basins (a) and schematic presentation for calculating the concentration distributions:

j is number of basins ,

V_j is volume of each basin ,

Q_{in_j} and Q_{out_j} are characteristics of net water advective transport , and

C_i is concentration of specific constituents.

——→	input of C_i by water flow ;
----→	input of C_i by precipation ;
—∘—→	input of C_i from other sources (e.g., watershed runoff) ;
—‖—→	output of C_i by water flow ;
·····→	output of P_D by sedimentation.

is shallow concentrations of all compounds mentioned above are considered as average for a water volume of each basin as a whole. It was assumed that transport of all compounds in the space between each basin takes place by means of advective transport. Effect of mixing between adjacent basins is ignored in the given model.

DATA AND FORCING FUNCTIONS

Since the ecological system under consideration includes physical, chemical, and biological processes the interactions between them are extremely important. Detailed analysis of all Lake Balaton observation data available at IIASA were presented by van Straten et. al. (1979). These data include not only phosphorus measurements in different basins of Lake Balaton but also: (1) daily magnitudes of temperature and light intensity; (2) weekly measurements of dissolved inorganic and particulate phosphorous fractions and phytoplankton chlorophyll-a in the Zala River water discharged in Lake Balaton; (3) water balance data that include weekly measurements of discharge flow rates of the Zala River, and monthly calculated values of flow input-output rates and precipitation rates for all basins of Lake Balaton.

Before model application, various quantities known as forcing functions must be specified. External nutrient loads are important forcing functions in the present study and they were taken from the report by van Straten et. al. (1979). Magnitudes of all rate constants in mass balance equations are presented in a special report that generalizes the results of the study of phosphorus transformation in Lake Balaton for 1977 (Leonov, 1980b).

MODELING RESULTS OF PHOSPHORUS TRANSFORMATION

The Runge-Kutta - 4 method was used to solve the differential model equations with a constant time step equal to 0.1 day. The oxygen cycle in the water environment and phosphorus transformation in sediment were not considered at this step of the study because the information about these processes is not sufficient for modeling.

Simulation results of phosphorus transformation in water environment for different basins of Lake Balaton are presented in Figures 3-6. All measurements are shown in these figures by points, while curves are simulation results. These model outputs are only an attempt to describe an existing set of observed data for 1977. At the present study step the model is not intended to be used for predictive purposes.

For obtaining model outputs for chlorophyll"a", the phytoplankton biomasses were converted from phosphorus units to chlorophyll"a" centrations with the help of a simple ratio:

$$\mu g \, Chl"a"/l = 2{,}100 \; mg \; P/l \quad .$$

Preliminary simulation results for phytoplankton chlorophyll"a" dynamics in Keszthely Bay (Basin I) showed that the model output was almost 2-2.5 time higher than the data during summer months (Leonov, 1980a). This problem has been eliminated in the present work by using the hypothesis of three phytoplankton groups characterized for winter-spring, summer, and autumn periods (Herodek, 1979). These phytoplankton groups have various temperature dependencies. Summer phytoplankton population also have higher nutrient requirements than winter-spring and autumn phytoplankton groups. In this case, the calculated concentrations of phosphorus compounds and phytoplankton chlorophyll"a" agree reasonably with data of measurements considering the precision of the chemical and biological analytical techniques. Also in the model the effect of wind on the Lake Balaton ecosystem behavior is not taken into account and in the periods of strong storms, when concentrations of particulate inorganic phosphorus (this phosphorus fraction is not taken into consideration by the model), in the water environment can increase 2-3 times there are differences between model output and data. However, the general pattern of observations in all basins of Lake Balaton are reproduced by model.

In accordance with the general eutrophication research of the Lake Balaton Project, it is interesting at this step of study to examine and compare the role of different ecological processes in phosphorus transformation for various basins within Lake Balaton. The simulation results presented in Figures 3-6 were used to assess the contributions of main ecological processes considered by the model in phosphorus transformations and its seasonal cycling. The data of these calculations are shown in Table 2. The data provide a preliminary basis for estimating and understanding the role and the efficiency of external P-loading and internal phosphorus transformation processes in a general direction of eutrophication changes in individual basins of Lake Balaton.

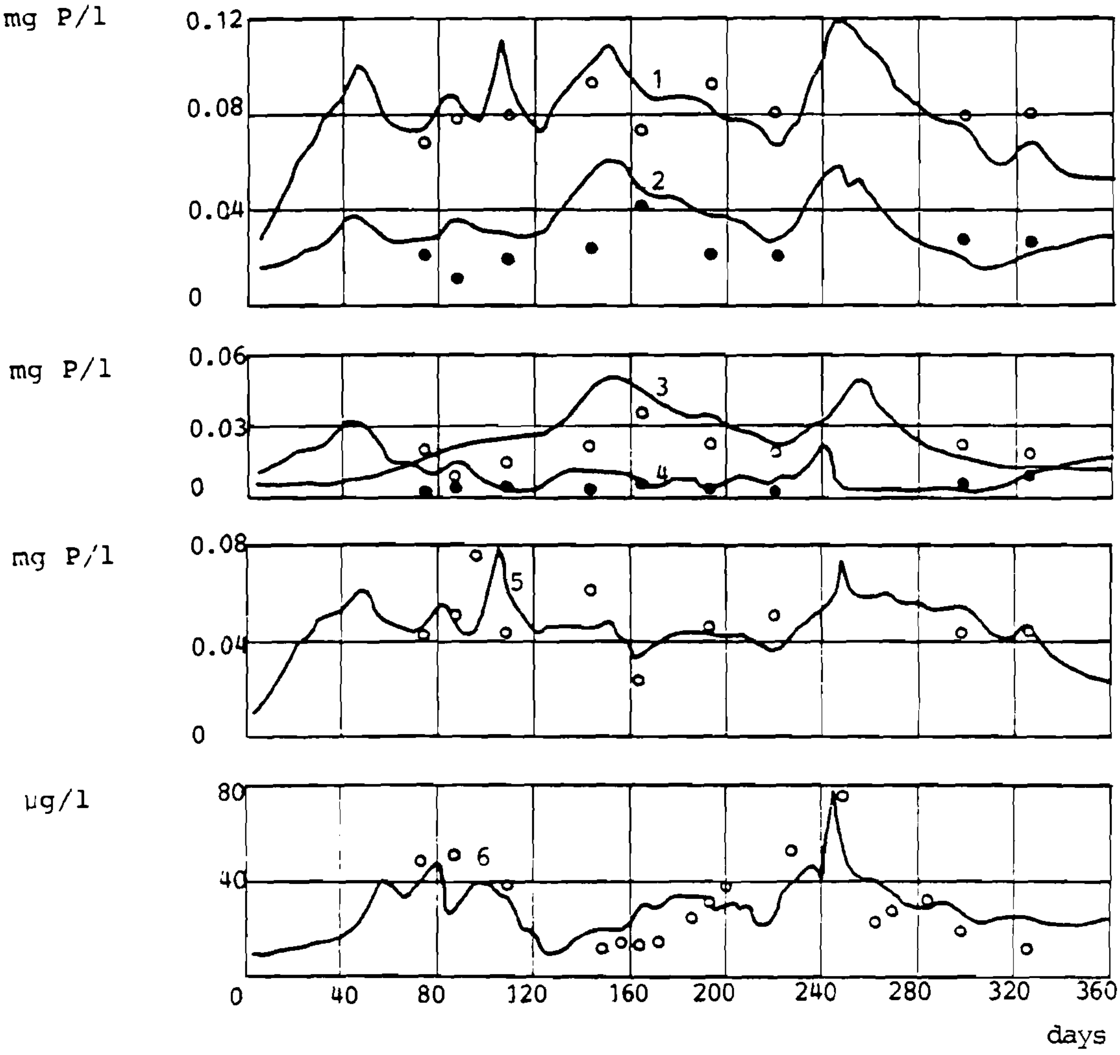


Figure 3. Comparison between model output (curves) and field data (points). Lake Balaton, Keszthely Bay, 1977.

1. total phosphorus (o)
2. dissolved phosphorus (●)
3. DOP (o)
4. DIP (●)
5. particulate organic phosphorus
6. phytoplankton chlorophyll "a"

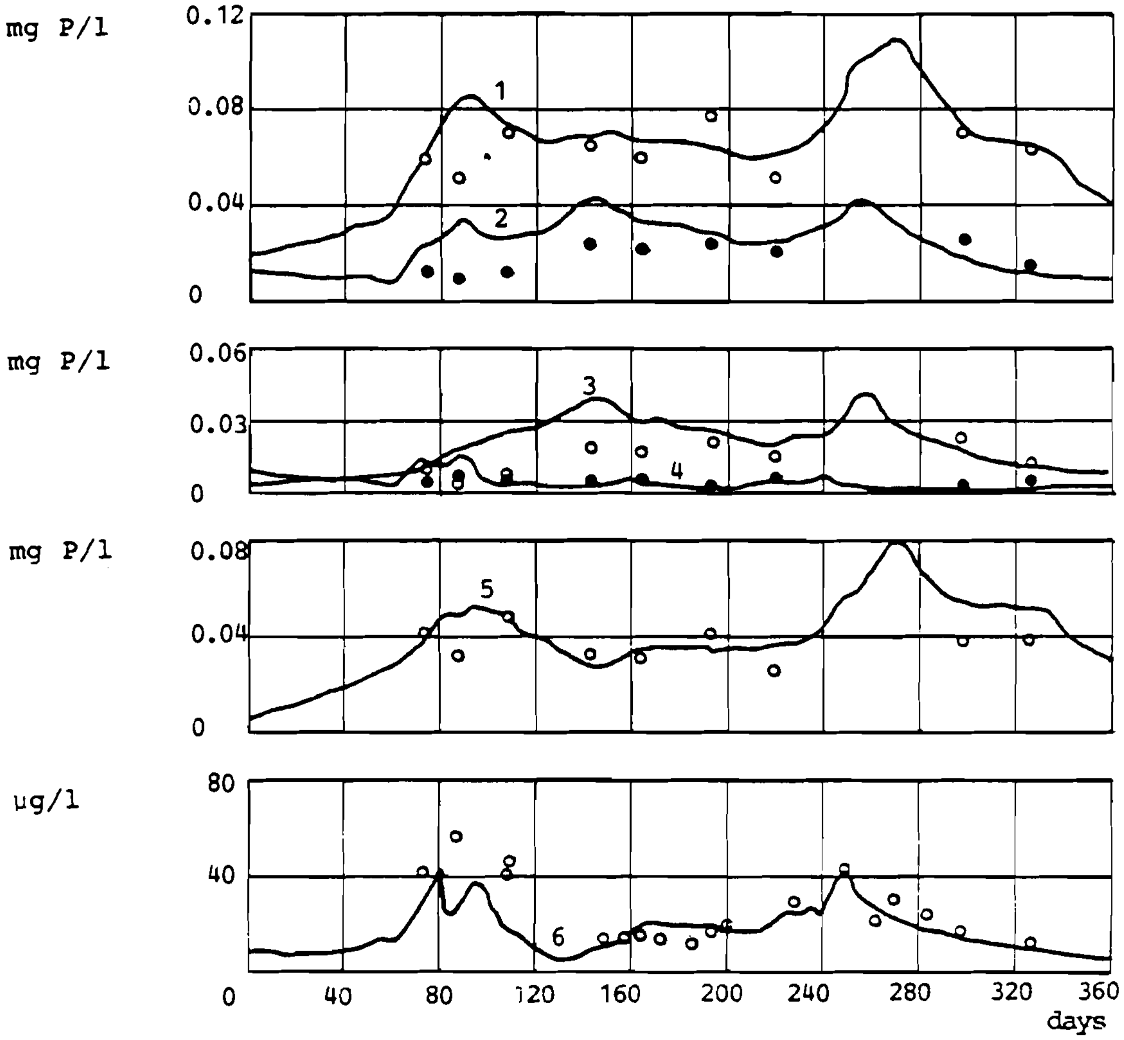


Figure 4. Comparison between model output (curves) and field data (points). Lake Balaton, Szigliget Basin, 1977.

1. total phosphorus (o)
2. dissolved phosphorus (●)
3. DOP (o)
4. DIP (●)
5. particulate organic phosphorus
6. phytoplankton chlorophyll "a"

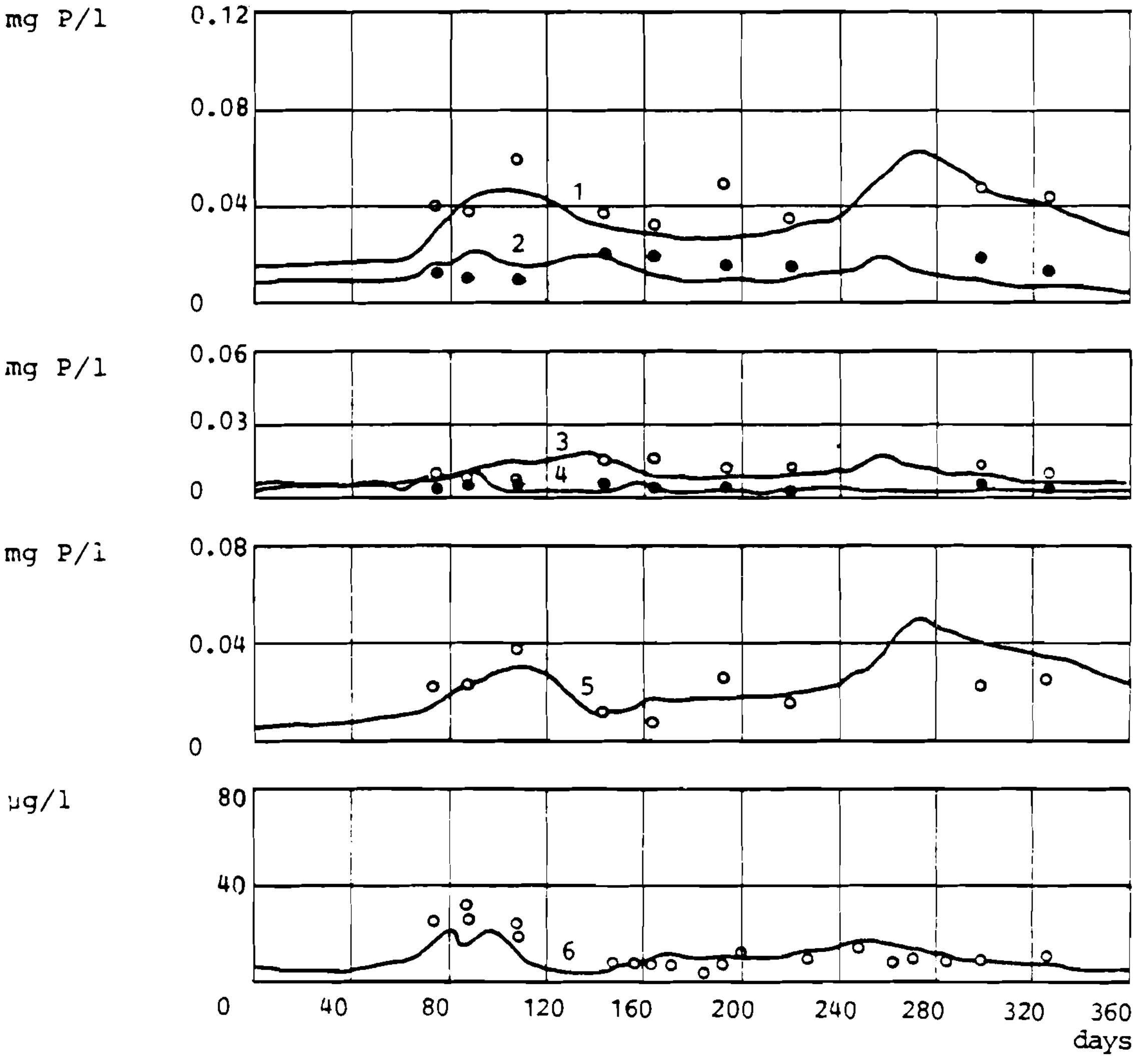


Figure 5. Comparison between model output (curves) and field data (points). Lake Balaton, Szemes Basin, 1977.

1. total phosphorus (o)
2. dissolved phosphorus (●)
3. DOP (o)
4. DIP (●)
5. particulate organic phosphorus
6. phytoplankton chlorophyll "a"

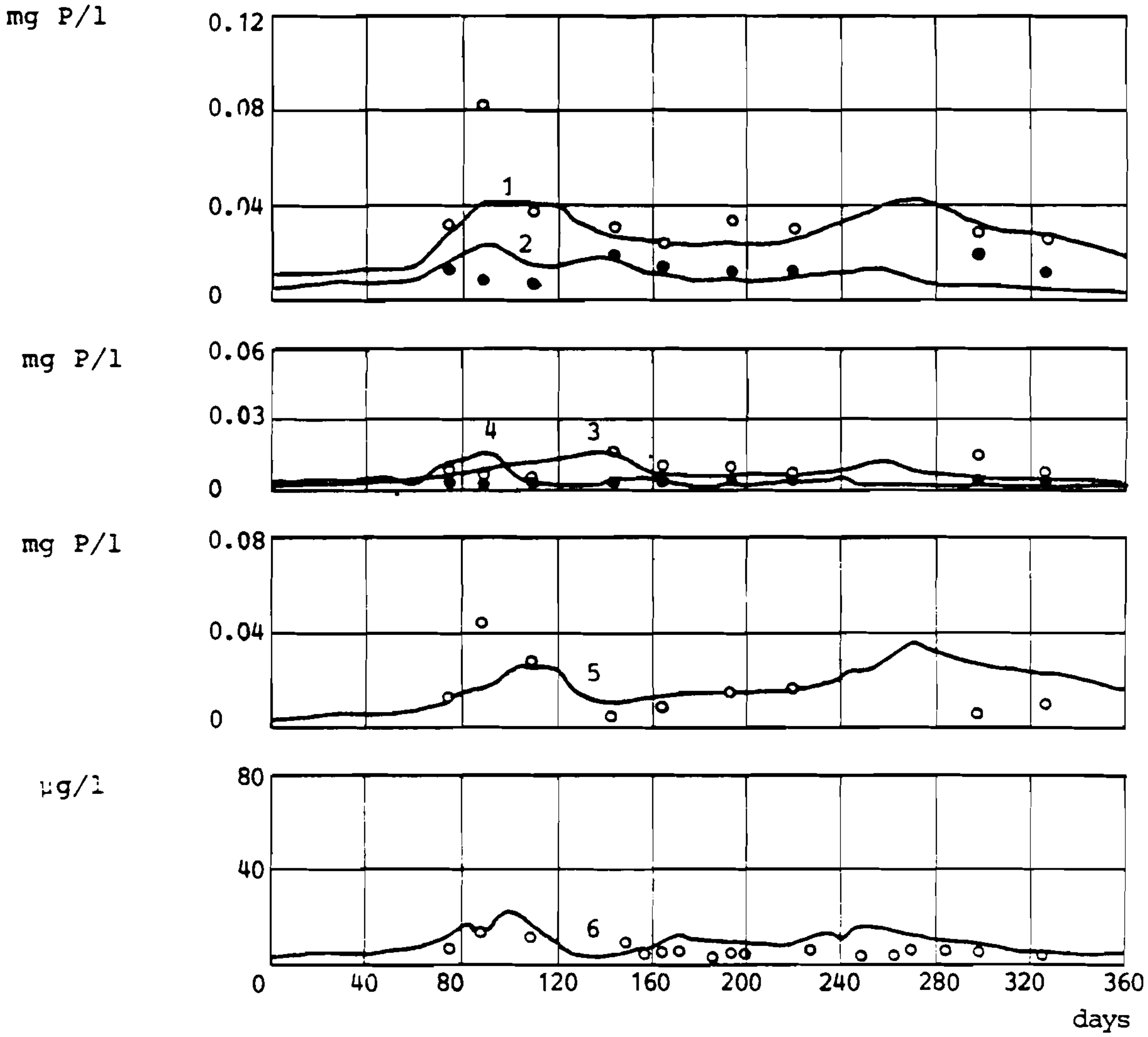


Figure 6. Comparison between model output (curves) and field data (points). Lake Balaton, Siófolk Basin, 1977.

1. total phosphorus (o)
2. dissolved phosphorus (●)
3. DOP (o)
4. DIP (●)
5. particulate organic phosphorus
6. phytoplankton chlorophyll "a"

Table 2. Contributions of different ecological processes in material phosphorus flow, (mg P/l) for Lake Balaton basins, 1977. (*denotes inflow from Zala river to Keszthely Bay)

Process	Water transfer of P_D				Water transfer of DIP				Water transfer of DOP				Water transfer of F and B			
Basins / Seasons	I*	II	III	IV	I*	II	III	IV	I*	II	III	IV	I*	II	III	IV
Spring	.2303	.0069	.0056	.0016	.1079	.0019	.0014	.0008	.0000	.0049	.0040	.0014	.0214	.0029	.0020	.0009
Summer	.0224	.0015	.0012	.0003	.0927	.0009	.0003	.0001	.0000	.0037	.0024	.0004	.0043	.0030	.0019	.0005
Autumn	.0356	.0026	.0035	.0014	.0856	.0005	.0001	.0001	.0000	.0020	.0017	.0004	.0035	.0021	.0014	.0006
Annual	.5590	.0196	.0145	.0048	.3880	.0087	.0033	.0022	.0000	.0124	.0097	.0032	.0431	.0105	.0067	.0028
Process	Phytoplankton mortality				Bacterial mortality				P_D decomposition to DOP				DOP uptake by bacteria			
Basins / Seasons	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Spring	.1134	.0616	.0295	.0273	.0087	.0096	.0076	.0061	.0543	.0371	.0146	.0120	.0270	.0288	.0215	.0178
Summer	.1598	.0760	.0342	.0275	.1340	.1290	.0596	.0472	.1733	.1718	.0746	.0609	.2402	.2180	.0973	.0772
Autumn	.1319	.0599	.0282	.0223	.0898	.0881	.0503	.0368	.0794	.0942	.0547	.0373	.1344	.1270	.0709	.0504
Annual	.4509	.2109	.0997	.0818	.2383	.2327	.1214	.0929	.3075	.3034	.1462	.1104	.4084	.3804	.1941	.1487
Process	DIP uptake by phytoplankton				DOP excretion by phytoplankton				DIP excretion by bacteria				Sedimentation of P_D			
Basins / Seasons	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Spring	.1344	.0829	.0376	.0358	.0339	.0209	.0094	.0089	.0106	.0113	.0081	.0069	.2652	.0580	.0348	.0264
Summer	.2370	.1108	.0490	.0403	.0608	.0280	.0123	.0100	.0938	.0845	.0367	.0290	.1479	.0349	.0163	.0129
Autumn	.1736	.0708	.0337	.0261	.0442	.0177	.0083	.0064	.0515	.0484	.0266	.0187	.1603	.0902	.0386	.0257
Annual	.6223	.2822	.1307	.1089	.1583	.0710	.0325	.0271	.1584	.1466	.0732	.0558	.8422	.2347	.1085	.0775
Process	P_D input from other sources (e.g. watershed runoff)				DIP input from other sources (e.g. watershed runoff)				DOP input by precipitation				DIP input by precipation			
Basins / Seasons	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
Spring	.0000	.0190	.0075	.0045	.0150	.0690	.0270	.0270	.0033	.0025	.0022	.0020	.0055	.0041	.0037	.0034
Summer	.0000	.0030	.0030	.0030	.0550	.0220	.0060	.0060	.0052	.0039	.0035	.0032	.0086	.0065	.0058	.0053
Autumn	.0000	.0660	.0315	.0135	.0175	.0100	.0000	.0000	.0036	.0027	.0024	.0022	.0061	.0046	.0040	.0037
Annual	.0000	.1180	.0420	.0210	.0905	.1010	.0330	.0330	.0163	.0122	.0109	.0100	.0272	.0204	.0182	.0166

The analysis of conditions for phytoplankton growth in Lake Balaton is one of the main purposes of the eutrophication study. This analysis together with material phosphorus flows data, gives comprehensive information concerning the possible water quality changes of the lake in spatial and time aspects. The dynamics of net phytoplankton production, calculated in μgChl"a"/1-day, in various basins of Lake Balaton is shown in Figure 7. These calculations summarize the basic assumption and hypothesis concerning the phytoplankton dynamics in relation to phosphorus transformation and its cycling in the Lake Balaton ecosystem for environmental conditions of 1977.

DISCUSSION

Since the model permits the computations of the dynamic behavior of phosphorus compounds and phytoplankton and also estimates of the material phosphorus flows in the Lake Balaton ecosystem, some remarks may be arrived by analysis of these simulation results.

1. The main process in total P-loading are water transport, precipitation, and P-input from external sources. Analysis of simulation results show that during January-April, 1977, the largest part of phosphorus, e.g., 55-78% transports by water flow from the Zala River are in particulate form. The role of DIP in P-loading of the Zala River water flow becomes significant from May, 1977, and from the May-December period its quota is 52-86%. The annual input of particulate-P and DIP by the Zala River water flow comprises of 56.5% and 39.2%, respectively, of the total P-input, while the annual inputs of phytoplankton- and bacterial-phosphorus are estimated to be equal to 4.2% and 0.1%, respectively. The Zala River water flow contributes annually 88% of the total P-input, while precipitation and P-input from other sources give just 4% and 8% of total P-input, respectively.

The role of the Zala River water flow is very important in P-loadings of Basin I, because the annual P-input from the Zala River in 1977 was estimated at 0.99 mg P/l, then annually for other basins the water flow in the lake transfers just 0.05-0.013 mg P/l, i.e. 14-25% of total P-loadings of basins. Approximately the same amounts of P, i.e., 11-28% of total P-loading, are provided by precipitation in Basins II-IV. The P-input from external sources of the watershed area is the main P-loading in Basins II-IV, which gives 54-72% of the total external P-input into Lake Balaton.

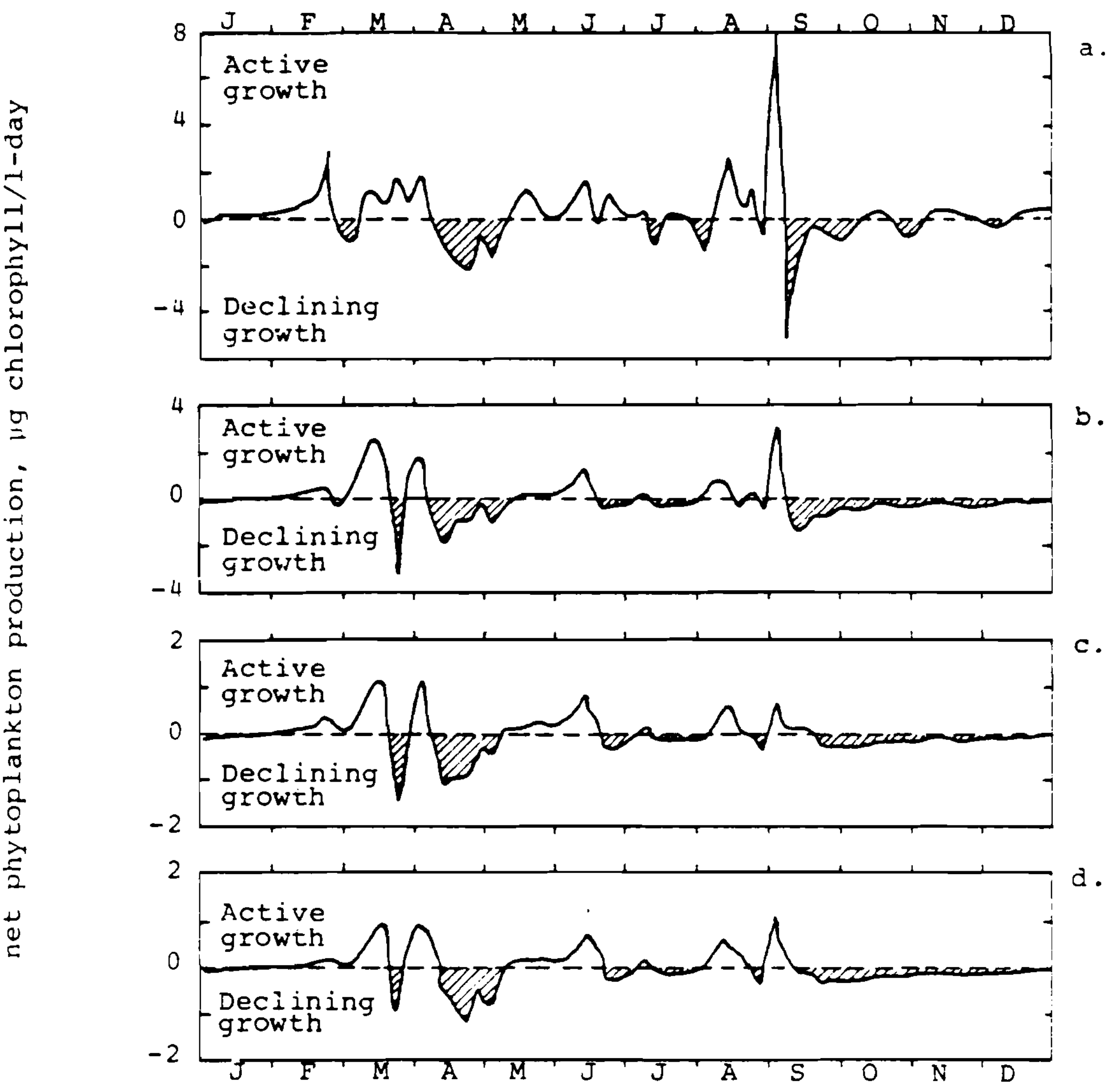


Figure 7. Dynamics of phytoplankton net production in different basins of Lake Balaton, 1977.

a. Keszthely Bay

b. Szigliget Basin

c. Szemes Basin

d. Siofók Basin

2. The particulate organic phosphorus in Lake Balaton is composed of three main compounds, namely phytoplankton, bacteria, and unliving particulate phosphorus, as taken into account by the model. The simulation results show that the total amount of particulate organic phosphorus in Lake Balaton basins were varied three-fivefold in concentrations in 1977. The living part of particulate phosphorus comprises an average of 20-40% of the total and this portion increases up to 60-70% in periods of active growth of phytoplankton and bacteria. The proportion of phytoplankton phosphorus to bacterial phosphorus in the living part of particulate matter is not constant during the year in Lake Balaton basins. The phytoplankton phosphorus is dominated in the winter-spring months, contributing during this period 88-95% of phosphorus in the living part of particulate matter. The role of bacteria becomes essential in summer-autumn months, during this period they comprise 40-60% of phosphorus in living matter.

3. The major proportion of particulate organic phosphorus is composed of unliving particulate matter or detritus. It comprises 60-80% of the total particulate phosphorus most of the year. Just in warm months when growth of microorganisms becomes active, the role of detritus in providing the particulate phosphorus pool decreases to 30-40%.

4. In total balance of particulate phosphorus the role of internal processes in the Lake Balaton ecosystem is extremely important. The phytoplankton and bacteria mortalities are considered by the model as the main internal sources of particulate matter. Phytoplankton mortality provides annually 0.08-0.45 mg P/l in particulate P-pool in all basins that equal to 36-40% of the total P-input. The role of this process is especially important in spring months (Table 2). Bacterial mortality contributes the essential part of particulate phosphrus in the summer-autumn period, namely 35-62% of the total in various Lake Balaton basins.

5. The detritus is decomposed to DOP in the phosphorus transformation process considered by the model. Quantitative estimation of detrital phosphorus amounts decomposed to DOP is essential for better understanding the role of suspended organic matter in transformation cycles of phosphorus in the water environment. The role of this process in phosphorus transformation is extremely small in the January-April period, when water temperatures were low. The effect of this process may be considered to be important in the May-September period: about 0.05-0.06 mg P/l in each month during this period has been

transformed from detritus to DOP in Basins I and II. Contributions of this process to total P balance in Basins III and IV are 0.01-0.04 mg P/l for the same period. Total annual contributions of nonliving particulate phosphorus decomposition to DOP are practically similar for Basins I and II and equal to about 0.3 mg P/l, while for Basins III and IV they are almost two times lower (Table 2).

6. Among all transformation processes, sedimentation is one of the major regulators of phosphorus content in the water environment. The estimation of phosphorus losses in sediment were received for each basin on a monthly and seasonal basis. They show that the significant part of phosphorus is settled annually in Basin I, while the total annual P-losses in Basins II, III, and IV are 3.6, 7.8, and 10.8 times lower than in Basin I. However, the percentage of phosphorus annual losses by sedimentation consists approximately of the same part from total phosphorus loading in all basins. These are 75%, 78%, 79%, and 83% for Basins I-IV, respectively.

The composition of phosphorus settled to sediment is changeable in various seasons. In winter months a suspended material entering into Lake Balaton with river inflows is dominated in settled phosphorus, while in spring, summer, and autumn months the detritus generated by biochemical processes in the lake is prevailed in the particulate phosphorus fraction settled to the sediment.

7. Mechanisms of phosphorus cycling in water environments, in a large degree, depend on the bacterial activity so that any quantitative assessment of bacterial significance in phosphorus transformation processes in Lake Balaton is desirable at this step of study. It is especially interesting to know the bacterial efficiency in the process of DOP uptake, DIP excretion, detritus formation and also the estimation of the seasonal change of net bacterial production rates in different basins of Lake Balaton.

Estimates of simulation results show that the release of dissolved phosphorus as inorganic orthophosphate in bacterial metabolisms is equal to 37-40% of the total phosphorus uptake by bacteria in an observed range of DOP concentration in Lake Balaton basins. Net bacterial production rates were found to vary seasonally. During January-April all processes in bacterial metabolism were balanced and the net bacterial production rate was very close to zero. Bacterial uptake of DOP begins to be noticeable at the beginning of May. To approximately the end of May the net bacterial production rate reaches maximum level due to increasing water temperature. These values at peak are equal to about 1-2 μg P/l-day in various basins of Lake Balaton.

In the July-September period the bacterial effect on phosphorus transformation is very essential: the monthly uptake - 0.07-0.08 mg P/l (Basins I-II) and 0.03-0.04 mg P/l (Basins III-IV) of DOP, excrete - 0.01-0.03 mg P/l of DIP, and they form 0.02-0.05 mg P/l as detrital phosphorus in all basins within Lake Balaton. Analysis of material flows of bacterial phosphorus transformation show that during the summer months just 20-30% of uptake in phosphorus is used by bacteria on the biomass construction. Bacterial excretion of DIP is a very important source of phosphorus for phytoplankton growth. The amount of DIP excreted by bacteria in the June-September period in Keszthely Bay is comparable with DIP inputs from external sources. Annual inputs of DIP by bacterial excretion in Basins II-IV are estimated to be equal to 50-60% of the total DIP inputs. The role of this process is especially significant for the maintenance of phytoplankton production in the summer-autumn months when DIP input from watershed areas is decreased to 15-25% of the total.

8. One of the key facts of water body eutrophication is certainly the dynamics of phytoplankton with relation to processes of phosphorus transformation in time and space aspects. Phytoplankton growth in water environments is controlled by a combined influence of temperature, light, and nutrition. Only through quantitative estimations of all processes defining the phytoplankton metabolism and controlling the growth it is possible to assess and predict the aqua system responses in a wide range of state variable concentration changes.

Analysis of phytoplankton net production rates (Figure 7) and phosphorus material flows (Table 2) allow us to receive some important quantitative characteristics concerning the features in behavior of the Lake Balaton ecosystem with the given set of environmental conditions.

The intensive growth of phytoplankton in Keszthely Bay at the end of February was due to favorable physical conditions and especially nutrients. Just low concentrations of DIP can explain the absence of intensive net production of phytoplankton at this period in other basins of Lake Balaton. Favorable conditions for phytoplankton growth is observed in all basins during mid-March til the beginning of April.

Spring peaks of net phytoplankton production rates are about 2 µg Chl-a/l-day for Basins I-II and 1 µg Chl-a/l-day for Basins III-IV. Amounts of DIP uptaken by phytoplankton in spring bloom are estimated as 0.13, 0.08, 0.038, and 0.036 mg P/l for Basins I, II, III, and IV, respectively.

After the spring peak of phytoplankton biomass, the growth is limited by DIP content in April and at the beginning of May in all basins. For this period the phytoplankton DIP uptake is smaller than its mortality and metabolic excretion losses. In this period the phytoplankton biomass slightly decreased and phytoplankton net production was negative.

To approximately mid-May the phytoplankton growth is increased from the results of DIP input by bacterial regeneration. In summer uptake of DIP by phytoplankton is most essential in comparison with DIP uptake in other seasons. It is estimated as 0.237, 0.111, 0.049, and 0.04 mg P/l for four basins from Keszthely to Siofók, respectively, although the DIP content in these basins are almost similar, about 0.004-0.006 mg P/l. This is a result of equilibrium between all biochemical processes defining the nutrient cycling in water environment. Data presented in Table 2 gives a possibility to estimate efficiencies of individual processes in phosphorus cycling for different basins on the basis of combined effect of external P-sources and internal processes of phosphorus transformation.

Analysis of simulation results show that, although the bacterial excretion of DIP in May-June is effective, the nutrient level is not enough for maintaining the active phytoplankton growth at favorable physical conditions in all basins, and in July the active growth phase changes to a negative growth phase. In mid-August the phytoplankton growth becomes essential as a result of the complex effect of bacterial DIP regeneration, DIP inputs from watershed areas, and favorable physical conditons. This relatively short phase of active phytoplankton growth is continued to the end of August til the beginning of September when phytoplankton growth becomes to be limited by DIP content. In the next months, the phytoplankton growth is regulated mainly by temperature and light conditons.

As shown in Table 2, the effect of phytoplankton is very significant in phosphorus transformation in Lake Balaton, and especially in Basin I. Annual uptake of DIP by phytoplankton is estimated to be equal to 0.622 mg P/l in Keszthely Bay, that is about 63% from total p input in Basin I from the watershed area. However, phytoplankton efficiency is completly a result of all simultaneous biochemical processes in P-cycling and it is determined in the first instance by processes of nutrient uptakes and excretion by microorganisms.

CONCLUSIONS

The hypothesis concerning the phosphorus transformation processes and phytoplankton growth were used for development of the mathematical model of detailed biogeochemical phosphorus cycling intended for studying the eutrophication phenomena in Lake Balaton. The specific objectives of the study are to increase the understanding of the dynamic behavior of the Lake Balaton ecosystem. The main focus of this report was given to the model application for reproduction of observation data on phosphorus compounds in different basins of Lake Balaton (1977), in connection with phytoplankton dynamics.

The degree to which the model outputs agree with the available set of observation data was considered here as an important criteria of model examination. It appears reasonable to claim that agreement of model outputs in four basins is quite satisfactory for all phosphorus compounds, when hypothesis of three phytoplankton groups was used.

In order to analyze the simulation results from the point of view of phosphorus control, the special calculations of phosphorus material flows were made for all phosphorus-using activities and sources. In this case, the model gives a considerable degree of insight in understanding the behavior of the Lake Balaton ecosystem and, in particular, phosphorus transformation processes, which forms the first basis in estimating the role of external nutrient load and internal processes of phosphorus cycling in different parts of the lake. Estimated phosphorus mass flows quantitatively explain the importance of individual processes in total phosphorus cycling on the basis of observed data, while calculated rates of phytoplankton net production indicate direct response of algae on content of nutrients from different sources. These estimations may be used for quantitative explanation of changeable conditions in a trophic state and nutrient limitations in four basins of the Lake. They also may be considered useful in formulation of management alternatives in the future.

In the next step of study of Lake Balaton eutrophication, an attempt will be made to use this model for an analysis of phosphorus compounds and phytoplankton dynamics in 1976, an abnormally dry year on the basis of estimated rate constants and available data on water temperature, radiation, water balance, and external phosphorus inputs from the Zala River and watershed area.

In this step of study the hydrodynamic processes of Lake Balaton are represented in the model in the simplest way. From the results of this study it is possible to suggest that a more complete description of eutrophication phenomena in Lake Balaton must include better estimations of hydrodynamic effects upon biological and chemical processes in water environment and especially influences of wind-induced circulation on exchange processes in water-sediment interface.

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