

## Phosphorus flux in Lake Peipsi *sensu stricto*, Eastern Europe

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**Abstract.** Phosphorus distribution in sediments and monitoring data from Lake Peipsi *sensu stricto* (*s.s.*) were used to elucidate the distribution of P fractions in the lithological and geochemical composition of the lake's sediments. The composition of P fractions in the sediment cores was rather constant in layers with porosity lower than 88%. The decay of biota during the compression and genesis of sediments leading to the liberation of P to interstitial water and its further diffusion along the concentration gradient towards the sediment–water surface are directed by environmental conditions. During phytoplankton blooms the release of P fractions from sediments may be as high as 875 tonnes of P in Lake Peipsi *s.s.* Calculations show that the average annual total P accumulation in Lake Peipsi *s.s.* is ca 270 mg m<sup>-2</sup> y<sup>-1</sup>.

**Key words:** Lake Peipsi, sedimentation, phosphorus cycling, phosphorus accumulation, release.

### INTRODUCTION

The biogeochemistry of phosphorus in lakes is rather complicated and its distribution depends on many environmental factors (Boström & Pettersson, 1982; Boström et al., 1988; Eckert et al., 1997; Søndergaard et al., 2003) including sediment properties and functioning. Lake sediments are composed of complex aggregations of minerals and organic matter and, depending on the composition and physical-chemical properties of water, they act as either sinks or sources of P in the form of readily diluted phosphates (Reddy et al., 1995; Ramm & Scheps, 1997; Zhou et al., 2001).

Because of the complex mechanisms in the exchange of P between sediments and water, part of P may be released from sediments. Here two mechanisms can be distinguished: (1) chemical and biochemical factors occurring in dysoxic conditions liberate P to the pore water and support its diffusion to the sediment surface, and (2) the mixing event, i.e. transport from bottom layers to the photic zone (Holdren & Armstrong, 1980; Moore et al., 1991; Haggard et al., 2005).

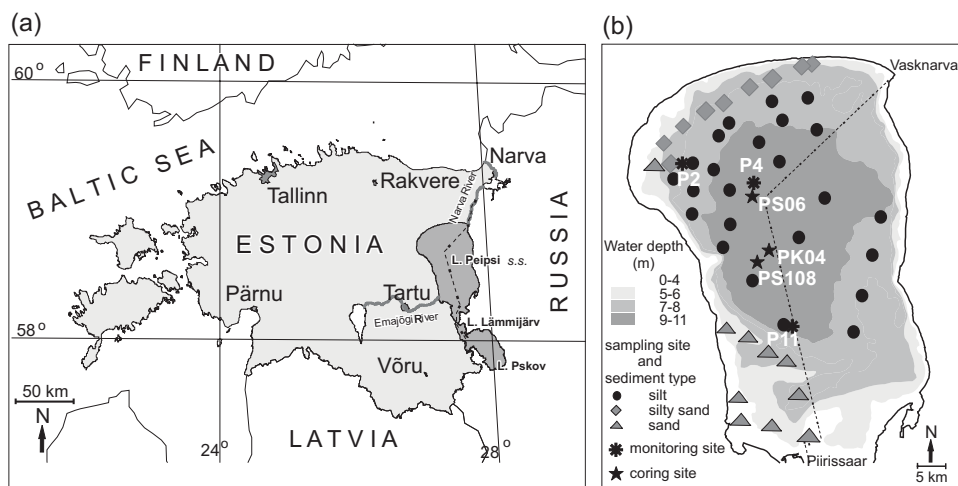
Although there are numerous detailed studies on the P dynamics in relatively shallow lakes (Anderson, 1997; Pettersson, 1998; Jordan & Rippey, 2003; Malmaeus et al., 2006), the processes in large lakes are described inadequately. Still, quite thorough descriptions of the distribution of P in sediments are available

for large and shallow Lake Ladoga in Russia (Ignatieva, 1996), Lake Okeechobee in the United States (Brezonik & Engström, 1998), and Lake Taihu in China (You et al., 2007).

In order to properly quantify the overall loadings of P in the lake ecosystem there is an utmost need to describe the spatio-temporal patterns of sediment biogeochemistry and assess how these relate to the internal loading. In this paper, we describe the distribution of P fractions in the sediments of the largest part of Lake Peipsi and their contribution to the total P balance in the lake. The previous nutrient balance calculations showed a decrease of the external loading of P since the beginning of the 1990s due to the reorganization of agriculture and industry on the catchment after the collapse of the Soviet Union (Loigu & Leisk, 1996; Iital et al., 2005; Mourad et al., 2006).

### STUDY AREA

The submeridionally elongated Lake Peipsi has a surface of 3555 km<sup>2</sup>, maximum length of approximately 150 km, and width of 42 km. Lake Peipsi is a shallow water body with the mean water depth of about 8 m (max 15 m). It consists of three parts named from north to south: Lake Peipsi *sensu stricto* (*s.s.*), Lake Lämmijärv, and Lake Pskov (Pihkva) (Fig. 1a). The current study focuses on processes in Lake Peipsi *s.s.* Its central part is 9–11 m deep; the coastal zone is shallow and the rather monotonous floor descends for some kilometres in the eastern and western coasts. The formation and distribution of the structural types of bottom deposits of Lake Peipsi *s.s.* are determined by hydro-meteorological processes (waves, currents, seasonal water-level fluctuations, lake ice impacts) as well as by



**Fig. 1.** Lake Peipsi (a), sediment types and location of the sampling, coring (PK04, PS06, PS108), and monitoring sites (P2, P4, P11) in Lake Peipsi *s.s.* (b).

lithological and geomorphological factors. Waves in the lake are steep and short and with the wind force of  $8 \text{ m s}^{-1}$  their height is 60–70 cm. The water of Lake Peipsi *s.s.* belongs to the hydrocarbonate class, its pH varies around 8.2, the concentration of Si is ca  $1 \text{ mg L}^{-1}$ , and that of Fe  $0.12 \text{ mg L}^{-1}$ . The lake is classified as a eutrophic waterbody (Kangur & Möls, 2008) with a mean concentration of total P  $30 \text{ mg m}^{-3}$  and P-PO<sub>4</sub>  $12 \text{ mg P m}^{-3}$ .

## METHODS

### Sampling

During the spring/summer seasons of 2006 and 2007 sampling of surface deposits of Lake Peipsi *s.s.* from a ship was undertaken. Altogether 58 grab samples of a thickness of 5 cm were taken for analysing the lithology (Punning et al., 2008b), polycyclic aromatic hydrocarbons (PAHs) (Punning et al., 2008c), diatoms, and P fractions. The site location was determined by GPS Garmin 12 (horizontal accuracy 3–5 m).

A Livingstone–Vallentyne piston corer (diameter 7 cm) operated by rods was used to obtain a 0.5-m-long core of unconsolidated surface sediments. During the winter season of 2006/2007 a 46-cm-long sediment core (PS06) was taken from the northern part of Lake Peipsi *s.s.* at monitoring station 4 where the water depth is 9.3 m. In autumn 2008, a 42-cm-long sediment core (PS108) was taken from the central part of Lake Peipsi *s.s.* where the water depth is 9.8 m (Fig. 1). The short cores were continuously sub-sampled in the field with intervals of 2 cm, packed in PVC bottles, and kept in a refrigerator prior to analyses. In addition, we used data of sediment core PK04 through the whole Holocene sequence obtained in 2004 by coring from the ice at a water depth of 10 m in the central part of Lake Peipsi *s.s.* and described earlier by Punning et al. (2008a).

To obtain continuous information on P in water the time series covered the period 2005–2007. Sampling sites P2, P4, and P11 (depths 8–9 m) (Fig. 1b) were investigated. Water samples were obtained from the surface layer of 0.5 m and from the near-bottom layer of water (0.5 m above bottom), both with a Ruttner sampler, as part of the National Environmental Monitoring Programme (Monitoring of Inland Water Bodies, Hydrochemical Monitoring of Lake Peipsi) by Tartu Environment Research Ltd. Monthly samples were collected from April to November in 2005–2007.

### Analysis

First the wet mass of the surface samples was measured at a fixed volume, then the samples were dried at  $105^\circ\text{C}$  to constant mass and the dry mass was calculated. Thereafter the samples were kept for 3.5 h at  $550^\circ\text{C}$  to get organic matter content and at  $950^\circ\text{C}$  to determine the carbonate content. Grain-size spectra were obtained from samples treated with hydrochloric acid and hydrogen

peroxide using a Fritsch Laser Particle Sizer 'Analysette 22'. The upper layers of sediment cores (PS06 and PS108) were dated and the sediment accumulation rate was calculated by the  $^{210}\text{Pb}$  method (Appleby et al., 1992) at the Centre for Environmental Monitoring and Technology, Ukrainian Hydrometeorological Research Institute, in Kiev. For the measurement of the P fractions in sediment cores PS06 and PS08 the modified Hieltjes & Lijklema (1980) method was used (Kapanen, 2008). For P analysis the dried sediments were subjected to separate chemical extraction with  $\text{NH}_4\text{Cl}$  (1 M) to extract loosely sorbed P ( $\text{NH}_4\text{Cl-P}$ ),  $\text{NaOH}$  (0.1 M) to extract metal oxide bound P ( $\text{NaOH-P}$ ), and  $\text{HCl}$  (0.5 M) to extract apatite P or calcium bound P ( $\text{HCl-P}$ ). To extract total P (P-tot), after burning (180 min,  $550^\circ\text{C}$ ) the samples were reworked with 0.5 M  $\text{HCl}$ . The inorganic P fraction (P-inorg) was calculated as the sum of  $\text{NH}_4\text{Cl-P}$ ,  $\text{NaOH-P}$ , and  $\text{HCl-P}$  fractions and the organic P fraction (P-org) as the difference between P-tot and P-inorg. For each P fraction at least three independent replicates were made. In samples of core PK04 P-tot and P-inorg in the upper 0.5 m were measured according to the ammonium molybdate spectrometric Finnish Standard Methods (SFS 3025, 1986; SFS 3026, 1986). Phosphorus concentrations (P-tot and  $\text{P-PO}_4$ ) in the water of Lake Peipsi *s.s.* were obtained from the Estonian Environmental Information Centre (the P concentrations were determined in the lake water samples by the ammonium molybdate spectrometric method EVS-EN 1189).

## RESULTS

On the basis of grain size the studied surface sediments fall into three groups: (1) silt (deepest central part of the lake), (2) silty sand (shallow coastal regions and the northern part of the lake), and (3) sand (these sediments mainly dominate in the southern area of the lake) (Fig. 1b, Table 1). On average the P-tot concentrations in surface sediments of Lake Peipsi *s.s.* ranged from 0.64 to 1.10, from 0.456 to 0.724, and from 0.069 to  $0.358 \text{ mg g}^{-1}$  dry mass for silt, silty sand, and sand, respectively (Table 2). The highest content of the P-tot fraction was in silt samples. Its content incorporated in the organic matter reached up to 52% of total, while  $\text{NH}_4\text{Cl-P}$  averaged only 1% (Table 2). In silty sand the contents of  $\text{NH}_4\text{Cl-P}$ ,  $\text{NaOH-P}$ , and  $\text{HCl-P}$  were estimated at 2%, 9%, and 74% of the total extracted P, respectively. The lowest values of all P fractions were in sand samples, while the highest content of the P-tot fraction was in apatite P ( $\text{HCl-P}$ ): on average 90% of P-tot within the range from 0.059 to  $0.350 \text{ mg g}^{-1}$ . In the sand samples the  $\text{NH}_4\text{Cl-P}$  fraction was not present.

The base of cores PK04, PS06, and PS108 consists of unconsolidated homogeneous dark gyttja. The water content of sediment core PS108 in the deepest layer, from 43 up to 30 cm, was 88%, from 30 to 20 cm 89%, and then increased up to 97% in the surface layers. The Pearson's correlation coefficients between all cores (PK04, PS06, and PS108) in the water content were very good ( $r = 0.90\text{--}0.95$ ;  $P < 0.01$ ).

**Table 1.** Characteristics of surface deposits

Deposit	Water depth, m	Sand, %	Silt, %	Clay, %	Organic matter, %	Carbonate, %	Porosity, %	Specific surface area, cm <sup>2</sup> cm <sup>-3</sup>
Silt (14.8 to 22.2 μm)	9.5 (8.3–11.8)	0–5	88–93	3–9	3.55–24.02	2.54–5.47	95	9.696 (8.00–11.36)
Silty sand (21.9 to 100.4 μm)	6.9 (3.9–8.2)	14–54	38–66	6–21	1.63–14.68	1.94–8.11	80	10.270 (4.75–20.98)
Sand (128.5 to 193 μm)	6.6 (3–9.3)	100	–	–	0.22–0.56	0.16–0.51	65	1.810 (0.69–3.99)

**Table 2.** The concentration of different P fractions (mean and range) and their relative contribution to P-tot in the surface deposits

Deposit	Number of samples	Concentration, mg g <sup>-1</sup>							Relative contribution to P-tot, %		
		P-tot	NH <sub>4</sub> Cl-P	NaOH-P	HCl-P	P-org	NH <sub>4</sub> Cl-P	NaOH-P	HCl-P	P-org	
Silt	25	0.925	0.013	0.070	0.334	0.509	1	7	40	52	
		(0.64–1.10)	(0.007–0.022)	(0.027–0.150)	(0.091–0.800)	(0.172–0.819)					
Silty sand	10	0.583	0.012	0.554	0.430	0.085	2	9	74	7	
		(0.456–0.724)	(0.008–0.021)	(0.027–0.082)	(0.321–0.564)	(0.038–0.292)					
Sand	10	0.183	0	0.014	0.175	3.42	0	7	90	3	
		(0.069–0.358)		(0–0.109)	(0.059–0.350)	(0–0.006)					

The  $^{210}\text{Pb}$ -derived sedimentation rate at coring site PS108 during the 20th century was between 0.06 and 0.01  $\text{g cm}^{-2} \text{y}^{-1}$  with a mean value of 0.04  $\text{g cm}^{-2} \text{y}^{-1}$  in Lake Peipsi *s.s.* Results show that the sediment accumulation rate at this site has been higher during the last 20 years compared to the previous century. The distribution of  $^{210}\text{Pb}$  in the surface high-porosity layers and the elevated sedimentation rate (up to 0.06–0.07  $\text{g cm}^{-2} \text{y}^{-1}$ ) during the last decades indicate mixing of sediments. The concentration of particulate P is mainly affected by flocculation, growth of phytoplankton and, depending on the energy regime, by resuspension as shown by Jensen et al. (2006). The calculated sedimentation rate at site PS06 was 0.03–0.04  $\text{g m}^{-2} \text{y}^{-1}$  and it increased in the surface layers up to 0.08  $\text{g m}^{-2} \text{y}^{-1}$ .

Phosphorus, which is related directly to the trophic state of a lake, is also sorbed onto the surface of sediment. Using  $^{210}\text{Pb}$  data it is possible to calculate the interruption of the process of sediment accumulation or sediment mixing.

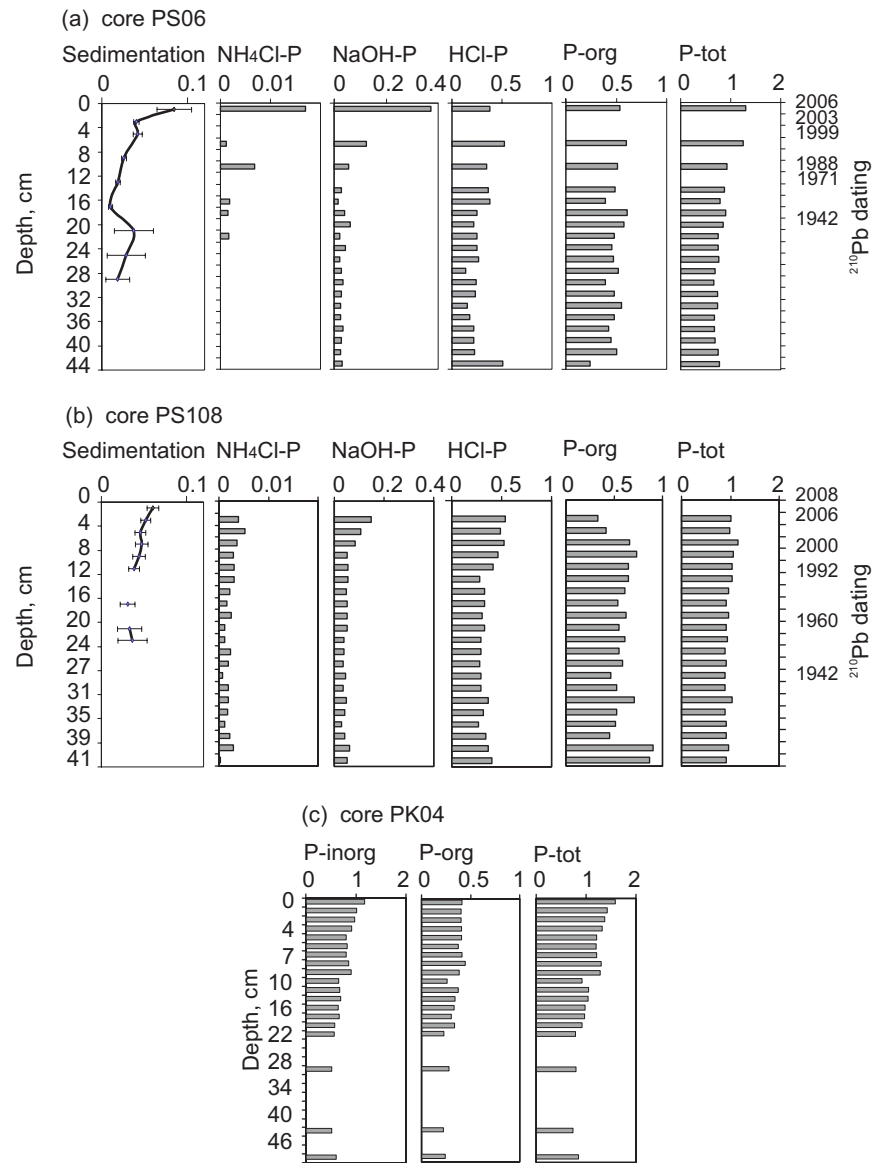
The vertical distributions of P fractions in the surface layer were measured in 37 samples from 0.5 m in core PK04, in 18 samples from 0.46 m in core PS06, and in 22 samples from 0.41 m in core PS108 (Figs 1, 2). Major changes in the sediment cores were observed in the upper 30 cm, which was deposited during the 20th century (Punning et al., 2008c).

In core PK04 the content of P compounds (total and inorganic, reaching 1.6 and 1.17  $\text{mg g}^{-1}$  dry mass, respectively) was much higher than in the older, more consolidated sediments covering the whole Holocene (Punning et al., 2008a). The concentration of P-tot in sediment cores PS06 and PS108 ranged from 1.157 to 0.881 and from 1.3 to 0.668  $\text{mg g}^{-1}$ , respectively (Fig. 2). In both these cores (PS06 and PS108)  $\text{NH}_4\text{Cl-P}$  showed a very low value. The  $\text{NaOH-P}$  fraction had maxima near the sediment surface and decreased with depth. The high content of the P-tot fraction is due to apatite P ( $\text{HCl-P}$ ), which ranged from 0.273 to 0.539  $\text{mg g}^{-1}$  in core PS06 and from 0.139 to 0.525  $\text{mg g}^{-1}$  in core PS108.

## DISCUSSION

### Distribution of phosphorus fractions within surface sediments

In Lake Peipsi *s.s.* P fluxes are highly dependent on sediment lithology and spatial differences in geochemistry. The current research showed a direct relationship between the P-tot content in sediments and sediment lithology. This indicates an essential role of the cohesiveness and sorption of P in sediment flocs. The greatest variations in the content of P fractions were observed in silt samples, whose structure and composition are relatively unsteady. The dominance of P-org in sediments pointed to the essential role of biota in transporting P between water and sediments. The relatively low OC/N values (from 8.8 to 8.0 in core PS06) testify that organic matter in silt is mainly of autochthonous (planktonic) origin (Punning & Tõugu, 2000) and plays a significant role in the sink and release of P. The fine-grained suspended particles have tendencies of repackaging into large



**Fig. 2.** Distribution of P fractions ( $\text{mg g}^{-1}$ ) in three coring sites and sedimentation rate ( $\text{g cm}^{-2} \text{y}^{-1}$ ) obtained using  $^{210}\text{Pb}$  CRS data (except PK04) in sediment cores PS06 (a), PS108 (b), and PK04 (c).

aggregates – flocs (Roberts et al., 1998; Punning et al., 2008b). During this process most of the particulate organic matter, as well as various macro- and micro-components, will become associated with suspended mineral particles and will be transported within the lake. The differences of the lithological and statistical characteristics of the particles in the surface area (Table 1), high surface energy, and electrostatic charge drive coagulation. During the adsorption strongly binding

organic compounds displace those that are weakly bound (Gu et al., 1996). The essential role of flocculation and the fact that silt particles act as pollutant carriers in Lake Peipsi *s.s.* are evidenced also by the distribution of PAHs in the surface sediments.

The HCl-P fraction reflects mainly physically bound and easily exchangeable P. This fraction is dominant in sand (90% of P-tot) and silty sand (74% of P-tot) sediments. In sand sediments the content of P-tot was the lowest. It is in correspondence with the low organic matter content and lower specific surface area of sand particles, which thus have the lowest sorption ability. The low Fe content (2–4%) is in good correspondence with the low concentration of NaOH-P.

### Phosphorus balance

Based on the data of lithological and geochemical mapping of the surface deposits (Tables 1, 2) and knowing the mean annual sediment accumulation rate, it is possible to calculate the content of P in the homogeneous upper 5-cm layer of sediments in Lake Peipsi *s.s.* (Table 3). Due to the cohesive character of sediments and their high mobility caused by the complicated bottom shear stress, the obtained values vary between 0.025 and 0.04 g cm<sup>-2</sup> y<sup>-1</sup>. For the upper layers a trustful accumulation value is 0.03 g cm<sup>-2</sup> y<sup>-1</sup>. Naturally, this value is valid only for the accumulative silt sediments in the deeper area of the lake, mostly contoured by the 9–11 m isobase. There is a zone with stable accumulation of sedimentary material originating from the Piirissaar glaciofluvial delta. On the silty-sand area mainly erosion rather than accumulation took place. Sands originate from older eroded sediments and P is mainly of apatite origin. Thus, in compiling the P balance those sediments were not taken into account in the further calculations. As the average P-tot content in silt sediments is ca 0.9 mg g<sup>-1</sup> the annual average P accumulation is ca 270 mg m<sup>-2</sup> y<sup>-1</sup>. In Lake Ladoga the corresponding figure is 190 mg P m<sup>-2</sup> y<sup>-1</sup> (Ignatieva, 1996).

Considering that accumulative silt sediments cover 1830 km<sup>2</sup>, i.e. ca 70% of the total bottom area of Lake Peipsi *s.s.* (Table 3), it is possible to calculate the total amount of P accumulated in the sediments. By multiplying the average sedimentation rate, sediment density, the area, and average P-tot concentration, we obtained that the retention in the upper 5-cm layer of Lake Peipsi *s.s.* was ca 490 tonnes of P-tot.

**Table 3.** The areas of surface deposits and P-tot content in the 5-cm surface layer

Deposit	Area, km <sup>2</sup>	Area, %	Porosity, upper 5-cm layer	P-tot, mg cm <sup>-2</sup>	P-tot, tonne
Silt	1830	70	95	90	1700
Silty sand	260	10	80	120	300
Sand	520	20	65	90	470
Total	2610	100			2470



Our experiences show that the distribution of P depends mainly on the composition of sediments. Aside from the geochemical processes controlling the release of nutrients from the sediments into the pore water, diffusive processes are often cited as the control on the transport of those nutrients into the overlying water body (Jorgensen & Revsbech, 1985). Oldham & Lavery (1999) illustrated the effects of the overlying hydrodynamics on P fluxes from the sediments and suggested that interactions between faunal activity and these hydrodynamics have a profound impact on nutrient fluxes.

The chemical and physical properties of sediments (presence of iron, grain size, and porosity), the records of the redox potential (Eh), pH, and microbiological activity in the phosphorus compounds are most important. The water content in surface silt sediments in Lake Peipsi *s.s.* is very high, reaching 95%; it decreases downwards and stabilizes at 90–88% at a depth of ca 29–30 cm (accumulated during the last 50–100 years). Our calculations showed that the decrease of porosity from 95% to 88% was related to a 2.5-fold compaction of sediments and thus the expulsion of interstitial fluid was up to 60%. The decreasing and stabilizing of the values of porosity are in good correspondence with the changes in Eh (revealed as notable changes in sediment colour) (Heinsalu et al., 2007), and in the chemical composition of pore-water pigments and dissolved organic matter (Leeben et al., 2008). Our data showed also a sharp decline in the P content towards the surface from the layers where the porosity exceeded 88%.

It is pointed out by many researchers that a typical exponential increase of the P content in surface layers of lake sediment cores does not always mark an increasing human load, but is a result of a comprehensive increase of sediment porosity (Perrone et al., 2008). In the large and shallow Lake Peipsi *s.s.*, where due to wind and wave mixing the thermal and oxygen stratification are weak and sediments are highly cohesive, the depth of active layers can be preliminarily estimated to reach the depth of 88% porosity where our data showed a decline of the P content towards the surface. If we presume that the diffusion rate in the denser sediments is insignificant and the P content in the active layers composes the pool for exchange with lake water, we can estimate the annual flux of dissolved P in the sediment cores.

Calculations with data obtained studying core PK04 show that the distribution of P-tot from 10-cm depth (P-tot 1.0 mg g<sup>-1</sup>) towards the surface (P-tot 1.5 mg g<sup>-1</sup>) is approximately 200 mg m<sup>-2</sup> y<sup>-1</sup>. Data of core PS06 show that the diffusion of P-tot from 10-cm depth (P-tot 0.9 mg g<sup>-1</sup>) towards the surface (P-tot 1.3 mg g<sup>-1</sup>) is approximately 160 mg m<sup>-2</sup> y<sup>-1</sup> and data of core PS108 show the diffusion of P-tot from 10-cm depth (P-tot 0.9 mg g<sup>-1</sup>) towards the surface (P-tot 1.0 mg g<sup>-1</sup>) to be approximately 60 mg m<sup>-2</sup> y<sup>-1</sup>. Thus, the total from the whole accumulation area (1830 km<sup>2</sup>) would range ca from 110 to 370 tonnes of P per year. While in strongly stratified lakes the P transport from sediments to the photic layers is mainly controlled by the terminally directed changes in the water density then in large and shallow lakes wind and wave energy are responsible for the water mixing and transport of P-rich waters within the lake. Hydrochemical and limnological studies

in Lake Peipsi *s.s.* show that the absence of or rather weak chemical and thermal stratification, disturbed by modest storms, is typical of this lake. Raudsepp et al. (2006) modelled the resuspension of silty sediments in the north-eastern part of Lake Peipsi *s.s.* They found that in 2002 the maximal near-bed water velocity was  $1.9 \text{ cm s}^{-1}$ , which shows that the P-rich waters will be permanently mixed within the water column. Thus the bottom water transfer to the lake surface occurs during most of the year and might be hindered only seldom during long-term still periods.

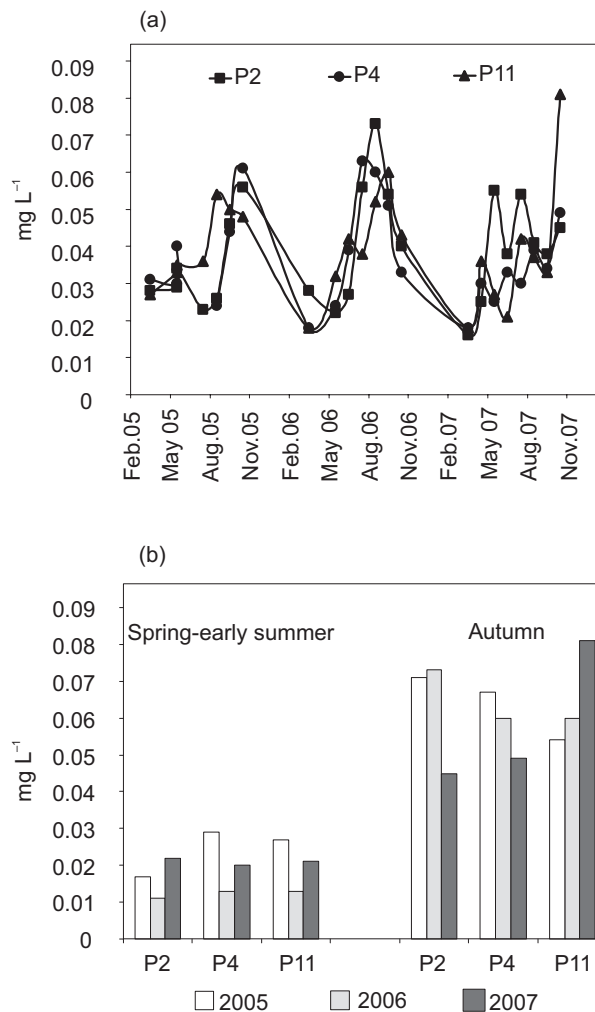
### Phosphorus release

Since 1950 regular hydrochemical and since 1962 annual hydrobiological monitoring have been carried out on all parts of Lake Peipsi (Kangur et al., 2001; Starast et al., 2001). The compiled P balance models show an essential decrease of the external load to the lake since the 1990s (Vassiljev et al., 2001; Iital et al., 2005), but the average statistically calculated weighted total P in Lake Peipsi *s.s.* has not changed significantly (Kangur & Möls, 2008).

The detailed monitoring data show typical seasonal variations in the content of P fractions in the water of Lake Peipsi *s.s.* (Fig. 3). In spring–early summer 2005–2007 the P-tot content had minimum values and varied from 0.011 up to  $0.029 \text{ mg L}^{-1}$ . The maximum concentrations in the monitoring areas were reached in autumn (September–October) when the P-tot content was  $0.045\text{--}0.081 \text{ mg L}^{-1}$ . The differences in P-tot between bottom and surface water samples were rather small and had no distinct pattern.

Calculated values show that the amount of P-tot in the surface water of Lake Peipsi *s.s.* varied during 2005–2007 from 300 tonnes of P in spring–early summer up to 1370 tonnes of P in late autumn. Because the external load did not vary much (Loigu et al., 2008) and the residence time of water in the lake is about 2 years, the main source of the seasonal variation could not be connected with changes in the external load but had to come from the ecosystem itself. This means that the changes in the dynamics of P exchange on the water–sediment interface had to be the main cause of variation. Thus, the release of P fractions from sediments during autumn might be as large as 875 tonnes of P in Lake Peipsi *s.s.* If to calculate it for the area of silt sediments (ca  $1830 \text{ km}^2$ ), then the average P release is ca  $200 \text{ mg m}^{-2} \text{ y}^{-1}$ . It is about 5–10 times more than in large and deep Lake Ladoga (Ignatieva, 1996). Therefore, the P flux at the sediment–water interface is far from negligible and must be taken into account in lake management activities.

In 2007 the flux of P fractions from sediments into the water was remarkably lower than in 2005 and 2006 (Fig. 3). It is in good correlation with the chlorophyll *a* concentration, which was in autumn on average  $20 \text{ mg m}^{-3}$  in 2005,  $22 \text{ mg m}^{-3}$  in 2006 and  $16 \text{ mg m}^{-3}$  in 2007 (Kangur, 2007), showing the leading role of biota in the transformation of P from sediments. The decay of biota and changes in the structure of sediments during their compression and genesis leading to the liberation of P to the interstitial water and its further diffusion along the concentration gradient towards the sediment–water surface are directed by environmental conditions. The



**Fig. 3.** Seasonal variations of the P-tot content at monitoring sites P2, P4, and P11 (see Fig. 1) during 2005–2007: (a) in the near-bottom water; (b) spring–early summer (minimum) and autumn (maximum).

release of P from sediments requires a permanent concentration gradient, i.e. the anoxic bottom waters richer in P must be transferred to the lake's surface where P can be used by primary producers.

The P fractions released from sediments will be incorporated into biota during the phytoplankton bloom in late summer. At this time the concentrations of P fractions in the lake water increase 2–3 times. During the processes of the dying of phytoplankton, its settling, and mineralization the adsorption of orthophosphate on sediment particles leads to an increase of P fractions in surface sediments. Naturally, the concentrations of P fractions increase also in the outflowing water in the Vasknarva monitoring station at the source of the Narva River, but part of

the released P will return into sediments in the form of the organic fraction. During the mineralization (chemical or microbiological) P-org is liberated. So the share of P-org in the surface silt sediments is about 30% and in the deeper layers it decreases to 20% (Punning et al., 2008a).

## CONCLUSIONS

Due to their important role in matter cycling in lakes the water and the sediments have a close interaction, at least in shallow lakes. We hypothesized that there should be a certain accordance between the sediment composition and structure in Lake Peipsi *s.s.*, explaining the lateral distribution of the concentration of the P fractions in the sediments. The study revealed a direct relationship between the P-tot content in sediments and the mean diameter of sediment grains and their specific surface area. This indicates an essential role of cohesiveness and sorption of P in the sediment flocs. The greatest variations in the content of P fractions were observed in silt samples. In sandy sediments the content of P-tot was the lowest.

In the case of cohesive sediments porosity plays a most important role in P diffusion. In large and shallow Lake Peipsi *s.s.*, where due to wind and wave mixing the thermal and oxygen stratification are weak and sediments are highly cohesive, the depth of active layers can be preliminarily estimated to reach the depth of 88% porosity where our data showed a decline of the P content towards the surface.

In Lake Peipsi *s.s.* the annual average phosphorus accumulation is ca 270 mg m<sup>-2</sup> y<sup>-1</sup>. The retention of P into the upper 5-cm sediment layer is ca 490 tonnes. The release of the P fractions from sediment during autumn might be as high as 875 tonnes of P. If to calculate it for the area of silt sediments (ca 1830 km<sup>2</sup>), then the average P release would be ca 200 mg m<sup>-2</sup> y<sup>-1</sup>.

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## Fosforivoog Peipsi järves

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Fosfori fraktsioonidel on Peipsi järve litoloogilises ja geokeemilises koostises oluline osa järve põhjasetete resuspensioonis. Tähtis on fosfori dünaamika pindmistes setetes, ulatudes kuni  $1,1 \text{ mg g}^{-1}$ . Tuginedes sedimentatsiooni viimaste aastakümnete dünaamikale ( $^{210}\text{Pb}$ ), on fosforiühendite sisalduse osakaal järve läbilõigetes suhteliselt ühesugune. Toetudes Peipsi järve akumulatsiooniala (umbes  $1830 \text{ km}^2$ ) mõõtmisandmetele, on võimalik välja arvutada summaarne fosfori jagunemine setetes. Arvestades kogu akumulatsiooniala fosfori settimistihedust ja -dünaamikat, saab välja arvutada fosfori jagunemise erinevates setetes ning fraktsioonides. Lähtudes vastavatest andmetest, saame 5 cm paksusega sette kohta 490 tonni kogufosforit. Pika aja jooksul saadud lainemõõtmise andmed võimaldavad hinnata järves asetleidnud hoovusi. Nii näitasid seirealadel P2, P4 ja P11 kevadel ning varasuvel 2005–2007 läbi viidud lainemõõtmise andmed umbes  $0,01\text{--}0,02 \text{ mg l}^{-1}$  ja sügisel  $0,05\text{--}0,07 \text{ mg l}^{-1}$  fosforit veesambas. Järves on lainetuse ja hoovuste koosmõju oluline setete jagunemisel nii fosfori fraktsioonides kui veesambas.