IMPORTANCE OF EPILMNION PHOSPHORUS LOADING AND WIND-INDUCED FLOW FOR PHYTOPLANKTON GROWTH IN ŘÍMOV RESERVOIR

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ABSTRACT

Total reservoir phosphorus loading and epilimnion phosphorus loading were estimated and their relations to phytoplankton quantity examined for spring-summer periods during 1984-1991 in Rímov Reservoir, a stratified, moderately eutrophic reservoir with variable surface and deep outlets operation. Epilimnion phosphorus loading was quantified from the volumes of water entering the epilimnion due to the inflow temperature-density currents and due to the surface discharges that were determined by the one-dimensional dynamical simulation model of reservoir hydrodynamics DYRESM 5. The fraction of total phosphorus input into the reservoir entering the epilimnion varied between 12 and 31% in different years. Chlorophyll a concentration measured near the dam correlated only with the epilimnion phosphorus loading due to surface discharges. The phosphorus input by river water entering directly the epilimnion caused an increase of the chlorophyll a concentration at the dam only occasionally if the wind was of sufficient velocity and favourable direction to induce mixing and transport of epilimnion water masses from the headwater part of the reservoir to the dam.

KEYWORDS

Reservoir, eutrophication, phosphorus loading, inflow density currents, river temperature.

INTRODUCTION

Numerous trophic-state indices and nutrient loading - trophic response empirical models for the prediction and management of eutrophication of lakes have been developed during the last three decades (reviewed e.g. by Henderson-Sellers, 1984, and Haith et al., 1989). However, for several reasons, these models often yield less precise or equivocal results when applied to reservoirs. Reservoirs often have lower in-lake concentrations of total phosphorus and chlorophyll a than natural lakes at a similar level of nutrient loading. This difference has been related to the shorter water residence times, higher sedimentation rates and decreased light transparency of reservoirs (Kennedy and Walker, 1990; Thornton, 1990). Occurrence of density currents and operation of deep outlets have also been stated to influence the input of nutrients to the euphotic zone of reservoirs (Ford, 1990).

The nutrient load - trophic response models usually assume that the entire nutrient load (most often phosphorus load) to a waterbody during a given calendar year can affect its biological response (e.g. phytoplankton biomass). However, in a rapidly flushed waterbody, a part of the phosphorus load entering the waterbody at the beginning of the calendar year may be flushed out of the waterbody before the onset of growing season and therefore cannot have any impact on phytoplankton growth during the growing season (Loehr et al., 1989). In this situation, Ryding and Forsberg (1979) suggested to use in these models only the hydrologic relevant P-load which is defined as the nutrient load entering the waterbody during the growing season, plus the load entering the waterbody during the period corresponding to one
flushing time prior to the growing season.

In this study, we tried to identify the P-load relevant to biological response in Římov Reservoir, a stratified, phosphorus-limited reservoir which is discharged in summer both from hypolimnion and from surface and which contains a substantial fraction of rapidly sedimenting particulate phosphorus in the inflow. We modified further the concept of Ryding's and Forsberg's hydrologically relevant P-load because of some specificity of the seasonal flow pattern directly affecting phytoplankton growth in this reservoir. The growing season starts in Římov Reservoir with a period of overflow during which the warm river water flows in the surface layer along the reservoir and speeds up the formation of epilimnion (Hejzlar and Straškraba, 1989). The outflow is discharged through deep outlets during this time. The biomass of phytoplankton is determined in this period by the concentration of phosphorus in the inflowing water which fills the upper strata. The in-lake phosphorus concentration from the previous period of spring turnover is of a limited importance for phytoplankton growth because the original reservoir water is depressed by the inflowing river water into deeper layers (Vyhnašek, 1989). Later, phosphorus comes to the epilimnion only during periods of overflow and by the entrainment of metalimnion water caused by wind mixing (Vyhnašek et al., in press). In summer, when the outflow is partly discharged also from surface, phosphorus can be transported to the epilimnion from the metalimnion if the surface outflow volume is larger than the volume of river water entering directly the epilimnion. The biologically relevant P-load in Římov Reservoir was therefore estimated as the sum of dissolved phosphorus which enters the epilimnion with surface inflow currents and by the entrainment of metalimnion water due to the surface discharges during the period between the onset of thermal stratification and the end of growing season. The hypothesis that the average seasonal concentration of phytoplankton is determined by this biologically relevant P-load was tested on the basis of data from 1984 to 1991.

THE RESERVOIR, MATERIALS AND METHODS

Římov Reservoir, a drinking water reservoir located in South Bohemia, is 13 km long, has maximum volume 32x10⁶ m³, mean and maximum depths 17 and 43 m, and stratifies both in summer and winter (Hejzlar and Straškraba, 1989). Its morphology is elongated and narrow; it is situated in the north-south direction and sheltered against east and west winds by 50 to 80 m high slopes of the surrounding valley. The reservoir receives most of its inputs from the Malše River which drains 93% of its watershed area (488.5 km²). The watershed area is covered from 50% with forests and about 25% of it is agricultural, mostly arable land. It is inhabited by about 11 000 inhabitants of which 8 000 live in the town of Kaplice, 8 km upstream from the reservoir. River discharges average 4.3 m³.s⁻¹, but short-term flows, mainly related to spring snow melting and summer storms, frequently exceed 20 m³.s⁻¹. Average hydraulic residence time in the reservoir is 92 days. The raw water for the treatment plant (1.2 to 1.5 m³.s⁻¹) is withdrawn from the depths of about 15 or 20 m. The discharge to the river is released through the bottom outlets during October to May but during May or June to September from the surface to enable recreation downstream from the dam. The reservoir is moderately eutrophic with regular occurrence of anoxic conditions in the bottom layer from June to September. Phosphorus is limiting nutrient for phytoplankton growth during the spring to summer period with dissolved reactive phosphorus concentrations below 5 μg.l⁻¹ (Nedoma et al., 1993). Transparency of water is determined mostly by phytoplankton concentration; Secchi depth values range usually between 1.5 and 6 m during the growing season. The depth of the mixing layer is about 2.5 to 3 m in summer (Hejzlar and Straškraba, 1989; Hejzlar, 1989).

For the estimation of the volume of water entering the epilimnion of the reservoir, the one-dimensional dynamical simulation model DYRESM (Imberger and Patterson, 1981) was employed. Its performance was adjusted by optimizing input parameters with selected data (May to August 1986). The best agreement between the measured and simulated temperatures was obtained by employing wind data reduced only to their north-south component and inflow data input 4 times per day considering the diurnal cycle of inflow temperature. In this case the simulated temperatures at the surface differed by ±1.7°C, at a depth of 5 m by ±2.2°C and at a depth of 10 m by ±1.9°C at most. The outputs of the model were arranged to obtain daily volumes of inflow which entered the desired layer.

The inflow was sampled at the gauging station situated on the Malše River 3 km upstream from the reservoir where river discharges are continuously recorded. Samples for the phosphorus analysis were taken at regular three-week intervals during 1984 to 1991 and during 1988 to 1991 also occasionally during elevated discharge events. Water temperature was continuously recorded at this station in several periods during 1987 to 1991 to obtain data for calibrating relationships describing its dependence on meteorological variables. The reservoir was sampled at a distance of about 200 m from the dam. Temperature stratification and chlorophyll a concentration were determined at intervals ranging from 3 days to 3 weeks according to the rate of change (3 days to 1 week during the onset of thermal
stratification, spring phytoplankton bloom and the following clear-water phase, and 3 weeks during the summer season). Daily meteorological and hydrological data were obtained from the climatological station at the dam. Average daily values of wind speed and wind direction (measured 10 m above the reservoir surface), cloudiness, air temperature and relative humidity were calculated from three measurements made at 0700, 1400 and 2100 hours. Global radiation data were taken from the climatological station at České Budějovice, about 10 km north of the reservoir.

Average daily inflow temperature and daily inflow temperature amplitude were determined from the measured data at the inflow sampling station or, if these data were not available, estimated from regression models. The model for the average daily inflow temperature was based on the finding of Kothandaraman and Evans (1972) who showed that river temperature can be estimated from the average daily air temperature of the same day and several previous days. Models with different numbers of previous days were tried using multiple linear regression analysis, and the best results were obtained with the following equation (n=254; R=0.95):

$$T_w = 2.46 + 0.309 T_{a,i} + 0.292 T_{a,i-1} + 0.228 T_{a,i-2}$$ (1)

where $T_w$ is average water temperature [°C] on the day $i$, and $T_{a,i}$, $T_{a,i-1}$, $T_{a,i-2}$ are average air temperatures [°C] at the dam on the days $i$, $i-1$ and $i-2$. The model for the daily amplitude of inflow temperature was based on an assumption of its dependence on the daily air temperature amplitude. Several different functions were tried (hyperbolic, logarithmic, exponential, linear) but the polynomial function was in the closest agreement with the measured data (n=254; R=0.72):

$$AT_w = 1.40 - 0.0945 AT_{a} + 0.0226 AT_{a}^2 - 0.00047 AT_{a}^3$$ (2)

where $AT_{w}$ is daily inflow temperature amplitude [°C] and $AT_{a}$ is daily air temperature amplitude [°C] at the dam. Maximum and minimum daily river temperatures ($T_{w,\text{max}}$ and $T_{w,\text{min}}$) were calculated provided that the daily course of temperature is regularly distributed above and below the average. Some characteristics of errors made by estimating $T_w$, $AT_w$, $T_{w,\text{max}}$ and $T_{w,\text{min}}$ using equations (1) to (2) are given in Table 1.

Total reservoir phosphorus loading (TP) was quantified from the average daily volumes of inflow and the relationships between total dissolved phosphorus (TDP) or particulate phosphorus (PP) concentrations and discharge. The relationships were calculated by linear regression from all the data analyzed during 1984 to 1991:

$$TDP = 165 Q^{0.639}$$ (n=72, R=0.63) (3)

$$PP = 19.8 Q^{0.819}$$ (n=72, R=0.61) (4)

where TDP is total dissolved phosphorus concentration [µg·l⁻¹], PP is particulate phosphorus concentration [µg·l⁻¹], and Q is average daily discharge [m³·s⁻¹]. The predicting errors of TDP and TP concentrations by these relationships are in Table 1. This method was more reliable than the method of calculating phosphorus loads from original interpolated data and daily discharge which seriously underestimated PP.

<table>
<thead>
<tr>
<th>TABLE 1 Predicting Errors of Equations (1) to (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution characteristic</td>
</tr>
<tr>
<td>T_w</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>5th percentile</td>
</tr>
<tr>
<td>Lower quartile</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Upper quartile</td>
</tr>
<tr>
<td>95th percentile</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
</tbody>
</table>

Calculated from: *equation (1), **equation (2), ***equation (3), +equation (4)
load and overestimated TDP load, especially in years 1984 to 1987 for which only data in 3-week intervals were available (confer also with Walling and Webb, 1982). Other sources of phosphorus loading than the Malše River were not considered because their contribution was small. Streams flowing directly to the reservoir and precipitation supplied less than 5% of TP comparing with the Malše River (Porcalová and Jindra, 1982; Procházková, unpublished data). Internal loading from sediments was believed to be also small because the bottom area which is in contact with the epilimnion during the growing season is relatively small and, moreover, no increase of phosphorus concentration in the bottom layer was observed (Hejzlar, unpublished data).

The epilimnion phosphorus load due to inflow intrusions (TDP\textsubscript{ep}) was determined from the daily volumes obtained by DYRESM and the average daily TDP concentrations from equation (3). The epilimnion phosphorus load due to surface discharges (TDP\textsubscript{sp}) was calculated from the difference of the daily surface discharge volume minus the daily volume of inflow which entered the epilimnion and TDP concentration of the metalimnion which was considered to equal the average monthly inflow TDP concentration.

TP and TDP were determined by the perchloric acid digestion method of Popovský (1970). PP was calculated as the difference between TP and TDP. Samples for TDP analysis were filtered through Whatman GF/C filters (porosity 1 μm). The distribution of PP settling velocities in river water was measured according to Turek (1983). Chlorophyll \( \alpha \) was determined according to Lorenzen (1967).

RESULTS AND DISCUSSION

Variation of Inflow Temperature and Its Influence on the Inflow Distribution in the Reservoir

The importance of diurnal changes of river temperature for the inflow distribution in Římov Reservoir is demonstrated in Fig. 1. It shows the diurnal cycle of temperature stratification in the reservoir and the changes of the inflow intrusion depth estimated from the river temperature during a typical clear and calm summer day, August 10, 1986. The thermocline was located on that day in the depth of about 3 m at the temperature of approximately 19°C. River temperature varied from the minimum at 0500 hours (15.3°C) to the maximum at 1600 hours (20.1°C). The inflowing river water entered depths between 4.8 and 2.2 m. The direct river flow to the epilimnion layer (0 to 3 m) occurred from 1300 to 2100 hours and comprised 33% of the daily inflow volume. If the inflow intrusion depth was estimated from its average temperature (17.4°C), no direct flow to the epilimnion could be detected.

Fig. 2 summarizes the results of modelling the inflow intrusions to the epilimnion and the metalimnion water entrainment to the epilimnion due to surface discharges. The coefficient of direct epilimnion inflow, \( R_e \), is defined as the ratio between the daily inflow volume which entered the epilimnion (0-3 m) with temperature-density currents and the daily total inflow volume. The coefficient of metalimnion water

![Fig. 1. Temperature stratification [°C] and estimated position of inflow intrusion depth (dotted line) in Římov Reservoir during August 10, 1986.](https://iwaponline.com/wst/article-pdf/28/6/5/103509/5.pdf)
Phosphorus and epilimnion phosphorus loading

Fig. 2. Monthly averages of the coefficient of direct epilimnion inflow, $R_{e1}$, (A) and of the coefficient of metalimnion-to-epilimnion entrainment due to surface discharges, $R_{e2}$, (B) during 1984 to 1991. Vertical lines indicate range from minimum to maximum values.

entrainment to the epilimnion, $R_{e2}$, is defined as the ratio between the difference of the daily surface outflow volume minus the daily inflow volume which entered directly the epilimnion and the total daily inflow volume. The values of $R_{e1}$ are highest in the early stages of summer stratification (avg. 0.58 in April) when the temperature of river water reacts more rapidly to the increase of air temperature than surface temperature of the reservoir. However, already during late spring (May) the inflow has a sufficiently high temperature to enter the surface layers only during very warm days or on sudden warming after periods of longer cool weather. This trend is even more pronounced in summer. Average values of $R_{e1}$ vary during June to August from about 0.15 to 0.23 but occasionally, during periods of very warm weather, they can also reach higher values (e.g. 0.53 in August 1989). The coefficient of indirect epilimnion inflow, $R_{e2}$, depends primarily on outflow manipulation but it is also influenced by the total inflow and the direct epilimnion inflow. When the total inflow and the direct epilimnion inflow are small, the value of $R_{e2}$ increases and vice versa. Usually it is small during spring months and increases during summer months.

Phosphorus loading

Seasonal phosphorus loading which was brought to the reservoir by the Malše River during April to September periods of 1984 to 1991 is summarized in Table 2. Total phosphorus input (TP$_{i}$) varied in the range between 5.7 and 14.6 t. Most of the variations were caused by particulate phosphorus input (PP$_{i}$) that was highly flow-dependent and ranged from 2.5 t in dry 1984 season to 10.2 t in wet 1987 season.

<table>
<thead>
<tr>
<th>Year</th>
<th>TP$_{i}$ [t]</th>
<th>TDP$_{1}$ [t]</th>
<th>PP$_{i}$ [t]</th>
<th>TDP$_{s1}$ [t]</th>
<th>TDP$_{s2}$ [t]</th>
<th>Q$_{i}$ [m$^3$.s$^{-1}$]</th>
<th>CHLA [µg.l$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>5.7</td>
<td>3.2</td>
<td>2.5</td>
<td>0.74</td>
<td>0.53</td>
<td>2.80</td>
<td>17.2</td>
</tr>
<tr>
<td>1985</td>
<td>10.5</td>
<td>4.0</td>
<td>6.5</td>
<td>0.95</td>
<td>0.47</td>
<td>4.61</td>
<td>13.5</td>
</tr>
<tr>
<td>1986</td>
<td>6.7</td>
<td>3.6</td>
<td>3.1</td>
<td>1.63</td>
<td>0.42</td>
<td>3.15</td>
<td>19.2</td>
</tr>
<tr>
<td>1987</td>
<td>14.6</td>
<td>4.4</td>
<td>10.2</td>
<td>1.34</td>
<td>0.49</td>
<td>5.78</td>
<td>11.4</td>
</tr>
<tr>
<td>1988</td>
<td>12.2</td>
<td>4.0</td>
<td>8.2</td>
<td>0.89</td>
<td>0.97</td>
<td>4.67</td>
<td>26.4</td>
</tr>
<tr>
<td>1989</td>
<td>7.6</td>
<td>3.7</td>
<td>3.9</td>
<td>1.3</td>
<td>0.48</td>
<td>3.59</td>
<td>11.1</td>
</tr>
<tr>
<td>1990</td>
<td>6.4</td>
<td>3.5</td>
<td>2.9</td>
<td>0.97</td>
<td>0.67</td>
<td>2.57</td>
<td>28.2</td>
</tr>
<tr>
<td>1991</td>
<td>12.9</td>
<td>3.9</td>
<td>9.0</td>
<td>0.97</td>
<td>0.55</td>
<td>4.11</td>
<td>14.3</td>
</tr>
<tr>
<td>Average</td>
<td>9.6</td>
<td>3.8</td>
<td>5.8</td>
<td>1.11</td>
<td>0.57</td>
<td>3.91</td>
<td>17.7</td>
</tr>
</tbody>
</table>
Total dissolved phosphorus load (TDP) fluctuated less within the range between 3.2 and 4.4 t. TDP in the Malše River originated predominantly from point sources. The sewage treatment plant of the town of Kaplice was the source of about 50% of TDP, 25% of TDP came from small point sources, and only about 25% were estimated to originate from agricultural and forested area of the Malše basin (Hejzlar, unpublished). The predominant point-source origin of TDP is demonstrated by the negative relationship between its concentration and the river discharge (Figure 3A). Unlike TDP, PP originated mostly from erosion processes in the basin and the dependence of its concentration on river discharge was positive (Figure 3B).

Most of the PP load cannot be utilized in the reservoir by phytoplankton even when inflow intrudes surface layers because it is rapidly removed from the water column by sedimentation. Table 3 presents the results of PP settling velocity measurements during three different discharge situations. During the storm flow event on June 6, 1988, 72% of PP had settling velocities faster than 10 m.d$^{-1}$ and 80% faster than 1 m.d$^{-1}$. The character of the PP particles was predominantly inorganic. Because the shortest observed throughflow times of inflow to the dam are longer than 6 days (Hejzlar, 1989), most of this PP had to deposit at the headwaters of the reservoir. It corresponds with the finding of Porcalová (1990) who measured more than ten times higher phosphorus sedimentation rates at the sampling site situated 1.5 km from the upper reach of the reservoir than at the dam. During the periods of lower discharge the fraction of slowly sedimenting PP increases and the character of PP-containing particles is more organic due to algal growth in the shallow and slowly flowing river water (Vyhndel et al., in press). However, their concentrations are in absolute values significantly lower than that of TDP which increase during periods of low discharge. For this study this fraction of PP was considered unimportant taking into account the uncertainty of TDP estimation which may be of about ±20% or more for this size of river and intervals of sampling (Walling and Webb, 1982).

The biologically relevant P-load calculated as the sum of TDP loading due to the inflow epilimnion intrusions (TDP$_{in}$) and due to the surface discharges (TDP$_{de}$) ranged between 1.27 and 2.05 t which is

### Table 3: Distribution of Settling Velocities ($u_{pp}$) of Particulate Phosphorus* in the Malše River

<table>
<thead>
<tr>
<th>Date</th>
<th>Discharge [m$^3$.s$^{-1}$]</th>
<th>$u_{pp}$ [m.d$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-0.1</td>
<td>0.1-1</td>
</tr>
<tr>
<td>June 6, 1988</td>
<td>14.3</td>
<td>10(2)</td>
</tr>
<tr>
<td>May 13, 1991</td>
<td>6.7</td>
<td>15(19)</td>
</tr>
<tr>
<td>April 29, 1991</td>
<td>2.5</td>
<td>30(51)</td>
</tr>
</tbody>
</table>

* in μg.l$^{-1}$; percentage in parentheses
12% and 31% of the TP input or 36% and 57% of the TDP input. These values indicate that only a relatively small and variable fraction of the total phosphorus input may be available for phytoplankton growth in the reservoir in different years. This conclusion can be made in spite of the fact that TDP$_{ie1}$ and TDP$_{ie2}$ may not exactly represent all phosphorus fluxes in the reservoir.

The other processes by which phosphorus can be supplied to the epilimnion are, for example, the entrainment of the inflow to the epilimnion at the plunge point where river water, in the case of interflow, sinks beneath the water surface, or the entrainment of metalimnion water to the epilimnion due to mixing by wind (Ford, 1990). The entrainment at the plunge point would apparently increase TDP$_{ie1}$. Its estimates vary from less than 10% to over 100% in some reservoirs (Ford, 1990). In Rímov Reservoir it is probably usually of lesser importance (up to about 10 to 20%); this view is based on the observed mixing patterns during periods when the composition of the inflowing river water differed from the composition of the reservoir water masses (Hejzlar, 1989).

Wind mixing acts together with the effect of discharging from surface. During periods of weather cooling, when the epilimnion deepens, it can provide a considerable flux of phosphorus from the metalimnion into the euphotic layer. It may also modify the longitudinal distribution of TDP$_{ie1}$ and TDP$_{ie2}$ along the reservoir due to epilimnion circulation and is probably the main reason for the decrease of phosphorus concentration in the metalimnion between the inflow part of the reservoir and the dam (Hejzlar, 1989; Vyhňalek et al., in press). These processes, however, could not significantly bias the calculated values of epilimnion phosphorus loading because they function together with the processes that were considered.

**Phytoplankton Response**

The significance of relationships between the average seasonal chlorophyll $a$ concentration at the dam and the seasonal phosphorus loads or other variables (inflow discharge, air temperature, coefficients $R_1$ or $R_2$) was tested by linear correlation analysis. The only significant dependence was obtained for TDP$_{ie2}$ ($n=8$, $R=0.78$, probability level=0.022) (Fig. 4A). It indicates that about 60% of the variability ($R^2=0.61$) of the chlorophyll $a$ concentration at the dam can be explained by the variation of phosphorus epilimnion loading due to surface discharging. The rest of the variability may be caused by other processes by which phosphorus is transported into the euphotic zone (e.g. direct inflow epilimnion intrusions or wind mixing), or by various biological processes influencing phytoplankton concentration (e.g. grazing by zooplankton or inter-seasonal differences in the phytoplankton community structure). The high average seasonal concentration of chlorophyll $a$ in 1986, 1988 and 1990 were caused by summer dominance of cyanobacteria, especially *Aphanizomenon flos-aquae* and *Microcystis aeruginosa*, which are less prone to sedimentation due to their buoyancy, and can accumulate in the epilimnion in high concentrations. Colonial green algae and diatoms dominated in summer phytoplankton communities of the other years with less distinct summer maximum of chlorophyll $a$ concentration.

![Fig. 4. Relationships between average seasonal chlorophyll $a$ concentration (CHLA) and seasonal TDP epilimnion loading due to surface discharges (TDP$_{ie2}$) (A), and seasonal TDP epilimnion loading due to direct inflow intrusions (TDP$_{ie1}$) (B).](https://iwaponline.com/wst/article-pdf/28/6/5/103509/5.pdf)
In contrast, the relationship between TDP\textsubscript{ie1} and the average seasonal chlorophyll \textit{a} concentration at the dam was negative but not significant (n=8, R=-0.29, probability level=0.484) (Fig. 4B). The reason is probably in the existence of a gradient in phytoplankton and phosphorus concentrations along the reservoir. Phosphorus loading which enters the euphotic layer in the headwater part of the reservoir is rapidly incorporated into phytoplankton. However, most of these phytoplankton cells do not reach the dam (especially in summer months) because the transport of epilimnion water masses from the headwaters to the dam is slow (in weeks) as it takes place usually only due to the surface discharges and due to the inflow epilimnion intrusions. The phytoplankton cells are removed on their way along the reservoir from the surface layer by sedimentation and zooplankton grazing. As a result, the increase of chlorophyll \textit{a} concentration at the dam after the input of phosphorus to the the epilimnion in the headwaters is usually small, variable and temporally shifted. This situation applies especially for the summer months; during the spring overflow period the transport of phytoplankton cells from the inflow to the dam can last only several days (Vyhnálek \textit{et al.}, in press). However, because the spring maximum of phytoplankton biomass is short (usually 1-2 weeks), the seasonal average chlorophyll \textit{a} concentration is determined primarily by the summer values of chlorophyll \textit{a} concentration.

\textbf{Role of Wind-Induced Mixing}

Rapid transport may occur due to the long-term action of southern winds which can create whole-epilimnion circulation with the transport times from the inflow part of the reservoir to the dam of order of several days. The transport of this type was recognized several times during the examined years by the sudden increase of phytoplankton concentration at the dam without a previous increase of TDP\textsubscript{ie2} loading but preceding by several days lasting southern winds and by input of TDP\textsubscript{ie1}. During the period from June 16 to June 21, 1986 (Fig. 5) a southern wind acted synchronously with the epilimnion inflow intrusion. It resulted in fast distribution of TDP\textsubscript{ie1} loading along the whole reservoir and rapid growth of the diatom, \textit{Asterionella formosa}, forming a sharp maximum at the dam on June 20 (Vyhnálek, 1989). A similar increase of phytoplankton concentration was noticed at the dam after a long period of southern wind in July 1988 when the transport of TDP\textsubscript{ie1} loading from the headwaters of the reservoir probably caused massive blooming of the cyanobacterium, \textit{Aphanizomenon flos-aquae}.

![Graph A](https://iwaponline.com/wst/article-pdf/28/6/5/103509/5.pdf)

![Graph B](https://iwaponline.com/wst/article-pdf/28/6/5/103509/5.pdf)

Fig. 5. Chlorophyll \textit{a} concentration, TDP\textsubscript{ie1} and TDP\textsubscript{ie2} loads (A) and wind speed (B) during June 1 to July 15, 1986. Negative or positive values of wind speed represent southern or northern components of the wind vector.

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CONCLUSIONS

The study indicated that only a relatively small fraction of the external P-load was biologically relevant in Řimov Reservoir during 1984 to 1991. Particulate phosphorus in the inflowing river water was shown to be rapidly lost from the water column by sedimentation. Dissolved phosphorus was available for phytoplankton growth only partly because some inflow was short-circuited through the meta- and hypolimnion due to temperature-density currents and operation of deep outlets. The particulate phosphorus load and the dissolved phosphorus load comprised on average 43% and 57% of the external phosphorus load, respectively. From the dissolved phosphorus load only 44% entered the epilimnion due to direct inflow intrusions and due to the entrainment of metalimnion water caused by surface discharges from the reservoir.

The average seasonal concentration of chlorophyll $a$ at the dam was positively correlated with the dissolved phosphorus epilimnion load caused by surface discharges ($R^2=0.61$, probability level=0.022). The total dissolved phosphorus epilimnion load due to direct inflow intrusions influenced chlorophyll $a$ concentration at the dam only exceptionally in case of simultaneous acting of long-lasting winds in the direction along the longitudinal reservoir axis.

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