Working Paper

TRANSFORMATIONS AND TURNOVER OF PHOSPHOROUS COMPOUNDS IN THE LAKE BALATON ECOSYSTEM, 1976-1978

A.V. Leonov

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WP-82-27

International Institute for Applied Systems Analysis
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THE AUTHOR

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PREFACE

One of the principal projects of the Task "Environmental Quality Control and Management" in IIASA's Resources and Environment Area is a case study of eutrophication management for Lake Balaton in Hungary. The case study is a collaborative project involving a number of scientists from several Hungarian institutions and IIASA (for details see WP-80-187 and WP-80-108).

This report, one part of the Lake Balaton Case Study, briefly describes the mathematical model BALSECT (Balaton Sector Model), which models phosphorous transformation in the lake. This model is one of three ecological models that have been developed for the analysis of data characterizing recent variations of phosphorous concentrations and water quality in different parts of the lake. The report gives further details on the practical application of the model to the simulation of phosphorous transformation processes in Lake Balaton (see WP-80-88, WP-80-149 and WP-81-118). The results reported make possible a comparison of the model's performance with the observations recorded for 1976-1978, as well as an explanation of features of phosphorous cycling in the lake basins for these three years.

ACKNOWLEDGMENTS

Special thanks are due to my colleagues, in IIASA's Resources and Environment Area (REN), Drs. M.B. Beck and L. Somlyódy, for their support and useful advice. The technical assistance offered by Serge Medow in programming is gratefully acknowledged. I would also like to express my gratitude to Pam Hottenstein for her editorial assistance and Vicky Hsiung for typing the manuscript.

ABSTRACT

Transformation of the phosphorous compounds in Lake Balaton was described in the mathematical model BALSECT (Balaton Sector Model). This model, which deals with five types of phosphorous compounds--dissolved inorganic P, dissolved organic P, nonliving particulate organic P, bacterial P, and phytoplankton P--reflects the basic interactions between these compounds in accordance with the consecutive conversion of phosphorous compounds in the water environment. The rates of change in the phosphorous transformation processes are modeled to be dependent on and regulated by environmental factors such as temperature, radiation, water balance, and nutrient watershed load. The model also takes into account the wind action on the horizontal interbasin transport of phosphorus as well as phosphorous exchange between sediment and water. The measurements of temperature, radiation, wind, water balance, and phosphorous loading were used to examine the feasibility of the model in reproducing the phosphorous dynamics in the fourth basin of Lake Balaton for the environmental conditions of 1976-1978. The improved version of the possible watershed nutrient loading was used in this study. On the basis of the analysis of the turnover time values, the details of the cycling of the individual phosphorous compounds and the total P are presented in this report. The explanation of the trends in the phosphorous cycling in the terms of turnover time is considered useful and important for understanding the regime of the phosphorous transformation within the Lake Balaton Ecosystem for the different environmental conditions and changeable nutrient loading. Thus, the simulation results and calculated values of turnover time may be used for the formulation of suggestions concerning the water quality management of this lake.

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1. INTRODUCTION

In the Lake Balaton Ecosystem, phosphorus exerts a basic influence on the direction of trophic changes within the given water body. Therefore, the principal goal of the present study was to develop a mathematical model of phosphorous transformation and to apply this model to the analysis and explanation of phosphorous cycling in Lake Balaton as well as to the prediction of the potential response of the Lake Balaton Ecosystem to different nutrient loadings. It was assumed that the mathematical model will provide a necessary and obviously improved degree of understanding of the eutrophication problem of the given lake from the aspect of the system's level of organization; furthermore its application might be especially useful in the assessment of the critical phosphorous levels in the lake as well as in the search for the relationship between nutrient loading and major limnetic properties of this water body.

The phosphorous system modeled was organized into subunits or compartments functionally divided into chemical and biological categories, in accordance with the mechanisms of the phosphorous transformation in the water environments. The phosphorous quantities in the model compartments, flux rates through the compartments and the phosphorous recycling from one compartment to another, can be analyzed during simulation of the phosphorous dynamics in the lake to increase understanding of the phosphorous transformation, cycling, and movements of the flows of the individual phosphorous fractions in different areas of Lake Balaton. The ecosystem nutrient behavior may be characterized in terms of turnover times to explain the system's properties and phosphorous cycling as a consequence of certain environmental conditions and nutrient loading, and to quantify the phosphorous balance and the extent and rate of phosphorous regeneration and its exchange with sediments. Thus, it was assumed that this additional information on the phosphorous behavior in Lake Balaton should help in understanding the relative importance of the natural phosphorous cycling within this lake and in indicating the role of the individual phosphorous compartments in the material flows and the nutrient dynamics which are considered of primary interest in explaining the water quality changes and solving the eutrophication problem in particular.

A preliminary report (Leonov, 1981) shows the results of the application of the phosphorous model in the description and analysis of the phosphorous dynamics in the different parts of Lake Balaton in 1976-1978, in the assessment of the role of sediments in the phosphorous balance for every basin, and in the study of the model's response to the changes of the environmental factors (temperature, radiation, and nutrient loading). This report describes the results of the model application with an improved version of the phosphorous watershed loading of Lake Balaton Basins in 1976-1978. The specific emphasis of this study was to evaluate the dynamics of turnover time values for the individual phosphorous compartments as an additional criterion of the phosphorous balance and cycling in this aquatic ecosystem.

2. THE MODEL

The Balaton Sector Model (BALSECT) describing phosphorous transformation processes was developed at IIASA for the study of the eutrophication phenomenon in the Lake Balaton Ecosystem. Phosphorous compartments in this model are nonliving particulate organic phosphorus (P_D), dissolved organic phosphorus (DOP), bacterial phosphorus (B), dissolved inorganic phosphorus (DIP), and phytoplankton phosphorus (F). The interactions of these phosphorous compartments are shown in Figure 1. Thus, this model takes into account the following ecological processes:

(i) phytoplankton production and nutrient uptake which are characterized as a function of temperature, light, and DIP content;

(ii) bacterial production which is temperature dependent and an important step in DOP transformation and DIP regeneration;

(iii) metabolic excretion of DOP and DIP by phytoplankton and bacteria respectively;

(iv) nonpredatorial mortality of bacteria and phytoplankton which are essential mechanisms in phosphorous cycling;

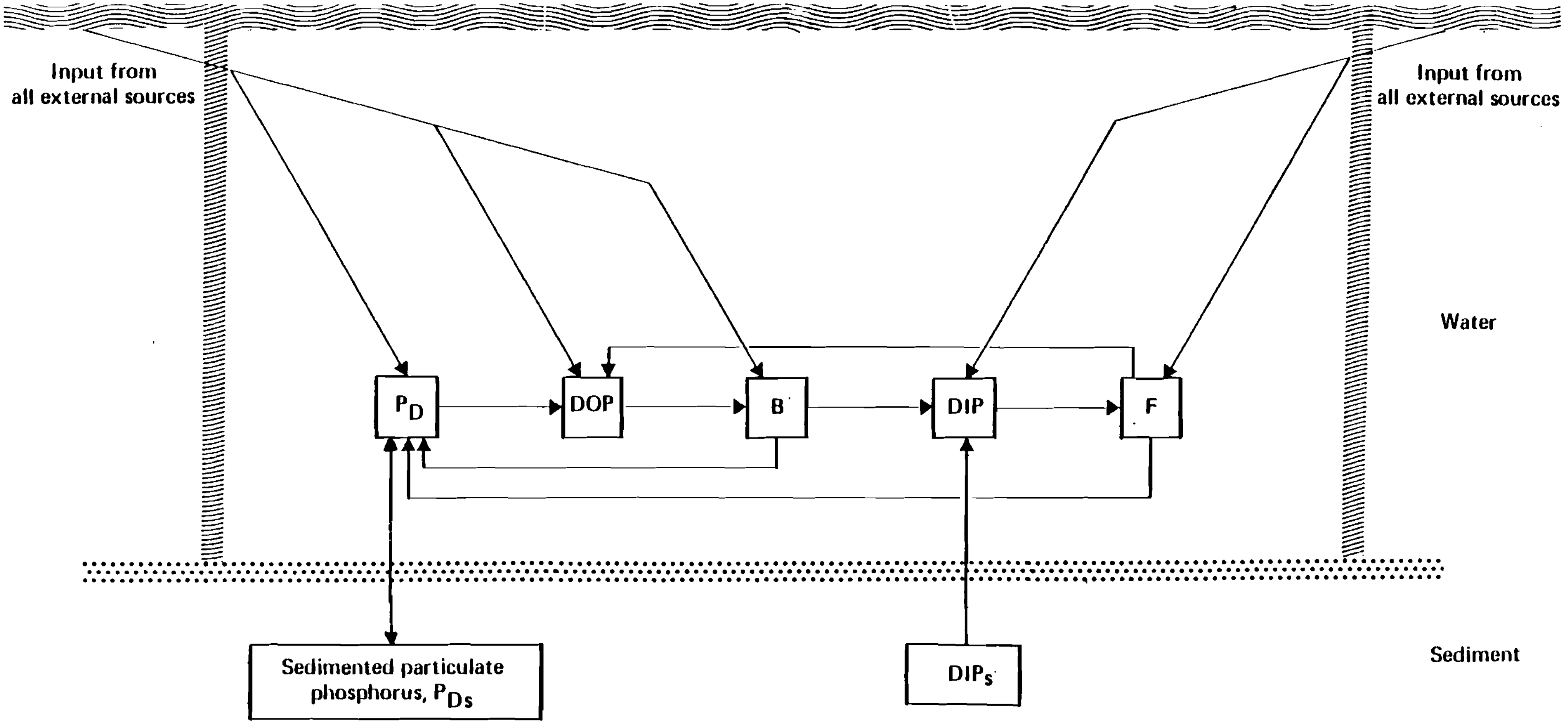

Figure 1. Diagram of Phosphorous Compartment Interactions considered in the Model

(v) decomposition of nonliving particulate organic phosphorus which is an important stage of phosphorous transformation in the release of chemical energy stored in detritus;

(vi) phosphorous exchange through the sediment-water interface which includes the interactions of resuspension-sedimentation of nonliving particulate organic phosphorus and the release of dissolved inorganic phosphorus from the sediments.

The model considers these processes in four Lake Balaton Basins: Keszthely Bay, Sligliget, Szemes and Siofók Basins, from which Basin I (Keszthely Bay) is the most polluted area of the lake (van Straten et al., 1979).

The general form of the model equation written as an ordinary differential equation is:

$$\frac{dC_{i,j}}{dt} = R_{i,j} + LOAD_{i,j} + TR_{i,j} \qquad (1)$$

Rates of biochemical transformation of the individual phosphorous fractions ($R_{i,j}$) in each of the basins are given by the following expressions :

- for P_D, i=1 $R_{PD_j} = M_{F_j} \cdot F_j + M_{B_j} \cdot B_j - K_3 \cdot P_{D_j} - S_j$ (2)
- for DOP, i=2 $R_{DOP_j} = K_3 \cdot P_{D_j} + L_{F_j} \cdot F_j - UP_{B_j} \cdot B_j$ (3)
- for B, i=3 $R_{B_j} = (UP_{B_j} - L_{B_j} - M_{B_j}) \cdot B_j$ (4)
- for DIP, i=4 $R_{DIP_j} = L_{B_j} \cdot B_j - UP_{F_j} \cdot F_j$ (5)
- for F, i=5 $R_{F_j} = (UP_{F_j} - L_{F_j} - M_{F_j}) \cdot F_j$. (6)

The equations used for the description of microorganisms' functions - nutrient uptake, excretion and mortality - plus detritus decomposition and sedimentation, are presented in Table 1.

Extreme phosphorous loading ($LOAD_{i,j}$) includes the atmospheric pollution for DIP and DOP, sewage load for DIP, urban runoff, and tributary and sediment loads for DIP and P_D. The phosphorous loading terms for the individual phosphorous fractions are written as

- for PD, i=1 $LOAD_{PD_j} = P_{DZ} \cdot (\gamma_{1_j} + \gamma_{2_j}) \cdot (V_1/V_j) + + P_{Dr} \cdot (4.3/d_j)^2 \cdot W^U$ (7)

- for DOP, i=2 $LOAD_{DOP_j} = C^r_{DOP} \cdot (Q_{pr_j}/V_j)$ (8)

- for DIP, i=4 $LOAD_{DIP_j} = C^r_{DIP} \cdot (Q_{pr_j}/V_j) + CZ_{DIP_j} + DIP_Z \cdot (Y_{1_j} + y_{2_j}) \cdot (V_1/V_j) + DIP_{r_j} \cdot \exp(K_{yr} \cdot T) \cdot W$. (9)

The horizontal transport ($TR_{i,j}$) of phosphorous fractions from basin to basin is considered the result of two prevailing mechanisms, the net hydrological transport and the transport by the wind-induced water flow. The general equation for the transport term is written as

$$TR_{i,j} = C_{i,j-1} \cdot (Q_{in_j} + Q^a_{win_j})/V_j - C_{i,j} \cdot (Q_{out_j} + Q^b_{wout_j})/V_j - C_{i,j} \cdot (Q^a_{wout_j})/V_j + C_{i,j+1} \cdot (Q^b_{win_j}/V_j) \quad . \tag{10}$$

Table 1. Model Equations Used for the Description of Ecological Processes.

Ecological Processes	Main equations	Additional terms
I. Microorganism's growth		
- for phytoplankton	$UP_{F_j} = \frac{K_1 \cdot R_{TF} \cdot R_{IF}}{1 + F_j/(\beta \cdot DIP_j)}$	$R_{IF} = (e/K_e \cdot h)\left[\exp(-r_x) - \exp(-r_1)\right]$ $r_1 = I/I_{opt}$ $r_x = r_1 \lvert \exp(-K_e \cdot h) \rvert$ $K_e = K_a + K_b \cdot (\mu g\ Chl/\ell)$ $I = I_{max} \cdot h \cdot \left[1 + \cos\frac{2\pi(t_n - t_p)}{f}\right]$ $I_{max} = 2 \cdot I_{av}/f$ $R_{TF} = 0.2 + \frac{0.022 \cdot (e^{0.21 \cdot T} - 1)}{1 + 0.028 \cdot e^{0.21 \cdot T}}$
- for bacteria	$UP_{B_j} = \frac{K_2 \cdot R_{TB}}{1 + B_j/DOP_j}$	$R_{TB} = 0.3 + \frac{3.68 \cdot 10^{-3}(e^{0.403 \cdot T} - 1)}{1 + 5.25 \cdot 10^{-3} e^{0.403 \cdot T}}$
2. Microorganism's metabolical excretions		
- for phytoplankton	$L_{F_j} = r_{F_j} \cdot UP_{F_j}$	$r_{F_j} = \frac{(a_1/a_2) \cdot UP_{F_j}}{(1/a_2) + UP_{F_j}} + (1 - a_1/a_2)$
- for bacteria	$L_{B_j} = r_{B_j} \cdot UP_{B_j}$	$r_{B_j} = \frac{(a_3/a_4) \cdot UP_{B_j}}{(1/a_4) + UP_{B_j}} + (1 - a_3/a_4)$
3. Microorganism's mortality		
- for phytoplankton	$M_{F_j} = v_1 \cdot F_j/UP_{F_j}$	
- for bacteria	$M_{B_j} = v_2 + v_3 \cdot B_j/UP_{B_j}$	
4. Temperature-dependent rate of detritus decomposition	$K_3 = \frac{1.2 \cdot 10^{-4}(e^{0.351 \cdot T} - 1)}{1 + 3.0 \cdot 10^{-4} e^{0.351 \cdot T}}$	
5. Detritus sedimentation	$S_j = K_{sed} \cdot (4.3/d_j) \cdot P_{D_j}$	

The rate of wind-induced flow providing the phosphorous exchange through the interbasin cross-sections is calculated on the basis of wind data by the next expression:

$$Q_w = \text{abs}\,|\,k \cdot W \cdot A_j \cdot \cos(\alpha - 30)\,| \quad . \tag{11}$$

Equations (1)-(11) together with those presented in Table 1 provide a complete description of the structure of the phosphorous transformation model used for the study of eutrophication phenomena in the Lake Balaton ecosystem.

3. DATA BASE

All data available at IIASA on Lake Balaton can be subdivided into three groups:

(i) physical, meteorological, and hydrological data;

(ii) nutrient loading data;

(iii) phosphorus, nitrogen, and phytoplankton measurements in the different parts of Lake Balaton.

The first group of data contains the measurements of the water temperature, solar radiation, and wind and water balance characteristics. The fluctuation of the daily mean water temperature and solar radiation for 1976-1978 is presented in Figures 2 and 3 respectively. The dynamics of wind speed measured every 3 hours in 1976-1978 are presented in Figure 4. The water balance data contains the weekly measurements of the Zala river discharge flow rates and monthly average input-output rates as well as precipitation rates for all basins. Figures 5 and 6 show, respectively, the input and output flow rates available for 1976-1978. Table 2 contains the monthly mean precipitation rates for 1976-1978. All data from the first group is used in

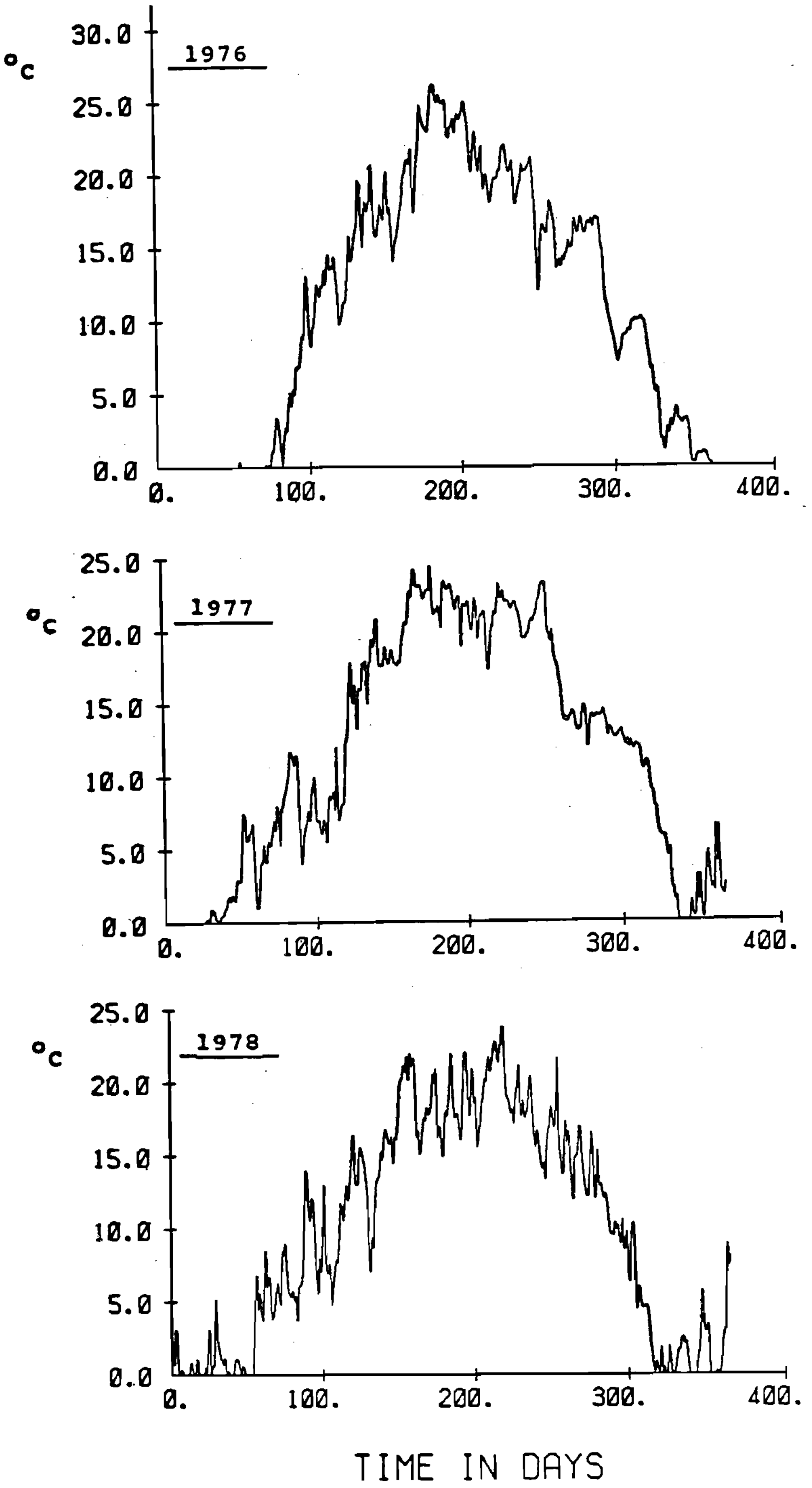

Figure 2. Dynamics of daily average water temperature in Lake Balaton for 1976-1978.

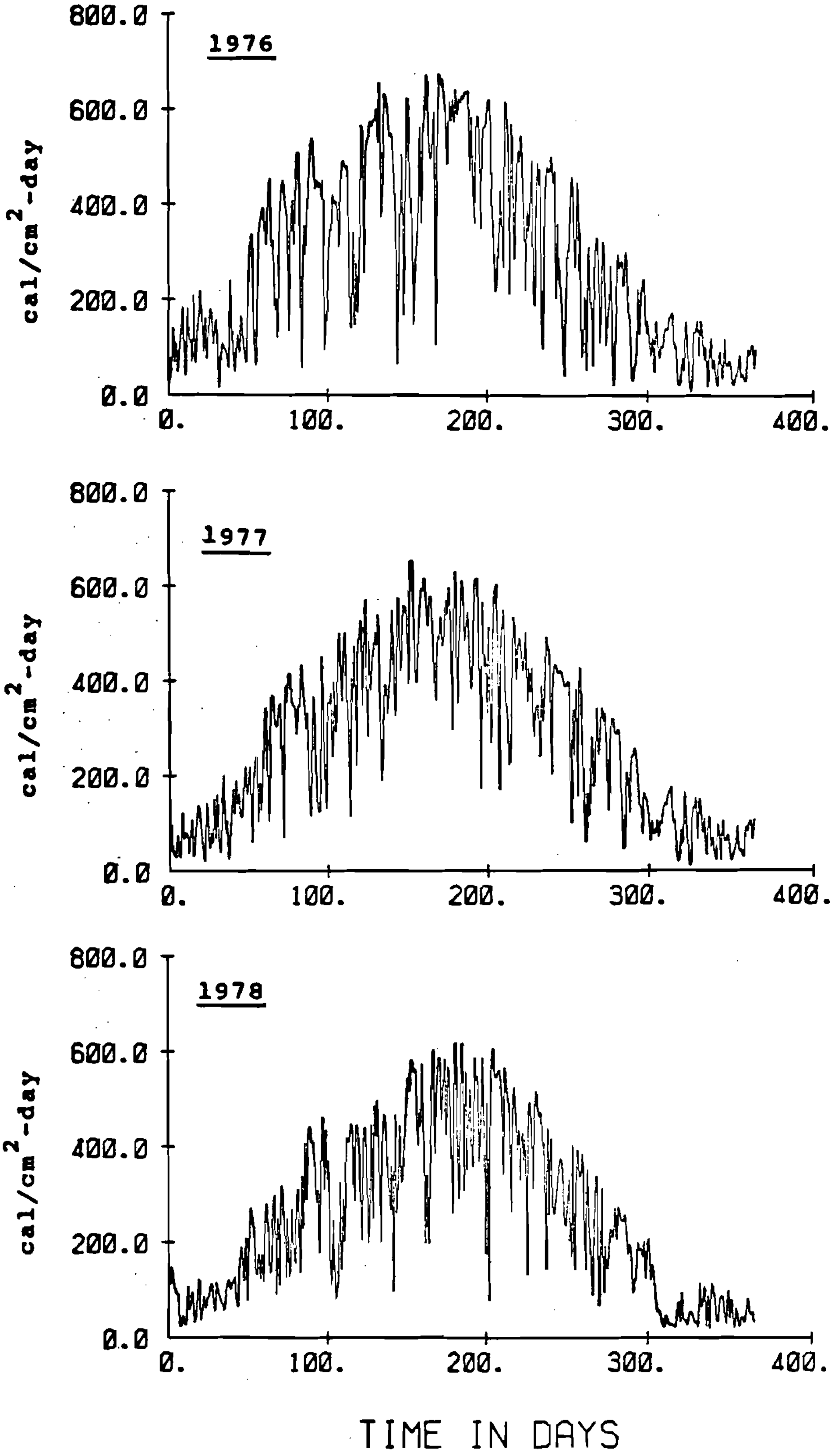

Figure 3. Dynamics of daily average values of solar radiation for 1976-1978.

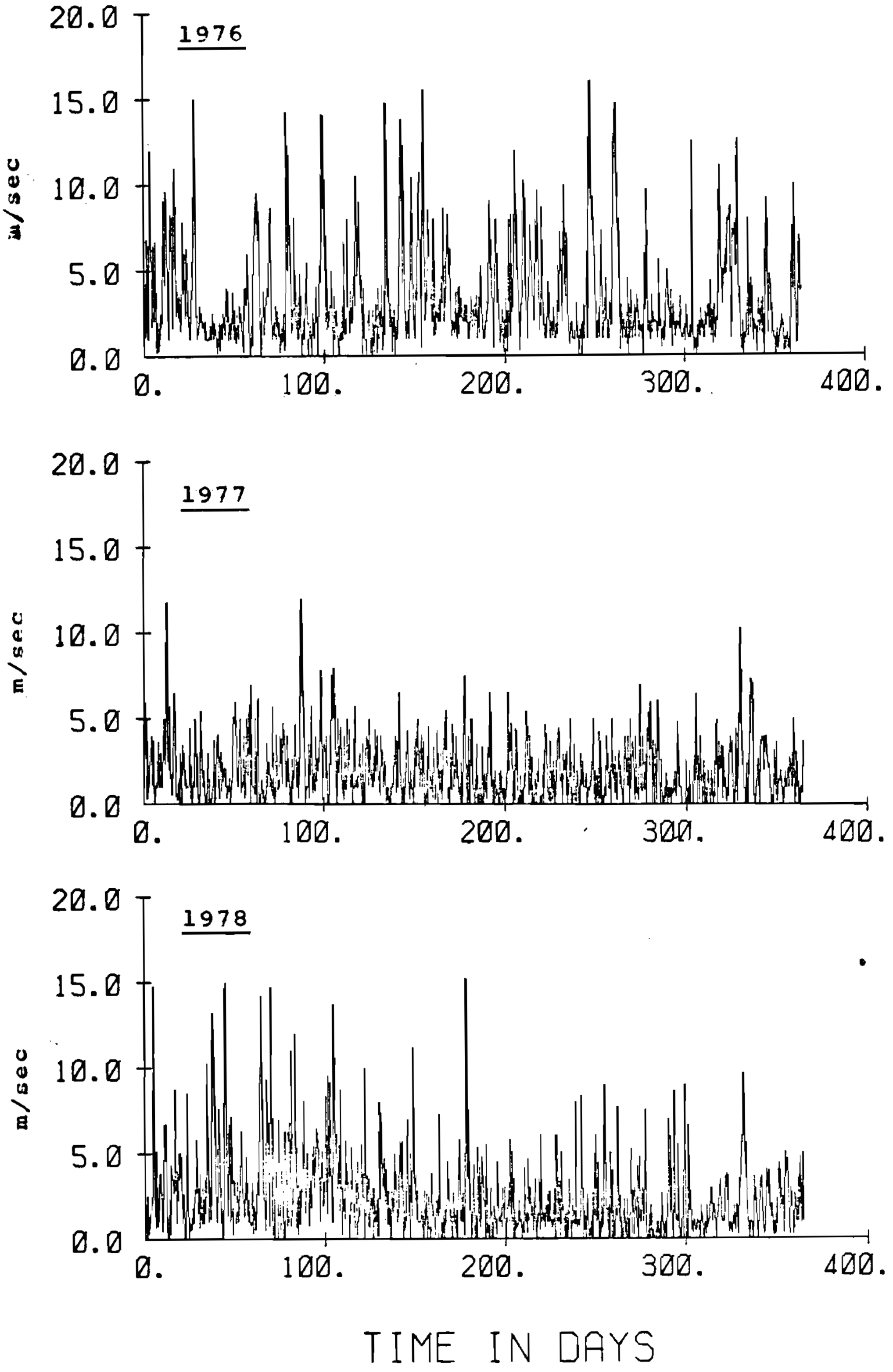

Figure 4. Directly measured wind speeds for Keszthely Bay (1976-1978).

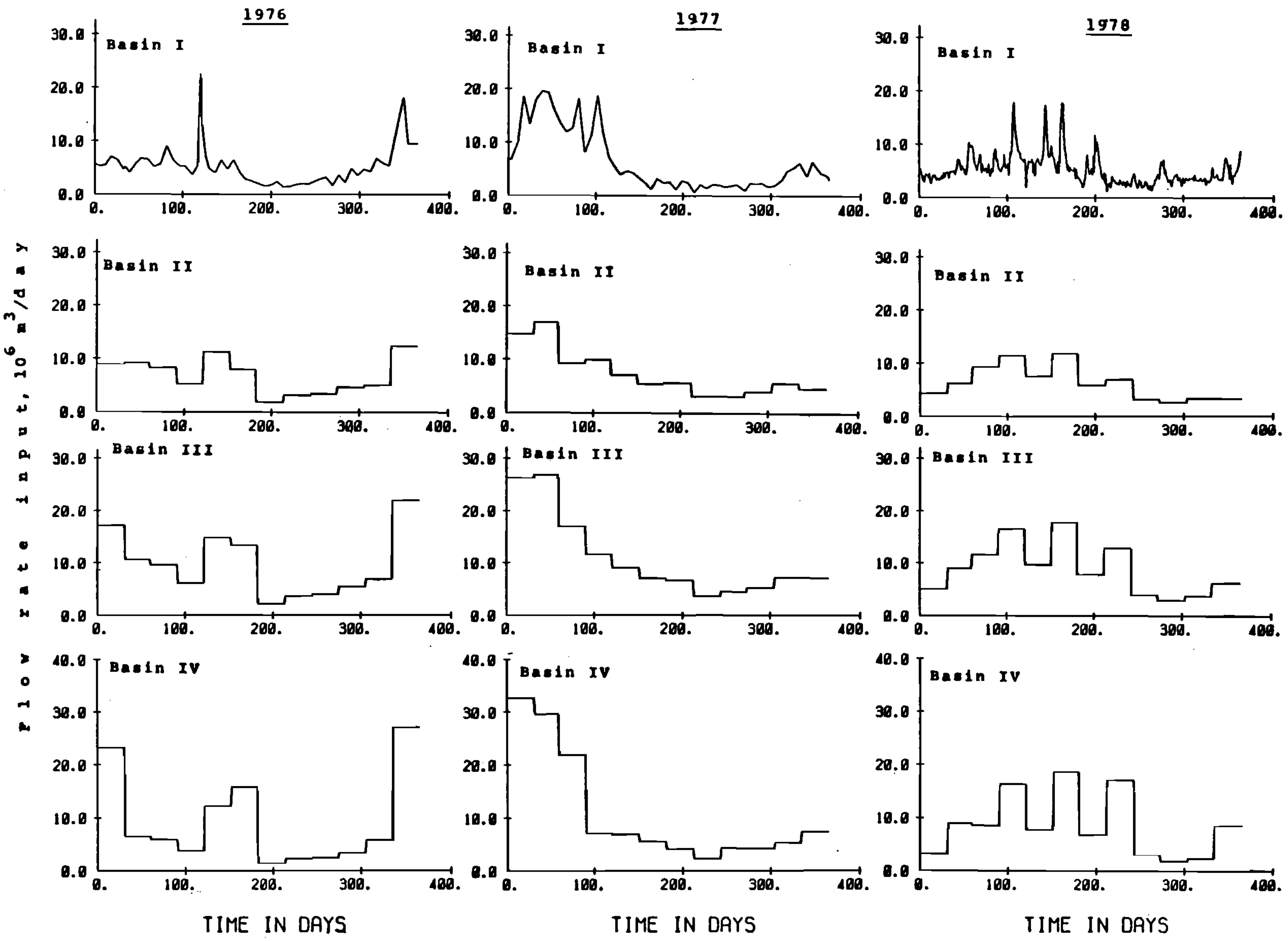

Figure 5. Water balance data: flow rate input for Lake Balaton Basins (1976-1978).

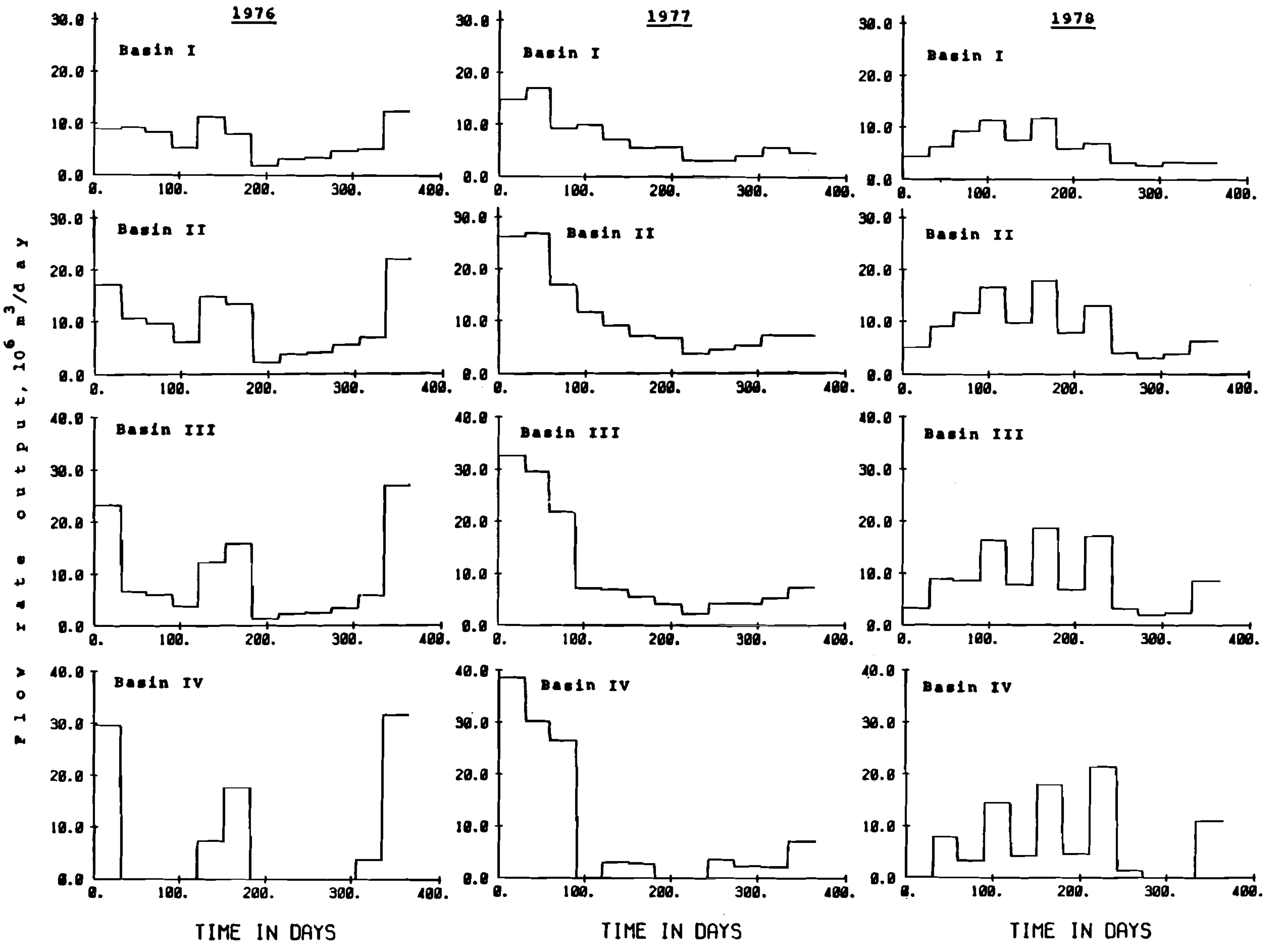

Figure 6. Water balance data: flow rate output for Lake Balaton Basins (1976-1978).

Table 2. Water Balance Data: Monthly Average Precipitation Rates (10^6 m^3/day) for Lake Balaton Basins, 1976-1978.

Months	Basins											
	I			II			III			IV		
	1976	1977	1978	1976	1977	1978	1976	1977	1978	1976	1977	1978
Jan	0.576	0.650	0.135	2.183	2.462	0.511	2.820	3.180	0.660	3.457	3.898	0.809
Feb	0.131	0.760	0.421	0.496	2.880	1.594	0.641	3.720	2.059	0.786	4.560	2.524
Mar	0.429	0.601	0.319	1.626	2.276	1.208	2.100	2.940	1.560	2.574	3.604	1.912
Apr	0.697	0.583	0.608	2.640	2.208	2.304	3.410	2.852	2.976	4.180	3.496	3.648
May	0.417	0.319	0.993	1.579	1.208	3.763	2.040	1.560	4.860	2.501	1.912	5.957
June	0.545	0.975	1.165	2.064	3.696	4.416	2.667	4.774	5.704	3.268	5.852	6.992
July	0.723	0.613	1.226	2.741	2.323	4.645	3.540	3.000	6.000	4.339	3.677	7.355
Aug	0.613	0.797	0.355	2.323	3.019	1.347	3.000	3.900	1.740	3.677	4.781	2.133
Sept	0.912	0.557	0.304	3.456	2.112	1.152	4.464	2.728	1.488	5.472	3.344	1.824
Oct	0.563	0.233	0.404	2.137	0.883	1.532	2.760	1.140	1.980	3.380	1.397	2.427
Nov	0.659	0.899	0.165	2.496	3.408	0.624	3.224	4.402	0.806	3.952	5.396	0.988
Dec	1.213	0.429	0.404	4.599	1.626	1.532	5.940	2.100	1.980	7.281	2.574	2.427

the simulation runs as environmental factors regulating the rates of the phosphorous transformation.

The second group of data includes the nutrient loading data from the Zala river discharge water, urban run-off, sewage, tributaries, rainfall, and sediments. Figure 7 shows the fluctuations of the total P, DIP, F, and P_D in the Zala river discharge water. The concentration of the bacterial-P in the Zala river discharge water was assumed to be constant throughout the year and equal to $4 \cdot 10^{-4}$ mgP/ℓ, while the DOP content, due to a lack of data, was assumed to be negligible. The DIP and DOP concentrations in the rainfall were assumed to be constant for each year and equal to 0.1 and 0.06 mgP/ℓ respectively. Together with the water balance data presented in Figures 5-6 and in Table 2, this phosphorous loading data is used in the simulation runs and takes into account the direct influence of the Zala river and precipitation on the phosphorous dynamics in Lake Balaton.

The influence of the sewage as a DIP source is also taken into account in the runs. Table 3 shows the rates of monthly average values of sewage DIP load evaluated on the basis of later assumptions about the four-basin extrapolation of the Zala river DIP load and on the double DIP load from sewage discharges in the tourist season (van Straten and Somlyódy, 1980).

The entry of DIP and P_D from the tributaries with urban run-off was considered proportional to that from the Zala river, according to the hypothesis of longitudinal distribution of nonpoint sources over the Lake Balaton Basins (from Keszthely Bay to Siofók) discussed by van Straten and Somlyódy (1980) and Jolankai and Somlyódy (1981).

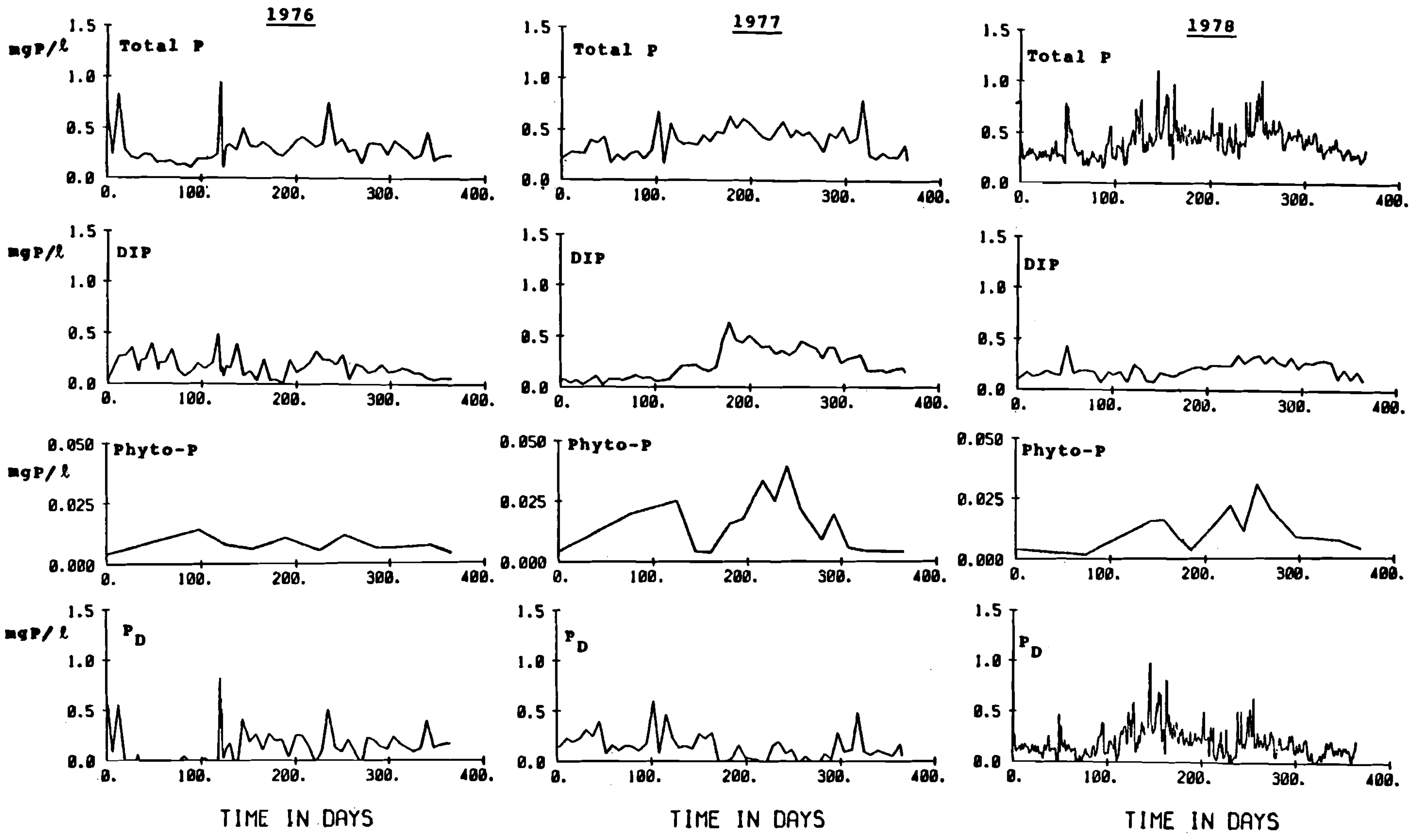

Figure 7. Dynamics of phosphorous concentrations in River Zala discharge in 1976-1978.

Table 3. Monthly Average Values of Sewage DIP Loading Rates (mgP/ℓ-day) used in Simulation Runs

Months	Basins			
	I	II	III	IV
January	.00008	.00007	.00006	.00008
February	.00008	.00007	.00006	.00008
March	.00008	.00007	.00006	.00008
April	.00008	.00007	.00006	.00008
May	.00008	.00007	.00006	.00008
June	.00008	.00007	.00006	.00008
July	.00016	.00014	.00012	.00016
August	.00016	.00014	.00012	.00016
September	.00008	.00007	.00006	.00008
October	.00008	.00007	.00006	.00008
November	.00008	.00007	.00006	.00008
December	.00008	.00007	.00006	.00008

Finally, the sediments are considered as an additional nutrient source. The time-averaged flux of DIP from the sediments, calculated on the basis of the field studies, was assumed to be equal to $1.45 \cdot 10^{-5}$, $0.52 \cdot 10^{-5}$, $0.42 \cdot 10^{-5}$ and $0.33 \cdot 10^{-5}$ (all mgP/ℓ-day) for Basins I through IV respectively. The time-averaged flux of nonliving particulate-P from the sediment to the water was assumed to be equal to $7 \cdot 10^{-4}$ mgP/ℓ-day for all Lake Balaton Basins during 1976-1978. The actual fluxes of the phosphorus from the sediment are considered in the model as dependent on the environmental factors and it is assumed that the resuspension of the nonliving particulate-P is regulated by wind, while the sediment release of DIP is defined by temperature and wind conditions (equations (7) and (9) respectively).

The direct measurements of phosphorous concentrations in different parts of Lake Balaton were taken from the third group of data. The phosphorous fractions measured directly include the dissolved inorganic phosphorus or orthophosphate phosphorus (PO_4), the total dissolved phosphorus (TDP), the particulate inorganic phosphorus (PIP),* and total phosphorus (TP). The concentrations of the other phosphorous compounds that are important when considering the behavior of the phosphorous system can be calculated from those directly measured:

(i) dissolved organic phosphorus, DOP = TDP - PO_4;

(ii) particulate phosphorus, PP = TP - TDP;

(iii) particulate organic phosphorus, POP = PP - PIP.

Because of the varying number of sampling stations in the different parts of Lake Balaton (van Straten et al., 1979), the average concentrations of phosphorous fractions mentioned above were calculated for each basin of the lake. All data from the third group was used only for a comparison with the simulation results from 1976-1978 for the different basins.

4. SIMULATION

The mathematical model written as a set of ordinary nonlinear differential equations was coded in FORTRAN and implemented on IIASA's computer. The model equations were solved numerically using the Rung-Kutta 4 algorithm and a time step equal to 0.1 day.

The initial concentrations of the phosphorous fractions were selected from the Lake Balaton observation file available at

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*This phosphorous fraction is not taken into account in the given model.

IIASA. These concentrations correspond to the environmental conditions of January 1, 1976. All rate constants used in the model runs were determined earlier during the model application for the simulation of phosphorous transformation in the different lake basins for the environmental conditions of 1977 (Leonov, 1980). In contrast to the input data used for the simulation of phosphorous dynamics in Lake Baláton Basins for 1976-1978 (Leonov, 1981), the input data here takes into account a new version of the phosphorous loading discussed by Jolankai and Somlyódy (1981). All input data used, which includes the initial values of the phosphorous fractions on January 1,1976, and the rate constants and phosphorous loading coefficients, is presented in Table 4.

A comparison of the modeling results with average concentrations of the phosphorous measurements in individual basins for 1976-1978 is shown in Figures 8-12 for particulate organic-P (that is the sum of phytoplankton-, bacterial- and detrital phosphorus), DIP, DOP, total dissolved P, and total P, respectively. All observations of phosphorus are plotted in Figures 8-12 as arithmetic means, with the indicated range of the fluctuations from the minimum to the maximum in the measured phosphorous concentrations from the different sampling stations within Basins II-IV. Since there was only one sampling station in Basin I, the expected range of analytical error in the phosphorous measurements, assumed to be equal to ±10%, is indicated in Figures 8-12 for the phosphorous concentrations in this lake basin.

Table 4. Values of Initial Phosphorous Concentrations and Rate Coefficients Used in Simulation.

Parameters	Units	Symbols	Basins			
			I	II	III	IV
State variables (1 Jan, 1976):						
Dissolved inorganic phosphorus	mgP/ℓ	DIP	.002	.002	.0015	.001
Dissolved organic phosphorus	- " -	DOP	.005	.010	.005	.004
Phytoplankton phosphorus	- " -	F	.005	.003	.0025	.002
Bacterial phosphorus	- " -	B	.001	.0008	.0007	.0006
Non-living particulate organic phosphorus	- " -	P_D	.010	.004	.003	.002
Chlorophyll "a"	µg/ℓ	Chl	10.6	6.4	5.3	4.3
Rate constants and other parameters						
Maximum uptake rate for phytoplankton	day^{-1} at 20°C	K_1	2.8	2.8	0.9	0.9
Excretion efficiency of phytoplankton	day	a_1	.057	.057	.057	.057
- " - " - " - " - " - " - " -	- " -	a_2	.075	.075	.075	.075
Phytoplankton mortality as function of biomass and nutrient level	$(mgP/ℓ)^{-1}day^{-2}$	v_1	.2	.2	.2	.2
Coefficient of substrate conversion by phytoplankton	unitless	β	.6	.6	.6	.6
Maximum uptake rate for bacteria	day^{-1} at 20°C	K_2	.3	.3	.3	.3
Excretion efficiency of bacteria	day	a_3	.3	.3	.3	.3
- " - " - " - " - " - " - " -	- " -	a_4	.45	.45	.45	.45
Natural mortality of bacteria	day^{-1}	v_2	.053	.053	.053	.053
Bacterial mortality as function of biomass and nutrient level	$(mgP/ℓ)^{-1}day^{-2}$	v_3	1.0	1.0	1.0	1.0
Detritus decomposition	day^{-1} at 20°C	K_3	.1	.1	.1	.1
Extinction coefficient	m^{-1}	K_a	1.8	1.8	1.5	1.5
- " - " - " - " - " -	- " -	K_b	.0088	.0088	.0088	.0088
Rate constant of detritus sedimentation	day^{-1}	K_{sed}	.25	.25	.25	.25
Rate constant of phosphorus transformation in sediment	day^{-1}	K_{tr}	.125	.125	.125	.125
Empirical coefficient for dependence of detritus resuspension on the wind speed	unitless	U	1.0	1.0	1.0	1.0
Proportionality coefficient in equation of wind-induced water flow	- " - " -	k	.0018	.0018	.0018	.0018
Proportionality coefficient of tributary DIP load	- " - " -	y_1	1.0	.55	.05	.0
Proportionality coefficient of urban run-off DIP load	- " - " -	y_2	.01	.04	.05	.10
Proportionality coefficient of tributary P_D load	- " - " -	γ_1	1.0	.9	.3	.2
Proportionality coefficient of urban run-off P_D load	- " - " -	γ_2	.05	.2	.25	.5

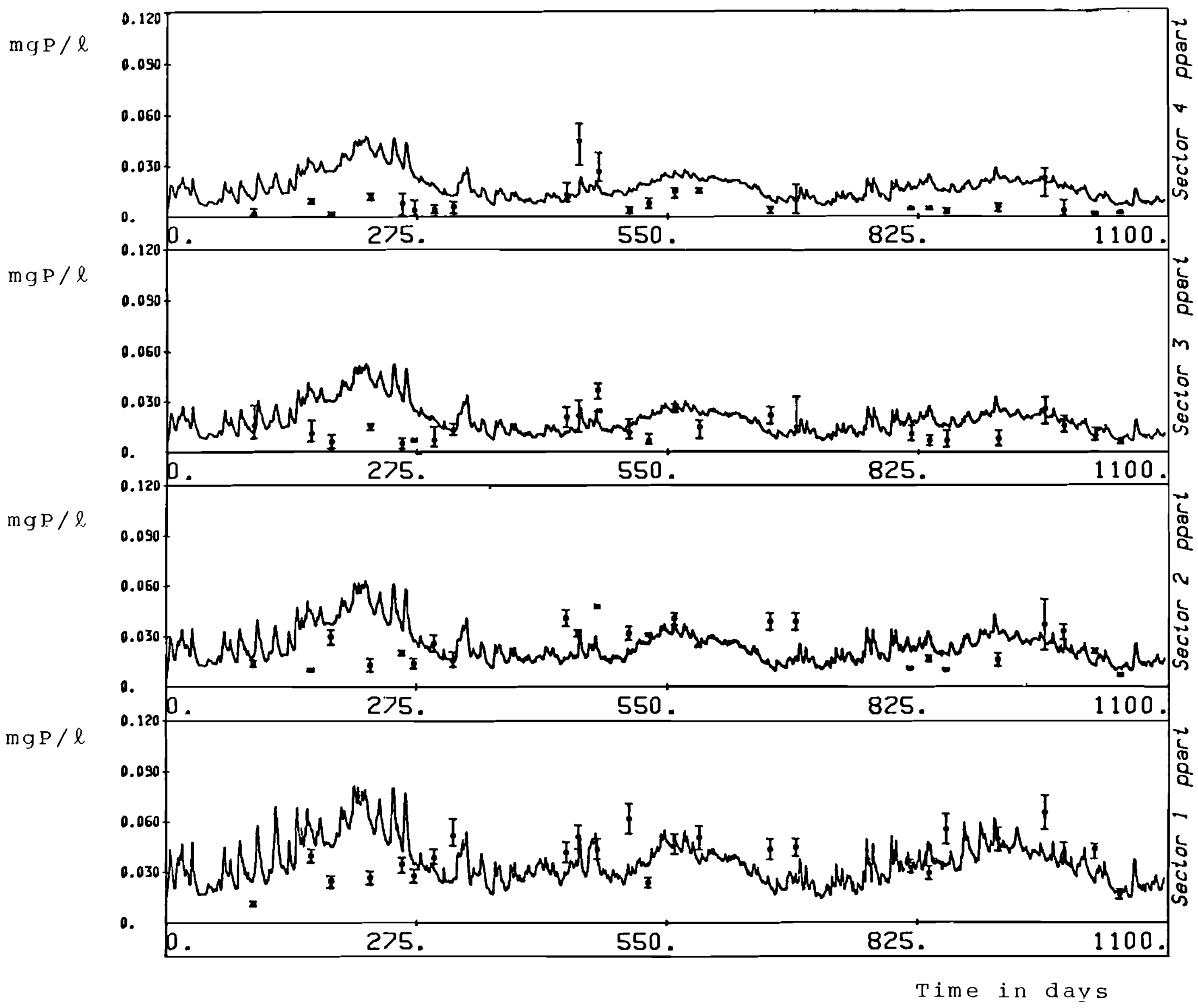

Figure 8. Comparison of model calculations (curves) and observed data for particulate organic phosphorus. Lake Balaton Basins I-IV,1976-1978.

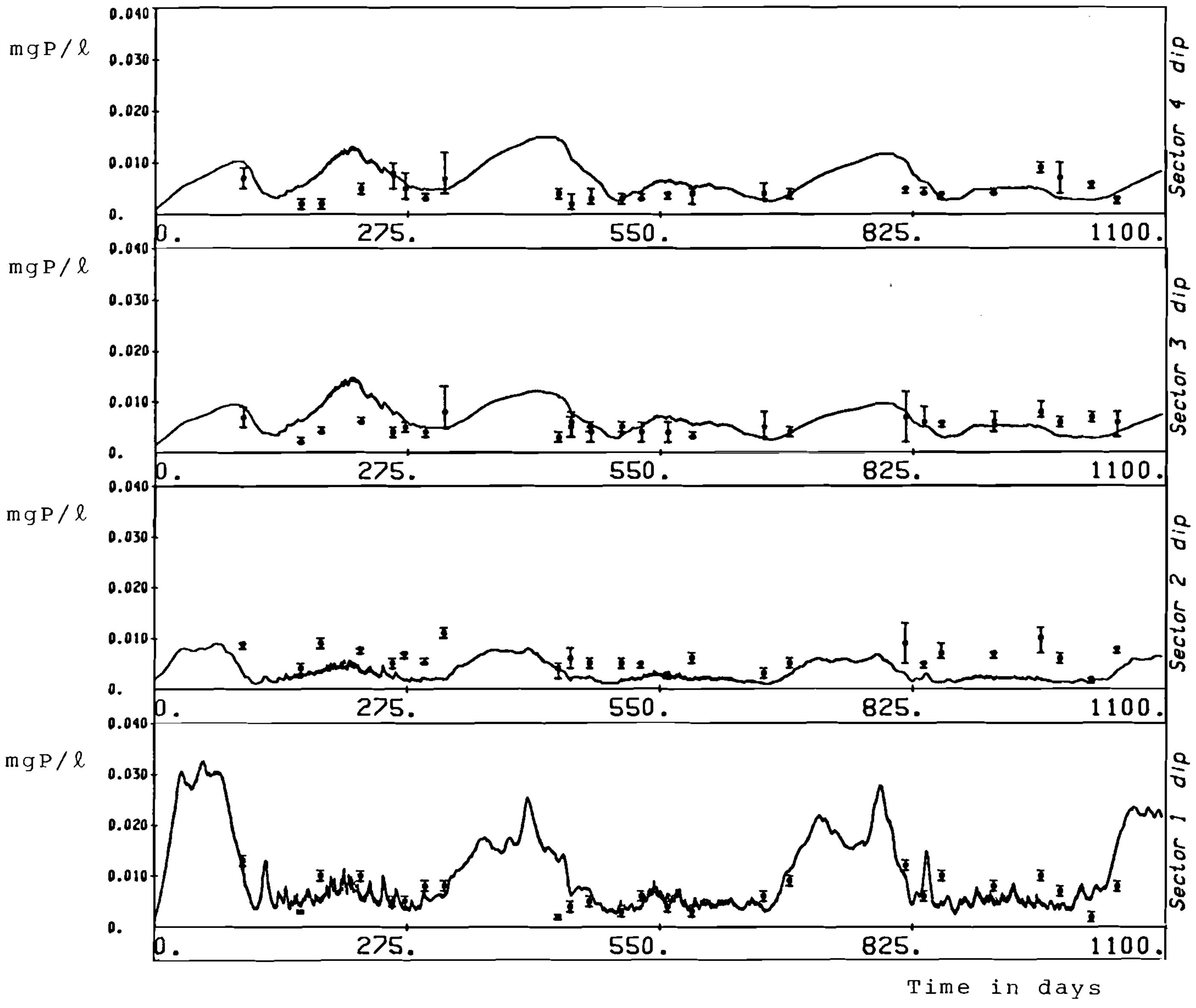

Figure 9. Comparison of model calculations (curves) and observed data for dissolved inorganic phosphorus. Lake Balaton Basins I-IV, 1976-1978.

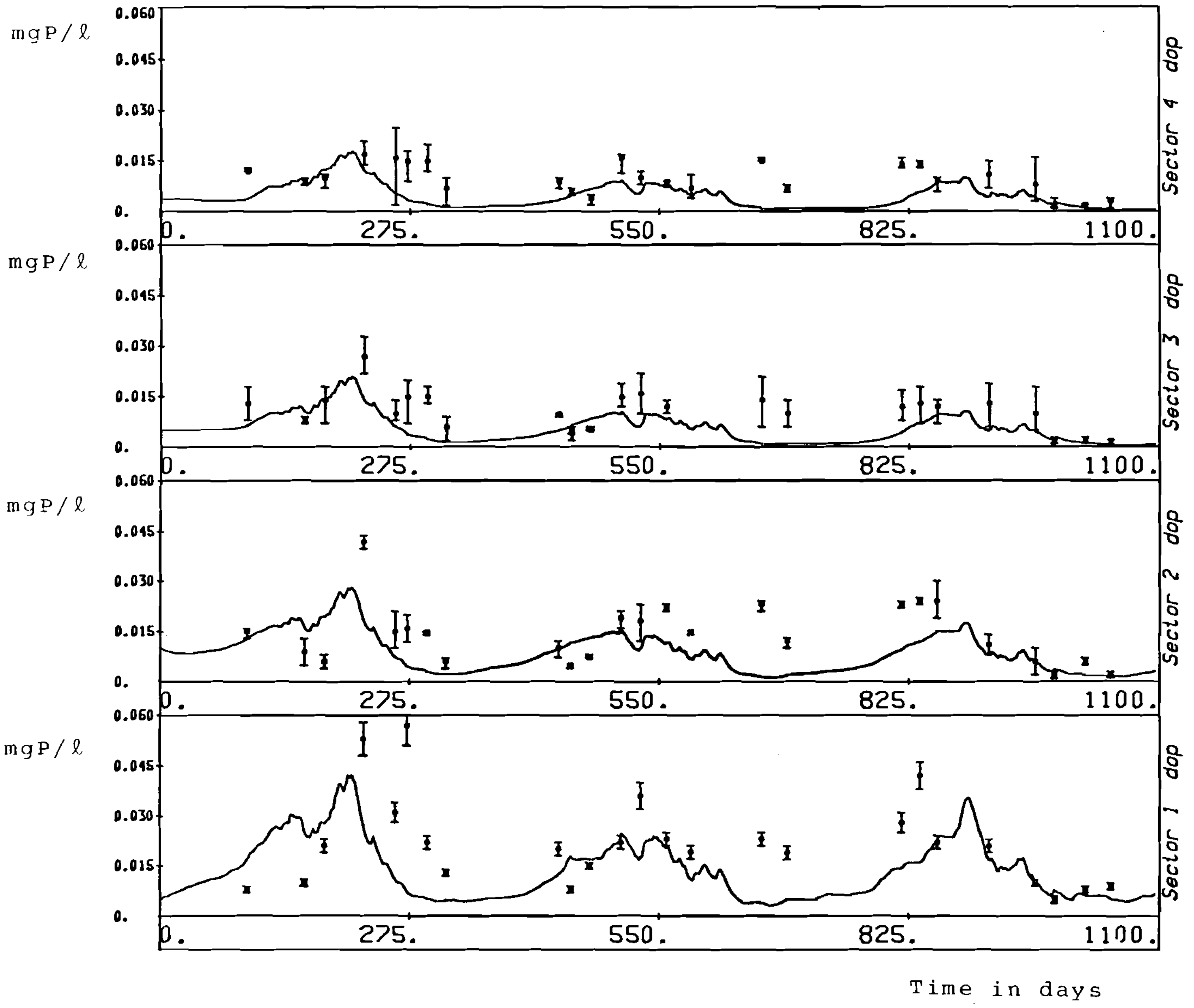

Figure 10. Comparison of model calculations (curves) and observed data for dissolved organic phosphorus. Lake Balaton Basins I-IV, 1976-1978.

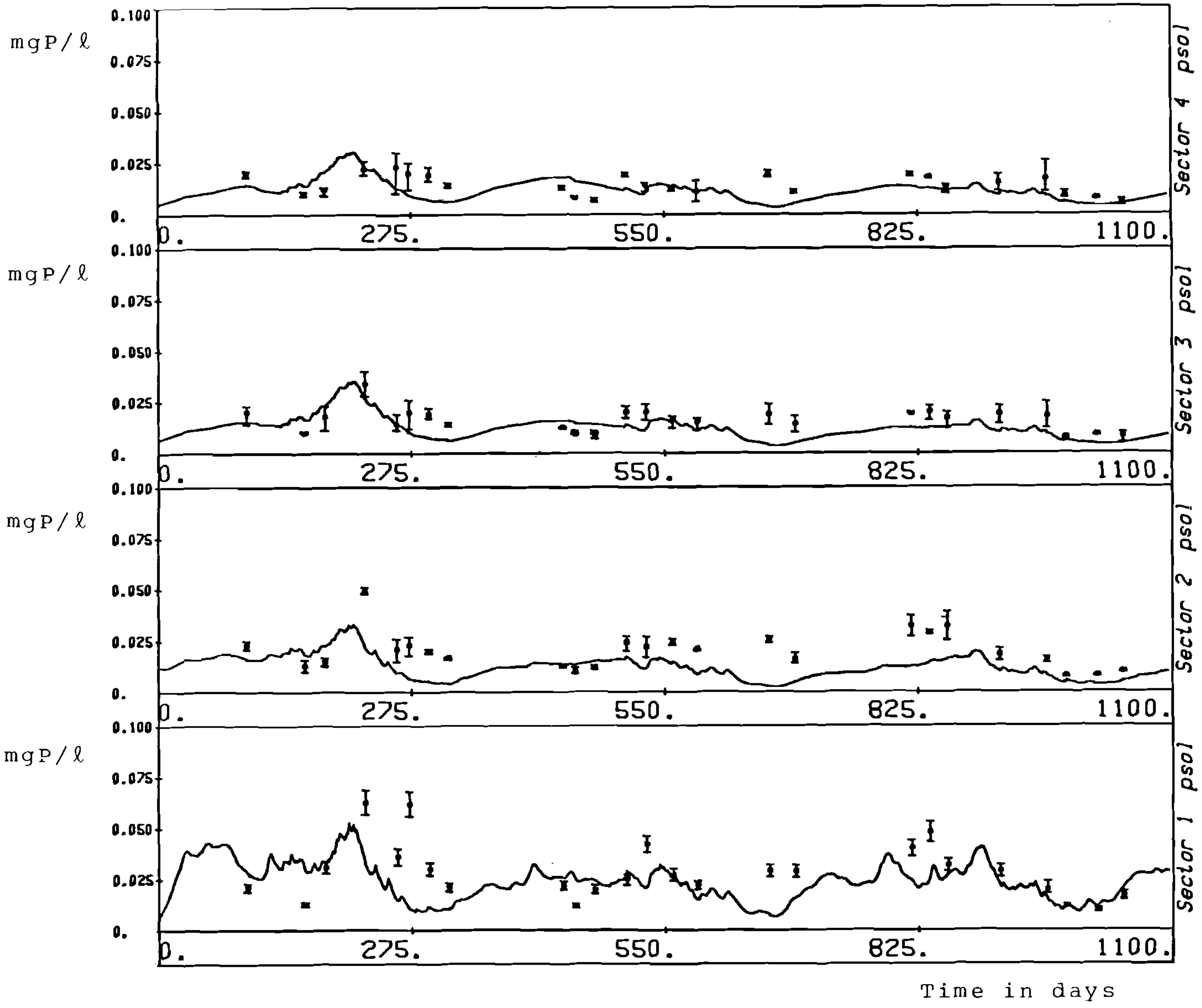

Figure 11. Comparison of model calculations (curves) and observed data for total soluble phosphorus. Lake Balaton Basins I-IV, 1976-1978.

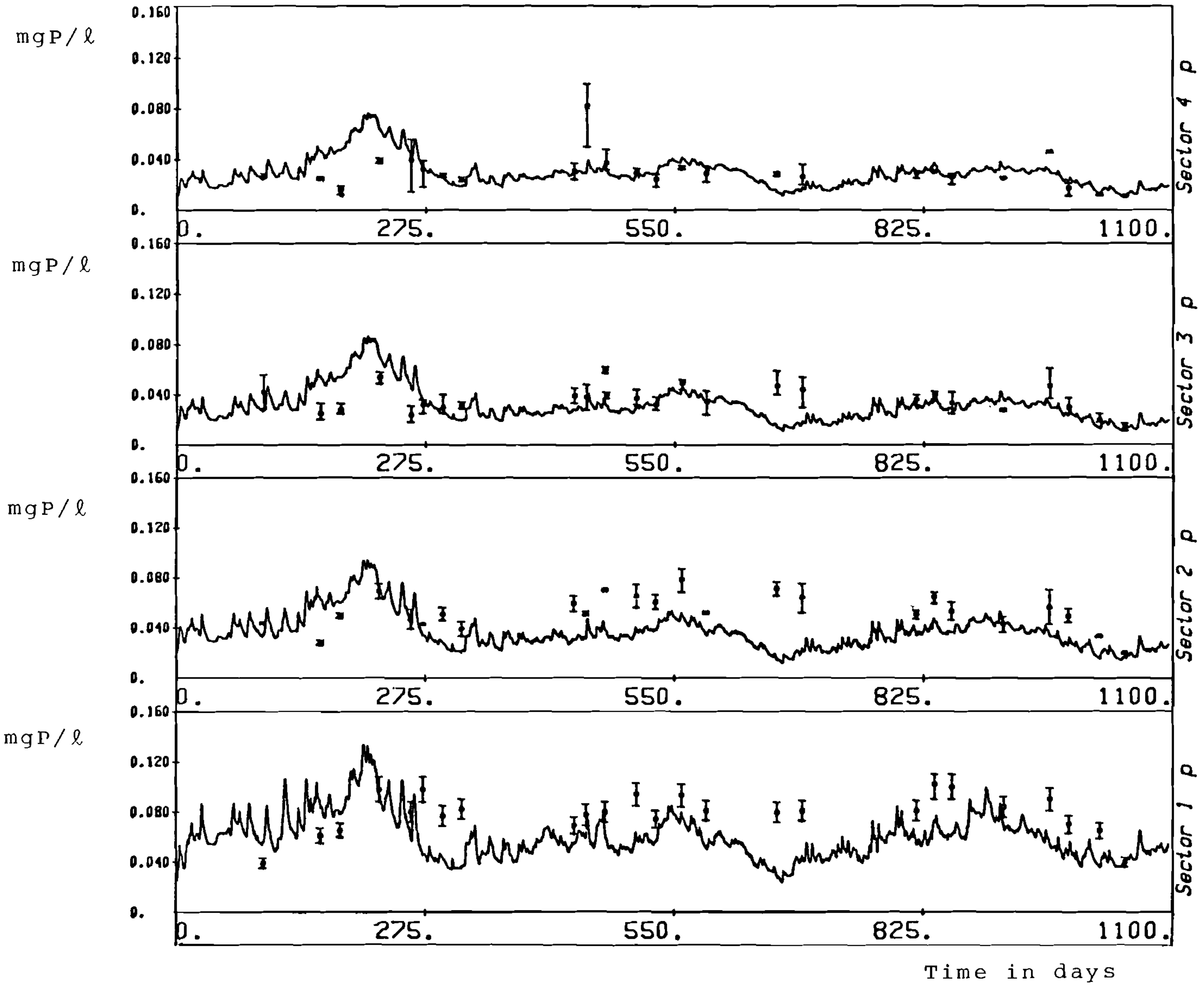

Figure 12. Comparison of model calculations (curves) and observed data for total phosphorus. Lake Balaton Basins I-IV, 1976-1978.

For the analysis of the simulation results, it is interesting to obtain additional information which can help in understanding the role of external sources in the phosphorous loading as well as the significance of the internal phosphorous cycling in the functioning of the Lake Balaton ecosystem. The possible influence of sediment on the phosphorous load, based on data used during the simulation, was discussed in detail in an earlier report (Leonov, 1981). Among the different sources of the phosphorous load, this model takes into account the phosphorous inputs from rainfall, the Zala river, and external nonpoint sources (or watershed P-load). The dynamics of DIP and DOP load from rainfall for each month between 1976-1978 were calculated with the model and are presented in Figures 13 and 14 respectively. Annual inputs of DIP from rainfall for 1976-1978 changed in the ranges 0.024-0.0277, 0.0181-0.0209, 0.0161-0.0185 and 0.0147-0.0170 mgP/ℓ-year for Basins I-IV respectively. For DOP, the annual inputs from rainfall fluctuated from 0.0144-0.0166, 0.0109-0.0125, 0.0097-0.0111 and 0.0088-0.0102 mgP/ℓ-year for the same basins. In 1976 the rainfall contribution of DIP and DOP was higher than in other years studied, while in 1978 these rainfall loads were lowest within 1976-1978.

From the input data used in the simulation, the model calculates the quantities of phosphorus entering the lake from the Zala river. Table 5 shows the monthly and annual amounts of the phosphorous load from the Zala river to Keszthely Bay as calculated by the model. One immediately sees that the total phosphorous input from the Zala river discharge water significantly increases from 0.711 mgP/ℓ in 1976 to 0.997 mgP/ℓ in 1977, which results

Table 5. Amounts of Phosphorous Inputs (in mgP/ℓ and in Percentages of Total P-load) to Keszthely Bay from Zala river

Year	Months	Nonliving particulate - P		Dissolved inorganic P		Phyto-plankton P		Bacterial P		Total phosphorus load	
		mgP/l	%	mgP/l	%	mgP/l	%	mgP/l	%	mgP/l	%
1976	Jan	0.0422	43.5	0.0535	55.2	0.0012	1.2	0.00009	0.1	0.09699	13.6
	Feb	0.0006	1.1	0.0498	95.4	0.0018	3.4	0.00008	0.1	0.05228	7.4
	Mar	0.0023	5.0	0.0408	88.5	0.0029	6.3	0.00010	0.2	0.04610	6.5
	Apr	0.0225	30.1	0.0495	66.3	0.0026	3.5	0.00008	0.1	0.07468	10.5
	May	0.0524	54.1	0.0424	43.8	0.0019	2.0	0.00010	0.1	0.09680	13.6
	June	0.0313	64.0	0.0165	33.7	0.0011	2.2	0.00006	0.1	0.04896	6.9
	July	0.0134	58.7	0.0087	38.1	0.0007	3.1	0.00003	0.1	0.02283	3.2
	Aug	0.0124	43.3	0.0158	55.2	0.0004	1.4	0.00003	0.1	0.02863	4.0
	Sept	0.0106	37.4	0.0167	59.0	0.0010	3.5	0.00003	0.1	0.02833	4.0
	Oct	0.0189	49.0	0.0187	48.6	0.0009	2.3	0.00005	0.1	0.03855	5.4
	Nov	0.0279	50.4	0.0268	47.2	0.0013	2.3	0.00008	0.1	0.05548	7.8
	Dec	0.0887	72.9	0.0300	24.7	0.0027	2.2	0.00019	0.2	0.12159	17.1
Annual Phosphorus Input		0.3232	45.4	0.3686	51.9	0.0185	2.6	0.00092	0.1	0.71122	100.0
1977	Jan	0.0989	77.5	0.0252	19.7	0.0035	2.7	0.00018	0.1	0.12778	12.8
	Feb	0.1581	74.4	0.0458	21.6	0.0083	3.9	0.00026	0.1	0.21246	21.4
	Mar	0.0639	54.7	0.0437	37.4	0.0090	7.7	0.00019	0.2	0.11679	11.7
	Apr	0.1385	76.6	0.0326	18.0	0.0096	5.3	0.00017	0.1	0.18087	18.1
	May	0.0279	45.0	0.0316	51.0	0.0024	3.9	0.00006	0.1	0.06196	6.2
	June	0.0123	28.1	0.0308	70.2	0.0007	1.6	0.00004	0.1	0.04384	4.4
	July	0.0041	9.2	0.0390	87.1	0.0016	3.6	0.00003	0.1	0.04473	4.5
	Aug	0.0059	19.2	0.0229	74.5	0.0019	6.2	0.00003	0.1	0.03073	3.1
	Sept	0.0031	9.8	0.0268	84.7	0.0017	5.4	0.00003	0.1	0.03163	3.2
	Oct	0.0056	17.4	0.0255	79.4	0.0010	3.1	0.00003	0.1	0.03213	3.2
	Nov	0.0270	44.2	0.0333	54.6	0.0007	1.1	0.00005	0.1	0.06105	6.1
	Dec	0.0174	33.0	0.0344	65.3	0.0008	1.6	0.00008	0.1	0.05268	5.3
Annual Phosphorus Input		0.5627	56.5	0.3916	39.3	0.0412	4.1	0.00115	0.1	0.99665	100.0
1978	Jan	0.0208	49.2	0.0209	49.5	0.0005	1.2	0.00006	0.1	0.04226	4.3
	Feb	0.0317	39.7	0.0474	59.4	0.0006	0.8	0.00008	0.1	0.07978	8.1
	Mar	0.0187	32.8	0.0376	66.0	0.0006	1.0	0.00010	0.2	0.05700	5.8
	Apr	0.0575	55.0	0.0445	42.5	0.0025	2.4	0.00012	0.1	0.10462	10.6
	May	0.1121	71.8	0.0400	25.6	0.0040	2.5	0.00011	0.1	0.15621	15.9
	June	0.1152	70.6	0.0445	27.3	0.0033	2.0	0.00011	0.1	0.16311	16.6
	July	0.0488	51.2	0.0447	46.9	0.0017	1.8	0.00008	0.1	0.09528	9.7
	Aug	0.0137	31.4	0.0281	64.4	0.0018	4.1	0.00004	0.1	0.04364	4.4
	Sept	0.0259	43.6	0.0313	52.6	0.0022	3.7	0.00004	0.1	0.05944	6.0
	Oct	0.0274	38.4	0.0417	58.4	0.0022	3.1	0.00006	0.1	0.07136	7.2
	Nov	0.0120	24.8	0.0354	73.0	0.0010	2.1	0.00005	0.1	0.04845	4.9
	Dec	0.0278	43.5	0.0347	54.4	0.0013	2.0	0.00009	0.1	0.06389	6.5
Annual Phosphorus Input		0.5116	51.9	0.4508	45.8	0.0217	2.2	0.00094	0.1	0.98504	100.0

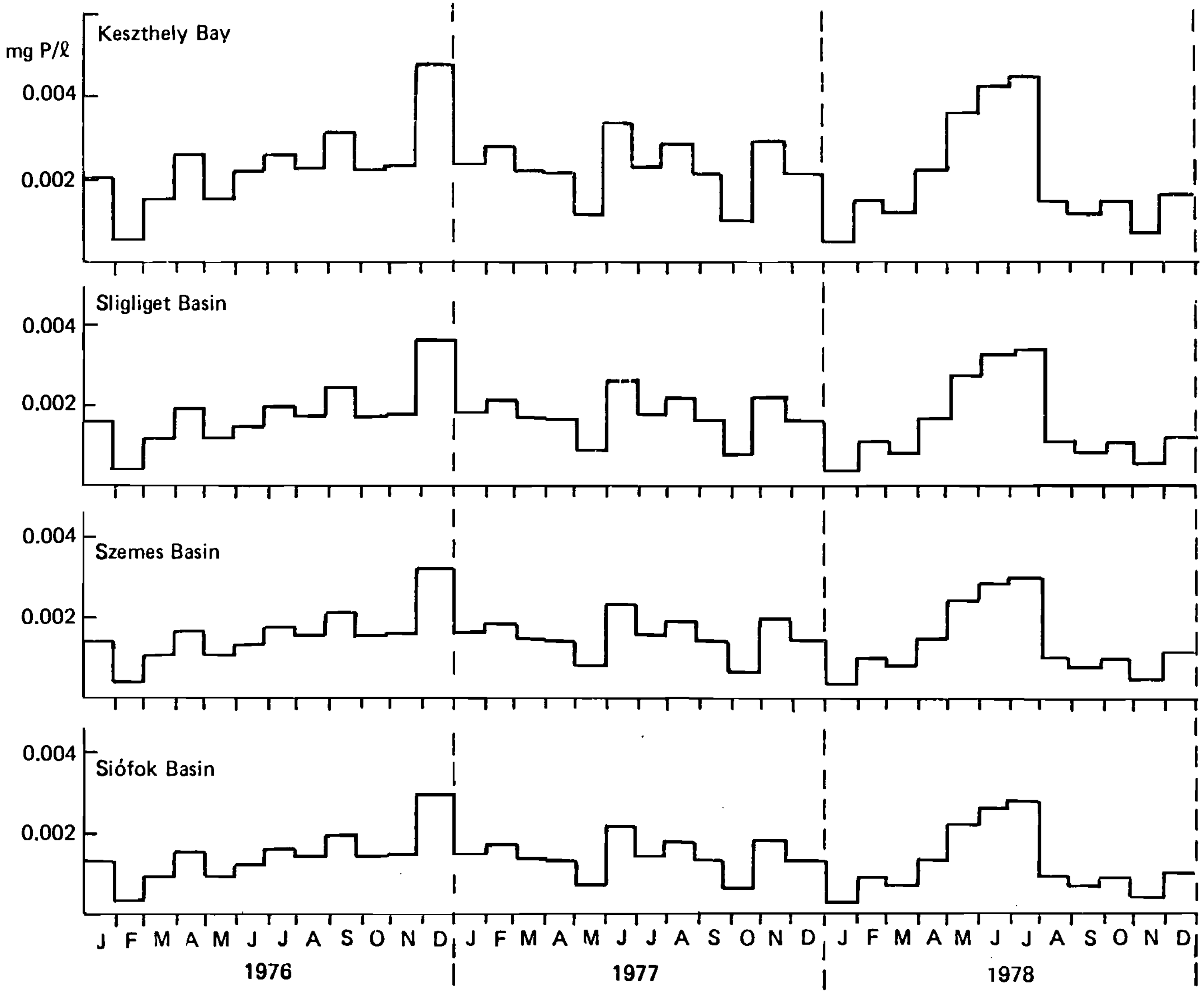

Figure 13. Dynamics of DIP inputs to Lake Balaton Basins by rainfall.

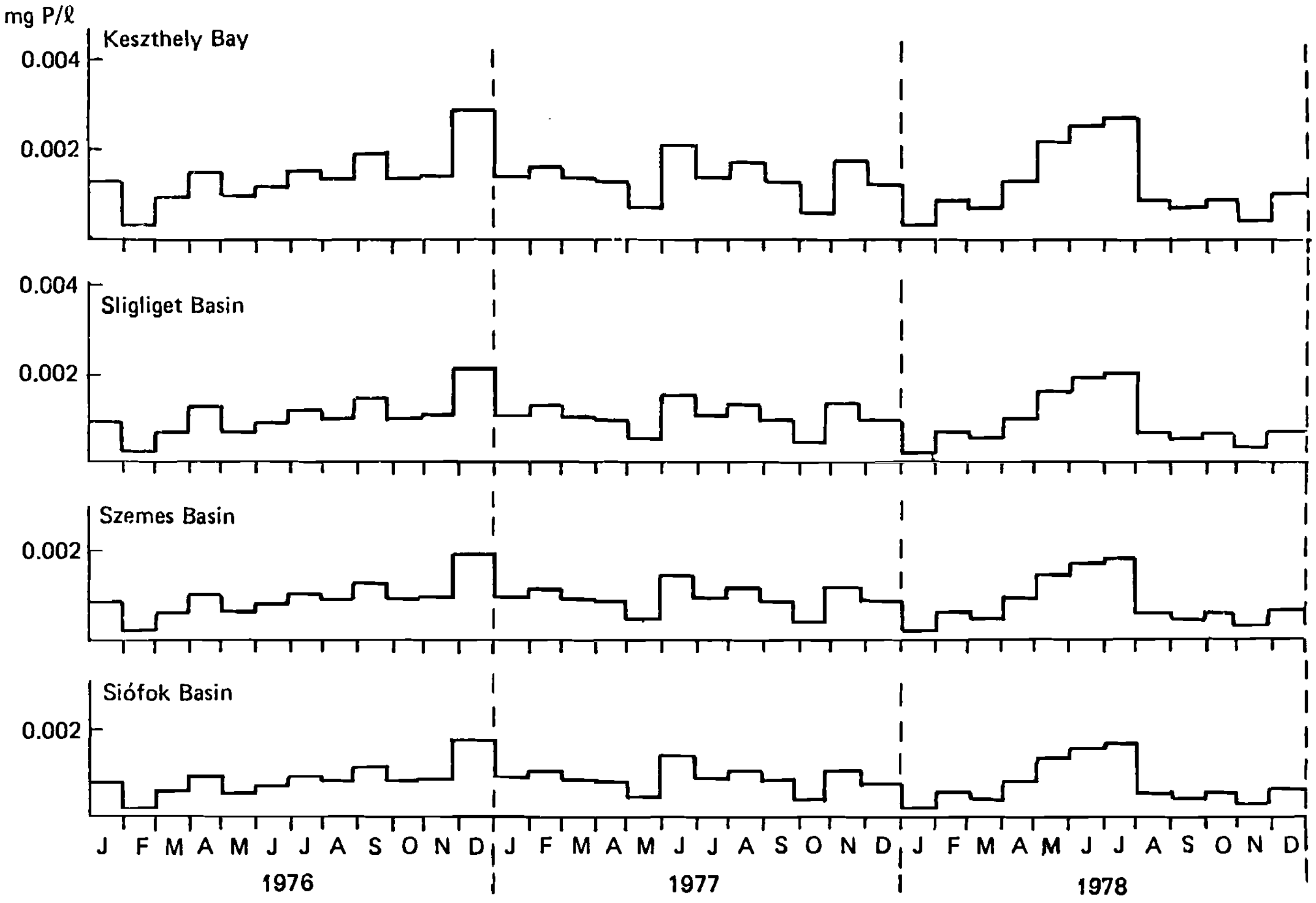

Figure 14. Dynamics of DOP inputs to Lake Balaton Basins by rainfall.

primarily in an increase of nonliving particulate phosphorus in the annual phosphorous input to the lake from the Zala river. The quantities of the nonliving particulate phosphorus and DIP in the Zala river phosphorous load for 1976 were estimated as 0.323 mgP/ℓ (or 45.4%) and 0.369 mgP/ℓ (or 51.9%) respectively. For 1977, these quantities equal 0.563 mgP/ℓ (or 56.5%) and 0.392 mgP/ℓ (or 39.3%). From 1977 to 1978, the total annual flux of phosphorus to the lake from the Zala river decreased slightly to 0.985 mgP/ℓ. However, in contrast to 1977, the proportions of nonliving particulate phosphorus and DIP in the total phosphorous load changed in 1978, so that the annual input of nonliving particulate phosphorus and DIP were 0.512 mgP/ℓ (or 51.9%) and 0.451 mgP/ℓ (or 45.8%) respectively.

The data in Table 5 also shows that the time distribution of the total phosphorous load from the Zala river varied from 1976 to 1978. In 1976, the highest phosphorous loading occurred in January, April, May, and December, and the total phosphorous input for these months was 0.075-0.122 mgP/ℓ-month (or 10.5-17.1% of the annual phosphorous load). In 1977, the highest phosphorous loading took place in the period January-April (0.117-0.213 mgP/ℓ-month or 11.7-21.4%) while in 1978, the highest phosphorous load coming from the Zala river was in April-July (0.095-0.163 mgP/ℓ-month or 9.7-16.6% of the annual phosphorous load).

Furthermore, on the basis of the data in Table 5, it is possible to estimate the role of the nonliving particulate phosphorus and DIP as major phosphorous fractions in the Zala river's phosphorous load for individual months between 1976-1978. In 1976, the nonliving particulate phosphorus dominated over DIP only in June and December, when monthly inputs of nonliving particulate-P were 0.031 mgP/ℓ (or 64.0% of total P-load) and 0.089 mgP/ℓ (or 72.9%) respectively. Contributions of DIP for the same months in 1976 were 0.016 mgP/ℓ (or 33.7%) and 0.030 mgP/ℓ (or 24.7%). The dominance of DIP in the Zala river's P-load in 1976 occurred in February-April (0.041-0.050 mgP/ℓ-month or 66.3-95.4% of total P-load). For other months of 1976, the quotas of these phosphorous fractions in the Zala river's P-load were in the appropriate balance. For 1977, the dominance of nonliving particulate-P over DIP was noted for the period January-April, so that the total monthly inputs of this phosphorous fraction from the Zala river were 0.064-0.138 mgP/ℓ-month (or 54.7-77.5% of total P-load). In May 1977, the quantities of nonliving particulate-P and DIP in the Zala river's P-load were almost equivalent, 0.028 mgP/ℓ-month (or 45.0%) and 0.032 mgP/ℓ-month (or 51.0%) respectively. For the period from June-December 1977, the amount of DIP transferred by the Zala river to the lake was higher than that of nonliving particulate-P; the value of the DIP is 0.023-0.039 mgP/ℓ-month (or 54.5-87.1%). In 1978, the nonliving particulate-P prevailed over DIP in the Zala river P-load only in May and June; the quantity of this phosphorous fraction in the total P-load of the Zala river was 0.112–0.115 mgP/ℓ-month or 70.6-71.8% compared to DIP, which was 0.040-0.044 mgP/ℓ-month (or 25.6-27.3%) for each of these months. The predominance of DIP over nonliving particulate-P in the Zala river P-load in 1978 was observed in February, March, August and November when the contributions of DIP were evaluated at 0.028-0.047 mgP/ℓ-month (or 59.4-73.0% of the total P-load). In the other months of 1978, the inputs of these phosphorous fractions from the Zala river to the lake were similar.

The model also evaluates the inputs of phosphorus to Lake Balaton from the watershed area. These inputs are identified as the additional external load. In the preliminary model runs, the inputs of DIP from the sewage and nonliving particulate-P from the watershed area were taken into account (Leonov, 1981). In this prior report, the improved version of the external phosphorous loading of the Lake Balaton Basins was used. This model accounts for the inputs of DIP and nonliving particulate-P from the tributaries and urban run-off, plus the DIP input from sewage discharge water. Table 6 compares the different annual phosphorous inputs to the Lake Balaton Basins in 1976-1978, which result from the different phosphorous load estimates used then and now.

The analysis of the data in Table 6 shows that in the given study, the phosphorous loading from the external sources was essentially changed and the total amounts of the annual phosphorous inputs to Basins I-IV are, on average, 0.6, 1.6, 1.3 and 1.4, respectively, compared to those values used previously (Leonov, 1981). The comparison of the simulation results (Figures 8-12) obtained now and earlier (Leonov, 1981) shows that the model outputs for Basins I, III and IV with both loading versions are virtually the same, while for Basin II, the present phosphorous loading data gives a better description of the phosphorous dynamics than before (Leonov, 1981). However, the level of some phosphorous fractions,especially DIP, should be higher than those calculated in the simulation. The model results lead to the reasonable assumption that of all external sources of phosphorus shown in Table 6, the role of sewage should be much more important (at least for Basin II) in contributing

Table 6. Comparison of Amounts of Annual Phosphorous Inputs to Lake Balaton from External Sources as Calculated by the Model.

Year	Source of P-load	Basins				Reference
		I	II	III	IV	
1976	Sewage DIP load	.0893	.0425	.0298	.0383	Leonov(1981)
	Watershed P_D load	-	.0640	.0200	.0087	
	Total P input(mgP/ℓ-year)	.0893	.1065	.0498	.0470	
1977	Sewage DIP load	.0893	.0425	.0298	.0383	
	Watershed P_D load	-	.1114	.0349	.0152	
	Total P input(mgP/ℓ-year)	.0893	.1539	.0647	.0535	
1978	Sewage DIP load	.0893	.0425	.0298	.0383	
	Watershed P_D load	-	.1013	.0317	.0138	
	Total P input(mgP/ℓ-year)	.0893	.1438	.0615	.0521	
1976	DIP load by:					In the given report
	1.tributaries	-	.04014	.00254	-	
	2.urban runoff	.00037	.00291	.00254	.00376	
	3.sewage	.03474	.02922	.02503	.03559	
	Total DIP load	.03511	.07227	.03011	.03935	
	P_D load by:					
	1.tributaries	-	.05753	.01328	.00659	
	2.urban runoff	.01616	.01280	.01109	.01648	
	Total P_D load	.01616	.07033	.02437	.02307	
	Total P input(mgP/ℓ-year)	.05127	.14260	.05448	.06242	
1977	DIP load by:					
	1.tributaries	-	.02537	.00270	-	
	2.urban runoff	.00039	.00309	.00270	.00400	
	3.sewage	.03474	.02922	.02503	.03559	
	Total DIP load	.03513	.05768	.03043	.03959	
	P_D load by:					
	1.tributaries	-	.10016	.02313	.01148	
	2.urban runoff	.02814	.02228	.01930	.02870	
	Total P_D load	.02814	.12244	.04243	.04018	
	Total P input(mgP/ℓ-year)	.06327	.18012	.07286	.07974	
1978	DIP load by:					
	1.tributaries	-	.04909	.01025	-	
	2.urban runoff	.00045	.00356	.02102	.00460	
	3.sewage	.03474	.02922	.02503	.03539	
	Total DIP load	.03519	.12368	.05630	.04019	
	P_D load by:					
	1.tributaries	-	.09106	.02102	.01044	
	2.urban runoff	.02558	.02026	.01755	.02609	
	Total P_D load	.02558	.11132	.03857	.03653	
	Total P input(mgP/ℓ-year)	.06077	.23500	.09487	.07672	

mineral and apparently organic phosphorus to the lake. In this context, the new ideas formulated recently by Jolánkai and Somlyódy (1981) concerning the time distribution of the phosphorous loading from the sewage, should be examined by the model.

5. PHOSPHOROUS CYCLING IN LAKE BALATON

All biogenic elements in water environments circulate many times through the system between living and nonliving entities. On the basis of direct measurements in the water body, it is diffficult to analyze the passive pathways of cycled material, because the observed concentrations of the chemical and biological compounds in the water body are in dynamic equilibrium. The application of the model provides the opportunity of assessing the nature of the material cycling among all the compartments considered. As Odum (1971) indicated, quantitative studies of the biogeochemical cycles of elements are needed for better understanding and controlling of man's role in material cycles and community metabolism. Therefore, in the case of Lake Balaton, studying the phosphorous cycle as a key element of eutrophication in the given lake is useful for understanding the features of the phosphorous budget and determining the structural functioning of this ecosystem as a whole.

The biogeochemical cycling of the phosphorus may be quantitatively evaluated on the basis of the flux rates of the phosphorus, which characterize the transfer of the phosphorus from one compartment to another, the concentration levels of individual phosphorous compartments, and the total phosphorus. The peculiarity of phosphorous cycling in water may be elucidated by the values of the turnover times, that is, the time required to replace a quantity of the matter equal to the amount in the compartment (Odum, 1971). This characteristic is especially important in studies of water body eutrophication and productivity (Pomeroy, 1970).

The values given in the literature for turnover times of the phosphorous compartments are reviewed in Table 7. These values were obtained through calculations from (i) experiments with additions of dry phosphate fertilizers, (ii) experiments with radioactive phosphate phosphorus, (iii) the data on the primary production (or biomass values) and phosphate concentrations in water bodies, and (iv) the applied mathematical models. The turnover time values in Table 7 are shown in days (d), hours (h) or minutes (m). The analysis of the data in Table 7 shows that:

(i) the turnover time assessments are dependent on the method used; for example, for orthophosphate phosphorus, the shortest turnover times were obtained in experiments with ^{32}p isotope while other methods yield a higher and approximately similar order of magnitude;

(ii) the majority of turnover time assessments were done for the orthophosphate phosphorus during the productive season; usually the orthophosphate turnover time is very short when a low concentration of orthophosphate is present in the water, but the turnover time appears to be longer when large quantities are present;

Table 7. Literature Review of Turnover Times for Phosphorus Compartments.

Water body	Characteristics of water body		Experimental conditions/ Calculation method	Characteristics of equilibrium system in experiment	Phosphorus fractions	P levels µg/ℓ	Turnover time		Reference
	Area ha	Max depth m					water	sediment	
Ullswater (stratified)	900	63	Experiments with spring water, nothing added	-	phosphorus	1-10	29 d	-	Pearsall(1930)
Eight English lakes(stratified)	100-900	19-79	Experiments with spring water, nothing added	-	phosphorus	-	26-40 d	-	
Lake Crecy,NB (unstratified)	20.4	3.8	Addition of dry phosphate fertilizer	Solids(mud&plants)*vs* water incl.bacteria	phosphorus	20-280	17 d	176 d	Smith(1945)
Marine Loch Craiglin,Scot.(unstratified)	7.3	6	Addition of dry phosphate fertilizer to:	Solids(mud&plants)*vs* water incl.bacteria					Orr(1947)
			a.July water		phosphorus	10-70	1.6$\pm$0.5 d	-	
			b.August water		- " - " -	10-400	4.7$\pm$0.6 d 3.2$\pm$0.7*d	-	
Marine Pond Cohasset,Mass.,(unstratified)	-	0.7	Addition of dry phosphate fertilizer to May water	Solids(mud&plants)*vs* water incl.bacteria	phosphorus	20-340	2.4$\pm$0.5 d	-	Pratt(1949)
Lake Punchbowl,NS (stritified)	0.3	6.2	^{32}P experiments with epilimnion water	Solids(mud&plants)*vs* water incl.bacteria	phosphorus	-	7.6 d	37 d	Coffin et al (1949);Hayes et al(1952)
Lake Bluff,NS (unstratified)			^{32}P experiments with July water	Solids(mud&plants)*vs* water incl.bacteria	phosphorus	31	5.4 d	39 d	Hayes et al (1952)
Lake Oiseau,Ontario(Oligotrophic)	3.6	-	^{32}P experiments with September water	Bacteria & algae cells *vs* water	PO$_4$-P	0.3	3.6 m	-	Rigler(1956)
Lake Toussaint,Ontario(stratified, oligotrophic)	4.7	9.8	^{32}P experiments with September water	Bacteria & algae cells *vs* water	PO$_4$-P	0.8	4.5 m	-	
					"Mobile" P of water & phytoplankton in epilimnion	-	3.6 d	-	
Lake Maskinonge,Ontario(oligotrophic)	160	-	^{32}P experiments with September water	Bacteria & algae cells *vs* water	PO$_4$-P	0.12	26 m	-	
Ottawa River	-	-	^{32}P experiments with September water	Bacteria & algae cells *vs* water	PO$_4$-P	0.49	30 h	-	
Lake Chocolate,Halifax(polluted)	-	-	^{32}P experiments with filtered surface water	Inorganic-P in sol.& in bacteria *vs* organic-P in sol.& in bacteria	PO$_4$-P	-	1.1 d	-	Harris(1957)
					Organic-P	-	0.79 d	-	
					P in *Arthemia*	-	14 h	-	
					P in *Gammarus*	-	1.8 d	-	
Grenadier Pond, Ontario	16	6	^{32}P experiments with: a.Summer water	Total P,total soluble P & inorganic-P in sol.*vs* seston-P & soluble organic-P in sol.	PO$_4$-P	6.4**	0.9-285 m	-	Rigler(1964)
			b.Winter water	- " - " - " - " -	- " -	- " -	25 h	-	
Lake Heart,Ontario	15	9	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	2.1**	7.3 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	6.9 d	-	
Lake Teaport, Ontario	0.5	12	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	1.6**	1.9 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	7 m	-	
Lake Mary,Ontario	13	16	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	1.8**	3.3 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	2.1 d	-	
Lake Eos,Ontario	1.5	6	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	0.9**	2.2 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	1.6 h	-	
Lale Costello, Ontario	39	18	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	0.9**	5.4 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	18.3 h	-	
Lake Opeongo, Ontario	2,180	53	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	0.4**	7.3 m	-	
Lake of two rivers,Ontario	296	45	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	0.4**	7.5 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	12.8 h	-	
Lake Found,Ontario	0.3	6.2	^{32}P experiments with:						
			a.Summer water	- " - " - " - " -	- " -	0.4**	6.6 m	-	
			b.Winter water	- " - " - " - " -	- " -	- " -	1.1 d	-	

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Table 7 (contd..)

Water body	Characteristics of water body: Area ha	Max depth m	Experimental conditions/ Calculation method	Characteristics of equilibrium system in experiment	Phosphorus fractions	P levels µg/l	Turnover time: water	sediment	Reference
Lake Punchbowl, NS(stratified)	0.3	6.2	^{32}P experiments with filtered water	Inorganic-P in sol.& in bacteria *vs* organic-P in sol.& in bacteria	PO_4-P	-	0.21 d	0.21 d	Hayes, Phillips(1968)
Nine NS Lakes	-	-	^{32}P experiments with filtered water	Mud *vs* water with bacteria present, oxidized system	PO_4-P	-	2.7 d	3.6 d	
				Mud *vs* water with bacteria present, reduced system	- " -	-	2.6 d	3.5 d	
				Mud *vs* water with bacteria absent, oxidized system	- " -	-	2.6 d	15.5 d	
				Mud *vs* water with bacteria absent, reduced system	- " -	-	2.9 d	12.5 d	
Lake Grand, NS (unproductive)	-	-	^{32}P experiments with filtered water	Inorganic P in sol.& in bacteria *vs* organic-P in sol.& in bacteria	PO_4-P	-	0.2 d	0.2 d	
			^{32}P experiments with phytoplankton culture *Chlamydomonas dysostus* in nutrient solution	Phytoplankton culture *vs* water	- " -	-	1 m	0.5 m	
			^{32}P experiments with 1 g sprigs in 150 ml water, bacteria absent	Flowering plant *Eriocaulon* *vs* water	- " -	-	0.34 d	3.0 d	
			^{32}P experiments with 1.5 g sprigs in 150 ml water, bacteria absent	Peat mass (*Sphagnum*) *vs* water	- " -	-	0.09 d	3.5 d	
Lake Toussaint, Ontario(stratified, oligotrophic)	4.7	9.8	^{32}P experiments with September water	Bacteria & algae cells *vs* water	phosphorus	-	10.2 d	29 d	
Lake Lucerne, SW	-	-	Calculations from primary production & phospha-concentrations for:	-					Gachter(1968
			a. Summer period		particulate-P(primarily phytoplankton-P)		10 d	-	
			b. Winter period		- " - " -	-	30 d	-	
-	-	-	Calculations from amounts of biomass & phosphate concentrations	-	PO_4-P	-	-	18-20 d	Fuhs(1973)
Lake Char(unfertilized)	-	27.5	-	-	PO_4-P	-	63*** m	-	Rigler(1973)
Lake Toussaint, Ontario(stratified, oligotrophic)	4.7	9.8	-	-	phosphorus	-	20 d	-	
Lake Upper Bass	5.8	-	-	-	phosphorus	-	27 d	-	
Lake Linsley Pond	9.4	-	-	-	phosphorus	-	45 d	-	
Trophic stratified Lakes	-	-	-	-	PO_4-P	-	1-8 m	-	
Lake Zurich	-	-	Calculations from spring primary production & phosphate concentrations	-	PO_4-P	-	5-10 d	-	Golterman (1973)
Lake Vechta	-	-	Calculations from spring primary production & phosphate concentrations	-	PO_4-P	-	5-10 d	-	
Obersee, Austria(oligotrophic)	1.4	15	^{32}P experiments with July water from:	Inorganic-P in sol. *vs* seston-P in sol.					Peters(1975)
			a. Surface		PO_4-P	-	4.2 m	-	
			b. 2.5 m		- " -	-	1.1 h	-	
			c. 12.5 m		- " -	-	1.2 h	-	
			^{32}P experiments with October water from:						
			a. Surface	- " - " -	- " -	-	6 h	-	
			b. 2.5 m		- " -	-	9.8 h	-	
			c. 12.5 m		- " -	-	18.9 h	-	
Mittersee, Austria(oligotrophic)	0.2	3	^{32}P experiments with July water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO_4-P	-	1.7 h	-	
			^{32}P experiments with October water from Surface	- " - " -	- " -	-	3 h	-	
Untersee, Austria(oligotrophic)	6.8	34	^{32}P experiments with July water from:	Inorganic-P in sol. *vs* seston-P in sol.					
			a. Surface		PO_4-P	-	11.2 m	-	
			b. 2.5 m		- " -	-	8.3 m	-	
			^{32}P experiments with October water from:						
			a. Surface	- " - " -	- " -	-	1.6 h	-	
			b. 2.5 m		- " -	-	2.3 h	-	
			c. 25 m		- " -	-	2.7 d	-	

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Table 7 (contd..)

Water body	Characteristics of water body		Experimental conditions/ Calculation method	Characteristics of equilibrium system in experiment	Phosphorus fractions	P levels µg/l	Turnover time		Reference
	Area ha	Max depth m					water	sediment	
Worthersee, Austria (mesotrophic)	194	84	^{32}P experiments with April water from:	Inorganic-P in sol. *vs* seston-P in sol.					
			a. Surface		PO$_4$-P	-	1.3 h	-	
			b. 2.5 *m*		- " -	-	0.9 h	-	
			c. 6 *m*		- " -	-	1.2 h	-	
			d. 25 *m*		- " -	-	19.8 h	-	
Mondsee, Austria (oligotrophic)	140	68	^{32}P experiments with October water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	44.6 m	-	
Klostersee, FRG (eutrophic)	4.6	15	^{32}P experiments with April water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	24.7 m	-	
Maggiore, Italy (mesotrophic)	2,120	370	^{32}P experiments with July water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	1.7 h	-	
			^{32}P experiments with August water from Surface	- " - " -	- " -	-	14 m	-	
			^{32}P experiments with September water from:						
			a. Surface	- " - " -	- " -	-	33 m	-	
			b. 25 *m*		- " -	-	16.7 h	-	
			c. 125 *m*		- " -	-	3.5 d	-	
			^{32}P experiments with October water from:						
			a. Surface	- " - " -	- " -	-	20 m	-	
			b. 25 *m*		- " -	-	33 m	-	
			c. 125 *m*		- " -	-	1.8 h	-	
			^{32}P experiments with December water from:						
			a. Surface	- " - " -	- " -	-	6.9 d	-	
			b. 25 *m*		- " -	-	8.7 d	-	
			c. 125 *m*				69.4 d	-	
			^{32}P experiments with February water from:						
			a. Surface	- " - " -	- " -	-	3.5 d	-	
			b. 25 *m*		- " -	-	11.6 d	-	
			^{32}P experiments with April water from:						
			a. Surface	- " - " -	- " -	-	2.4 h	-	
			b. 25 *m*		- " -	-	11.6 d	-	
			c. 125 *m*		- " -	-	23 d	-	
			^{32}P experiments with May water from:						
			a. Surface	- " - " -	- " -	-	2.8 h	-	
			b. 25 *m*		- " -	-	6.9 d	-	
			c. 125 *m*		- " -	-	7 d	-	
			^{32}P experiments with June water from :						
			a. Surface	- " - " -	- " -	-	5.5 h	-	
			b. 25 *m*		- " -	-	2.3 d	-	
			c. 125 *m*		- " -	-	3.5 d	-	
di Mergozzo, France (eutrophic)	18	74	^{32}P experiments with August water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	17.3 m	-	
			^{32}P experiments with February water from Surface	- " - " -	- " -	-	1.8 d	-	
di Monate, France (oligotrophic)	25	34	^{32}P experiments with July water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	63.4 m	-	
			^{32}P experiments with January water from Surface	- " - " -	- " -	-	2.4 d	-	
di Varese, France (hypertrophic)	150	26	^{32}P experiments with July water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	5.8 m	-	
			^{32}P experiments with January water from Surface	- " - " -	- " -	-	51.7 d	-	
d'Endine, France (eutrophic)	23	9.4	^{32}P experiments with October water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	-	2.6 h	-	
Lake Texoma	-	-	Mathematical model calculations at 18°C	-	PO$_4$-P	-	0.6 d	-	Patten et al (1975)
Lake Naivasha, main basin, Kenya	1150	4.6^{****}	^{32}P experiments with June water from Surface	Inorganic-P in sol. *vs* seston-P in sol.	PO$_4$-P	3	1 m	-	Peters (1976)
Lake Naivasha Crater, Kenya (alkaline, saline)	1.8	3.8^{****}	- " - " -	- " - " -	- " -	3	5 m	-	
Lake Elmenteita, Kenya (alkaline, saline)	4.2	1.4^{****}	- " - " -	- " - " -	- " -	3	0.7 m	-	
Lake Nakuru, Kenya (alkaline, saline)	420	1.4^{****}	- " - " -	- " - " -	- " -	23	5.7-16.7 h	-	
			Same with July water		- " -	7	4.3 h		

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Table 7 (contd..)

Water body	Characteristics of water body		Experimental conditions/ Calculation method	Characteristics of equilibrium system in experiment	Phosphorus fractions	P levels µg/ℓ	Turnover time		Reference
	Area ha	Max depth m					water	sediment	
Artificial water	-	-	^{32}P experiments with four speciesof freshwater algae	Dis.inorganic-P & organic-P in sol. vs *Anabaena* in sol. with bacteria absent at incubation time (in hours):					Lean,Nalewajko(1976)
				a. 91	PO_4-P	41.1	4.8 h	-	
					Algae-P	15.7	1.9 h	-	
				b.163.5	PO_4-P	3.6	0.54 h	-	
					Algae-P	44.9	6.7 h	-	
				c.235.5	PO_4-P	0.8	2.7 m	-	
					Algae-P	55.5	3.1 h	-	
				Same with algae *Navicula* at incubation time (in hours):					
				a. 44	PO_4-P	38.4	2.7 d	-	
				b. 89	PO_4-P	4.5	1.6 h	-	
					Algae-P	50.4	20.5 h	-	
				c.237	PO_4-P	0.11	19.6 m	-	
					Algae-P	55.9	6.7 d	-	
				Same with algae *Chlorella* at incubation time (in hours):					
				a. 45	PO_4-P	45.1	7.9 d	-	
				b.140	PO_4-P	14.2	1.6 d	-	
					Algae-P	41.9	7.1 d	-	
				c.212	PO_4-P	1.6	9.7 m	-	
					Algae-P	56.3	1.5 d	-	
				Same with algae *Scenedesmus* at incubation time(in hours):					
				a. 42	PO_4-P	18.3	9.7 h	-	
					Algae-P	37.8	1.0 d	-	
				b.114	PO_4-P	0.4	29.7 m	-	
					Algae-P	54.9	2.8 d	-	
				c.210	PO_4-P	0.2	10.0 m	-	
					Algae-P	56.0	1.7 d	-	
Lake Wingra,USA (small,shallow, eutrophic)	-	-	Mathematical model calculations for:	-					Watson,Loucks (1979)
			a. Spring period		Green Algae-P	-	0.72 d	-	
					Diatoms-P	-	2.9 d	-	
					Blue-green algae-P	-	1.3 d	-	
					Winter Algae-P	-	6.7 d	-	
					Settled detritus-P	-	1500 d	-	
					Suspended detritus-P	-	10 d	-	
					PO_4-P	-	0.59 d	-	
			b. Summer period		Green Algae-P	-	0.54 d	-	
					Blue-green algae-P	-	0.88 d	-	
					Settled detritus-P	-	1400 d	-	
					Suspended detritus-P	-	6.8 d	-	
					PO_4-P	-	0.52 d	-	

Note: *) Mean value; **) Annual mean concentrations; ***) Evaluated for July;

****) Mean depth.

(iii) there is a marked seasonal fluctuation of turnover time primarily as a consequence of the changeable weather conditions affecting the rates of the internal phosphorous cycling in water bodies; according to the little data available, the possible range in turnover time for orthophosphate phosphorus, evaluated by applying the ^{32}p isotope technique, equals some minutes to some hours for the productive season and some hours to some days for the winter period;

(iv) the turnover time of phosphorus and its individual fractions depends on the water body depth and it is shorter in surface than in deeper water;

(v) the turnover time also decreases as the area of the lakes decreases.

In this step of the Lake Balaton eutrophication study, specific attention was given to the analysis of the phosphorous cycling in terms of the instantaneous flux rates, intermediate concentrations, and turnover times for the individual phosphorous compartments in the model, plus the total phosphorus. Analysis of these characteristics has been conducted throughout the three year period, 1976-1978, in order to obtain a functional understanding of the phosphorous cycling under various environmental conditions in the different Lake Balaton Basins.

Because the assessment of turnover times as well as flux rates strongly depends upon the model structure and the coupling between the model compartments (Watson and Loucks, 1979), in the given study all instantaneous internal and external phosphorous flows were considered in the calculations of the instantaneous turnover times for the individual phosphorous compartments, while for the estimate of turnover time for the total phosphorus, only the external instantaneous flows were taken into account. All calculations of the turnover times were done on every time step during the numerical solution of the model equations by the computer. The instantaneous pool sizes for each of the phosphorous compartments were divided by the instantaneous input-output flux rates through the given pool to obtain the instantaneous turnover times. The values of turnover times obtained in this way were then averaged on a daily, monthly, and annual basis.

The dynamics of the daily mean turnover times for nonliving particulate organic-P, phytoplankton-P, bacterial-P, DOP, and DIP in the Lake Balaton Basins from 1976-1978 are shown in Figures 15-19 respectively. These figures provide a picture of the seasonal and spatial changes in turnover times of the individual phosphorous fractions. The analysis of these figures shows that:

(i) all phosphorous fractions are much more mobile in the water of Basin I than in other Lake Balaton Basins;

(ii) amplitudes of the turnover time fluctuations as well as the seasonal differences in the turnover time values for phytoplankton-P, DIP, and DOP increase from Basin I to Basin IV as a result of the different phosphorous loading and the levels of phosphorous concentrations in the lake water and the phytoplankton activities in these Basins;

(iii) the variations in the turnover times for all phosphorus fractions are much less in summer than other seasons for each year between 1976-78.

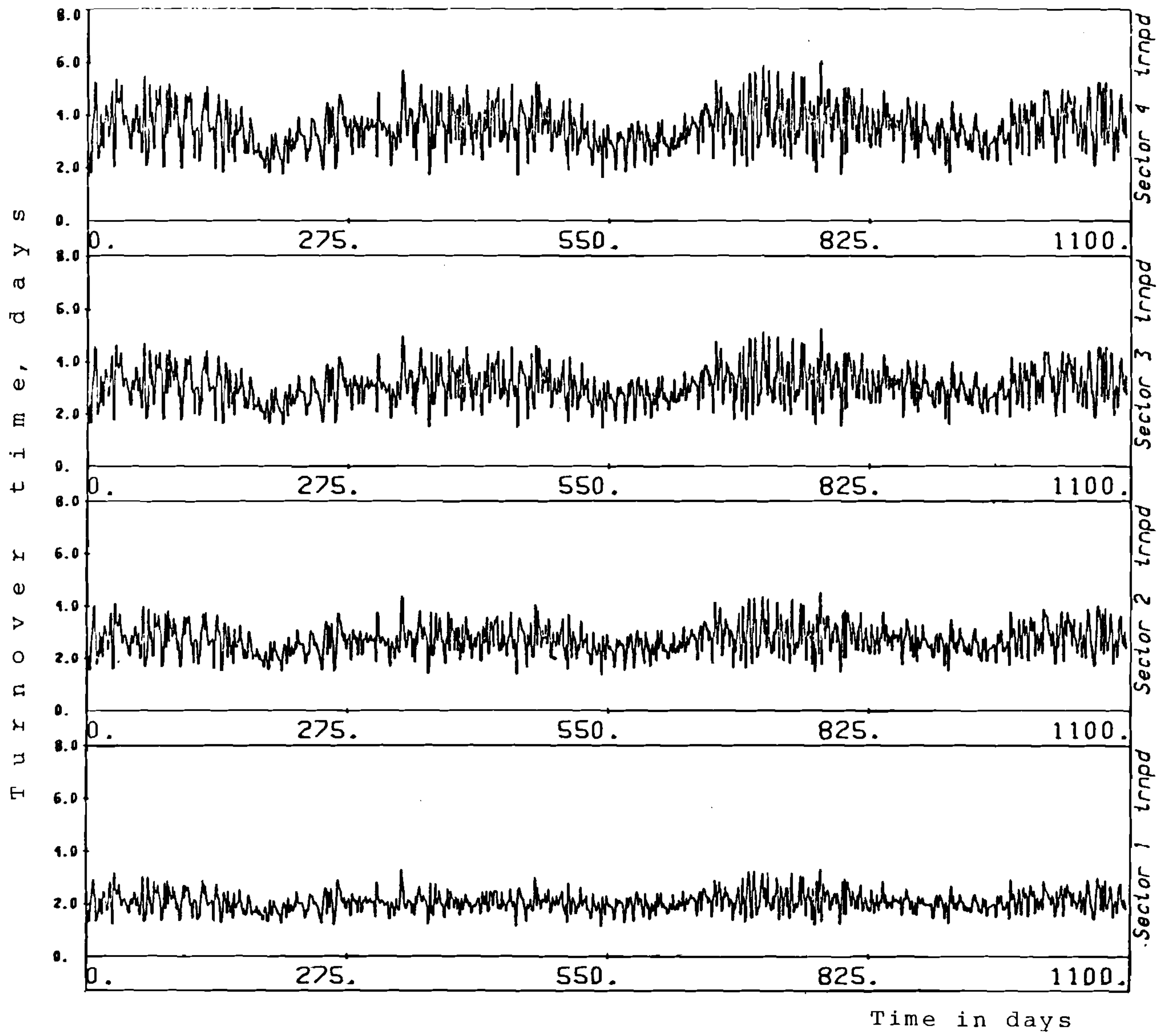

Figure 15. Computed dynamics of turnover time for nonliving particulate organic phosphorus. Lake Balaton Basins I-IV, 1976-1978.

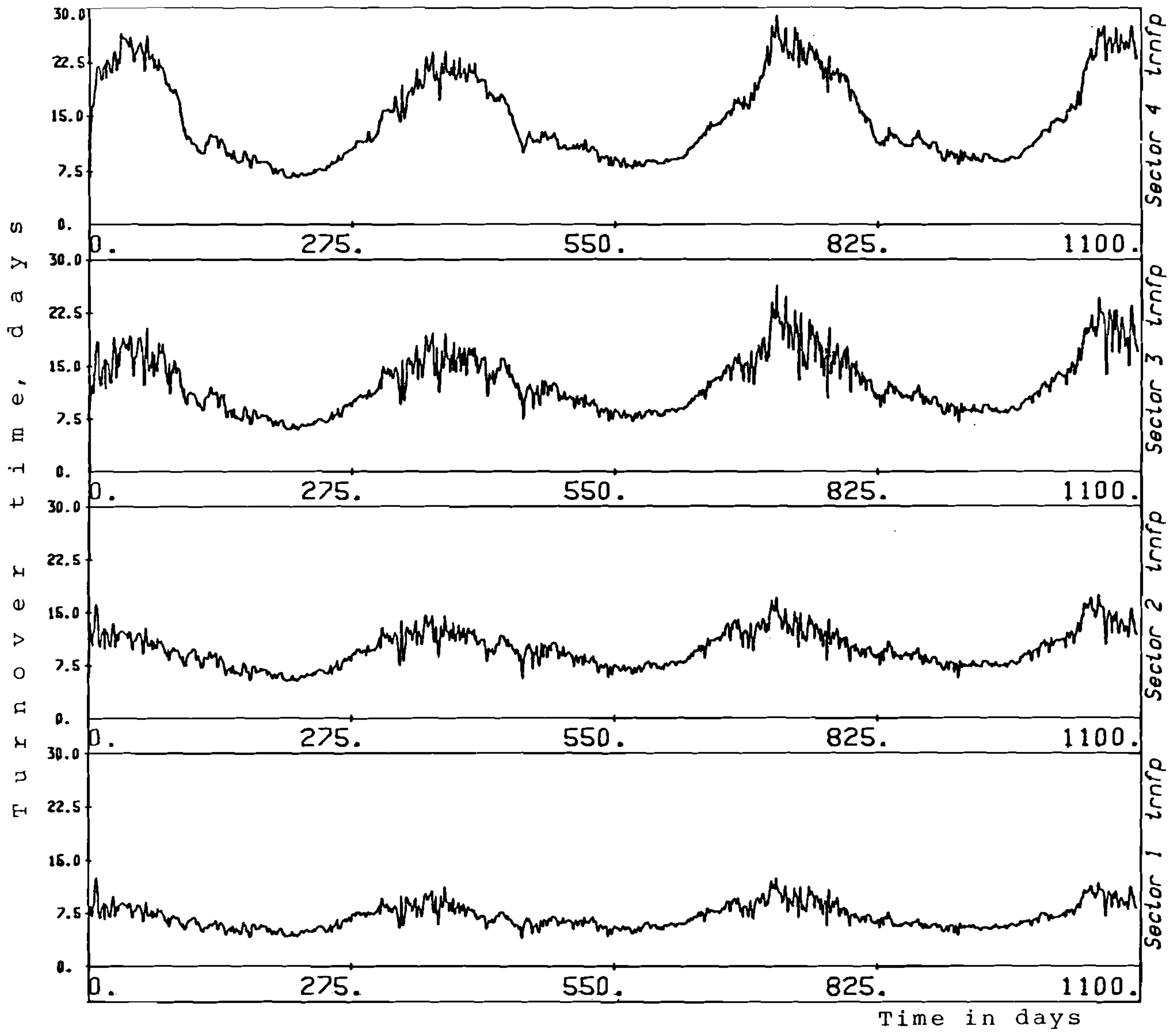

Figure 16. Computed dynamics of turnover time for phytoplankton phosphorus. Lake Balaton Basins I-IV, 1976-1978.

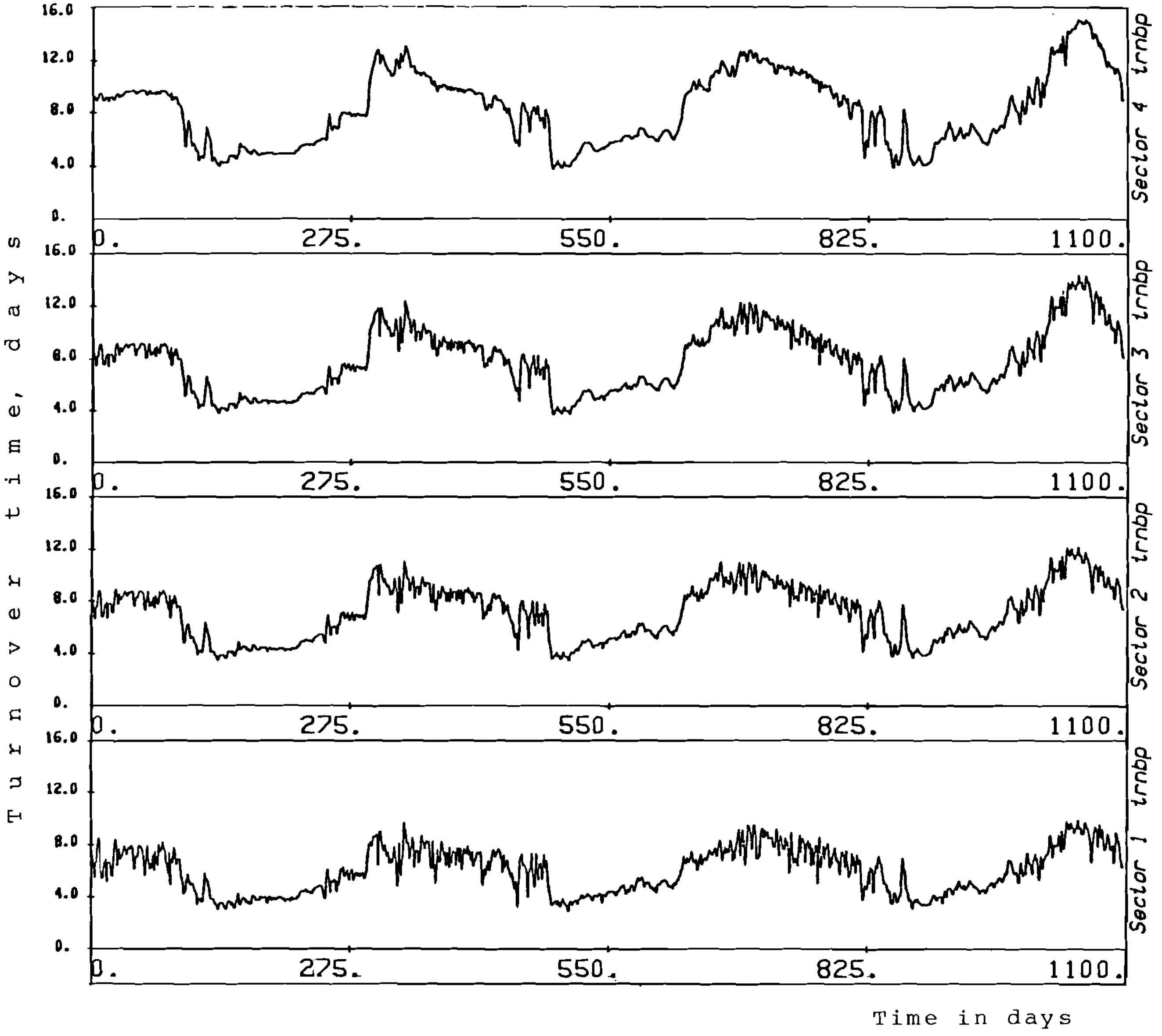

Figure 17. Computed dynamics of turnover time for bacterial phosphorus. Lake Balaton Basins I-IV, 1976-1978.

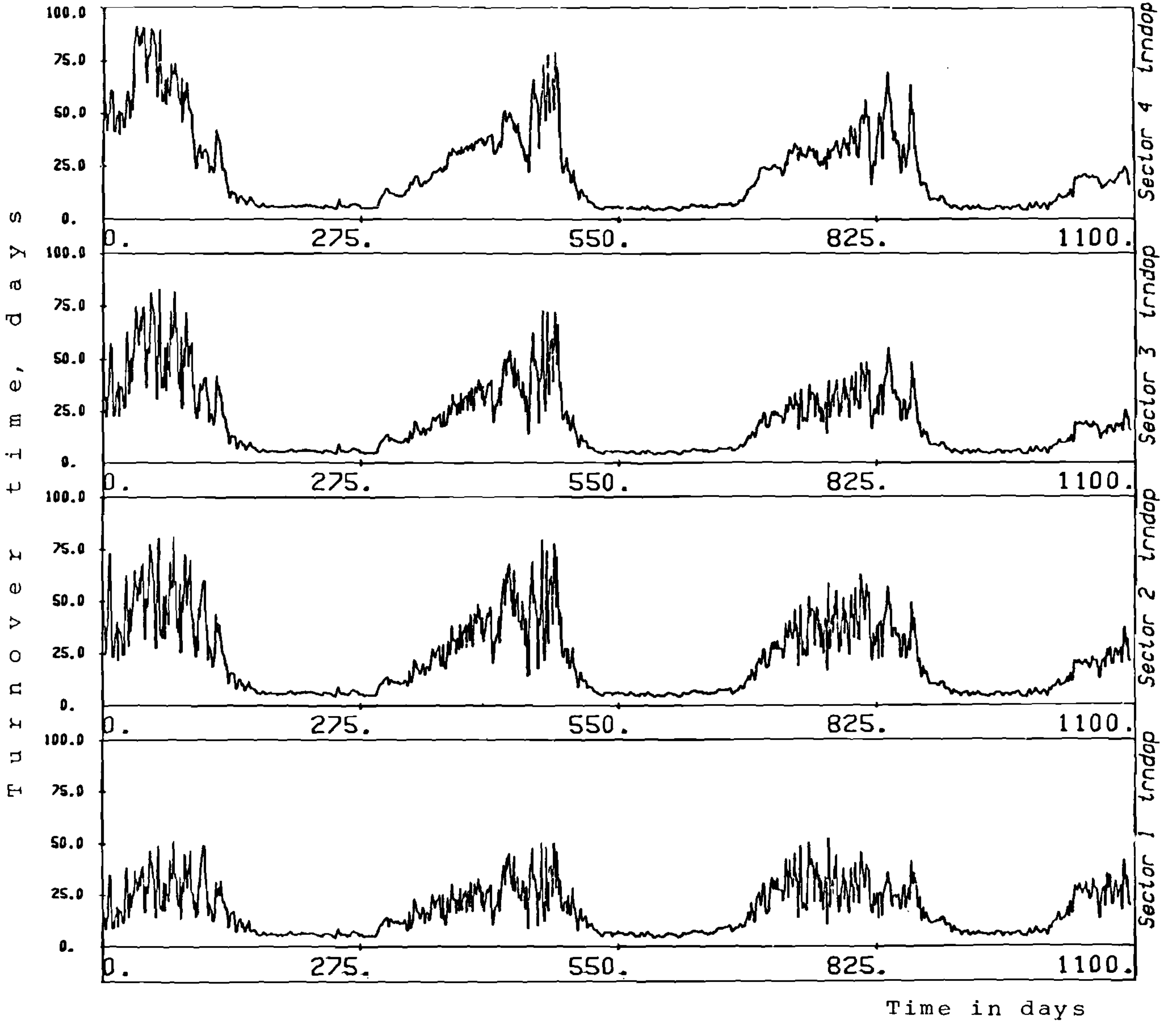

Figure 18. Computed dynamics of turnover time for dissolved organic phosphorus. Lake Balaton Basins I-IV, 1976-1978.

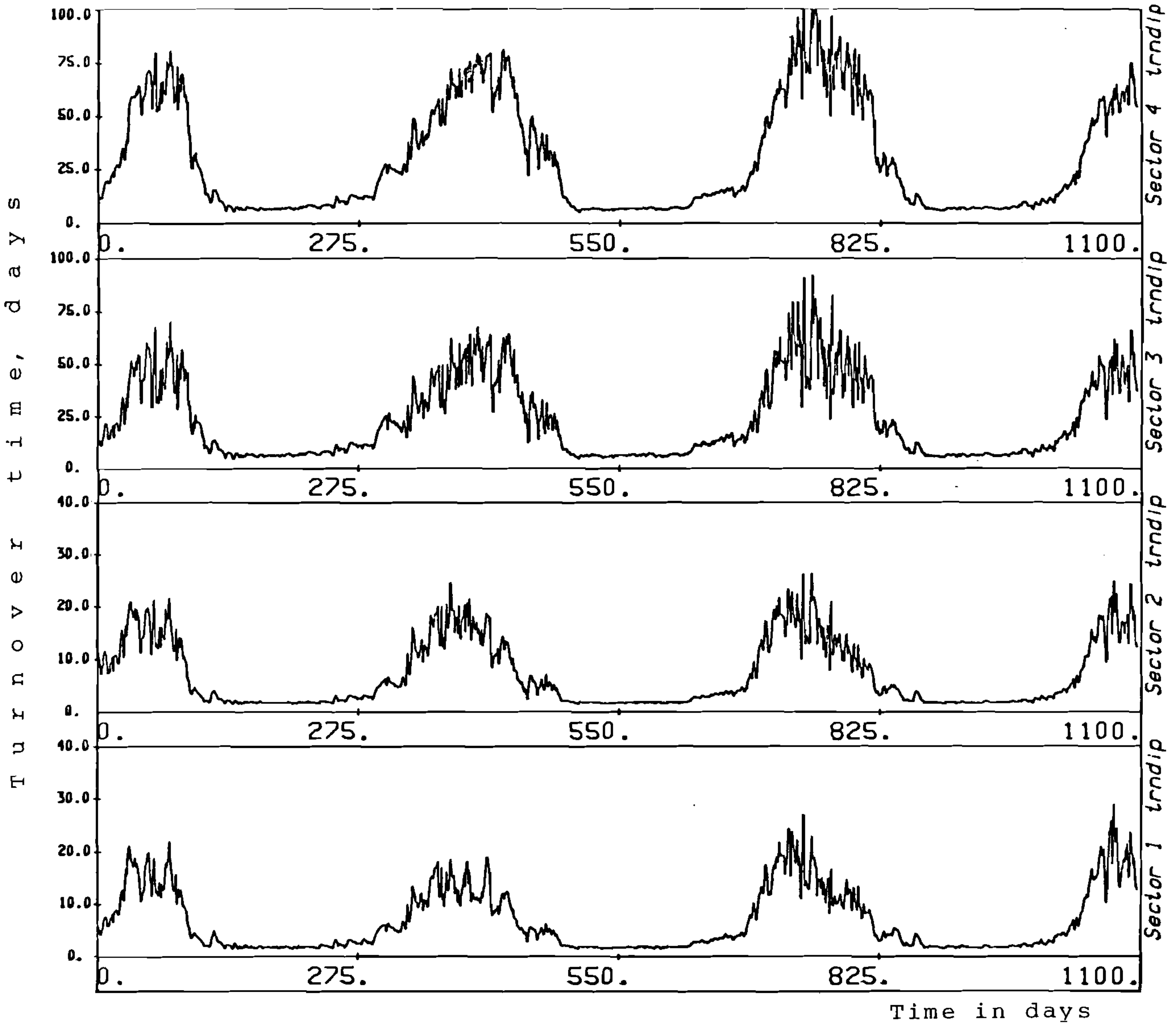

Figure 19. Computed dynamics of turnover time for dissolved inorganic phosphorus. Lake Balaton Basins I-IV, 1976-1978.

The turnover time of the system's total phosphorus was also calculated as an instantaneous characteristic by dividing the average pool size of total phosphorus by the external flux rates for every time step. Consequently, the instantaneous turnover time of the system's total phosphorus does not account for the internal phosphorous cycling within the system, and it is based on the combined data, the model output data (or temporary levels of the system's total P), and available observations (all external phosphorous inputs to the lake system). The dynamics of the daily mean turnover time of the system's total P are shown in Figure 20.

The turnover time values obtained on monthly and annual bases in this model are summarized for all phosphorous compartments in Tables 8 through 11 for Basins I-IV respectively. The dates and values of minimum and maximum turnover times within each month, plus monthly and annual mean turnover times for all phosphorus fractions, appear in these tables.

The following conclusions can be reached from the analysis of Figures 15-20 and Tables 8-11:

(i) Turnover of phosphorous pools appears to be fastest in the biological compartments of bacteria and phytoplankton, and in the nonliving particulate organic-P which is directly dependent on the microorganism activities and regulated by environmental factors.

(ii) In the summer season, the phosphorous turnover is accelerated so that the differences in values of turnover times of the various phosphorous compartments are significantly reduced; the phosphorous turnover in all compartments, except nonliving

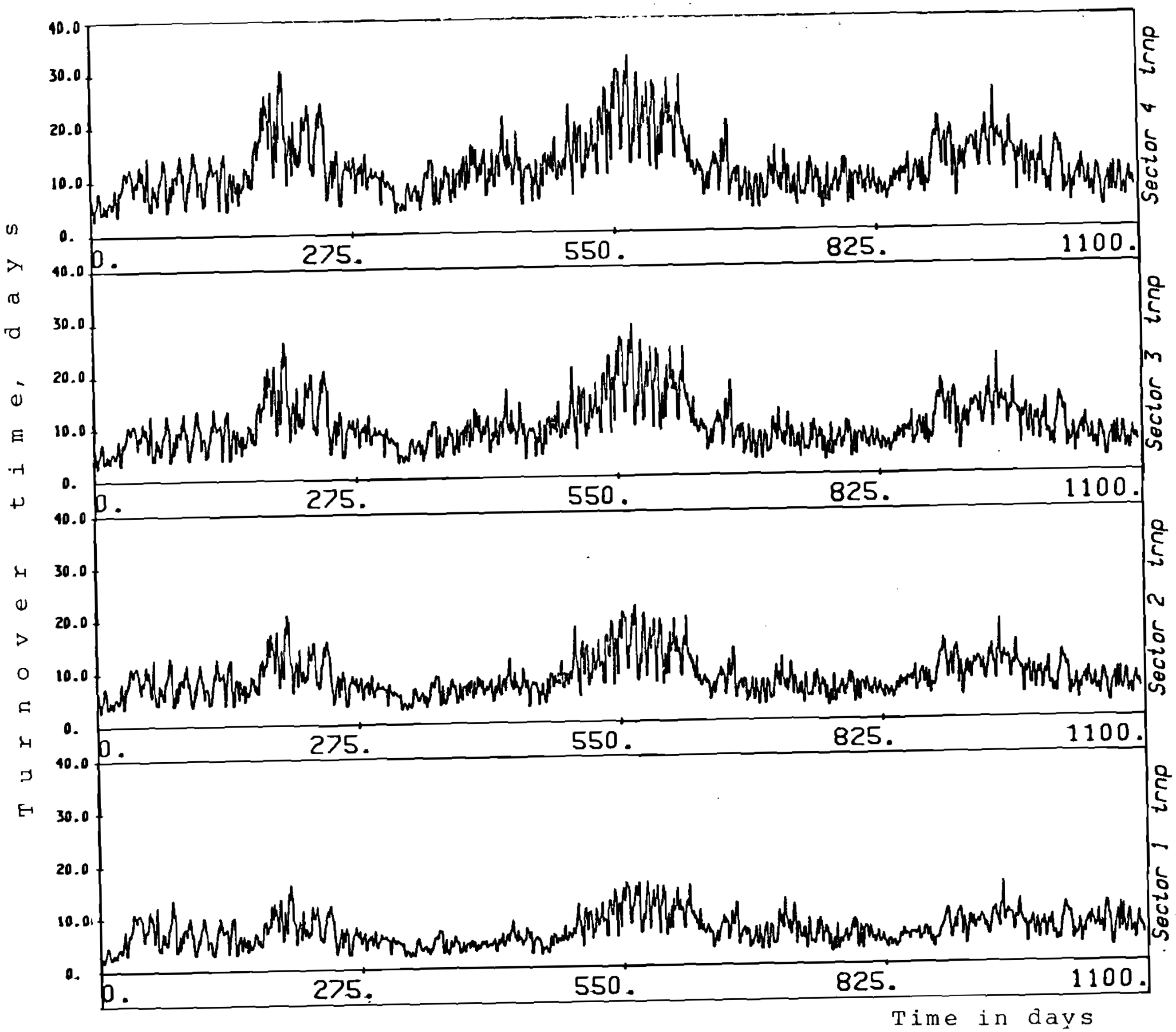

Figure 20. Computed dynamics of turnover time for total phosphorus. Lake Balaton Basins I-IV, 1976-1978.

Table 8. Data on Phosphorous Compartment Turnover Times as Calculated by the Model for Basin I.

Year	Phosphorus fractions	Data	Months												Annual mean
			Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
1976	Phytoplankton-P	Minimum: day	17	26	25	30	15	18	31	2	6	8	1	27	
		value	2.8	3.2	2.9	2.3	2.4	2.5	2.3	2.6	2.2	2.7	2.5	3.0	
		Maximum: day	8	5	1	2	14	11	2	30	17	10	30	29	
		value	17.2	12.2	11.8	10.0	8.8	9.2	8.5	7.2	9.6	11.2	13.0	13.1	
		Mean:	8.5	8.3	7.2	6.1	5.6	5.2	4.9	4.9	5.8	7.5	8.1	8.6	6.7
	Bacterial-P	Minimum: day	17	26	25	26	21	1	6	6	18	6	1	27	
		value	4.1	5.0	3.9	3.0	2.0	2.4	2.8	3.4	3.3	4.5	3.7	4.7	
		Maximum: day	8	5	1	4	1	5	21	31	29	28	29	2	
		value	9.1	8.7	8.5	7.6	6.2	4.7	4.2	5.1	6.7	10.1	10.2	9.6	
		Mean:	6.8	7.3	7.0	4.9	3.8	3.7	3.8	4.3	5.2	6.7	7.4	7.4	5.7
	P_D	Minimum: day	2	15	20	26	21	25	11	2	4	6	1	26	
		value	0.9	1.2	0.6	0.9	0.5	1.1	0.7	1.0	0.8	1.0	0.7	1.0	
		Maximum: day	30	10	29	18	4	21	17	13	22	7	28	29	
		value	4.1	3.7	4.1	4.0	3.9	3.4	3.3	3.1	3.8	3.4	3.6	3.4	
		Mean:	2.0	2.1	2.2	2.1	2.1	1.9	1.7	2.0	2.1	2.1	2.1	2.0	2.0
	DOP	Minimum: day	4	26	25	10	21	18	6	22	18	7	1	27	
		value	4.4	8.6	6.2	5.8	4.6	4.2	3.8	3.9	3.0	3.1	3.6	6.0	
		Maximum: day	26	28	17	4	1	5	19	1	8	28	29	29	
		value	54.9	81.3	82.6	90.4	58.7	20.0	9.0	9.2	12.1	19.5	32.6	35.5	
		Mean:	18.3	30.7	29.8	27.7	17.8	7.5	6.3	6.3	6.3	7.8	12.9	17.5	15.7
	DIP	Minimum: day	4	16	25	23	22	24	6	19	3	5	1	4	
		value	2.6	6.7	4.7	1.0	0.8	0.7	0.7	0.9	0.8	0.9	1.8	4.6	
		Maximum: day	30	3	17	2	4	5	13	24	8	28	29	25	
		value	20.7	27.6	31.7	15.7	9.6	4.3	3.8	3.9	5.4	8.6	17.9	23.0	
		Mean:	8.3	16.5	14.3	4.2	2.6	1.8	1.8	1.9	2.5	3.8	6.7	12.3	6.4
	Total P	Minimum: day	4	26	21	28	21	1	6	22	18	6	1	28	
		value	1.3	4.2	2.5	2.4	1.9	2.8	3.7	3.5	2.1	2.3	1.4	2.1	
		Maximum: day	26	21	18	4	19	29	21	31	1	5	9	23	
		value	9.9	16.5	18.4	15.0	13.7	14.8	24.6	17.3	13.0	10.3	8.1	9.4	
		Mean:	3.9	9.0	7.2	6.4	6.8	6.6	10.0	9.0	6.1	5.8	4.2	4.5	6.6
1977	Phytoplankton-P	Minimum: day	1	23	13	9	22	17	26	22	10	13	13	27	
		value	3.3	2.3	2.7	2.8	2.7	2.5	2.5	3.0	3.1	3.0	3.0	2.7	
		Maximum: day	7	1	6	4	2	8	13	10	21	31	3	14	
		value	13.4	10.0	9.8	9.3	10.2	10.3	8.7	8.8	10.1	11.8	12.6	14.7	
		Mean:	8.5	7.0	6.4	6.1	6.3	5.9	5.3	5.7	6.4	7.9	8.5	10.0	7.0
	Bacterial-P	Minimum: day	15	23	29	9	22	27	12	24	10	2	26	31	
		value	5.1	3.6	2.8	3.4	2.6	3.0	3.3	3.7	3.9	4.7	5.5	6.0	
		Maximum: day	7	3	3	1	1	30	30	10	30	31	30	5	
		value	8.7	8.0	8.1	8.1	4.9	4.4	5.1	5.6	8.2	8.5	10.0	10.0	
		Mean:	7.1	6.8	6.3	6.2	3.6	4.0	4.5	5.0	5.8	7.2	7.9	8.3	6.1
	P_D	Minimum: day	13	23	29	9	19	27	11	9	9	2	1	16	
		value	1.1	1.1	0.9	1.0	1.1	0.9	0.9	0.7	0.8	0.9	0.8	0.9	
		Maximum: day	3	23	31	18	23	8	24	12	17	13	30	5	
		value	3.4	3.2	3.8	3.5	3.6	3.4	3.5	3.5	3.4	3.9	3.8	3.9	
		Mean:	2.1	2.0	2.1	2.1	2.0	1.9	1.9	2.0	2.0	2.3	2.2	2.2	2.1
	DOP	Minimum: day	1	23	29	16	22	27	26	11	6	7	2	27	
		value	7.4	4.6	4.9	7.3	5.6	3.6	3.2	3.2	3.3	3.1	3.7	7.2	
		Maximum: day	31	16	9	1	2	2	17	4	22	31	30	30	
		value	44.5	43.6	70.8	84.1	56.3	14.1	9.7	9.0	10.4	13.1	34.3	51.8	
		Mean:	22.4	23.4	30.2	31.9	18.7	7.5	6.1	5.5	6.3	7.8	13.0	26.4	16.6
	DIP	Minimum: day	15	23	29	30	22	20	7	19	9	3	2	27	
		value	5.6	3.2	1.4	1.8	0.8	0.8	0.8	0.8	0.8	1.1	1.4	6.5	
		Maximum: day	24	16	9	18	2	5	27	2	29	25	30	31	
		value	25.0	25.4	16.7	9.7	5.3	3.6	3.3	3.4	5.2	6.2	16.0	33.5	
		Mean:	13.7	11.8	7.9	4.9	2.1	1.8	1.8	1.9	2.4	3.5	6.3	16.7	6.3
	Total P	Minimum: day	13	23	29	16	6	27	12	9	27	2	26	16	
		value	2.1	2.3	2.0	2.1	3.3	3.7	4.0	3.6	3.9	2.5	1.9	2.8	
		Maximum: day	8	26	28	3	25	25	7	14	9	31	1	31	
		value	8.0	7.9	10.3	8.0	14.5	19.9	21.9	18.9	19.3	13.9	11.2	15.9	
		Mean:	4.5	4.8	6.0	4.9	7.8	9.8	12.2	11.1	9.4	7.4	5.6	7.3	7.6
1978	Phytoplankton-P	Minimum: day	24	26	16	22	31	24	24	8	27	4	29	30	
		value	3.3	2.7	2.3	2.5	3.0	2.7	2.8	3.1	2.7	2.4	3.1	2.4	
		Maximum: day	25	13	1	12	16	30	1	18	22	31	23	2	
		value	14.9	13.6	11.6	10.9	9.5	8.9	9.1	8.6	10.4	11.8	14.7	14.1	
		Mean:	9.4	8.7	7.0	6.3	5.9	5.5	5.5	5.7	6.7	7.5	10.2	9.3	7.3
	Bacterial-P	Minimum: day	24	11	30	30	23	2	4	8	12	4	29	29	
		value	4.8	4.2	3.3	3.0	2.7	3.0	3.4	3.5	3.9	4.4	6.1	5.1	
		Maximum: day	6	1	1	8	12	29	11	31	22	29	14	2	
		value	9.3	9.0	8.3	7.4	7.4	5.1	5.6	6.6	8.2	10.0	10.5	9.9	
		Mean:	7.7	7.3	6.5	5.4	4.2	3.8	4.8	5.0	6.3	7.5	9.1	8.0	6.3
	P_D	Minimum: day	5	4	6	15	2	28	4	30	27	18	27	29	
		value	0.8	0.8	0.9	1.0	1.0	0.9	1.0	0.9	0.6	0.9	1.1	1.1	
		Maximum: day	23	15	14	20	15	30	6	19	1	6	21	26	
		value	3.9	4.0	4.2	3.5	3.4	3.1	3.4	3.4	3.6	3.7	3.7	4.0	
		Mean:	2.2	2.2	2.2	2.1	2.0	2.0	2.0	1.9	2.2	2.2	2.1	2.2	2.1
	DOP	Minimum: day	24	11	16	11	23	29	18	17	27	4	29	31	
		value	7.8	7.3	5.3	6.9	7.2	4.6	3.7	3.3	2.9	2.8	7.2	6.4	
		Maximum: day	24	21	20	15	14	14	10	10	22	29	26	23	
		value	75.6	73.2	81.1	60.5	69.4	19.4	10.0	8.8	12.9	31.2	43.4	55.6	
		Mean:	32.3	29.1	29.3	24.5	22.4	10.9	6.2	6.0	6.6	12.9	25.7	26.5	19.4
	DIP	Minimum: day	24	14	31	30	23	8	4	7	7	4	1	31	
		value	5.9	5.3	1.9	1.1	0.8	0.8	0.8	0.8	0.8	1.1	3.2	5.3	
		Maximum: day	14	3	13	24	13	30	26	29	22	29	26	7	
		value	36.1	21.3	20.8	9.2	6.4	3.3	3.6	3.7	5.7	10.5	30.0	37.7	
		Mean:	17.8	12.0	9.5	4.1	2.4	1.9	1.9	1.9	2.5	4.7	14.1	18.8	7.7
	Total P	Minimum: day	5	14	7	15	2	28	4	30	27	18	29	29	
		value	1.9	1.8	2.2	2.0	2.6	2.3	3.5	2.8	1.8	2.5	2.6	3.4	
		Maximum: day	24	3	4	24	2	10	28	6	6	14	23	7	
		value	11.6	10.4	12.1	9.1	9.2	14.4	13.7	19.0	11.9	13.1	17.3	14.1	
		Mean:	6.0	5.2	5.9	4.7	5.5	7.7	8.2	9.0	7.0	7.1	7.7	7.2	6.8

Table 9. Data on Phosphorous Compartment Turnover Times as Calculated by the Model for Basin II.

Year	Phosphorus fractions	Data	Months												Annual mean
			Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
1976	Phytoplankton-P	Minimum: day	17	26	25	30	15	17	31	2	6	8	1	27	
		value	4.2	4.6	4.3	3.9	3.4	3.4	3.0	3.2	3.2	3.9	3.8	4.1	
		Maximum: day	8	5	1	2	14	11	2	30	28	31	30	19	
		value	21.3	16.3	16.6	13.4	12.3	11.1	10.1	8.5	11.9	14.2	16.8	17.2	
		Mean:	12.1	11.5	10.2	8.7	8.0	6.6	6.0	6.0	7.3	9.6	11.1	12.0	9.1
	Bacterial-P	Minimum: day	4	26	25	27	21	1	6	2	6	6	1	27	
		value	5.5	6.7	5.6	3.7	2.8	3.2	3.6	4.1	4.4	5.8	5.5	6.6	
		Maximum: day	26	5	1	2	1	6	2	31	29	28	28	2	
		value	9.1	9.2	9.1	8.0	6.6	5.3	4.6	5.7	7.6	11.7	11.4	10.8	
		Mean:	7.8	8.4	8.1	5.4	4.2	4.4	4.3	4.9	6.2	8.0	9.3	8.8	6.7
	P_D	Minimum: day	2	15	20	28	21	25	11	2	4	6	1	26	
		value	0.9	1.6	0.7	1.2	0.7	1.4	0.9	1.3	1.0	1.2	0.9	1.1	
		Maximum: day	30	28	29	18	4	21	17	10	22	7	29	29	
		value	5.1	4.8	5.2	5.1	5.0	4.4	3.9	3.8	4.8	4.3	4.8	4.7	
		Mean:	2.7	2.8	2.9	2.7	2.8	2.4	2.1	2.5	2.6	2.7	2.7	2.7	2.6
	DOP	Minimum: day	17	26	25	10	21	24	6	22	18	7	1	4	
		value	12.4	17.1	11.9	10.6	6.1	4.5	4.1	4.1	3.4	3.3	4.4	7.7	
		Maximum: day	8	28	1	4	1	5	27	4	8	28	29	29	
		value	100.1	123.8	124.0	123.2	69.1	15.9	7.9	8.2	11.1	16.9	28.8	38.8	
		Mean:	39.2	54.8	51.0	40.0	20.3	7.1	6.0	6.0	6.1	7.4	12.5	20.6	22.4
	DIP	Minimum: day	4	26	25	23	22	24	6	18	3	5	1	4	
		value	3.9	5.8	4.1	1.0	0.8	0.8	0.8	0.9	0.8	0.9	1.7	4.3	
		Maximum: day	30	5	17	2	4	6	13	24	8	28	29	29	
		value	21.6	30.7	33.6	19.0	7.3	3.5	3.0	3.4	4.9	8.9	21.7	27.6	
		Mean:	10.6	17.2	14.9	4.3	2.4	1.8	1.7	1.9	2.4	3.8	7.1	13.9	6.8
	Total P	Minimum: day	4	27	21	9	21	4	6	22	18	6	1	27	
		value	1.8	4.2	2.3	2.7	2.3	3.5	4.9	4.3	2.7	2.8	1.6	2.3	
		Maximum: day	26	10	18	4	21	29	21	31	1	5	9	25	
		value	10.7	17.2	17.7	18.0	18.1	19.4	32.3	22.2	16.5	13.6	9.6	13.0	
		Mean:	4.9	9.0	7.4	7.4	8.4	8.7	13.0	11.4	7.4	6.9	4.8	5.6	7.9
1977	Phytoplankton-P	Minimum: day	1	23	29	9	22	27	26	22	10	7	13	27	
		value	4.3	3.2	3.8	4.3	3.7	3.5	3.4	4.1	4.1	4.7	4.8	3.9	
		Maximum: day	7	9	9	4	2	8	13	10	21	31	3	20	
		value	16.9	15.6	15.2	15.2	15.6	12.7	11.0	10.8	13.8	16.5	18.0	19.8	
		Mean:	12.0	10.7	9.9	9.5	9.0	7.6	6.9	7.5	8.5	11.2	12.2	13.8	9.9
	Bacterial-P	Minimum: day	1	23	29	9	22	1	12	24	10	2	12	31	
		value	5.3	5.2	3.7	4.7	3.2	3.9	4.3	4.6	4.8	6.5	7.3	7.7	
		Maximum: day	7	3	3	1	1	11	30	4	30	31	20	1	
		value	9.5	9.1	8.9	8.6	5.1	5.2	5.9	6.4	9.8	11.3	11.6	11.3	
		Mean:	8.5	8.1	7.1	7.0	3.9	4.8	5.3	5.8	6.9	9.2	9.8	9.5	7.2
	P_D	Minimum: day	13	23	29	9	19	27	11	9	9	2	2	31	
		value	1.2	1.3	1.0	1.2	1.2	1.0	1.0	0.9	1.0	1.1	0.9	0.9	
		Maximum: day	7	23	31	18	23	8	24	12	22	13	30	5	
		value	4.6	4.5	5.0	4.9	4.8	4.4	4.3	4.3	4.2	5.0	5.1	5.2	
		Mean	2.8	2.7	2.8	2.9	2.7	2.4	2.4	2.5	2.5	3.0	2.8	2.9	2.7
	DOP	Minimum: day	1	23	29	16	22	27	26	11	6	7	2	27	
		value	11.0	8.8	8.3	13.0	6.6	3.8	3.3	3.2	3.3	3.4	3.4	9.1	
		Maximum: day	31	18	9	18	2	2	17	4	22	31	30	30	
		value	60.1	65.1	97.7	114.5	68.4	10.5	8.3	7.7	8.8	9.8	27.1	45.7	
		Mean:	32.5	38.1	47.4	50.3	20.9	6.4	5.3	5.0	5.7	6.6	11.1	25.6	21.2
	DIP	Minimum: day	29	23	29	30	22	20	7	19	9	3	2	27	
		value	5.8	3.0	1.2	1.7	0.8	0.8	0.8	0.8	0.8	1.0	1.3	4.9	
		Maximum: day	7	16	4	18	2	5	25	19	30	25	30	31	
		value	32.2	27.0	20.4	11.7	5.6	3.3	3.1	3.1	4.9	5.6	17.4	29.3	
		Mean:	17.9	14.0	8.5	5.3	2.0	1.8	1.8	1.8	2.3	3.4	6.1	16.4	6.8
	Total P	Minimum: day	13	23	29	16	6	27	12	9	27	2	26	16	
		value	2.4	2.6	2.1	2.5	4.0	4.3	4.8	4.3	4.2	2.7	1.8	2.4	
		Maximum: day	8	26	9	30	17	25	7	15	9	31	1	20	
		value	11.5	11.0	14.0	13.0	22.0	27.8	29.7	24.7	25.5	15.9	12.5	14.7	
		Mean:	6.3	6.6	7.4	6.8	10.3	12.3	15.5	13.8	11.2	8.1	5.9	6.8	9.3
1978	Phytoplankton-P	Minimum: day	24	26	16	11	31	24	5	2	27	4	29	30	
		value	4.6	4.0	3.7	4.3	4.2	3.9	4.1	4.1	4.3	4.1	4.3	3.3	
		Maximum: day	25	13	1	12	16	4	4	18	27	31	23	2	
		value	18.9	17.2	15.3	15.0	13.9	12.4	11.8	10.9	15.4	17.9	21.4	19.9	
		Mean:	12.8	11.6	9.7	9.1	8.7	7.5	7.5	7.6	9.6	11.3	15.0	13.1	10.3
	Bacterial-P	Minimum: day	24	11	30	30	23	2	5	8	12	4	29	30	
		value	6.6	6.0	4.0	3.5	3.4	3.6	4.6	4.4	5.2	5.9	8.1	6.5	
		Maximum: day	2	1	1	17	12	29	22	31	30	29	14	2	
		value	10.1	9.6	8.9	8.2	8.0	6.4	6.7	7.9	9.9	12.4	12.7	11.3	
		Mean:	8.9	8.4	7.4	6.1	4.7	4.7	5.8	6.0	7.8	9.7	11.2	9.2	7.5
	P_D	Minimum: day	5	4	6	15	2	28	30	28	27	18	27	18	
		value	0.9	1.0	1.0	1.3	1.1	1.1	1.2	1.1	0.7	1.0	1.1	1.3	
		Maximum: day	23	15	14	2	15	7	3	19	1	6	21	26	
		value	5.2	5.2	5.3	4.8	4.8	4.2	4.3	4.1	4.7	4.8	4.9	5.2	
		Mean:	2.9	2.9	2.9	2.7	2.7	2.5	2.6	2.4	2.9	2.9	2.8	2.9	2.8
	DOP	Minimum: day	24	11	16	11	31	24	4	18	12	4	29	1	
		value	11.0	11.3	9.2	11.7	8.2	3.9	3.3	3.1	3.0	3.0	6.8	7.4	
		Maximum: day	24	21	20	15	14	14	10	10	22	29	26	28	
		value	72.5	82.8	102.2	81.5	67.1	14.0	8.2	7.5	10.7	20.8	30.4	47.6	
		Mean:	36.4	38.0	43.0	36.9	25.3	8.5	5.3	5.3	5.8	9.7	19.6	24.4	21.5
	DIP	Minimum: day	24	14	30	30	23	8	4	7	27	4	1	31	
		value	5.3	5.0	1.7	1.0	0.8	0.8	0.8	0.8	0.8	1.0	2.9	4.3	
		Maximum: day	23	13	1	20	14	29	26	29	22	28	26	7	
		value	36.9	27.6	22.4	8.5	6.1	3.3	3.3	3.7	5.2	10.1	28.4	32.8	
		Mean:	18.2	13.7	9.2	4.0	2.3	1.8	1.9	1.9	2.4	4.4	13.0	17.4	7.5
	Total P	Minimum: day	5	4	7	15	2	28	4	30	27	18	29	21	
		value	1.7	2.0	2.2	2.3	2.9	2.5	4.0	3.2	1.7	2.1	2.3	3.0	
		Maximum: day	27	3	3	24	9	10	29	6	6	14	25	17	
		value	11.9	11.0	12.6	11.2	13.2	21.8	18.0	23.5	14.3	15.3	13.6	12.5	
		Mean:	6.1	5.6	6.1	5.7	7.3	10.6	10.2	10.8	8.2	7.3	6.5	6.4	7.6

Table 10. Data on Phosphorous Compartment Turnover Times as Calculated by the Model for Basin III.

Year	Phosphorus fractions	Data	Months												Annual mean
			Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
1976	Phytoplankton-P	Minimum: day	1	26	26	8	24	28	31	2	18	13	1	27	
		value	4.6	7.6	5.9	4.2	4.8	4.4	3.9	4.0	4.3	5.0	5.3	6.6	
		Maximum: day	26	5	1	2	8	11	2	23	28	31	30	18	
		value	23.6	25.3	27.3	21.7	15.4	12.9	11.3	9.3	13.5	15.7	19.9	23.7	
		Mean:	14.7	17.3	15.5	11.0	10.0	7.9	6.9	6.7	8.3	10.9	13.6	15.7	11.5
	Bacterial-P	Minimum: day	4	26	25	23	21	1	6	2	5	6	1	27	
		value	6.4	7.6	6.6	3.9	3.3	3.7	4.1	4.5	5.0	6.4	6.9	7.6	
		Maximum: day	8	5	1	1	1	6	6	31	29	28	28	2	
		value	9.4	9.5	9.5	8.3	6.8	5.8	4.9	6.0	8.0	12.5	12.7	12.0	
		Mean:	8.3	8.9	8.6	5.7	4.6	4.7	4.7	5.3	6.7	8.7	10.6	9.8	7.2
	P_D	Minimum: day	2	26	20	9	21	25	11	2	4	6	1	27	
		value	0.9	1.7	0.8	1.3	0.7	1.5	0.9	1.5	1.1	1.3	1.0	1.2	
		Maximum: day	30	28	29	18	4	5	17	13	22	7	29	29	
		value	5.7	5.8	6.0	5.8	5.6	5.0	4.4	4.2	5.4	4.8	5.6	5.5	
		Mean:	3.0	3.2	3.3	3.1	3.2	2.7	2.3	2.8	3.0	3.0	3.1	3.1	3.0
	DOP	Minimum: day	4	26	25	10	21	15	6	22	3	7	1	4	
		value	13.6	22.0	14.0	10.4	6.2	4.4	4.2	4.1	3.7	3.6	5.5	9.0	
		Maximum: day	26	5	1	2	1	6	27	4	8	30	29	29	
		value	72.4	114.8	114.7	91.0	57.1	13.4	7.3	7.8	10.6	16.3	23.7	29.4	
		Mean:	37.2	60.7	53.4	33.1	17.7	6.5	5.7	5.8	6.0	7.5	12.2	18.0	21.8
	DIP	Minimum: day	4	26	25	28	22	1	6	19	3	5	1	4	
		value	7.1	19.5	14.1	3.9	2.7	3.0	3.0	3.6	3.4	3.9	6.4	14.3	
		Maximum: day	26	28	17	2	4	5	21	30	8	28	29	29	
		value	41.3	92.5	98.1	84.7	22.2	12.7	11.2	12.9	18.6	36.2	60.1	65.0	
		Mean:	20.4	47.0	46.7	21.7	8.3	6.3	6.6	7.6	9.8	15.0	23.7	35.2	20.6
	Total P	Minimum: day	4	27	21	9	21	4	6	22	19	6	1	27	
		value	1.8	4.1	2.3	2.9	2.5	3.8	6.2	5.5	3.6	3.6	2.0	2.5	
		Maximum: day	1	21	18	20	21	29	21	31	1	5	9	25	
		value	10.6	16.9	17.6	20.0	20.0	23.6	41.8	29.5	21.8	18.4	12.6	16.8	
		Mean:	5.0	8.8	7.5	8.4	9.2	10.3	16.3	14.8	9.6	9.1	5.9	6.7	9.3
1977	Phytoplankton-P	Minimum: day	29	23	29	9	4	27	26	22	10	7	2	27	
		value	7.1	4.5	4.1	5.5	5.2	4.6	4.7	5.1	5.1	6.2	6.9	6.7	
		Maximum: day	8	9	6	4	2	2	5	14	21	31	12	20	
		value	21.7	21.3	20.9	17.9	18.4	14.8	12.2	11.1	15.4	18.2	20.5	29.8	
		Mean:	15.9	15.1	13.2	11.5	10.6	9.1	8.0	8.4	9.6	13.0	15.1	19.6	12.5
	Bacterial-P	Minimum: day	1	23	29	24	22	27	12	24	10	2	12	31	
		value	7.1	6.0	4.3	5.1	3.5	4.4	4.8	5.1	5.2	7.6	8.5	8.9	
		Maximum: day	3	3	3	1	1	7	30	4	30	31	20	1	
		value	9.9	9.5	9.2	8.8	5.2	5.8	6.2	6.8	10.4	12.1	12.8	12.5	
		Mean:	9.1	8.6	7.5	7.4	4.2	5.2	5.7	6.1	7.4	10.0	11.0	10.8	7.8
	P_D	Minimum: day	13	20	29	9	19	27	11	9	9	2	2	31	
		value	1.3	1.3	1.1	1.3	1.3	1.1	1.1	1.0	1.1	1.3	0.9	1.3	
		Maximum: day	7	23	31	18	2	8	24	12	22	13	30	5	
		value	5.5	5.5	5.8	5.6	5.6	4.9	4.8	4.8	4.7	5.6	5.8	5.9	
		Mean:	3.3	3.1	3.2	3.3	3.0	2.7	2.6	2.7	2.8	3.4	3.2	3.3	3.1
	DOP	Minimum: day	1	23	29	9	22	17	26	11	5	7	2	31	
		value	14.2	10.3	8.4	15.2	6.4	3.8	3.4	3.3	3.3	3.7	3.7	11.2	
		Maximum: day	31	18	9	17	2	2	17	3	22	31	30	30	
		value	44.7	48.9	69.8	105.0	56.4	8.6	7.9	7.3	8.3	9.3	21.7	30.8	
		Mean:	28.9	33.2	39.5	49.1	18.2	5.8	5.1	4.9	5.6	6.4	10.6	21.6	19.0
	DIP	Minimum: day	1	23	29	9	22	27	11	19	9	3	2	3	
		value	12.8	12.3	6.0	8.0	2.6	2.9	3.0	3.1	3.0	4.3	4.6	18.7	
		Maximum: day	27	16	4	3	2	5	29	4	30	31	30	30	
		value	83.8	86.3	91.7	60.4	28.2	10.9	10.5	11.3	20.1	22.3	44.3	85.9	
		Mean:	49.1	50.9	42.8	25.3	7.9	6.2	6.7	6.7	9.1	13.8	18.6	46.2	23.6
	Total P	Minimum: day	13	23	29	16	22	27	12	9	27	2	26	16	
		value	2.8	3.2	2.7	2.9	4.5	5.3	6.0	5.6	5.4	3.5	2.0	2.5	
		Maximum: day	28	6	9	30	17	25	7	15	9	31	1	20	
		value	15.2	15.9	19.7	17.3	25.8	35.6	39.0	31.6	32.3	21.2	16.3	15.8	
		Mean:	7.8	9.1	9.8	8.7	12.0	14.7	19.7	17.6	14.2	10.1	6.9	7.3	11.5
1978	Phytoplankton-P	Minimum: day	24	26	16	11	23	24	30	2	27	4	29	31	
		value	7.1	6.9	4.3	5.5	5.3	5.0	5.2	5.2	5.7	5.6	8.2	5.8	
		Maximum: day	30	1	3	17	17	4	4	3	27	31	23	2	
		value	28.2	25.9	24.0	18.1	17.0	15.1	13.8	11.3	17.7	22.9	29.4	29.3	
		Mean:	18.6	16.3	13.8	11.2	10.6	9.1	8.9	8.7	11.0	14.1	19.9	19.5	13.5
	Bacterial-P	Minimum: day	24	11	30	30	1	2	5	8	12	4	29	30	
		value	7.6	6.8	4.2	3.7	3.7	3.9	5.0	4.8	5.8	6.9	10.0	7.3	
		Maximum: day	2	1	1	17	12	29	23	31	30	29	14	2	
		value	11.4	10.6	9.4	8.4	8.3	7.2	7.2	8.4	10.8	14.0	14.9	13.6	
		Mean:	10.1	9.2	7.8	6.3	4.9	5.3	6.3	6.3	8.4	11.0	13.4	10.6	8.3
	P_D	Minimum: day	5	4	6	15	2	28	30	28	27	18	27	18	
		value	0.9	1.1	1.1	1.4	1.2	1.1	1.3	1.1	0.7	1.0	1.3	1.4	
		Maximum: day	23	15	14	2	15	30	3	19	24	31	21	26	
		value	5.9	5.9	6.0	5.6	5.5	4.9	4.9	4.6	5.3	5.6	5.7	5.9	
		Mean:	3.3	3.4	3.3	3.2	3.1	2.9	2.9	2.7	3.3	3.4	3.2	3.3	3.2
	DOP	Minimum: day	24	11	16	11	31	24	4	18	11	4	29	31	
		value	10.8	10.6	8.7	11.7	7.2	3.5	3.1	3.1	3.0	3.2	8.2	8.4	
		Maximum: day	1	21	25	15	12	12	22	10	22	29	13	29	
		value	54.6	54.1	72.8	70.8	59.6	11.8	7.8	7.1	10.1	17.3	23.5	29.8	
		Mean:	27.8	28.5	34.9	34.3	23.3	7.4	5.1	5.1	5.7	9.0	17.7	17.3	18.0
	DIP	Minimum: day	24	14	30	30	23	8	4	17	27	4	1	31	
		value	19.0	17.3	8.7	4.3	3.1	2.9	2.9	3.0	2.9	3.5	12.1	16.4	
		Maximum: day	24	1	9	2	14	28	11	29	22	29	26	28	
		value	127.0	112.2	99.1	41.5	19.4	11.2	11.5	13.3	18.7	35.3	77.2	85.0	
		Mean:	61.7	51.4	43.4	18.5	8.3	6.5	6.8	7.0	9.1	16.1	39.2	47.1	26.3
	Total P	Minimum: day	5	4	7	15	2	28	4	30	27	21	29	21	
		value	1.8	2.2	2.4	2.6	3.1	2.8	4.6	4.0	2.0	2.4	2.3	3.2	
		Maximum: day	27	3	4	29	9	10	29	6	7	14	8	17	
		value	13.7	13.0	14.9	13.4	16.3	26.9	24.2	29.1	18.4	19.6	15.0	13.4	
		Mean:	6.8	6.4	7.0	6.6	8.3	12.8	12.7	13.2	10.1	8.7	7.1	6.6	8.9

Table 11. Data on Phosphorous Compartment Turnover Times as Calculated by the Model for Basin IV.

Year	Phosphorus fractions	Data	Months												Annual mean
			Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
1976	Phytoplankton-P	**Minimum**: day	1	26	25	8	23	25	22	2	3	15	13	27	
		value	4.2	9.7	8.4	4.0	5.6	4.8	4.3	4.4	4.9	5.4	6.6	8.8	
		Maximum: day	26	5	1	2	2	11	2	23	28	31	23	29	
		value	30.1	32.8	33.1	26.0	16.2	14.0	12.1	10.4	14.4	16.8	22.1	28.3	
		Mean:	20.9	24.7	21.2	12.5	11.1	9.0	7.6	7.2	9.0	11.9	16.0	19.9	14.2
	Bacterial-P	**Minimum**: day	4	26	25	24	14	1	16	2	4	6	1	28	
		value	8.4	9.1	8.4	4.3	3.9	4.3	4.7	4.9	5.8	7.4	10.4	9.6	
		Maximum: day	8	28	1	1	1	6	6	31	23	30	28	1	
		value	9.5	9.8	9.8	8.8	7.0	6.0	5.1	6.1	8.2	13.0	13.1	12.8	
		Mean:	9.1	9.6	9.4	6.1	4.8	5.0	4.9	5.5	7.2	9.3	11.8	10.7	7.8
	P_D	**Minimum**: day	2	26	20	9	21	24	11	2	4	6	1	26	
		value	1.0	2.0	0.9	1.5	0.9	1.7	1.0	1.7	1.3	1.6	1.2	1.4	
		Maximum: day	30	28	29	18	4	5	17	10	22	7	29	29	
		value	6.5	6.7	6.8	6.7	6.4	5.6	4.8	4.8	6.1	5.2	6.4	6.2	
		Mean:	3.5	3.8	3.9	3.6	3.7	3.1	2.5	3.1	3.5	3.5	3.6	3.6	3.4
	DOP	**Minimum**: day	17	26	25	10	23	24	11	22	3	15	13	4	
		value	29.5	40.5	26.3	13.8	6.4	4.6	4.6	4.2	4.0	3.7	6.5	10.8	
		Maximum: day	8	5	1	1	1	6	27	4	8	29	28	29	
		value	67.5	114.3	108.6	73.5	52.6	13.4	7.3	7.8	11.6	16.8	23.3	28.2	
		Mean:	50.3	80.7	62.8	32.3	18.1	6.8	5.8	5.8	6.2	7.8	13.6	19.8	25.5
	DIP	**Minimum**: day	4	15	25	28	22	24	6	18	4	5	1	4	
		value	8.1	31.3	27.1	4.5	2.9	3.1	3.3	3.7	3.5	4.2	8.7	19.9	
		Maximum: day	30	28	17	2	4	5	21	30	8	30	29	29	
		value	44.4	98.2	105.9	95.2	23.3	12.2	10.9	12.9	18.5	35.1	60.9	68.9	
		Mean:	23.3	61.2	65.2	28.1	9.0	6.5	6.8	7.9	10.3	15.9	28.6	44.5	25.5
	Total P	**Minimum**: day	4	27	21	9	15	4	11	22	19	6	1	27	
		value	2.0	4.9	2.7	3.4	3.1	4.4	7.6	6.9	4.3	4.6	2.6	3.2	
		Maximum: day	1	21	18	20	21	29	21	31	1	5	9	25	
		value	11.2	18.8	19.2	22.0	21.5	27.0	45.8	33.0	25.2	20.7	14.8	19.6	
		Mean:	5.6	10.1	8.8	10.0	10.5	12.3	19.9	17.8	11.6	11.1	7.3	8.2	11.1
1977	Phytoplankton-P	**Minimum**: day	29	22	29	9	4	27	26	22	10	14	7	27	
		value	8.6	5.5	4.7	5.9	5.0	5.2	5.2	5.6	5.5	6.7	7.3	7.2	
		Maximum: day	8	9	3	4	1	3	4	14	21	31	27	20	
		value	26.4	26.3	23.0	17.6	17.7	15.8	13.0	11.3	15.8	18.6	24.1	32.2	
		Mean:	21.2	19.6	14.8	12.1	10.9	9.9	8.6	8.8	10.1	13.8	16.9	23.5	14.2
	Bacterial-P	**Minimum**: day	1	23	29	25	5	1	1	22	10	15	12	28	
		value	8.0	7.6	5.2	5.4	3.6	4.9	5.5	5.7	5.8	9.4	10.3	10.3	
		Maximum: day	3	3	3	1	1	7	31	4	30	31	20	1	
		value	10.3	9.8	9.4	8.9	5.3	5.9	6.4	6.9	10.6	12.2	13.0	12.8	
		Mean:	9.8	9.2	7.8	7.8	4.3	5.4	6.0	6.3	7.8	10.5	11.8	11.6	8.2
	P_D	**Minimum**: day	13	20	29	9	22	27	11	9	9	22	2	31	
		value	1.5	1.6	1.3	1.6	1.6	1.2	1.3	1.1	1.3	1.6	1.1	1.2	
		Maximum: day	7	23	31	18	2	8	24	12	22	13	30	5	
		value	6.2	6.3	6.5	6.4	6.3	5.6	5.4	5.3	5.3	6.3	6.6	6.7	
		Mean:	3.9	3.6	3.7	3.8	3.4	3.0	2.9	3.1	3.1	3.9	3.7	3.8	3.5
	DOP	**Minimum**: day	1	23	29	9	31	16	26	11	6	8	2	27	
		value	17.3	16.1	12.2	21.4	7.5	4.0	3.6	3.4	3.5	3.9	4.0	12.1	
		Maximum: day	31	18	31	18	2	3	17	4	23	31	30	30	
		value	111.8	47.1	66.8	111.7	54.6	8.8	7.8	7.3	8.2	9.3	21.6	29.5	
		Mean:	32.5	36.5	40.7	59.8	19.3	5.9	5.1	5.0	5.6	6.5	11.5	23.4	20.9
	DIP	**Minimum**: day	1	23	29	30	22	20	11	22	9	3	2	1	
		value	26.7	24.1	9.2	9.2	2.8	3.0	3.2	3.3	3.1	4.5	5.1	24.0	
		Maximum: day	27	16	4	3	2	5	29	29	30	31	30	31	
		value	89.3	98.7	103.5	78.2	33.9	10.6	10.3	11.3	19.5	21.2	44.6	87.8	
		Mean:	65.1	69.9	57.0	35.5	8.9	6.3	6.7	6.8	9.3	14.1	20.6	54.5	29.5
	Total P	**Minimum**: day	13	23	29	16	22	27	11	9	26	11	26	16	
		value	3.5	4.5	3.9	4.1	5.8	7.0	7.6	7.4	6.6	4.5	2.5	3.2	
		Maximum: day	28	18	9	30	17	25	7	15	9	31	1	31	
		value	18.2	19.6	24.4	20.4	28.1	39.7	42.5	35.0	36.3	23.1	18.8	19.0	
		Mean:	9.9	11.7	13.0	11.1	14.4	17.4	23.0	20.6	17.0	11.9	8.4	9.0	14.0
1978	Phytoplankton-P	**Minimum**: day	30	26	31	4	31	10	29	2	27	4	29	30	
		value	8.1	7.0	4.9	5.4	6.0	5.5	5.5	5.4	6.7	6.4	9.8	5.9	
		Maximum: day	30	1	3	17	12	1	4	3	30	31	27	29	
		value	32.0	29.7	27.3	18.9	18.4	16.2	14.5	11.6	18.8	23.5	31.5	32.5	
		Mean:	24.0	21.3	16.5	11.9	11.4	9.9	9.4	9.1	11.7	15.2	23.3	24.6	15.7
	Bacterial-P	**Minimum**: day	29	26	31	30	1	2	5	8	12	4	1	30	
		value	10.1	8.7	4.4	3.9	3.8	4.0	5.6	5.4	6.7	8.1	11.9	8.2	
		Maximum: day	2	1	1	17	17	29	22	31	30	29	14	1	
		value	11.8	11.1	9.6	8.7	8.4	7.6	7.3	8.7	11.1	14.2	15.3	14.2	
		Mean:	11.2	10.1	8.4	6.6	5.0	5.4	6.5	6.6	8.8	11.6	14.5	11.5	8.9
	P_D	**Minimum**: day	5	4	6	15	2	28	30	28	27	18	27	18	
		value	1.1	1.2	1.3	1.7	1.4	1.3	1.6	1.3	0.9	1.2	1.4	1.7	
		Maximum: day	23	15	14	2	15	7	3	19	24	31	21	26	
		value	6.8	6.7	6.9	6.3	6.3	5.4	5.5	5.1	5.9	6.3	6.5	6.7	
		Mean:	3.8	3.9	3.9	3.6	3.5	3.2	3.3	3.0	3.7	3.9	3.6	3.8	3.6
	DOP	**Minimum**: day	30	4	30	1	31	24	4	17	11	4	30	1	
		value	14.3	14.7	10.9	13.7	8.2	3.8	3.2	3.2	3.1	3.3	8.9	8.3	
		Maximum: day	27	28	25	17	12	12	22	29	22	29	13	25	
		value	41.7	46.3	82.7	86.1	74.9	12.5	8.0	7.0	10.1	17.3	23.3	27.3	
		Mean:	31.7	30.5	39.1	42.1	28.2	7.8	5.2	5.2	5.7	9.3	19.4	18.5	20.2
	DIP	**Minimum**: day	5	14	31	30	31	8	4	7	27	4	1	31	
		value	34.7	34.7	12.3	5.0	3.2	3.0	3.1	3.2	3.3	3.8	12.3	25.9	
		Maximum: day	24	1	9	8	14	28	11	29	22	29	26	28	
		value	135.9	124.4	120.0	51.7	19.2	11.4	11.2	13.6	17.6	32.8	74.9	88.7	
		Mean:	84.5	75.0	62.1	24.5	8.9	6.6	6.9	7.1	9.2	16.4	45.2	58.6	33.7
	Total P	**Minimum**: day	5	14	7	15	2	28	4	31	27	21	29	18	
		value	2.3	2.9	3.1	3.4	4.0	3.5	6.0	5.0	2.6	2.9	2.9	4.1	
		Maximum: day	27	3	4	29	9	10	29	6	7	14	26	17	
		value	16.9	16.3	18.8	15.5	18.1	30.8	26.8	32.1	20.5	21.3	17.0	16.0	
		Mean:	8.6	8.2	9.0	8.2	9.8	14.9	15.0	15.7	12.0	10.2	8.7	8.2	10.8

particulate organic-P, is much more variable in winter months than in spring, autumn, or especially summer months.

(iii) The phosphorous pool in the phytoplankton turns over during the winter period in approximately 7-10 days, 15-20 days, and 20-25 days in Basins I-IV respectively. In the summer period, the biomass of phytoplankton-P turns over somewhat more quickly and its turnover times equal 5-6 days, 6-8 days, 7-9 days and 8-10 days. However, in the spring and autumn months, the phytoplankton-P turns over in 6-8 days, 8-10 days, 9-15 days, and 10-20 days in the same basins. The daily mean values of phytoplankton-P may fluctuate in the range 5-10 days and 1-2 days in the winter and summer months respectively, as a result of the changes in environmental factors and phosphorous loading. The diurnal fluctuations in the phytoplankton-P turnover time occur because of the diurnal changes in radiation. Therefore, phytoplankton activity in the phosphorous transformation is evaluated at approximately 10-12 days (Basins I-II) and 15-20 days (Basins III-IV) for the winter months. During the summer months, the duirnal fluctuations of this parameter (estimated at 4-5 days) are virtually the same in every basin. Annual mean turnover times of phytoplankton-P for 1976-78 equal about 7, 10, 12, and 15 days for Basins I-IV respectively. The order of turnover time values for the phytoplankton-P appears to be in agreement to those calculated by Gächter (1968).

(iv) In the summer period, the bacterial phosphorous pool exhibits a turnover time on the order of 3-4 days in Basin I and 4-6 days in Basins II-IV. During the winter period, the turnover of the bacterial-P becomes longer, estimated at 6-9 days (Basin I) and 9-14 days (Basins II-IV). In the spring and autumn months, the bacterial-P turns over in 5-7 days (Basin I) and in 6-12 days (Basins II-IV). The diurnal fluctuations of the turnover time for the bacterial-P may reach 4-5 days in Basins I-III, but drop to 2-3 days for the winter and summer months respectively. The diurnal changes in bacterial-P are the least in Basin IV, where they are estimated to be 2-3 days for each season. Annual mean values of the bacterial turnover of the phosphorus appear to be about 6-7 days for Basins I-II and 8-9 days for Basins III-IV.

(v) The nonliving particulate organic-P exhibits a daily mean turnover time of 1.5-3 days, 1.8-4 days, 1.8-5 days and 2-6 days in Basins I through IV respectively. The daily fluctuations of the detrital-P in shallow water bodies are to a large degree dependent on the sediment-water interactions with respect to the phosphorous exchange. The rapid circulation of the detrital phosphorus is defined by the marked wind action, a specific subject of the given study. According to the simulation results, during strong winds (more than 8-10 m/sec), the turnover time of the detrital-P is shortest, while it appears to be longest when light winds prevail. The annual mean values of turnover time for detrital-P were evaluated at 2.1, 2.7, 3.1, and 3.5 days for Basins I-IV. The seasonal course of the turnover time for this phosphorous fraction is revealed by the analysis of the monthly mean turnover time generalized for the three year period, 1976-1978. It shows a slight lowering of turnover time in summer months, expressed more in Basins III-IV than in Basins I-II. The assessments of the turnover times for the detrital-P obtained in this study may not be completely analogous to those available in the literature because of great differences in the model structure and mathematical functions used for the description of the dynamic behavior of the detrital-P. For example, Watson and Loucks (1979) calculated the turnover time of 10 days for the suspended detrital-P without taking into account the wind effect on the phosphorous exchange between sediments and the water.

(vi) The dynamics of the turnover for DOP show a well-expressed seasonal change in all basins. During winter-spring months, the turnover time of DOP may fluctuate in a relatively wide range--from 4.4 to 90.4 days (Basin I), from 10.6 to 124 days (Basin II), from 10.4 to 115 days (Basin III) and from 13.6 to 114 days (Basin IV). In summer months, the turnover time of DOP fluctuates much less as a consequence of the high activity of microorganisms that significantly accelerate the internal phosphorous cycling through compartments. The mean turnover time for the summer period is 5-8 days for the different Lake Balaton Basins in 1976-1978. The annual mean values of the turnover time of DOP may fluctuate for the individual years in the ranges 15.7-19.4 days (Basin I), 21.2-22.4 days (Basin II), 18-21.8 days (Basin III), and 20.2-25.5 days (Basin IV).

(vii) The turnover of DIP is more rapid in Basins I-II than in Basins III-IV as, first of all, a result of a larger activity of the phytoplankton in these Basins. During the winter-spring months the turnover time of DIP may change in the range 1.4-36 days (Basin I), 1.2-37 days (Basin II), 6-127 days (Basin III), and 8.1-136 days (Basin IV). Turnover of DIP for the summer months varies from 0.7 to 4 days in Basins I-II and from 2.6 to 13 days in Basins III-IV. According to the modeling results, the turnover of DIP in the summer months is shortest compared to those for other phosphorous compartments. This is indicative of the limiting phosphate conditions and the high microorganism activity. Because the phosphate levels are more or less similar in the different Lake Balaton Basins and equal to 0.004-0.006 mgP/ℓ during the summer period, the assessment of the turnover time of DIP allows one to estimate better the equilibrium among all processes responsible for the phosphate levels in the water of Lake Balaton. The seasonal course of the turnover time for DIP presented in the report suggests that rapid fluxes of DIP are typical for the summer months, during the periods of algae blooms, and high microorganism activity, and that the input-output flux rates through this phosphorous compartment are even more important than levels of DIP for maintaining the high rates of organic production and phosphorous cycling as a whole in Basins I-II. Further explanation of DIP turnover in the Lake Balaton Ecosystem may be obtained through the analysis of the ratio of particulate-P fractions to DIP. Because in the given model three particulate-P fractions were considered (nonliving particulate organic-P, bacterial- and phytoplankton-P), two ratios: total particulate organic-P (that includes all particulate-P fractions) to DIP, and phytoplankton-P to DIP, were computed with the monthly mean phosphorous concentrations obtained in the simulation runs. The first ratio shows the dominance of the particulate phosphorus above the DIP as the most important and mobile phosphorous fraction in the total phosphorous pool as a whole, while the second one shows the seasonal change of the phosphate requirements of the phytoplankton or, in other words, the dynamics of the limiting of phosphate. Figure 21 illustrates the changes (during 1976-1978) of these ratios in the different Lake Balaton Basins. Thus, in Basin I the level of particulate organic-P is higher than DIP approximately 8-10 times during the summer months. In Basins III-IV, the dominance of particulate organic-P is 4-6 times greater than DIP for the same period. The assessments for Basin II show that

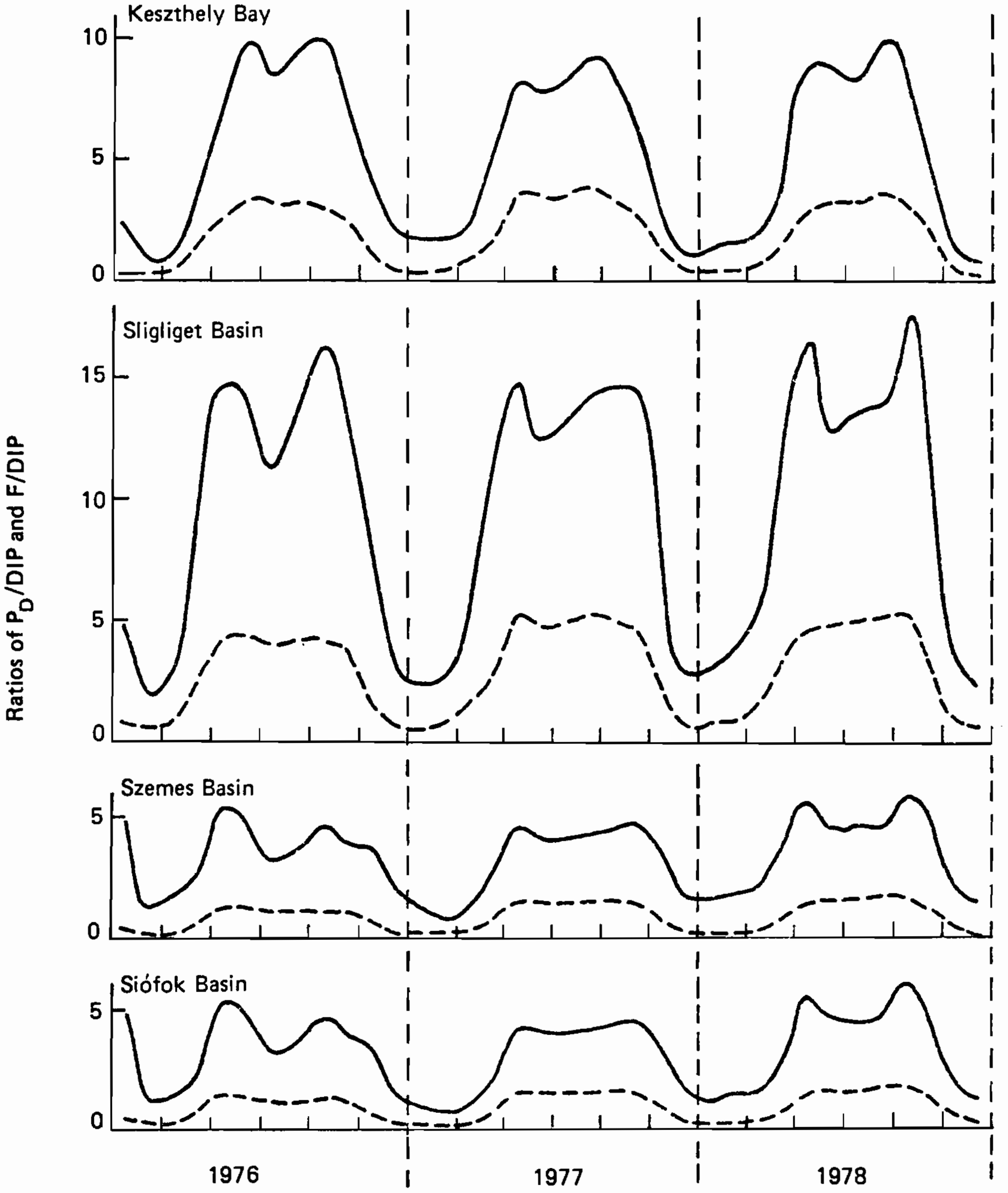

Figure 21. Dynamics of concentration ratios of P_D/DIP (——) and F/DIP (---).

during the productive period, the levels of the particulate organic-P may be 11-17 times higher than DIP content in the water. This means that the limitation of phosphate is expressed more strongly in Basin II than in other parts of the lake. Actually, the evaluated range of the phytoplankton-P to DIP ratio in the summer months 1976-1978 is 3.2-3.8 for Basin I, but is higher in Basin II, being equal to 4.2-5.4. In Basins III-IV, this ratio for the same period is much less and evaluated at 1-1.7. During the winter period, when the role of the living fractions of the particulate phosphorus appears to be lower and the DIP content in the water tends to be higher than in summer, these ratios may only differ 1-3 times from each other in the various Lake Balaton Basins.

As mentioned above, an order of the DIP turnover time in the existing assessments is dependent on the measurement or calculation techniques and the available ones are not always directly comparable to each other. Therefore, the comparison of turnover time values for DIP obtained in this study and elsewhere (Table 7), may be reasonable only when similar methods of measurement or calculation are used. As Table 7 shows, the majority of the assessments of turnover time for phosphate are made for the productive seasons and the comparison of the turnover time for DIP produced by the given model for the summer period shows an agreement with assessments obtained by mathematical modeling calculations (Patten et al., 1975; Watson and Loucks, 1979).

(viii) As mentioned above, the turnover of the total-P is determined by the external phosphorous fluxes and primarily by the nonliving particulate organic-P and DIP, since according to the hypothesis used, the role of other phosphorous fractions in the external load is not very important. The role of the internal phosphorous cycling for the turnover of the total-P is essential only for the regulation of the intermediate concentrations of the individual phosphorous compartments within the phosphorous system. According to available data and simulation results presented in Figure 12, the annual changes of the total-P concentrations are very specific for each Basin, so that the ranges of the possible annual fluctuations of the total-P are estimated as 0.03-0.12 mgP/ℓ, 0.02-0.09 mgP/ℓ, 0.015-0.08 mgP/ℓ and 0.012-0.07 mgP/ℓ in Basins I-IV respectively. At the same time, there is a certain trend typical for each Basin (Figure 12) in the annual changes of the total-P, whereby there is a slight marked increase in its level during the productive seasons of 1976-1978. Therefore, it is possible to make a reasonable assumption that the equilibrium among all processes responsible for the phosphorous levels in the lake water constantly changes within the year. This feature of the annual dynamics of the total-P is to a large degree exposed by the analysis of the total-P turnover time shown in Figure 20. The turnover time of the total-P is variable. Its fluctuations within a certain season may reach the order of magnitude of one. For example, during the winter period, the turnover time of the total-P may range from 1.3 to 16.5 days (Basin I), from 1.7 to 17.2 days (Basin II), from 1.8 to 16.9 days (Basin III), and from 2 to 19.6 days (Basin IV). In spring and autumn months, the fluctuations of this characteristic are estimated as 1.4-19.3 days, 1.6-25.5 days, 2-32.3 days and 2.5-28.1 days for the same Basins. In the summer period, the turnover time of total-P fluctuates within the range of 2.3-24.6 days, 2.5-32.3 days, 2.8-41.8 days and 3.4-45.8 days in Basins I through IV respectively. The analysis of the monthly mean turnover time of the total-P for the three years, 1976-1978, shows that in Basin I the turnover is the shortest in January (range 3.9-6 days, mean 4.8 days) and in April (4.7-6.4 days, 5.3 days). In Basins II-IV, the shortest turnover occurred in November-January with a mean turnover time of 6 days (Basin II), 7.3 days (Basin III) and 8.1 days (Basin IV) for these months. As model calculations show, the summer period, namely July and August, is characterized by the increased turnover time of the total-P, the mean turnover time for these months being 9.8 days (range 8.2-12.2 days), 12.5 days (10.2-15.5 days), 15.8 days (12.7-19.7 days), and 18.5 days (15-23 days) for Basins I-IV respectively.

The increase in the turnover time for the summer period is explained primarily by the significant reduction in the external phosphorous load (Table 5) and by some increase in the total-P concentration in the lake water as a consequence of the intensive biological processes in the general phosphorous transformation within the water body. The fluctuation of the turnover time for the total-P in the summer period depends first of all on the rapid wind-regulated phosphorous exchange through the sediment-water interface, while the effect of other processes in the phosphorous supply may be considered as negligibly low.

The general analysis of turnover times for the phosphorous compartments considered in this model shows that for the environmental conditions of 1976-1978, the annual circulation of the Lake Balaton phosphorus occurred without essential deviations from year to year. The calculations indicate that the annual mean values of phosphorous turnover times for the three year period are the function of the Lake Balaton Basins as a whole. Figure 22 illustrates the annual mean turnover times of the phosphorous fractions and total-P considered in the model, as functions of Lake Balaton Basin water volumes. The range of fluctuations in turnover times for each year between 1976-1978, is also shown in Figure 22 for all estimates. As follows from Figure 22, the dependence of the annual mean phosphorous compartment turnover time on basin volume appears to be linear for the phytoplankton-P, bacterial-P, detritus-P, and total-P, but for the chemical phosphorous fractions, DIP and DOP, this dependence does not seem to be linear. This conclusion suggests that the nutrient loading for Basin II should be higher than used in the simulation in order to maintain the general features and tendencies in the phosphorous cycling revealed in this analysis for Lake Balaton considered as a homogeneous ecosystem.

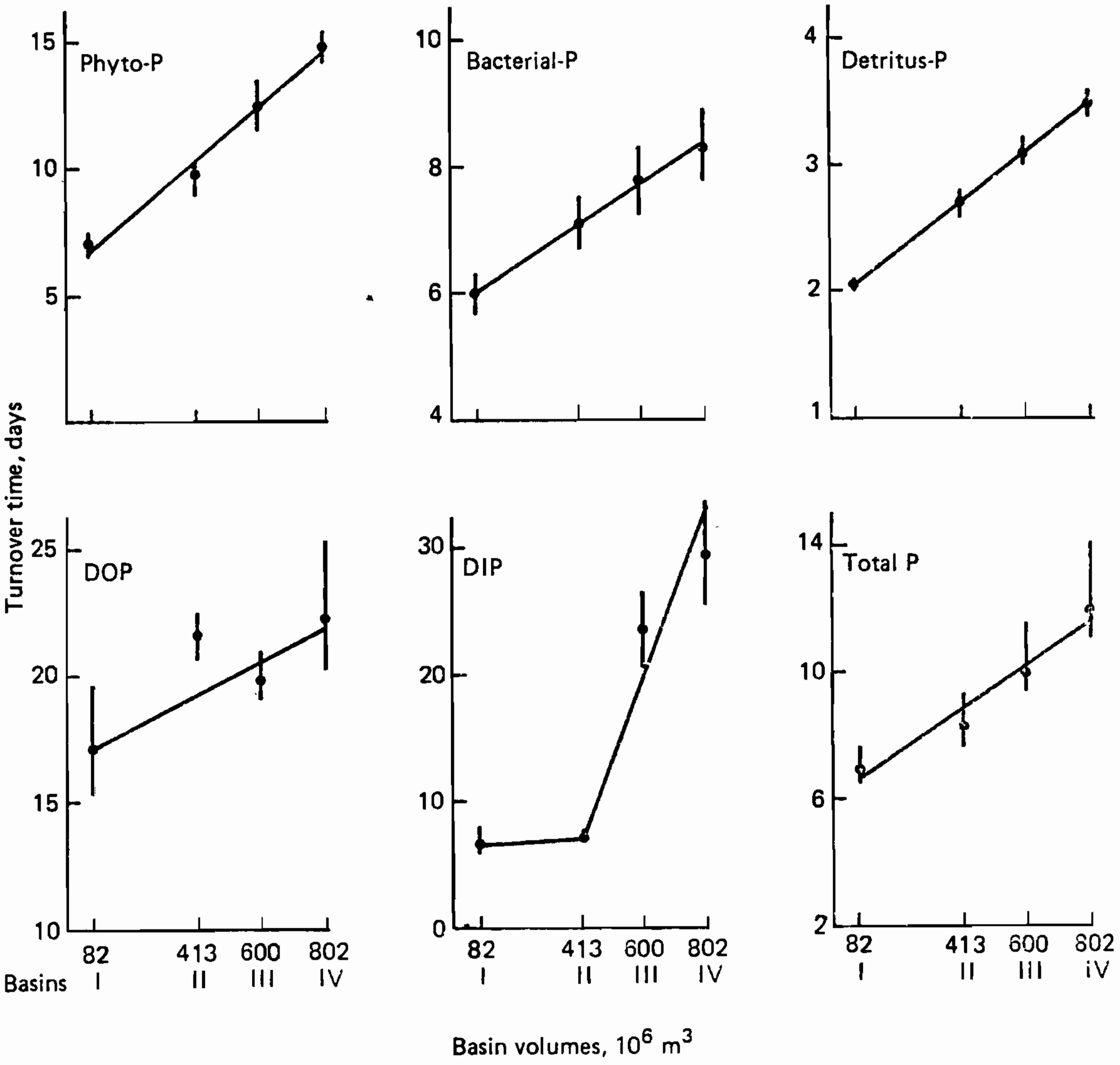

Figure 22. Dependence of phosphorous compartment turnover times, averaged for three year period (1976-1978), on the volume of the Lake Balaton Basins.

Some differences in the phosphorous turnover within 1976-1978 took place in the individual seasons as a consequence of the yearly changes in weather conditions and external loading. As model calculations show, the largest differences in the turnover times of the phosphorous fractions occurred in the winter period, while the lowest ones occurred in the summer period.

CONCLUSIONS

In the study, the emphasis was made on the application of the Balaton Sector Model to describing the interactions of five phosphorous fractions, which represent the phosphorous dynamics in the different Lake Balaton Basins under the environmental conditions of 1976-1978.

The set of observations for temperature, radiation, wind, water balance, and phosphorous concentrations in the Zala river, the main tributary of Lake Balaton, was used in the simulation of the phosphorous dynamics in this lake from 1976-1978. In this study, the phosphorous inputs from the different sources (rainfall, sewage, urban runoff, and tributaries) also were taken into account in accordance with the improved approach used for the watershed phosphorous load as suggested by our Hungarian colleagues.

The simulation results were used for the quantitative analysis of the role of the different external sources in the phosphorous loading of Lake Balaton Basins in 1976-1978. The model calculations allow one to obtain the time distribution of the phosphorous load for the comparative analysis of the phosphorous contributions from different external sources considered in the model. It is assumed from the simulation results that the DIP load for

Basin II should be higher than used in this study. It is also obvious that the additional input of DOP from as yet unidentified external sources, may improve the model representation of the phosphorous dynamics in the Lake Balaton Basins, and that the different scenarios of the possible DOP watershed (or internal) load may be examined in model runs. This load is considered rather important for the summer-autumn period when DOP levels, according to observations, reach a higher value, a tendency typical for all basins in 1976-1978.

This model calculates the instantaneous turnover time for the individual phosphorous compartments. The averaging of these values was done on a daily, monthly, and annual basis. The dynamics of the daily mean turnover times are presented in this report in Figures 15-20, and Tables 8-11 show the monthly and annual mean turnover time values for all phosphorous compartments. The comparison of the phosphorous turnover times calculated in this study and existing in the literature may be done using data from Figures 15-20, Tables 8-11, and Table 7, where the data on the phosphorous turnover time from the literature is shown.

The analysis of turnover times for the phosphorous compartments calculated by the model shows that the turnover time is a useful parameter in the interpretation of the conditions in phosphorous transformation and the cycling of individual phosphorous compartments. As a whole, the turnover time reflects the complex relationship existing between environmental conditions (or factors), nutrient loading, and limnetic properties of the water body considered. The turnover time values show that all phosphorous fractions are much more mobile in Basin I than in other Lake Balaton Basins, a consequence of the increased watershed phosphorous loading, higher levels of phosphorous concentrations in the water, and higher phytoplankton activity in the water of Basin I. The fluctuations of turnover time within the individual seasons and the seasonal differences in this parameter for phytoplankton-P, DIP, and DOP, increase from Basin I to Basin IV as a result of the different combined effects of all factors defining the phosphorous transformation and turnover of the individual phosphorous compartments in the different parts of the lake. During summer months, the possible daily variations of turnover times are much less than in other seasons. The phosphorous turnover appears to be fastest in the biological compartments (bacteria and phytoplankton) and in the detritus which are directly dependent on the microorganism activity and strongly regulated by wind action.

Some seasonal differences in the conditions of phosphorous cycling may be seen from the analysis of the monthly mean turnover time values for the individual phosphorous compartments in Basins I-IV. These differences are a consequence of the changeable environmental conditions in 1976-1978. However, the annual mean values of the turnover times indicate that approximately similar conditions in the phosphorous cycling existed in the period of the study, 1976-1978.

APPENDIX: Nomenclature

i is a subscript equal to 1, 2, 3, 4 and 5 for P_D, DOP, B, DIP and F respectively;

j is a subscript referring to the number of the Basin considered;

$C_{i,j}$, $C_{i,j-1}$ and $C_{i.j+1}$ are concentrations of particular phosphorous compounds in the basin under consideration, prior, and following basin respectively (all mgP/ℓ);

$R_{i,j}$ is the resultant rate of biochemical phosphorous transformation (mgP/ℓ-day);

$LOAD_{i,j}$ is the resultant rate of phosphorous loading (mgP/ℓ-day);

$TR_{i,j}$ is the resultant rate of horizontal phosphorous transport by water flow (mgP/ℓ-day);

UP_{B_j} and UP_{F_j} are specific rates of nutrient uptake by bacteria and phytoplankton respectively (both day^{-1});

L_{B_j} and L_{F_j} are specific rates of metabolical excretions by bacteria and phytoplankton respectively (both day^{-1});

M_{B_j} and M_{F_j} are specific rates of nonpredatorial mortality of bacteria and phytoplankton respectively (both day^{-1});

r_{B_j} and r_{F_j} are excretion activities of bacteria and phytoplankton respectively (unitless);

R_{IF} is the light reduction factor for the phytoplankton uptake rate (unitless);

I, I_{opt}, I_{max} and I_{av} are current, optimal, maximum and daily mean light intensities respectively (all cal/cm^2-day);

f is the photoperiod in hours;

K_e is the light extinction coefficient (m^{-1});

t_n and t_p are the current time of day (in hours) and time of maximum light intensity (12 o' clock);

S_j is the rate of detritus sedimentation (mgP/ℓ-day);

d_j is the average depth of the basin considered (m);

Q_{in_j}, Q_{out_j} and Q_{pr_j} are the input and output flow rates and precipitation rate respectively (all m^3/day);

$Q^a_{win_j}$ and $Q^b_{win_j}$ are the input rates of wind-induced flows through left and right interbasin cross-section areas respectively (both m^3/day);

$Q^a_{wout_j}$ and $Q^b_{wout_j}$ are output rates of wind-induced flows through left and right interbasin cross-section areas respectively (both m^3/day);

C^r_{DIP} and C^r_{DOP} are phosphorous concentrations in rainwater (both mgP/ℓ);

T is water temperature in ^oC;

W is wind speed in m/sec;

A_j is interbasin cross-section area (m^2);

α is wind direction;

CZ_{DIP} is sewage DIP load (mgP/ℓ-day);

DIP_Z and P_{DZ} are Zala river DIP and P_D load respectively (mgP/ℓ-day);

DIP_{r_j} is the variable time-average flux of DIP from the sediments in each basin (mgP/ℓ-day);

P_{Dr} is time-average flux of P_D from the sediments (mgP/ℓ-day);

V_j is volume of basin considered (m^3);

K_i, a_i, v_i, y_i, k, U, γ_i, β are model coefficients.

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