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SEASONAL CHANGES IN TOTAL PHOSPHORUS AND DISSOLVED INORGANIC PHOSPHATE IN FOUR SMALL ESTONIAN LAKES

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Abstract. The seasonality and variability of total phosphorus and dissolved inorganic phosphate concentrations in four small Estonian lakes of different trophy are discussed. In thermally stratified lakes the total surface phosphorus content decreased from spring through summer. Later phosphorus concentrations increased when nutrient-rich water from the hypolimnion (anoxic) was transported to surface water during periods of mixing. The seasonal pattern of dissolved inorganic phosphate for mesotrophic lakes was considerably less distinct (low values were frequent throughout the annual cycle). In the hypertrophic L. Kriimani the seasonal patterns of dissolved inorganic phosphorus and total phosphorus were found to be similar.

Key words: lakes, total phosphorus, dissolved inorganic phosphate, seasonal changes, Estonia.

INTRODUCTION

Most freshwater ecosystems are limited by phosphorus (OECD, 1982). Therefore, great emphasis has been placed on the content of phosphorus compounds in water. Temporal variation in total phosphorus content has been reported for lakes in North America (Chapra & Tarapchak, 1976), Sweden (Ryding, 1981), Poland (Zdanowski, 1982), Canada (Prepas & Trew, 1983), as well for L. Peipsi (Lindpere et al., 1990b). Seasonal variation in the total phosphorus concentration of surface water is quite low in many North American lakes (Chapra & Tarapchak, 1976). However, in West Canadian lakes, seasonal total phosphorus content can vary even four-fold in some lakes (Prepas & Vickery, 1984).

No studies of the seasonal variation of phosphorus compounds in small Estonian lakes have so far been conducted. The aim of this study was to follow the seasonality of total phosphorus and dissolved inorganic phosphate concentrations in lakes of different trophic state. Changes in total phosphorus and dissolved inorganic phosphate in the surface and near-bottom water layers were established by observations carried out during characteristic phenological periods: in spring and autumn circulation and in summer and winter stagnation.

THE LAKES STUDIED

Studies were conducted on four Estonian lakes: Nohipalu Valgjärv, Saadjärv, Lavatsi, and Kriimani. Nohipalu Valgjärv is located in Põlva County, the other three, in Tartu County. The lakes differ in their morphometric characters and in the main trophic parameters (Table 1). The mesotrophic Nohipalu Valgjärv has the highest water transparency, low chlorophyll *a* (Chl) concentration, and relatively small oxygen losses in the hypolimnion during stagnation. Oxygen deficit (O_2 below 1%) occurred in late summer and was confined to near-bottom water layers (Fig. 1). The deepest lake, Saadjärv, is mainly mesotrophic. Oxygen deficit occurs in the

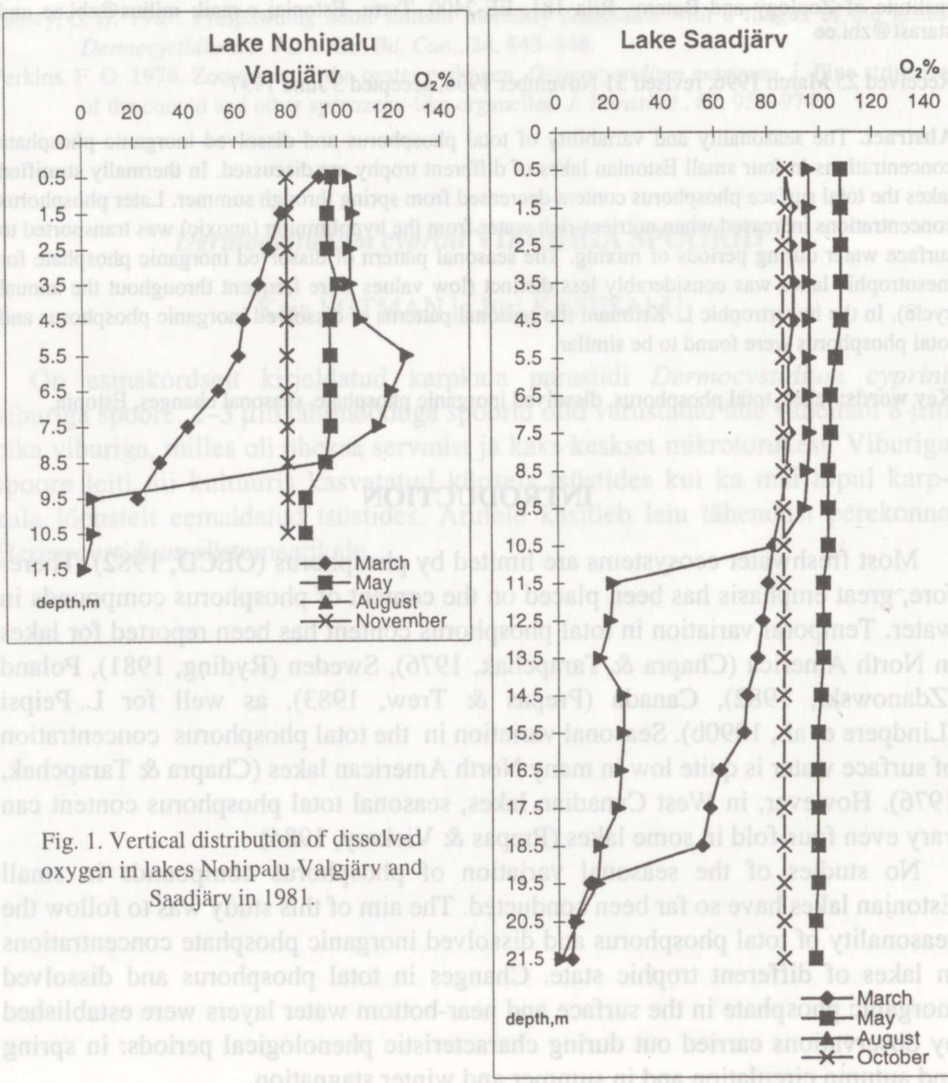


Fig. 1. Vertical distribution of dissolved oxygen in lakes Nohipalu Valgjärv and Saadjärv in 1981.

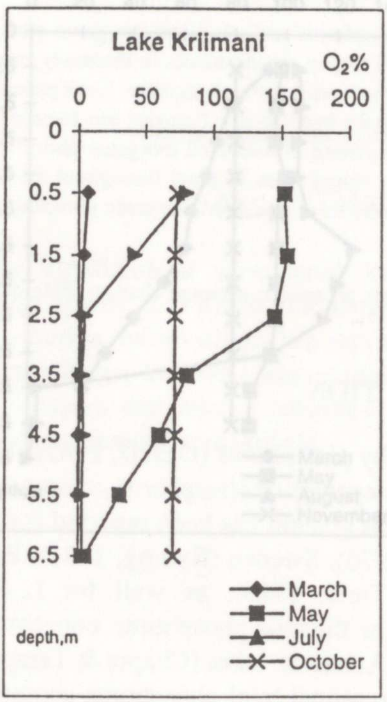
Table 1

Morphometric features* and general trophic parameters (mean of ANOVA ± SE) of the lakes studied during 1978–86

Lake (Years)	Surface area, ha	Depth, m		Volume, $\times 10^3$ m^3	TP, mg P m^{-3}	PO_4, mg P m^{-3}	Water transparency, m	Chlorophyll *a*, mg m^{-3}
		max	mean					
Nohipalu Valgjärv (1978–83)	6.3	12.5	6.2	391	14.1 ± 0.7	0.9 ± 0.2	6.6 ± 0.3	2.1 ± 0.2
Saadjärv (1978–86)	707.6	25.0	8.0	56608	17.7 ± 0.8	2.3 ± 0.2	4.3 ± 0.1	3.8 ± 0.3
Lavatsi (1978; 1980–86)	5.8	14.0	6.9	400	29.2 ± 1.2	4.5 ± 0.6	2.2 ± 0.1	9.4 ± 0.7
Kriimani (1978; 1980–86)	6.5	7.9	3.4	221	101.3 ± 4.4	16.1 ± 3.2	1.0 ± 0.13	31.3 ± 2.3

* After Kask, 1964.

hypolimnion (deeper than 10 m) from July to mid-September (Fig. 1). The rate of oxygen consumption during summer stratification is 0.11 mg l^{-1} per day (Lindpere et al., 1990a). In winter, oxygen losses are not so heavy. Lake Lavatsi is eutrophic and generally dimictic, although vernal mixing may be incomplete in some years. Oxygen deficit, starting already from 6 m, occurs from July to September or to early October (Fig. 2). Lake Kriimani is a shallow hypertrophic waterbody. This lake is undergoing severe eutrophication caused mainly by the nutrient load from a point pollution source (a farm near the shore). Oxygen deficit in the hypolimnion occurs as early as the end of May, the rate of oxygen consumption during summer stratification is 1.15 mg l^{-1} per day. During the winters of the study period progressive development of anoxia beneath the ice was observed: the entire water column was anoxic (Fig. 2). Oxic conditions normalized only after the ice had melted.



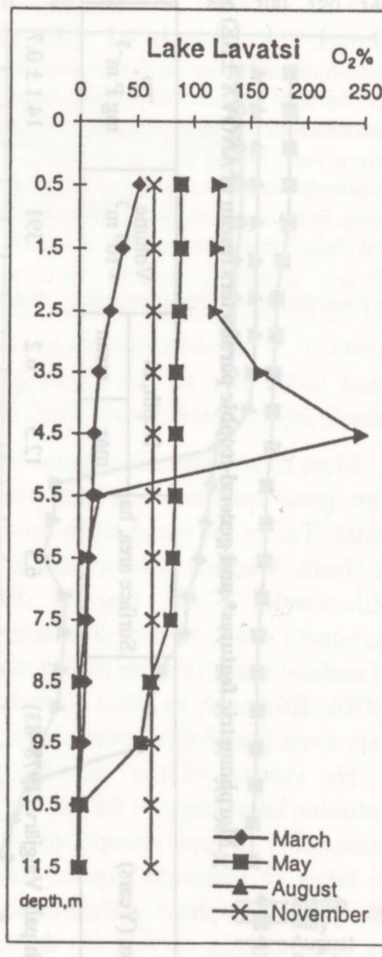


Fig. 2. Vertical distribution of dissolved oxygen in lakes Kriimani and Lavatsi in 1981.

MATERIAL AND METHODS

Investigations were carried out during 1978–86 (Table 1). In most years (except 1981–82) observations were performed after ice-out until late August or early September. In 1981 and 1982 the lakes were sampled monthly (except for April and December when the ice-cover was weak). In May sampling was performed at shorter intervals. Water samples were collected, using a Ruttner bathometer, from a deep-water site on each lake. The samples were taken from 0.5 m below surface and from about 0.5 m above bottom.

Of various forms of phosphorus occurring in lake water, only two forms, i.e. dissolved inorganic phosphate (PO_4) and total phosphorus (TP), were determined. Their concentrations were determined by the method of Koroleff (1983). TP was determined after digesting the water sample with potassium persulphate. The blue phosphomolybdic complex was measured with a spectrophotometer. The PO_4 content was determined directly spectrophotometrically by the molybdene blue method.

Table 1 shows the main trophic parameters of surface waters of the studied lakes. Data in the table represent mean values from May to August of the period under study, calculated from the analysis of variance (ANOVA). The effect of the lake and the effect of the observation year and month were taken into account as factors. ANOVA was selected since it enables to compare data collected in different years.

RESULTS

Total phosphorus and dissolved inorganic phosphate in surface water

Low mean concentrations of TP (< 20 mg P m^{-3}) and PO_4 (< 2.5 mg P m^{-3}) were recorded in lakes of a low trophic state: in mesotrophic Nohipalu Valgjärv and Saadjärv (Table 1). The TP content increased with the increasing trophic state: it was higher in the eutrophic Lake Lavatsi (29.2 mg P m^{-3}) than in the above-mentioned mesotrophic lakes. High concentrations of TP (>100 mg P m^{-3}) and PO_4 (>15 mg P m^{-3}) were observed in the hypertrophic Lake Kriimani. An increase in the trophic state of the lakes under study was accompanied by a steady increase in Chl content and a decrease in water transparency.

Table 2 gives a monthly survey of TP and PO_4 content over the whole investigation period of 1978–86. The amount of TP in the surface water of the lakes varied considerably during the observation period. In the mesotrophic lakes of Nohipalu Valgjärv and Saadjärv it varied in a broad range: from 5 to 77 mg P m^{-3}. In the eutrophic Lake Lavatsi, the variability in TP was high too (10–129 mg P m^{-3}). In the hypertrophic Lake Kriimani the range of TP variation was 52–415 mg P m^{-3}.

Table 2

Total phosphorus and dissolved inorganic phosphate concentration (mg P m^{-3}) in surface waters of the lakes of Nohipalu Valgjärv, Saadjärv, Lavatsi, and Kriimani during 1978–86 (above min–max; below mean ± SE; *n*)

Month	Nohipalu Valgjärv		Saadjärv		Lavatsi		Kriimani	
	TP	PO_4	TP	PO_4	TP	PO_4	TP	PO_4
I	23–30 26.5 ± 3.5; 2	0.5–0.9 0.7 ± 0.2; 2	22–30 26.0 ± 4.0; 2	0.5–11 0.8 ± 0.3; 2	26–45 35.5 ± 9.5; 2	4.0–5.9 5.0 ± 0.9; 2	210–267 238.5 ± 28.6; 2	89–238 163.5 ± 74.7; 2
II	6–11 9.0 ± 1.5; 3	0–1.4 0.5 ± 0.5; 3	5–38 15.8 ± 6.1; 5	1.1–3.2 2.0 ± 0.3; 6	13–129 52.0 ± 38.5; 3	4.1–6.4 5.2 ± 1.1; 2	165–315 226.0 ± 45.6; 3	74–300 172.6 ± 66.8; 3
III	10–38 23.3 ± 5.8; 4	0.7–3.2 2.0 ± 0.5; 4	24–77 46.0 ± 16.0; 3	2.2–5.5 2.8 ± 0.6; 6	44–63 53.5 ± 9.5; 2	5.6–9.9 7.8 ± 2.1; 2	210–415 312.5 ± 102.8; 2	107–334 220.5 ± 113.8; 2
IV	34	1.9	n.d.	3.8	53	13.3	213	88.5
V	8–75 27.0 ± 12.3; 5	1.0–11.7 3.2 ± 1.5; 7	7–68 37.2 ± 9.2; 6	1.3–8.5 3.4 ± 0.7; 8	22–109 52.3 ± 9.2; 12	1.3–94.4 12.0 ± 6.9; 13	52–267 135.5 ± 20.6; 11	3.8–201 41.4 ± 16.2; 12
VI	12–23 18.7 ± 3.4; 3	0–2.6 1.0 ± 0.4; 6	12–40 28.8 ± 7.1; 4	0.8–4.2 1.8 ± 0.5; 6	33–50 42.2 ± 3.5; 5	1.1–10.3 5.6 ± 1.6; 6	76–88 82.0 ± 6.0; 2	1.3–19.3 8.1 ± 5.7; 3
VII	6–39 18.8 ± 7.4; 4	0–3.2 1.8 ± 0.5; 7	10–43 23.2 ± 5.8; 5	1.3–4.9 2.6 ± 0.5; 6	27–45 38.0 ± 4.0; 4	2.6–13.1 7.1 ± 1.8; 6	79–202 132.0 ± 26.2; 4	3.2–75.3 33.6 ± 13.2; 6
VIII	10–18 15.3 ± 1.8; 4	0–3.2 1.7 ± 0.5; 7	18–36 22.3 ± 4.6; 4	1.9–4.6 3.2 ± 0.3; 6	21–45 32.7 ± 6.9; 3	1.9–13.8 6.6 ± 2.7; 4	54–114 91.0 ± 18.7; 3	3.2–64 22.3 ± 14.1; 4
IX	12–23 18.7 ± 3.4; 3	1.3–2.3 2.1 ± 0.5; 5	37–42 39.5 ± 2.5; 2	1.6–3.8 2.7 ± 0.4; 5	49–57 52.8 ± 3.8; 2	1.9–19.2 10.4 ± 5.0; 3	177–179 178.5 ± 1.0; 2	3.2–130 58.3 ± 38.8; 3
X	21–32 26.5 ± 5.5; 2	0.4–2.6 1.6 ± 0.5; 5	8–34 25.3 ± 8.7; 3	1.6–4.2 3.7 ± 0.7; 5	10–65 37.5 ± 27.6; 2	2.6–6.2 4.9 ± 1.2; 3	213–300 247.7 ± 26.6; 3	13.7–25 19.1 ± 3.3; 3
XI	20–30 25.0 ± 5.0; 2	0.3–2.6 1.7 ± 0.5; 4	29–35 31.0 ± 2.0; 3	1.3–1.9 1.7 ± 0.1; 5	18–76 47.0 ± 29.1; 2	5.9–8.7 7.2 ± 0.8; 3	200–370 260.3 ± 54.9; 3	58.7–173 108.6 ± 33.8; 3
XII	18	2.8	35	2.0	34	4.7	271	230

n.d. = not determined.

Annual seasonal variation in TP and PO_4 concentrations of the surface water of the lakes is shown in Figs. 3 and 4 for two years, 1981 and 1982. The concentration of TP showed a clearly downward trend over the studied two-year cycle (at the probability level $p = 0.12$ for L. Saadjärv, 0.0004 for L. Lavatsi, and 0.0015 for L. Kriimani). A similar decreasing trend in TP concentration was well revealed ($p = 0.002$) in our data on the surface water of 95 lakes studied during 1978–90 (Milius et al., 1991).

In winter the amount of TP increased under the ice and reached a maximum in the lakes in late winter. After ice-out, the lakes are thoroughly mixed (except for L. Lavatsi where vernal mixing was incomplete, see Fig. 2), and the same or higher TP level was observed in spring. Data from 1982 (sampling was performed earlier, in late April immediately after ice-break) show that the amount of TP in surface water was higher in spring than in late winter. This is undoubtedly caused by the fact that during spring circulation surface waters of stratified lakes are enriched with phosphorus compounds that have accumulated in the hypolimnion during winter. However, in May the amount of TP in the surface water of the lakes decreased rapidly in both years, as illustrated in Figs. 3 and 4 with data from L. Lavatsi and L. Kriimani. During summer stratification a clear lowering of the TP level occurs, which continues until the lowest level in August or September. However, sometimes, especially in 1982, the TP concentration fluctuated in the surface water. The increase of the TP content in September–October was pronounced at autumn circulation when anaerobic hypolimnetic water with a high TP concentration was mixed into the upper layers.

Seasonality of PO_4 was poorly revealed in the surface water of lakes with a low trophic state, Nohipalu Valgjärv and Saadjärv, since its concentration was always low (<5 mg P m^{-3}). In the eutrophic L. Lavatsi the PO_4 concentrations were considerably higher than in the mesotrophic lakes. A particularly high concentration (94 mg P m^{-3}) was observed in early May 1981 after which it decreased rapidly to 4 mg P m^{-3} in late May (Fig. 3). The PO_4 content and its variation was the highest in the hypertrophic L. Kriimani where it followed a seasonal pattern similar to that of TP. This is confirmed by a significant relationship between TP and PO_4 in 1981–82 ($r = 0.78$). The content of PO_4 was only slightly lower than TP in the winter stagnation period but considerably lower in the summer stagnation period. Thus, in winter the dissolved inorganic fraction prevails, while in summer the predominating form is organic phosphorus.

Total phosphorus and dissolved inorganic phosphate in the near-bottom water

The differentation of lakes with respect to the concentration of phosphorus compounds in the near-bottom water was consistent with the trophic character of the lakes. The lowest TP and PO_4 concentrations were observed in the mesotrophic lakes of Nohipalu Valgjärv and Saadjärv, whereas the highest concentrations occurred in the hypertrophic L. Kriimani.

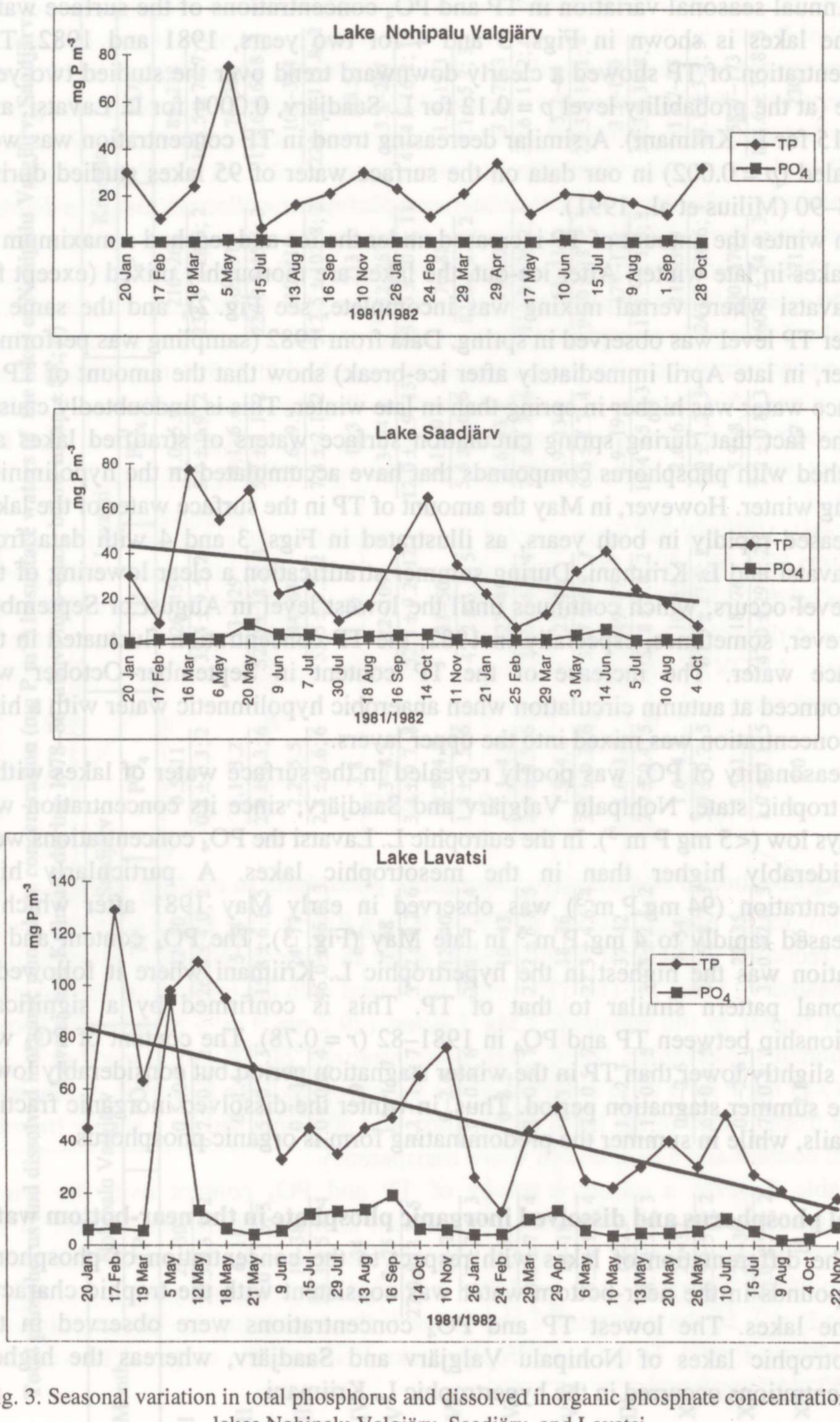


Fig. 3. Seasonal variation in total phosphorus and dissolved inorganic phosphate concentrations in lakes Nohipalu Valgjärv, Saadjärv, and Lavatsi.

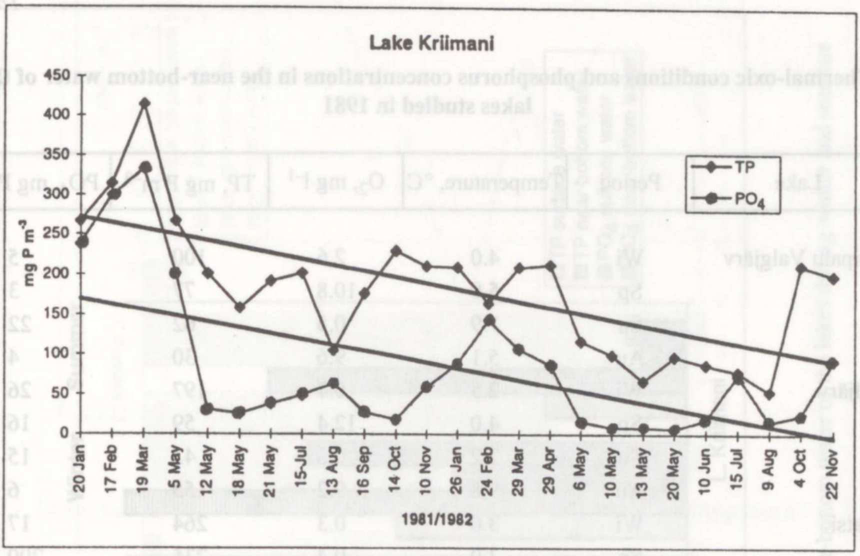


Fig. 4. Seasonal variation in total phosphorus and dissolved inorganic phosphate concentrations in L. Kriimani.

Table 3 presents thermal-oxic conditions and phosphorus concentrations in the near-bottom water of the studied lakes during spring and autumn circulation, and in periods of winter and summer stagnation. Figures 5 and 6 depict TP and PO_4 concentrations in the surface and near-bottom water during the stagnation and circulation periods. In both periods of stagnation anaerobic conditions ($O_2 < 1$ mg l^{-1}) prevailed in the near-bottom layers.

A significant accumulation of TP was found in the hypolimnion in all the studied lakes during the stagnation periods. The TP content showed a clearly increasing tendency in the near-bottom water during the winter stagnation period. The highest TP content was observed at the end of winter. During the summer stagnation period such an increasing tendency in TP concentrations was not clearly revealed. During some months the TP content decreased after which it increased again. Still, it was the highest at the end of the summer stagnation period. This phenomenon is caused by the low level of O_2 in the hypolimnetic water of the lakes (Table 3). It is well known that lake sediments release large amounts of phosphorus in anaerobic conditions. Although the mechanism of this process is not analysed in this study, the sedimentation of P-containing detritus and its subsequent resuspension in anaerobic conditions during the stagnation periods are supposed to be the major cause of such P accumulation. In both

Table 3

Thermal-oxic conditions and phosphorus concentrations in the near-bottom water of the lakes studied in 1981

Lake	Period	Temperature, °C	O_2, mg l^{-1}	TP, mg P m^{-3}	PO_4, mg P m^{-3}
Nohipalu Valgjärv	Wi	4.0	2.6	100	5
	Sp	5.0	10.8	77	3
	Su	7.9	0.5	62	22
	Au	5.1	9.6	30	4
Saadjärv	Wi	2.5	0.7	197	26
	Sp	4.0	12.4	59	16
	Su	7.2	0.8	43	15
	Au	9.8	9.2	55	6
Lavatsi	Wi	3.0	0.3	264	17
	Sp	3.0	0.4	235	200
	Su	4.0	0.6	202	32
	Au	4.5	8.2	80	8
Kriimani	Wi	4.0	0	800	540
	Sp	5.0	15.6	273	249
	Su	7.2	0.3	597	86
	Au	7.8	8.3	273	21

Wi, winter stagnation (March); Sp, spring circulation (May); Su, summer stagnation (July–August); Au, autumn circulation (October–November).

periods of circulation the O_2 concentration in the near-bottom water was high (8.2–15.6 mg l^{-1}). In spring the O_2 content was higher (10.8–15.6 mg l^{-1}) than in autumn (8.2–9.6 mg l^{-1}, Table 3). In general, during the autumn circulation period the temperature was higher than in spring. During the circulation periods the lakes are mixed thoroughly and nutrient-rich water from the hypolimnion is mixed with relatively dilute water from the epilimnion, making the P level uniform in the whole water column (Fig. 6).

It is evident from Fig. 7 that PO_4 levels increased rapidly over sediments in the near-bottom layer in case a severe O_2 deficit developed during stratified periods and, vice versa, the PO_4 content was at a very low level when the O_2 content was high.

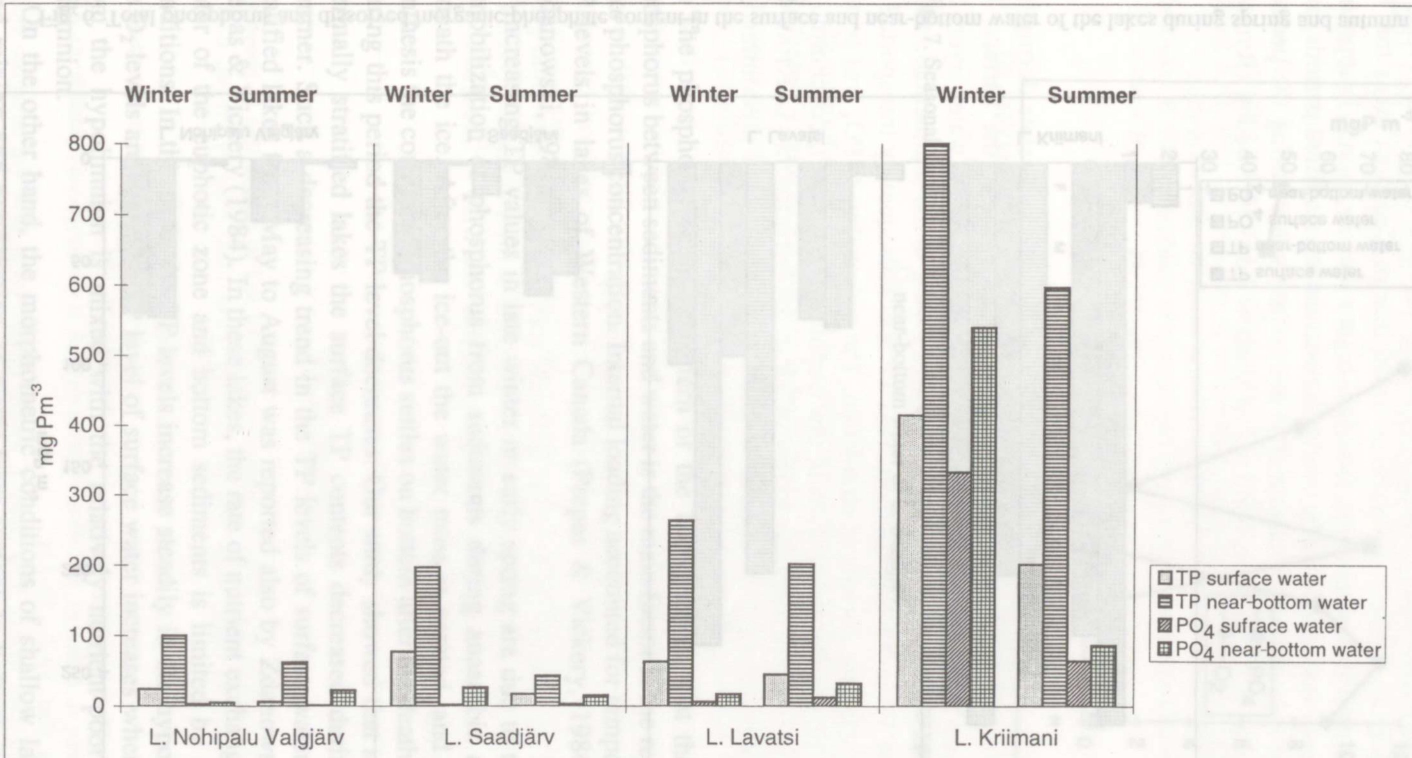


Fig. 5. Total phosphorus and dissolved inorganic phosphate content in the surface and near-bottom water of the lakes during winter and summer stagnation in 1981.

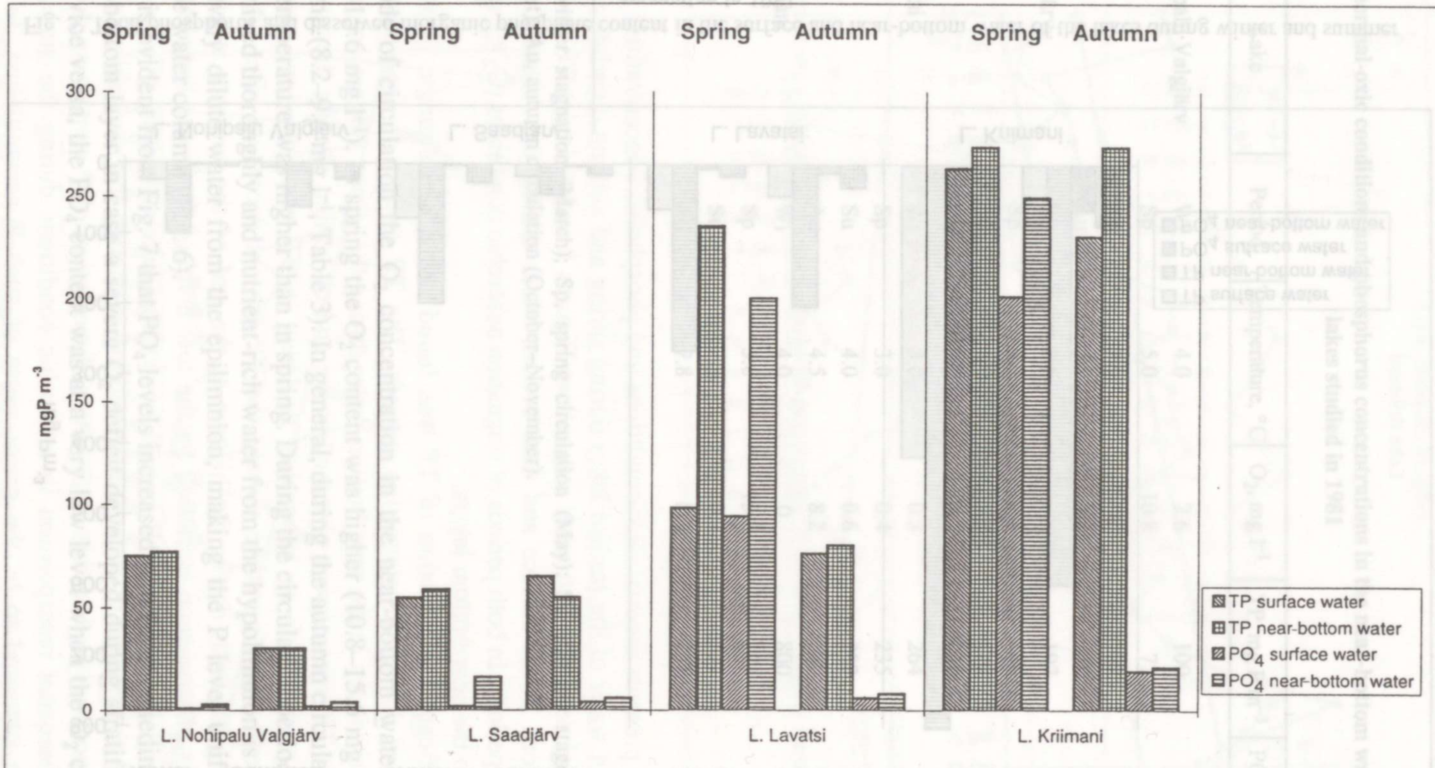


Fig. 6. Total phosphorus and dissolved inorganic phosphate content in the surface and near-bottom water of the lakes during spring and autumn circulation in 1981.

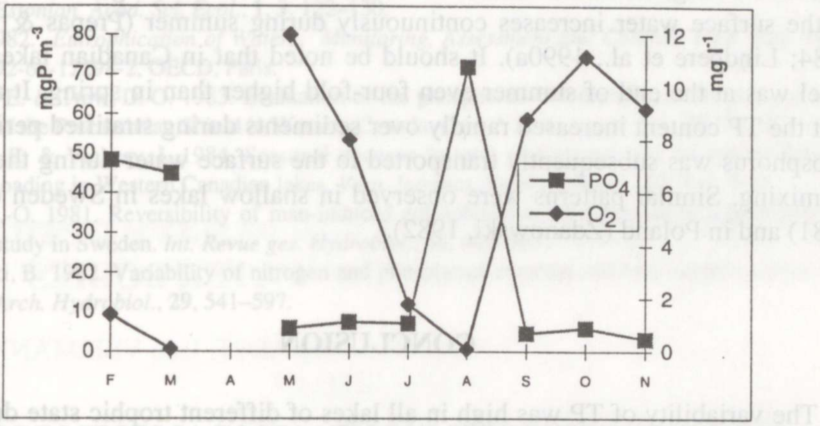


Fig. 7. Seasonal variation in dissolved inorganic phosphate and dissolved oxygen content in the near-bottom water of L. Saadjärv.

DISCUSSION

The phosphorus variation pattern of the lakes reveals that the recycling of phosphorus between sediments and water is the main factor in the regulation of the lake phosphorus concentration. Internal loading accounted for temporal changes in TP levels in lakes of Western Canada (Prepas & Vickery, 1984) and Poland (Zdanowski, 1982).

Increasing TP values in late winter or early spring are due to the continuous remobilization of phosphorus from sediments during anaerobic decomposition beneath the ice. After the ice-out the water mass is aerated, and during photosynthesis the consumed phosphorus settles on bottom after the death of organisms. During this period the TP level decreases. Our study showed that in permanently thermally stratified lakes the surface TP contents decreased during spring and summer. Such a decreasing trend in the TP levels of surface waters of deep and stratified lakes from May to August was reported also by Zdanowski (1982) and Prepas & Vickery (1984). In these lakes, the rate of nutrient exchange between the water of the euphotic zone and bottom sediments is limited by morphometric conditions. In this case, the TP levels increase steadily in the hypolimnion when the O_2 levels are low. The TP level of surface water increases when P-rich water from the hypolimnion is mixed with the relatively nutrient-poor water of the epilimnion.

On the other hand, the morphometric conditions of shallow lakes favouring good mixing and oxygenation of water from surface to bottom, contribute to a high rate of organic matter mineralization and nutrient exchange. The TP content in the surface water increases continuously during summer (Prepas & Vickery, 1984; Lindpere et al., 1990a). It should be noted that in Canadian lakes the TP level was at the end of summer even four-fold higher than in spring. It appeared that the TP content increased rapidly over sediments during stratified periods, and phosphorus was subsequently transported to the surface water during the periods of mixing. Similar patterns were observed in shallow lakes in Sweden (Ryding, 1981) and in Poland (Zdanowski, 1982).

CONCLUSION

The variability of TP was high in all lakes of different trophic state during the whole annual cycle. In permanently thermally stratified lakes the surface TP content decreased through spring and summer. In the near-bottom water layers (in anoxic conditions) the TP concentration increased owing to the sedimentation and accumulation of TP in the hypolimnion. This TP was subsequently transported to surface water during the periods of circulation. The seasonality of PO_4 was poorly revealed in the surface waters of lakes of low trophic state. The PO_4 concentration followed a seasonal pattern similar to that of TP in the hypertrophic L. Kriimani. In winter PO_4 prevails, while in summer organic phosphorus is the predominating form.

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ÜLDFOSFORI JA FOSFAATIOONI SESOONSED MUUTUSED NELJAS EESTI VÄIKEJÄRVES

Anu MILIUS ja Henno STARAST

On uuritud üldfosfori (TP) ja fosfaatiooni (PO_4) sesoonset dünaamikat mesotroofsetes Nohipalu Valgjärves ja Saadjärves, eutroofses Lavatsi ja hüpertroofses Kriimani järves. Kõigi järvede pindmises veekihis oli TP aastaringne varieeruvus suur. Termiliselt stratifitseerunud järvedes väheneb TP sisaldus kevade ja suve jooksul ning suurenes tsirkulatsiooniperioodidel, kui toitaineterikas vesi kandus hapnikuvaesest hüpolimnionist ringlusse. TP ja PO_4 sisalduse aastaringsed muutused olid erinevad, vaid suurima troofsusega Kriimani järve PO_4 ja TP kontsentratsioonid korreleerusid (r = 0,78). Madala troofsusega Nohipalu Valgjärve ja Saadjärve PO_4 dünaamikas ei täheldatud suuri muutusi. Talvel domineeris fosfaatne, suvel orgaaniline fosfor. Põhjalähedase veekihi TP ja PO_4 sisalduse muutusi jälgiti tsirkulatsiooni- ja stagnatsiooniperioodidel.