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HYDROCHEMICAL REGIME OF THREE PARTS OF LAKE PEIPSI DURING THE VEGETATION PERIOD

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Abstract. The concentration of total phosphorus (TP), chlorophyll *a* (Chl), total nitrogen (TN), dissolved oxygen (O_2), oxygen saturation (O_2%), pH, dichromate oxidizability (COD_{Cr}), water colour (Col), and transparency (SD) in three parts of L. Peipsi, which forms part of the border between Estonia and Russia, were studied from May to November 1985–90. From south to north the three parts are L. Pihkva, L. Lämmijärv, L. Peipsi *s.s.* By using the Scheffe test it was established that L. Pihkva, L. Lämmijärv, and L. Peipsi *s.s.* differ significantly from each other with respect to TP, Chl, COD_{Cr} and Col. The values of these parameters decrease in the direction from south to north. No significant differences were found between L. Pihkva and L. Lämmijärv with respect to TN and SD, while the level of TN in L. Peipsi *s.s.* was essentially lower and that of SD higher than the respective parameters in the southern parts of the lake. Water pH, O_2, and O_2% were quite uniform all over the lake. Great changes took place in the water composition of the lake during the vegetation period. Seasonal dynamics revealed three stages (spring, summer, and autumn) in the balance of production and destruction processes. Chemical composition as well as seasonal changes were relatively similar in L. Pihkva and L. Lämmijärv but different in L. Peipsi *s.s.*

Key words: L. Peipsi, its parts: L. Peipsi *s.s.*, L. Lämmijärv, L. Pihkva; hydrochemistry, seasonal changes.

INTRODUCTION

Lake Peipsi is one of the largest lakes in Europe. It forms most of the border between Estonia and the Russian Federation. The lake consists of three parts: L. Peipsi *s.s.* (Chudskoe ozero in Russian), L. Lämmijärv (Teploe ozero), and L. Pihkva (Pskovskoe ozero).

The concentration of total phosphorus, total nitrogen, and chlorophyll *a* as well as water transparency, colour, dichromate oxidizability, pH, dissolved oxygen, and oxygen saturation in the surface water of L. Peipsi were determined by the hydrochemistry team of the Institute of Zoology and Botany during the period 1985–90. The results of water analyses have been discussed in several papers. The chemical composition of water in L. Peipsi, its regionalities (Lindpere et al., 1986, 1987a, b, 1988, 1989, 1991; Möls et al., 1990; Starast et al., 1987a, b), as well as seasonal (Lindpere et al., 1990) and yearly changes (Lindpere et al., 1991; Möls et al., 1996) were characterized. The relationship between the above-mentioned parameters was investigated (Lindpere et al., 1987b, 1989; Starast et al., 1987a). The trophic state of the lake was estimated (Starast et al., 1988, 1989, 1990, 1991; Nõges et al., 1996). Mathematical methods for a fast monitoring of the lake's trophic state were elaborated (Möls et al., 1990; Möls & Saan, 1990). Using the SAS GLM procedure (SAS/STAT User's Guide, 1988) a 65-parameter polynomial regression model (Möls et al., 1996) was derived recently, which enables to describe temporal changes and the distribution of the water composition in L. Peipsi.

Up till present, little attention has been paid to the water characteristics in different parts of the lake. The aim of this paper is to give a survey of the chemical composition, transparency, and colour of water, to estimate differences between separate parts of L. Peipsi and to show monthly changes that took place from May to November 1985–90.

MATERIAL AND METHODS

Water samples in L. Peipsi were collected from May to September 1985–90, and in October and November 1986–89. The samples were taken monthly, usually in the middle of the month, from a depth of 0.1–1.0 m (twice in 1986 and 1988). The total number of sampling sites was 36, three of them being located in river mounths (Emajõgi, Velikaya, and Zhelcha rivers). Depending on the year, the number of sampling sites varied from 13 to 32. A map of L. Peipsi with sampling stations is given in Fig. 1.

Total phosphorus (TP) was determined spectrophotometrically (Pye Unicam SP6-550) with ascorbic acid as a blue phosphomolybdic complex (Koroleff, 1983). Chlorophyll *a* (Chl) was measured spectrophotometrically (CΦ-26) on methanol extracted samples (Talling, 1969). Total nitrogen (TN) was determined spectrophotometrically (Pye Unicam SP6-550) after the oxidation of a water sample: NO_3 was reduced to NO_2 using the Cd–Cu column. Sulphanilamide and *n*-(naphthyl)-ethylenediamine dihydrochloride were used for the determination of NO_2 (Koroleff, 1976). Water transparency (SD) was measured using a 30 cm white Secchi disk. Water colour (Col) measurements were made on a $CoSO_4$–$K_2Cr_2O_7$ standard solution scale (Alekin et al., 1973). Dichromate oxidizability (COD_{Cr}) was determined titrimetrically (Alekin, 1959). Dissolved oxygen (O_2) was measured with a thermooximeter. Water saturation with oxygen ($O_2\%$) was calculated from O_2 solubility at a certain water temperature. Water pH was determined on the colorimetric scale (Alekin, 1959). The bulk of data consists of 619 to 899 measurements per parameter, making up a total of 7389 measurements.

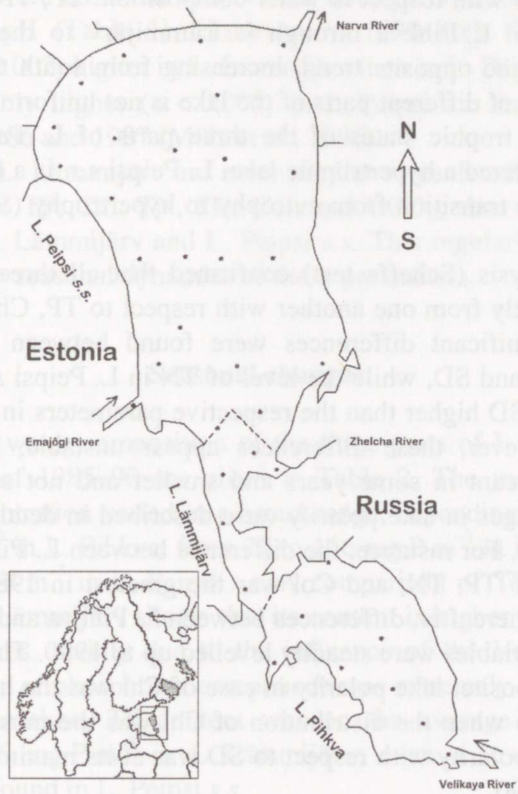

Fig. 1. Map of Lake Peipsi with sampling stations.

For distinguishing lake parts on the basis of the chemical composition of water, one-factorial analysis of variance and the Scheffe test (Table 1) were applied. The mean parameter value for a month was calculated each year. Monthly minimum and maximum values with the number of samples are given in Table 2. Figures 2–4 were constructed on the basis of average monthly values over six years. The relationship between the variables was estimated by regression analysis.

RESULTS AND DISCUSSION

Chemical composition of water in different parts of L. Peipsi

A survey on the chemical composition of water in lakes Pihkva, Lämmijärv, and Peipsi *s.s.* is given in Table 1. Earlier studies (Lindpere et al., 1987b, 1989, 1991; Möls et al., 1990, 1996) as well as the data of Table 1 reveal that L. Peipsi appears to be polar with respect to water composition: TP, TN, Chl, COD_{Cr}, and Col decrease from L. Pihkva through L. Lämmijärv to the northern part of L. Peipsi. SD has the opposite trend, increasing from south to north. Thus, the water composition of different parts of the lake is not uniform. According to TP, Chl, and SD, the trophic states of the three parts of L. Peipsi are different. L. Pihkva is considered a hypertrophic lake, L. Peipsi *s.s.* is a eutrophic lake, and L. Lämmijärv is in transition from eutrophy to hypertrophy (Starast et al., 1988, 1990).

Statistical analysis (Scheffe test) confirmed that all three parts of the lake differed significantly from one another with respect to TP, Chl, Col, and COD_{Cr} (Table 1). No significant differences were found between L. Pihkva and L. Lämmijärv in TN and SD, while the level of TN in L. Peipsi *s.s.* was essentially lower and that of SD higher than the respective parameters in the southern parts of the lake. However, these differences appear unstable, being greater and statistically significant in some years and smaller and not significant in other years. Yearly changes in lake polarity were described in detail in a recent paper (Möls et al., 1996). For instance, the difference between L. Pihkva and L. Peipsi *s.s.* with respect to TP, TN, and Col was the greatest in 1985, with respect to COD_{Cr}, in 1986. Thereafter, differences between L. Pihkva and L. Peipsi *s.s.* with respect to these variables were steadily levelled up to 1990. The trend of changes in Chl was the opposite: lake polarity in case of Chl was the highest in 1990 and the lowest in 1986 when the distribution of Chl was the most uniform over the whole lake. Lake polarity with respect to SD was at its maximum in 1988 and at its minimum in 1990.

Table 1. Chemical composition, transparency, and colour of water in three parts of L. Peipsi. Arithmetical means for 1985–90 and their standard errors; number of samples

Parameter	L. Pihkva	L. Lämmijärv	L. Peipsi *s.s.*	Evaluation
TP, mg P m^{-3}	67 ± 2; 186	57 ± 2; 130	33 ± 1; 581	*
Chl, mg m^{-3}	25.9 ± 1.4; 175	20.9 ± 1.3; 128	13 ± 0.5; 572	*
TN, mg N m^{-3}	1058 ± 27; 185	1021 ± 35; 130	724 ± 11; 584	**
SD, m	1.13 ± 0.03; 184	1.25 ± 0.03; 128	2.12 ± 0.03; 586	**
COD_{Cr}, mg O L^{-1}	35.6 ± 0.6; 181	33.3 ± 0.6; 124	27.8 ± 0.2; 566	*
Col,°	73 ± 1; 170	67 ± 1; 122	46 ± 1; 535	*
O_2, mg L^{-1}	10.8 ± 0.1; 136	10.7 ± 0.1; 96	11 ± 0.1; 387	***
O_2%	107 ± 1; 136	106 ± 1; 96	106 ± 1; 387	***
pH	8.17 ± 0.02; 184	8.16 ± 0.02; 129	8.21 ± 0.01; 571	***

* lake parts are statistically different;
** L. Peipsi *s.s.* is different from L. Pihkva and L. Lämmijärv;
*** lake parts are not statistically different.

No differences were observed between the three parts of the lake with respect to O_2, $O_2\%$, and pH (Table 1). However, in 1990 both O_2 and $O_2\%$ were significantly ($\alpha < 0.002$) higher in L. Lämmijärv than in L. Peipsi *s.s.* The pH of water was noticeably higher ($\alpha < 0.002$) in L. Peipsi *s.s.* in comparison with L. Lämmijärv in 1986 and 1987 (Möls et al., 1996).

L. Pihkva and L. Lämmijärv are more similar to each other with respect to the mean values of TP, Chl, TN, SD, Col, and COD_{Cr} than are L. Pihkva and L. Peipsi *s.s.*, or L. Lämmijärv and L. Peipsi *s.s.* This regularity is illustrated in Figs. 2 and 3 by the seasonal dynamics of these parameters.

Seasonal changes

Changes in the water composition of the three parts of L. Peipsi during the vegetation period of 1985–90 are given in Table 2. The monthly mean **total phosphorus** concentration varied in a broad range, depending on the year, from 27 to 123 mg P m^{-3} in L. Pihkva, from 27 to 116 mg P m^{-3} in L. Lämmijärv, and from 18 to 63 mg P m^{-3} in L. Peipsi *s.s.* A comparison of TP in L. Peipsi *s.s.*, L. Pihkva, and L. Lämmijärv shows that its content is higher and more variable in the last two lakes, mainly due to the influence of the Velikaya River. For example, the inflow of phosphorus compounds was extremely high in September 1985. At the same time, TP content was on the average 123 mg P m^{-3} in L. Pihkva and 116 mg P m^{-3} in L. Lämmijärv; even a lower concentration, 42 mg P m^{-3}, was found in L. Peipsi *s.s.*

Major sources of pollution with phosphorus compounds for L. Peipsi are agriculture and municipal sewage (Loigu et al., 1991). Besides phosphorus compounds carried into the lake from the catchment area, the TP content of lake water is influenced also by meteorological and morphometric factors. The high TP content of surface water in stormy weather may originate from sediments, as was the case in July 1986 when the concentration rose up to 63 mg P m^{-3} in L. Peipsi *s.s.*; such a content is considered very high. It should be mentioned that the lake enters a critical hypertrophic state at a point when the mean (from May to September) TP content exceeds the limit concentration (55 mg P m^{-3}) for the eutrophic level (Starast et al., 1990).

Seasonal variation in the TP content was well expressed in all parts of the lake: the amount of TP decreased from May (spring maximum) to June and started increasing towards autumn (Fig. 2). The increase in the TP content is related to the absence of permanent stratification in the lake. As a result of the mixing of water, the phosphate ions released from dead organisms settled on bottom are transported to the photic zone, which renders continuation of photosynthesis possible. According to the mean data of six years, a TP minimum occurred in June and a maximum, in September in both L. Pihkva (46 and 88 mg P m^{-3}, respectively) and L. Lämmijärv (41 and 76 mg P m^{-3}, respectively).

Table 2. Chemical composition, transparency, and colour of water. Minimum and maximum monthly arithmetical means in 1985–90; number of samples

Parameter	May	June	July	August	September	Oct.–Nov.
			L. Pihkva			
TP, mg P m^{-3}	34–81; 45	27–53; 30	55–89; 26	51–95; 35	68–123; 25	51–87; 25
Chl, mg m^{-3}	8.3–40; 43	8.6–24.2; 29	17.3–70; 25	25–67.7; 29	15.1–45; 24	15.3–36.7; 20
TN, mg N m^{-3}	700–1552; 45	637–1301; 30	380–1020; 26	679–1305; 34	668–1430; 25	720–1246; 25
SD, m	1.1–1.5; 45	1.1–1.6; 29	0.8–1.5; 26	0.8–1.3; 35	0.8–1.1; 24	0.8–1; 25
COD_{Cr}, mg O L^{-1}	23.7–35.3; 45	27.7–37.3; 30	31.6–41.1; 26	33.9–44; 35	36.4–44.6; 25	29.9–38; 20
Col, °	65–79; 45	53–87; 30	74–91; 15	63–108; 35	67–90; 25	51–86; 20
O_2, mg L^{-1}	11–11.5; 40	9.3–11; 26	8.2–12.4; 20	9.5–11.8; 24	8.6–10.1; 8	11.6–13.5; 18
O_2%	102–112; 40	96–116; 26	89–150; 20	97–131; 24	83–101; 8	103–104; 18
pH	7.7–8.5; 45	8–8.3; 29	8.2–9; 26	7.9–8.8; 35	7.8–8.3; 24	7.9–8.1; 25
			L. Lämmijärv			
TP, mg P m^{-3}	27–81; 31	31–50; 22	38–69; 18	47–89; 25	47–116; 17	43–79; 17
Chl, mg m^{-3}	4.4–24.3; 31	6.4–23.3; 22	15.4–24.4; 18	19.2–55.4; 25	11–45.7; 18	12.6–30.5; 14
TN, mg N m^{-3}	434–1865; 31	539–1369; 22	360–974; 18	777–1524; 25	535–1407; 18	563–1100; 16
SD, m	1.4–2.2; 29	1.2–1.9; 21	1–1.4; 18	0.9–1.3; 25	0.9–1.1; 18	0.9–1.4; 17
COD_{Cr}, mg O L^{-1}	24.1–29.9; 30	25–33.6; 20	29.3–37.3; 18	30–40; 25	30–48.8; 17	30.3–41.4; 14
Col, °	53–73; 31	47–68; 22	65–73; 12	51–76; 25	63–89; 18	48–86; 14
O_2, mg L^{-1}	10.8–11.6; 28	8.9–10.5; 18	8–10.2; 15	9.3–12.1; 17	8.3–10.5; 7	11.9–13.6; 11
O_2%	101–110; 28	95–109; 18	87–123; 15	99–136; 17	80–105; 7	104–105; 11
pH	7.8–8.4; 29	7.9–8.3; 22	8.1–8.4; 18	8–8.8; 25	7.8–8.2; 18	7.9–8.2; 17
			L. Peipsi *s.s.*			
TP, mg P m^{-3}	22–34; 129	18–26; 89	23–63; 77	26–44; 99	27–42; 87	23–54, 100
Chl, mg m^{-3}	3.8–18.8; 130	3.8–7.9; 89	9–18.2; 78	6.3–20.9; 96	8.1–18; 87	4–37; 92
TN, mg N m^{-3}	299–1091; 130	439–834; 93	299–879; 79	564–904; 98	422–848; 84	530–936; 100
SD, m	1.9–3; 129	2.3–3.6; 93	2–2.8; 79	1.6–2.8; 98	1.7–2.2; 87	1.2–1.9; 100
COD_{Cr}, mg O L^{-1}	23–31.7; 128	21.6–29.7; 91	26.2–31.0; 78	23.8–31.2; 99	24.1–31.9; 88	25.5–30.6; 82
Col, °	37–50; 129	34–51; 93	43–51; 47	35–59; 98	41–60; 76	38–54; 92
O_2, mg L^{-1}	10.5–13.6; 95	9.7–11.1; 80	8.5–9.8; 61	9.3–10.3; 60	8.9–11.8; 40	11.9–12.9; 51
O_2%	95–123; 95	97–115; 80	91–114; 61	100–110; 60	87–107; 40	98–103; 51
pH	8.1–8.5; 115	8.1–8.3; 93	8.2–8.4; 79	8.2–8.3; 98	8.1–8.2; 88	7.9–8.2; 98

In L. Peipsi *s.s.*, a summer maximum was observed in August (38 mg P m^{-3}), but the third and the highest peak occurred in October–November (44 mg P m^{-3}). The regularity for TP content to increase during summer is characteristic of shallow productive waterbodies where permanent stratification is lacking (Prepas & Trew, 1983; Prepas & Vickery, 1984). The summer TP : spring TP ratio for shallow productive Western Canadian lakes varied between 1.2 and 2.9 (mean 1.74) (Prepas & Trew, 1983). The mean August to June TP ratio was approximately the same for L. Peipsi, being in the range from 1.66 to 1.74 in its separate parts, whereas the August to May TP ratio was smaller, 1.36–1.45.

The **chlorophyll** content differed significantly for the same month in different years and revealed also the best pronounced dynamics during the vegetation period. Depending on the year, the monthly mean Chl content varied between 8.3 and 70 mg m^{-3} in L. Pihkva, from 4.4 to 55.4 mg m^{-3} in L. Lämmijärv, and from 3.8 to 37 mg m^{-3} in L. Peipsi *s.s.* (Table 2). This extremely high Chl content in L. Pihkva was observed in July 1988 and in L. Lämmijärv in August 1988. The lowest mean content of Chl during the observation period (Fig. 2) in L. Pihkva and in L. Peipsi *s.s.* occurred every June (17.6 and 6.5 mg m^{-3}, respectively), while in L. Lämmijärv its lowest value was recorded in May (13.4 mg m^{-3}). According to the literature (Laugaste, 1966; Nõges et al., 1989; Nõges, 1990, 1996), vernal algal bloom is completed in June or in early July. Thereafter Chl concentration increases until August when its mean content was 36.5 in L. Pihkva, 28 in L. Lämmijärv, and 13.5 mg m^{-3} in L. Peipsi *s.s.* During the summer peak in August, the content was on the average 2.1 times as high as it was at the time of its minimum.

Unlike in the southern parts of the lake, in L. Peipsi *s.s.* the Chl content started to increase abruptly in autumn and reached the third, the highest maximum in October–November. For instance, the summer maximums of 1987 and 1988 were observed in August (14.8 and 20.9 mg m^{-3}, respectively), and an extremely high Chl content (38.8 and 31.4 mg m^{-3}, respectively) occurred in late autumn, in November. According to Nõges et al. (1989), Nõges (1990, 1996), and Nõges et al. (1996), the so-called detrital chlorophyll, present in the cells of low productivity dead algae, starts to increase in the water of L. Peipsi *s.s.* from September. According to the above-mentioned authors the Chl content does not reflect the production of algae at this time. Inert Chl content continues to increase until the ice-cover is formed. In October–November, the Chl content was 3.9 times as high as it was in June in L. Peipsi *s.s.* Thus no great differences exist in the Chl content between the three parts of the lake in late autumn; the greatest difference with respect to Chl was found in July and August.

A highly significant positive correlation was established between Chl and TP ($r = 0.63$; $n = 565$) in L. Peipsi *s.s.* This relationship was weaker in L. Pihkva ($r = 0.50$; $n = 175$) and in L. Lämmijärv ($r = 0.39$; $n = 127$). Weaker relationships are due to the variable inflow of phosphorus compounds into the southern parts of the lake from the Velikaya River. No relationship was found between Chl and another major nutrient element, TN ($r<0.14$).

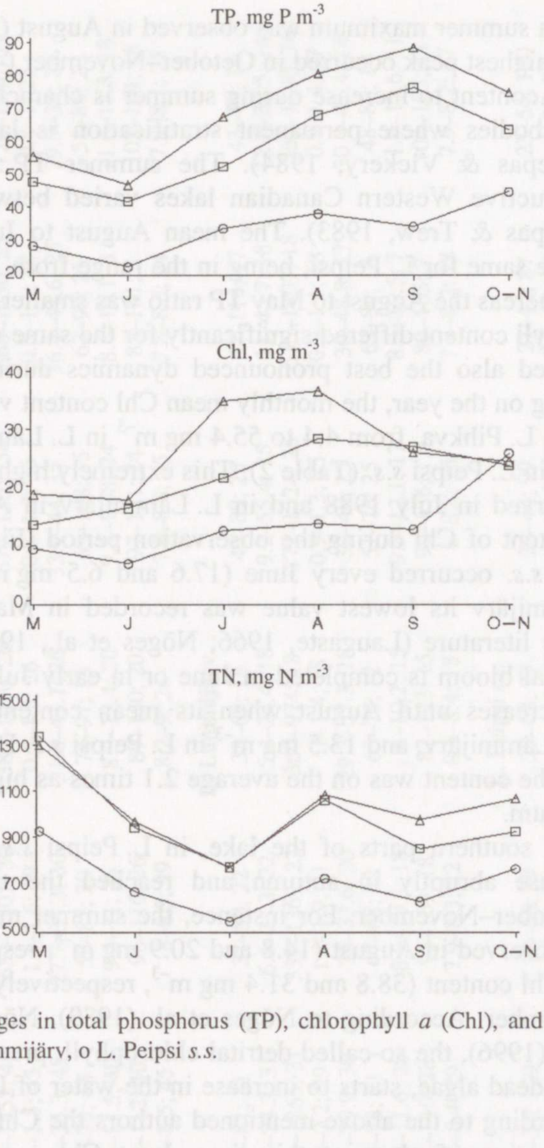

Fig. 2. Monthly changes in total phosphorus (TP), chlorophyll *a* (Chl), and total nitrogen (TN): Δ L. Pihkva, □ L. Lämmijärv, o L. Peipsi *s.s.*

The monthly mean **total nitrogen** concentration varied between 380 and 1552 mg N m^{-3} in L. Pihkva, between 360 and 1865 mg N m^{-3} in L. Lämmijärv, and between 299 and 1091 mg N m^{-3} in L. Peipsi *s.s.* during the period 1985–90 (Table 2). Seasonal variation in the TN content was well pronounced and synchronous in all parts of the lake (Fig. 2). The maximum TN content was established after the ice-out in May, while its minimum content occurred mostly in July. According to the monthly mean data, the content of TN in the months of May was 1303 mg N m^{-3} in L. Pihkva, 1340 mg N m^{-3} in L. Lämmijärv, and 927 mg N m^{-3} in L. Peipsi *s.s.* The mean TN content in July was 769, 771, and 534 mg N m^{-3}, respectively. The difference between spring maximum and summer minimum values was 1.7 fold, and even greater in some years (1985, 1986). For instance, the average TN content in L. Pihkva was 1450 mg N m^{-3} in May 1985, whereas it was about four times lower (380 mg N m^{-3}) in July. Depending on the year, the summer peak of nitrogen compounds was observed in August or September, while the autumn peak occurred in October–November; the spring maximum was usually the highest.

No highly significant relationships were observed between TN and other variables for our observation period. However, using the data set from 1985–87, highly significant relationships occurred between TN and several chemical variables (Lindpere et al., 1989).

Considering algal growth in a waterbody, not only the amount of nutrient elements but also the TN:TP ratio appears to be important. Values below 10 normally indicate nitrogen limitation, while values above 17 typically reveal phosphorus limitation. Cases where the ratio ranges from 10 to 17 indicate that either one or both elements may prove limiting (Forsberg et al., 1978). Consequently, the values of the TN:TP ratio in the three parts of L. Peipsi show that limiting elements may be different during different periods. Phosphorus is the element controlling algal biomass mainly in L. Peipsi *s.s.*, whereas either phosphorus or nitrogen may be the limiting element in L. Pihkva and L. Lämmijärv.

The monthly mean values of **water transparency** varied between 0.8 and 1.6 m in L. Pihkva, from 0.9 to 2.2 m in L. Lämmijärv, and from 1.2 to 3.6 m in L. Peipsi *s.s.* (Table 2). Seasonal variation in SD was well expressed; a clear decrease towards autumn, which has been observed also earlier (Karuna, 1983), took place in all parts of the lake. The largest decrease was registered before September. However, the dynamics of SD revealed also some differences in different lake parts (Fig. 3). In L. Peipsi *s.s.* SD increased from May to June, the water being most transparent in June. Thereafter, SD decreased noticeably until late autumn in L. Peipsi *s.s.* In the southern parts of the lake, whose water is darker and less transparent, changes in SD were quite small. Therefore, differences in SD between different parts of the lake are levelled by autumn, e.g. in June 1988 the range of SD over the lake was broad, 0.8–3.5 m, in October only 1.0–2.0 m. According to the monthly mean SD data over six years, the SD of L. Peipsi *s.s.* decreased by 1.6 m from June to November, in L. Lämmijärv 0.3 m and in L. Pihkva 0.5 m. In some sampling stations SD changed significantly during summer, e.g. at the sampling point with the clearest water in the northwestern corner of the lake SD decreased by 3.3 m (from 5.1 to 1.8 m) from June to August 1986.

The SD of L. Peipsi *s.s.* depends primarily on the development of phytoplankton, which is verified by a highly significant relationship between SD and Chl ($r = -0.72$; $n = 586$). No such clear relationship between transparency and phytoplankton was found either in L. Pihkva or L. Lämmijärv. In these lake parts SD depends on phytoplankton as well as on organic matter. A similar

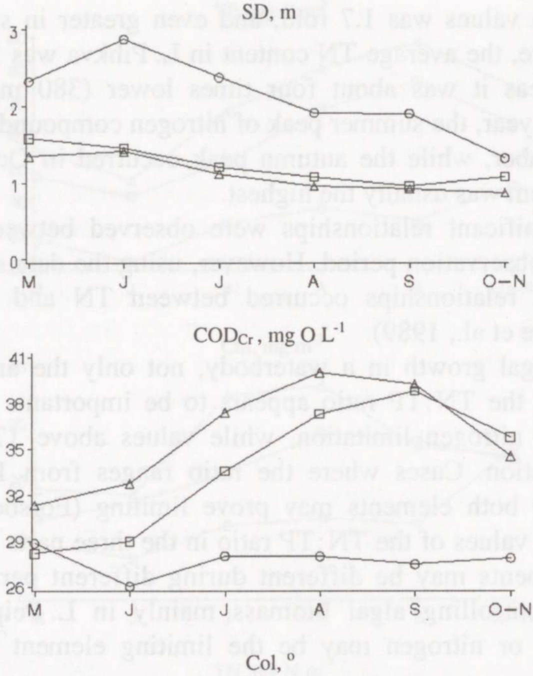

Fig. 3. Monthly changes in water transparency (SD), organic matter (COD_{Cr}), and colour (Col): Δ L. Pihkva, □ L. Lämmijärv, o L. Peipsi *s.s.*

relationship was observed between SD and Chl ($r = -0.50$; $n = 173$) as well as between SD and COD_{Cr} ($r = -0.49$; $n = 179$) in L. Pihkva. In L. Lämmijärv the influence of phytoplankton on SD ($r = -0.46$; $n = 125$) was slightly weaker than the influence of organic matter ($r = -0.64$; $n = 121$). Thus organic matter has the strongest effect on transparency in L. Lämmijärv and the weakest in L. Peipsi *s.s.* ($r = -0.34$).

The content of **organic matter** was estimated by COD_{Cr}. Earlier data (1955–75) for L. Peipsi *s.s.* indicate the lack of clear changes in the dynamics of the content of organic matter during the vegetation period. COD_{Cr} of L. Pihkva was the lowest in spring and the highest in summer (Kaputerko, 1983). According to the data for L. Peipsi *s.s.* over the period 1961–65, COD_{Cr} was usually the highest in summer when conditions for phytoplankton development are favourable (Simm, 1975).

During the vegetation period of 1985–90 (Table 2), changes in monthly means of COD_{Cr} were relatively negligible in L. Peipsi *s.s.* (21.6–31.9 mg O L^{-1}), but considerably greater in L. Pihkva (23.7–44.6 mg O L^{-1}) and in L. Lämmijärv (24.1–48.8 mg O L^{-1}). In L. Peipsi *s.s.* the whole range of monthly mean values of COD_{Cr} in 1985–90 was 26–29 mg O L^{-1}, being the lowest in June (Fig. 3). As seen from Fig. 3, three weakly developed peaks can be distinguished in the COD_{Cr} dynamics. The highest, the spring maximum, occurred in May, the summer maximum in July–August, and the autumn maximum in October–November. The seasonal trends of COD_{Cr}, Chl, and TP coincided, whereas the trend of SD was the opposite. It is obvious that the described dynamics reflects seasonal variation in phytoplankton. The COD_{Cr} level did not show any increasing trend during the vegetation period. The concentration of organic matter was quite similar in spring and before the formation of ice-cover. Thus, the self-cleaning ability of L. Peipsi *s.s.* can be considered sufficient. The monthly mean of COD_{Cr} range was 31–41 mg O L^{-1} in L. Pihkva and 28–39 mg O L^{-1} in L. Lämmijärv. The content of organic matter was the lowest in May, thereafter it increased and achieved a maximum in August–September. COD_{Cr} increased from June to August and decreased during autumn; however, its level before the formation of ice-cover was higher than it was in spring.

Water colour in L. Peipsi varied whithin a broad range, from dark reddish brown to light green. Monthly means for different years varied between 34 and 108° (Table 2). Water was darker in L. Pihkva and L. Lämmijärv (51–108 and 47–89°, respectively) compared with L. Peipsi *s.s.* (34–60°). The colour of water in L. Peipsi depends largely on the concentration of humic substances. The brown colour of water in Estonian lakes is derived mostly from fulvic acids in the composition of humic substances (Simm, 1961). The latter are carried into L. Pihkva in large amounts by the Velikaya River. In the river mouth the water is brown, often with a reddish or orange tone. The water of L. Pihkva is mainly brownish yellow, monthly means of six years varying from 63 to 82°. The colour of the water in L. Lämmijärv is strongly influenced by the water of both L. Pihkva and the Zhelcha River. In the region under the influence of the Zhelcha the water is brown, sometimes with a reddish tinge. The water in L. Lämmijärv is greenish or brownish yellow, the monthly means of Col being between 63° and 73°. According to the data from 1971–72 and 1974–75 (Karuna, 1983), the colour of the water in L. Peipsi has been the highest in spring with a decreasing tendency in autumn. Our study shows that although there exists no clear seasonal variation in the Col of L. Pihkva and L. Lämmijärv, an increasing tendency is obvious from June to September and a decreasing tendency in autumn (Fig. 3). The water of L. Peipsi *s.s.* is the lightest with a yellow or greenish yellow colour, the monthly means of Col being between 42° and 48°. The water of L. Peipsi *s.s.*

is the lightest in June and it turns darker towards autumn. A relatively high colour of water was observed in L. Peipsi in 1989 and 1990.

Among the studied variables, Col correlates most closely with COD_{Cr}; however, the correlation is quite weak ($r = 0.3–0.4$). The relationship between Col and organic matter decreased from L. Pihkva through L. Lämmijärv to L. Peipsi *s.s.*

The water of L. Peipsi is rich in **dissolved oxygen** and in most cases slightly under- or oversaturated. However, from time to time the water of L. Peipsi may be strongly oversaturated during the vegetation period. The monthly mean concentration of O_2 in surface water in different years was 8.2–13.5 mg L^{-1} (83–150%) in L. Pihkva, 8.0–13.6 mg L^{-1} (80–136%) in L. Lämmijärv, and 8.5–13.6 mg L^{-1} (87–123%) in L. Peipsi *s.s.* (Table 2). Strong oversaturation with O_2, as well as its high variation, characteristic of intensive photosynthesis, was most often observed in 1988. In May, the water in L. Pihkva was oversaturated with O_2 up to 138% (13.2 mg L^{-1}) and in L. Peipsi *s.s.*, up to 171% (17.2 mg L^{-1}). In June, oversaturation was replaced by undersaturation (down to 88%; 9 mg L^{-1}). Extremely strong oversaturation (189%; 15.6 mg L^{-1}) was registered in L. Pihkva in July of the same year. Significant oversaturation was noted also in August 1990: up to 13.5 mg L^{-1} (152%) in L. Pihkva and L. Lämmijärv. O_2 content is lower in river mouths (Velikaya, Emajõgi, Zhelcha) compared with surface water in the whole lake.

If calm weather lasts more than two weeks in summer, it may call forth a severe O_2 deficit in near-bottom water. Because of the stratification of water, O_2 decreases and CO_2 increases due to oxidation of organic matter in the hypolimnion. In case of a high gradient of water temperature and O_2 content fishkill may occur, as it happened in 1988 between June 23 and July 16.

Following changes in the monthly mean values of O_2 and O_2% over the observation period we can see that owing to lower water temperature, the O_2 content is the highest in spring (May) and late autumn (October–November) and quite low from June to September (Fig. 4). A similar course of O_2 was observed by Simm (1975) in L. Peipsi *s.s.* The monthly mean O_2 concentration of six years was 9.9–12.7 mg L^{-1} (99–119%) in L. Pihkva, 9.7–12.8 mg L^{-1} (98–111%) in L. Lämmijärv, and 9.4–12.9 mg L^{-1} (99–115%) in L. Peipsi *s.s.* Both this information and the data of Table 1 indicate a lack of differences between the three lake parts with respect to O_2 concentration and O_2%. However, the oxygen regimes of the different parts of the lake during the vegetation period differ. Release of O_2 during photosynthesis in summer plays an important role in the development of oxygen content in L. Pihkva and L. Lämmijärv. This is evidenced by synchronous changes of O_2 and O_2% running in the same direction from month to month, while water is oversaturated with O_2. On the other hand, changes in water temperature are important in the formation of the oxygen regime in L. Peipsi *s.s.* The lowest O_2 content occurs in July when water temperature is the highest. Saturation of subsurface water with O_2 in L. Peipsi *s.s.* was the highest in May, in L. Pihkva in July, and in L. Lämmijärv in August.

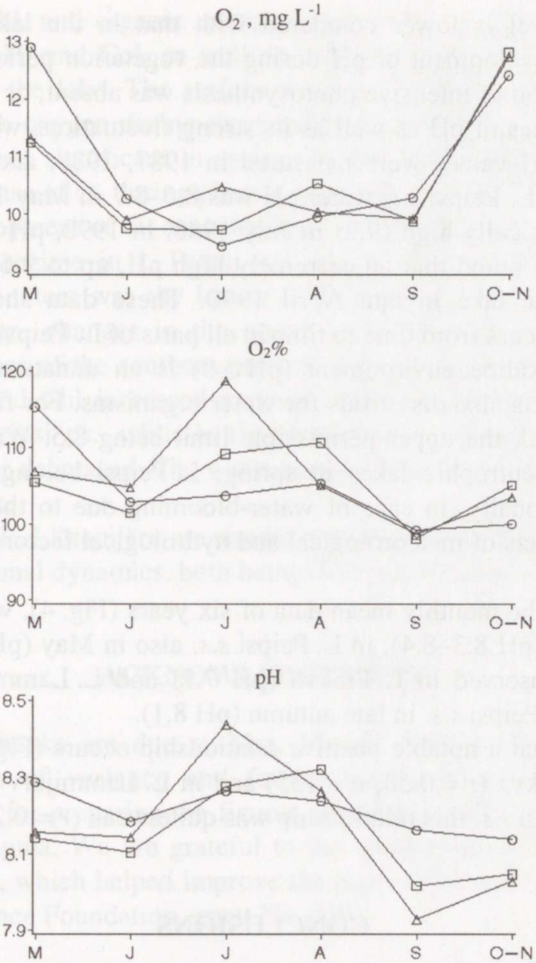

Fig. 4. Monthly changes in dissolved oxygen (O_2), water saturation with oxygen (O_2%), and pH: Δ L. Pihkva, □ L. Lämmijärv, o L. Peipsi *s.s.*

The data of Simm (1975) from 1962 and 1964 show, too, that saturation of water with O_2 in L. Peipsi *s.s.* was at its maximum in May. In all parts of the lake O_2% was at its minimum in September when algal life perishes but O_2 consumption continues in the oxidation process of organic matter. As a rule, at that time surface water is saturated with O_2. At other times from May to November water is oversaturated due to photosynthesis.

The water of L. Peipsi is slightly alkaline. The most common measured **pH** value was 8.2. Monthly mean values from different observation years in L. Peipsi *s.s.* varied less than those in the southern parts of L. Peipsi: in L. Pihkva 7.7–9.0; in L. Lämmijärv 7.8–8.8, and in L. Peipsi *s.s.* 7.9–8.5 (Table 2). In river mouths the water pH level is lower compared with that in the lake. Photosynthesis determines the development of pH during the vegetation period. In 1985, 1986, and 1989 the period of intensive photosynthesis was absent, or else it was missed because high values of pH as well as its strong fluctuations were not registered. However, high pH values were measured in 1987, 1988, and 1990. In several sampling sites of L. Peipsi *s.s.* water pH was 8.6–8.7 in May 1987. In L. Pihkva water pH was critically high (9.2) in July 1988. In 1990, pH was often high as well. It should be noted that an extremely high pH, up to 9.6, was observed in the middle of the lake in late April 1990. These data show that intensive photosynthesis occurs from time to time in all parts of L. Peipsi.

A strongly alkaline environment ($pH > 9$) is an unnatural phenomenon in Estonian lakes; it is also disastrous for water organisms. For fish-breeding water pH is standardized, the upper permissible limit being 8.5. Water pH 8.6–8.7 is characteristic of eutrophic lakes in spring; L. Peipsi belongs to this class of lakes too. Occasionally, in case of water-blooming due to the accumulation of unfavourable effects of meteorological and hydrological factors, water pH can be over 8.8 here.

According to the monthly mean data of six years (Fig. 4), water pH is high in July and August (pH 8.3–8.4); in L. Peipsi *s.s.* also in May (pH 8.3). The lowest pH value was observed in L. Pihkva (pH 7.9) and L. Lämmijärv (pH 8.0) in September; in L. Peipsi *s.s.* in late autumn (pH 8.1).

It is evident that a notable positive relationship occurs (Fig. 4) between $O_2\%$ and pH in L. Pihkva ($r = 0.58$; $n = 135$) and in L. Lämmijärv ($r = 0.57$; $n = 94$). In case of L. Peipsi *s.s.* this relationship was quite weak ($r = 0.28$; $n = 387$).

CONCLUSIONS

The three parts of L. Peipsi, L. Pihkva, L. Lämmijärv, and L. Peipsi *s.s.*, differ significantly from one another with respect to the contents of TP, Chl, and organic matter and water colour. The values of these parameters for surface water decrease from south to north in L. Peipsi. No significant differences were found between L. Pihkva and L. Lämmijärv considering TN and SD, while the level of TN in L. Peipsi *s.s.* was essentially lower and that of SD higher than the respective parameters for the southern parts of the lake. Water pH, O_2, and $O_2\%$ were quite uniform over the lake.

The dynamics of TP, Chl, TN, SD, COD_{Cr}, Col, O_2, $O_2\%$, and pH from May to November expresses basically three stages (spring, summer, and autumn) in the balance of production and destruction processes. In spring (from May to June) the content of TP, Chl, and TN, Col, O_2, $O_2\%$, and pH decreased in L. Peipsi, whereas SD had the opposite trend. L. Peipsi *s.s.* was the most pellucid in June after the decline of spring primary production when TP, Chl, organic matter, and Col were the lowest. In summer, a sharp increase took place in the content of TP, Chl, and organic matter, which led to a subsequent rise in the values of $O_2\%$, pH, and Col, as well as a decrease in SD, particularly in the southern parts of the lake. The surface water of L. Peipsi was mostly slightly oversaturated with oxygen during the vegetation period. In L. Peipsi *s.s.*, oversaturation was most significant in spring, in the southern parts of the lake, in summer. The release of O_2 during photosynthesis in summer played an important role in the development of O_2 concentration in L. Pihkva and L. Lämmijärv. On the contrary, O_2 regime in L. Peipsi *s.s.* depended mainly on summer water temperature: O_2 content was the lowest in July when water temperature is the highest. In autumn, changes in the water composition of L. Peipsi *s.s.* were different from those of the southern parts of the lake: in October–November the contents of TP and Chl increased to their maximum and SD decreased to its minimum in L. Peipsi *s.s.*, while in the southern parts the contents of TP, Chl, and organic matter decreased. The water composition was the most uniform over the lake in autumn.

L. Pihkva and L. Lämmijärv are similar considering the chemical composition of water and seasonal dynamics, both being different from those of L. Peipsi *s.s.*

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PEIPSI JÄRVE KOLME OSA HÜDROKEEMILINE REŽIIM VEGETATSIOONIPERIOODIL

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1985.–1990. aastal määrati maist novembrini Peipsi järve kolme osa – Pihkva järve, Lämmijärve ja Peipsi *s.s.* pindmise veekihi keemiline koostis (üldfosfori – TP, üldlämmastiku – TN, klorofüll *a* – Chl, orgaanilise aine – COD_{Cr} ja vees lahustunud hapniku – O_2 sisaldus ning vee pH), vee läbipaistvus (SD) ja värvus (Col) ning arvutati $O_2\%$. Scheffe testiga tõestati, et kõik kolm järveosa erinevad oluliselt TP, Chl, COD_{Cr} ja Col poolest. Näitajad vähenevad Pihkva järvest Lämmijärve kaudu Peipsisse *s.s.* (joon. 1). TN ja SD poolest Pihkva järv ja Lämmijärv ei erine, küll aga on TN Peipsis *s.s.* oluliselt väiksem ja SD suurem kui lõunapoolsetes järve osades. O_2, $O_2\%$ ja pH on üle järve üsna ühesugused (tab. 1). Järve vee keemiline koostis muutub vegetatsiooniperioodil palju, kusjuures aastati on muutuste ulatus erinev. Vee koostise dünaamikas eristub kolm etappi: kevadine, suvine ja sügisene. Erinevused järveosade vee keemilises koostises on kõige suuremad suvel, vee koostise dünaamikas aga sügisel (tab. 2; joon. 2–4). Vee keemiline koostis, läbipaistvus ja värvus, samuti nende sesoonsed muutused on Pihkva järves ja Lämmijärves võrreldes Peipsiga *s.s.* sarnasemad.