IS THE DESTABILISATION OF LAKE PEIPSI ECOSYSTEM CAUSED BY INCREASED PHOSPHORUS LOADING OR DECREASED NITROGEN LOADING?

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ABSTRACT
Lake Peipsi (3,555 km^2, mean depth 7.1m) located on the border of Estonia and Russia is the largest transboundary lake in Europe. L. Peipsi consists of three parts. The shared largest northern part L. Peipsi *s.s.* (2,611 km^2, 8.3m) and the southern L. Pihkva (708 km^2, 3.8m) which belongs mainly to Russia are connected by the river-shaped L. Lämmijärv (236 km^2, 2.5m). The catchment area (44,245 km^2 without lake area) is shared between Estonia (33.3%), Russia (58.6%) and Latvia (8%). Intensive eutrophication of L. Peipsi started in the 1970s. The biomass of N_2-fixing cyanobacteria was low at heavy nutrient loading in the1980s. After the collapse of soviet-type agriculture in the early 1990s, the loading of nitrogen sharply decreased. A certain improvement of L. Peipsi *s.s.* was noticed at the beginning of the 1990s together with the temporary reduction of phosphorus loading from Estonian catchment while in recent years a destabilisation of the ecosystem has been observed. This deterioration has been expressed mainly as intensive blue-green blooms and fish-kills in summer. Reappearance of blooms has been explained by the decrease in N/P loading ratio due to reduced N discharge while in some periods increased phosphorus loading could have supported this trend.

Key words: cyanobacterial blooms, nutrient loading, transboundary lake

INTRODUCTION
At present Lake Peipsi is the largest transboundary lake in Europe, located on the border between Estonia and Russia (Fig. 1). By its surface area (3,555 km^2) L. Peipsi occupies the fourth place among European lakes. The lake consists of three parts. The area of the largest northern part, L. Peipsi *sensu stricto* is 2,611 km^2, mean depth 8.3 m and the greatest depth 12.9 m. The southern part, L. Pihkva with an area of 708 km^2 and mean depth of 3.8 m is connected with L. Peipsi by the narrow river-shaped L. Lämmijärv having an area of 236 km^2 and mean depth of 2.5 m. The catchment area (44,245 km^2 without lake area) involves parts of Estonian (33.3%), Russian (58.6%) and Latvian (8%) territories. The amount of water in L. Peipsi is 25 km^3 and the residence time of the water is about 2 years. The outflow, the River Narva, runs its waters into the Gulf of Finland (Jaani, 2001).

L. Peipsi is an unstratified eutrophic lake with some mesotrophic features, L. Lämmijärv has some dyseutrophic features, while L. Pihkva is an unstratified eutrophic, or even hypertrophic water body. L. Peipsi has an importance for recreation and fishery. Considering its annual fish catches (9,000 - 12,000 tons or 25 - 34 kg ha^{-1}) L. Peipsi exceeds all large lakes in North Europe. The main commercial fishes are lake smelt (*Osmerus eperlanus eperlanus),* perch (*Perca fluviatilis*), pikeperch (*Sander lucioperca*) and bream (*Abramis brama)*, till the 1990s also vendace (*Coregonus albula*). The stock of formerly important commercial fish vendace decreased sharply in the beginning of 1990s and has not recovered. This has been explained by the occurrence of unfavorable spawning conditions in several successive years, the impact of eutrophication can not be neglected as well. At the same time, the abundance of pike-perch increased remarkably (Pihu & Kangur, 2001). Benthic fauna of L. Peipsi has been subjected to strong modification by invasion of zebra mussel in 1935, and a gammaridean amphipod from L. Baikal in the 1970s. Nevertheless, high species diversity, stable abundance of the benthic community and survival of sensitive clean water species demonstrates rather good water quality (Timm *et al*., 2001).

The majority of phosphorous and nitrogen compounds are carried into the lake by the rivers Velikaya and Emajõgi, the former carrying biologically treated sewage from the Russian town Pskov, with 210,000 inhabitants, the latter transporting waste water from the Estonian town Tartu, with 120,000 inhabitants. The sewage water of Tartu remained untreated for a long time; the treatment plant has been in operation since 1998 but still 20% of the sewage water is not subjected to purification. In 1998 the rivers Velikaya and Emajõgi contributed, respectively, 48 and 27% of the total riverine loading of nitrogen and 17 and 63% of that of phosphorus (Fig. 2).

The measurement of total phosphorus (TP) and nitrogen (TN) started in the Estonian rivers in 1984 and in L. Peipsi in 1985. Until 1997, only mineral forms of nutrients (ammonium, nitrites, nitrates, phosphates) have been measured in Russian rivers and waters of L. Peipsi. The data series on mineral N and P compounds in L. Peipsi start from 1968 and in the rivers from 1976. A regular biological data series dates back to 1962.

Figure 1. Location map of Lake Peipsi and its inflows

According to long-term limnological data and paleolimnological evidence (A. Heinsalu *et al.*, unpublished), intensive eutrophication of L. Peipsi started in the 1970s. After the collapse of the soviet-type agriculture in the early 1990s, the loading of nutrients (first of all N) from Estonia has sharply decreased. A certain improvement of the lake status was noticed in the beginning of the 1990s while in recent years the ecosystem of L. Peipsi *s.s.* has destabilised. Summer water blooms caused by blue-green algae have become the most serious problem for L. Peipsi considering its ecological quality. An exteremely heavy bloom accompanied by fish-kill in late summer 2002 rised the question what has caused the destabilisation of the ecosystem. One possible reason for that could be the changed structure of nutrient loading discussed in present paper.

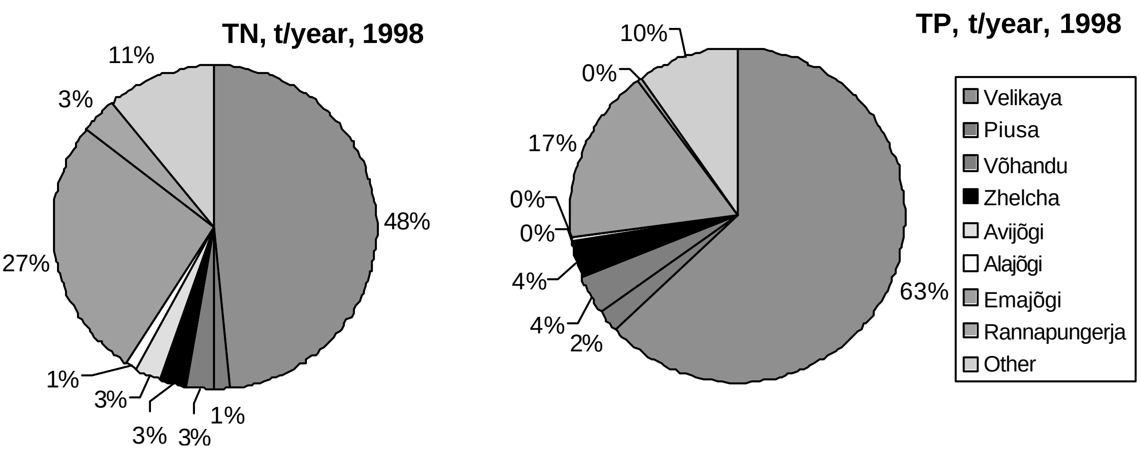

Figure 2. Share of the main rivers in the total N and P loading into L. Peipsi in 1998 (according to Nõges et al.*, 2003).*

MATERIAL AND METHODS

Data on riverine discharges and nutrient concentrations collected within different monitoring programs and scientific projects were used in present analysis. In Estonia total and mineral forms of N and P were analysed according to the methods described by Grasshoff *et al*. (1982). In Russian waters only mineral forms of nutrients were measured until 1997. Daily water discharges and monthly measured nutrient concentrations were used to calculate annual river loads (L):

$$L = \sum_{i=1}^{12} W_{ki} \cdot C_{ki} \quad (1)$$

where, W_{ki} - volume of monthly runoff; C_{ki} - monthly mean concentration

Loads from the coastal zone of L. Peipsi and inputs from non-monitored small rivers were calculated as:

$$L_n = L_m \frac{A_n}{A_m} \qquad (2)$$

L_n - loading from non-monitored area; L_m - loading from monitored area; A_n - area not monitored ; A_m - area monitored.

Phytoplankton samples were preserved with formaldehyde (1962-1995) and Lugol’s iodine (since 1996). Microscopic counting was performed at 400^x magnification in a Fux-Rosenthal chamber (1962-1999), since 2000 the Utermöhl (1958) method was used.

ECOLOGICAL STATUS OF LAKE PEIPSI

If to apply to L. Peipsi the the water quality criteria developed for Estonian small lakes (Ott, 2001), the lake will be qualified mostly as 'good' according to chlorophyll and phosphorus concentrations (Table 1) while nitrogen concentration and water transparency describe rather ‘moderate’ situation. Summer **water bloom** caused by blue-green *Gloeotrichia echinulata* was noticed in L. Peipsi already in 1895 by Spindler and Zengebusch (Kullus, 1964). Mass development of *Anabaena flos-aquae* and *Microcystis aeruginosa* was observed in August 1912 (Samsonov, 1914). *Anabaena flos-aquae, A. spiroides* and *G. echinulata* caused water blooms in L. Pihkva in August 1929, while in August 1934, a bloom of *Aphanizomenon flos-aquae* ocurred in all three parts of the lake (Voronikhin, 1950). Yearly water blooms from July to September with a maximum in August were a common phenomenon in the lake already in the 1930s (Vinkel-Voore, 1935). **A fish-kill** during the bloom was first described in L. Pihkva in summer 1959 (Semenova, 1960), a massive smelt kill occurred in the whole Lake Peipsi in 1972 (Kuderskij & Fedorova, 1977). Most recent fish-kills in the northen part of the lake occurred in summer 1988, in spring 1989, and in summer 2002. Most of the fish kills coincided with summer blue-green blooms while in 1989 a spring bloom of the diatom *Aulacoseira islandica* resulted in fish-kill as well.

Table 1. Indices reflecting the trophic status of L. Peipsi (Laugaste *et al.*, 2001; Starast *et al.*, 2001)

Parameter	Units	Years	Mean	L. Pihkva	L.Lämmi-järv	L. Peipsi *s.s.*
TP	µg/l	1985-96	42	63	53	35
TN	µg/l	1985-96	768	1010	923	678
Chl a	µg/l	1983-97	17.3	26	25	14
Secchi depth	m	1983-2000	1.76	1.25	1.42	1.8

There have been only small changes among dominant species and in the total abundance of phytoplankton during the last 40 years. Observing changes in cyanobacterial dominance since 1962, one can notice its increase in L. Peipsi *s.s.* in late 1960s and 1970s, decline in the 1980s and a new increase starting from the 1990s (Fig. 3). Cyanobacterial blooms are mainly attributed to declining water quality. In case of L. Peipsi where cyanobacteria constituted a half of the summer phytoplankton biomass already 40 years ago and where the cyanobacterial blooms have been documented since the 19th century (Laugaste *et al*., 2001), the relationship between between blooms and water quality becomes vague. The blooms almost disappeared during heavy nitrogen loading in the 1980s and reappeared in the1990s when N loading was reduced.

Changes in nutrient loading

The discharge of nutrients by the R. Emajõgi, as well as by other Estonian rivers increased rapidly during the 1980s while in early 1990s a sharp decrease occurred, first of all in TN loadings (Fig. 4). This change was caused mainly by the collapse of extensive agriculture. Application of large amounts of fertilizers in the 1980s was often accompanied by substantial nutrient leakage into water bodies. As in the 1990s the TN loading decreased more than TP loading, the TN/TP ratio in Estonian rivers decreased. A decrease in the ratio of inorganic N and P compounds was also observed in the River Velikaya. Because only inorganic nutrients were investigated until 2000 and data for 1990-1994 are completely lacking from the Russian side, it is quite hard to estimate the nutrient loading from Russian catchment and to analyse its changes. This knowledge is, however, rather critical as 58.6% of the catchment area belongs to Russia. Nevertheless, even if we knew Russian loading, one has to consider that its impact to L. Peipsi is not straightfoward. As the R. Velikaya which gives the majority of Russian loading enters L. Pihkva from the south (Fig. 1), this lake acts as a purification pond for L. Peipsi *s.s.*

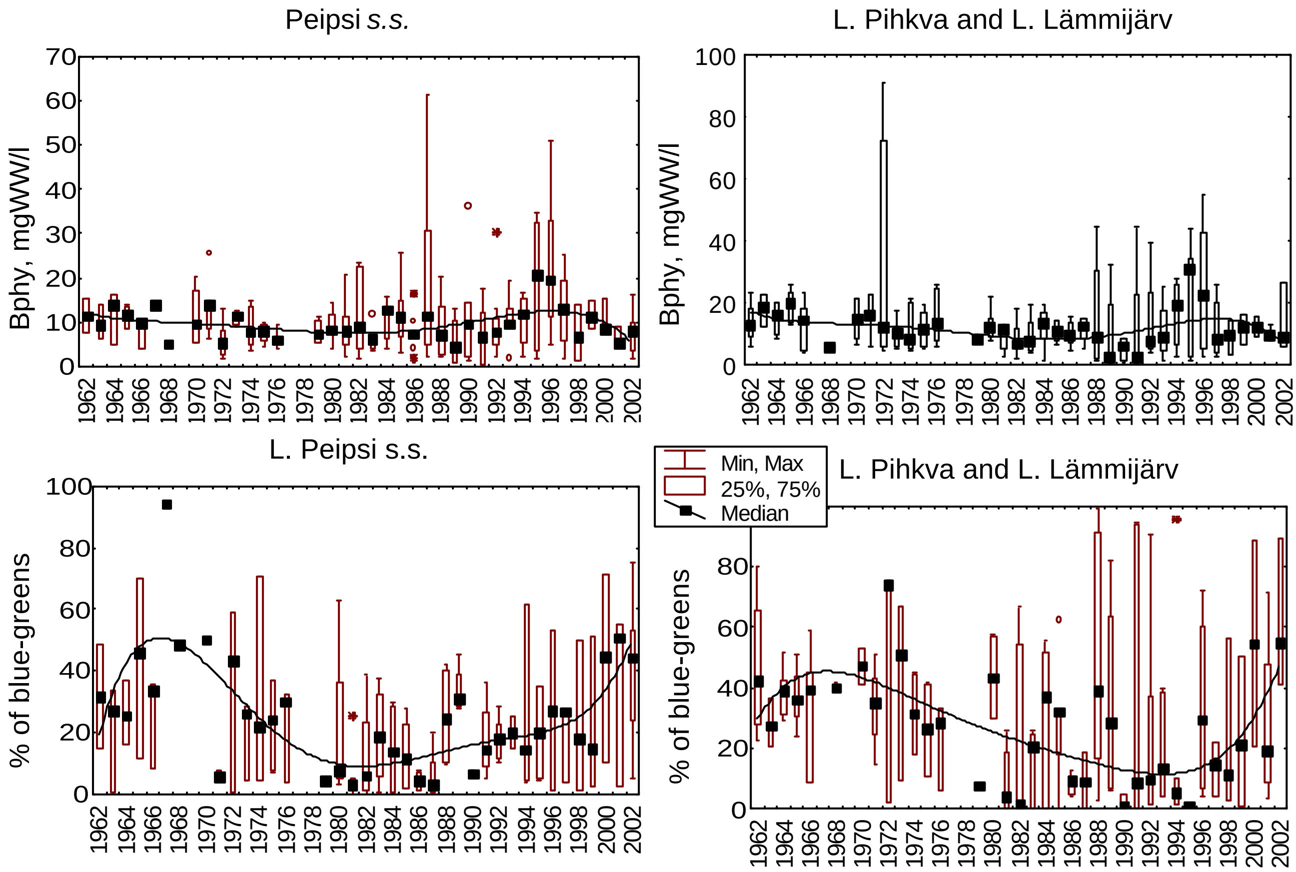

Figure 3. Long-term changes of phytoplankton biomass and blue-green dominance in L. Peipsi s.s., and lakes Pihkva and Lämmijärv. Data from May, July and October collected by Võrtsjärv Limnological Station, by Pskov Pedagogical Institute and by the Hydrometeorological Survey are included.

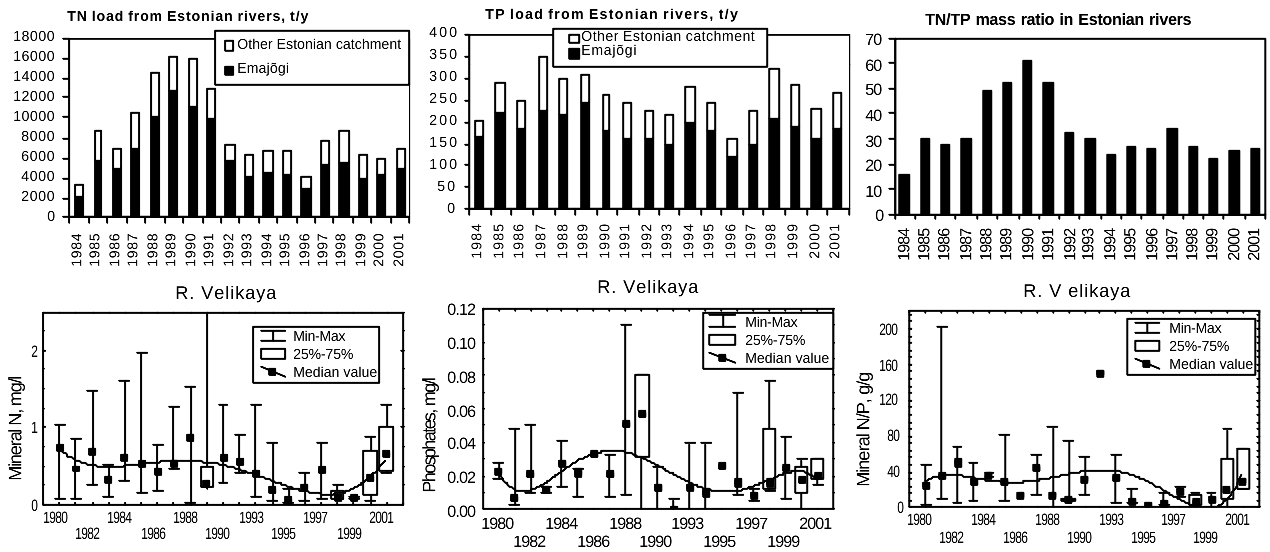

Figure 4 Long-term changes of total nitrogen (TN) and phosphorus (TP) loading and their ratio in the Estonian rivers of L. Peipsi watershed, and concentration and ratio of mineral N and P in the River Velikaya

To get an insight into the dynamics of the nutrient loading from Russia, we collected all available data on loading from both sides of the catchment (Fig. 5.). From these data one can follow that present loadings are almost equal to those at the beginning of the 1980s. Data reveal that phosphorus loading from Russian catchment was quite high in mid 1990s even exceeding that of the 1980s. On the basis of the data presented it is, however, quite hard to make any firm conclusions because of uncertanties of the quality of Russian data. In additon to the data in Fig. 5 Loigu & Leisk (1996) reported that in 1985-1989 average annual TN and TP load into whole L. Peipsi was 55350 and 1163 tonnes, accordingly. These values are substantially higher then the values reported by Russian researchers. Though, in 1998 phosphorus loading increased even this value.

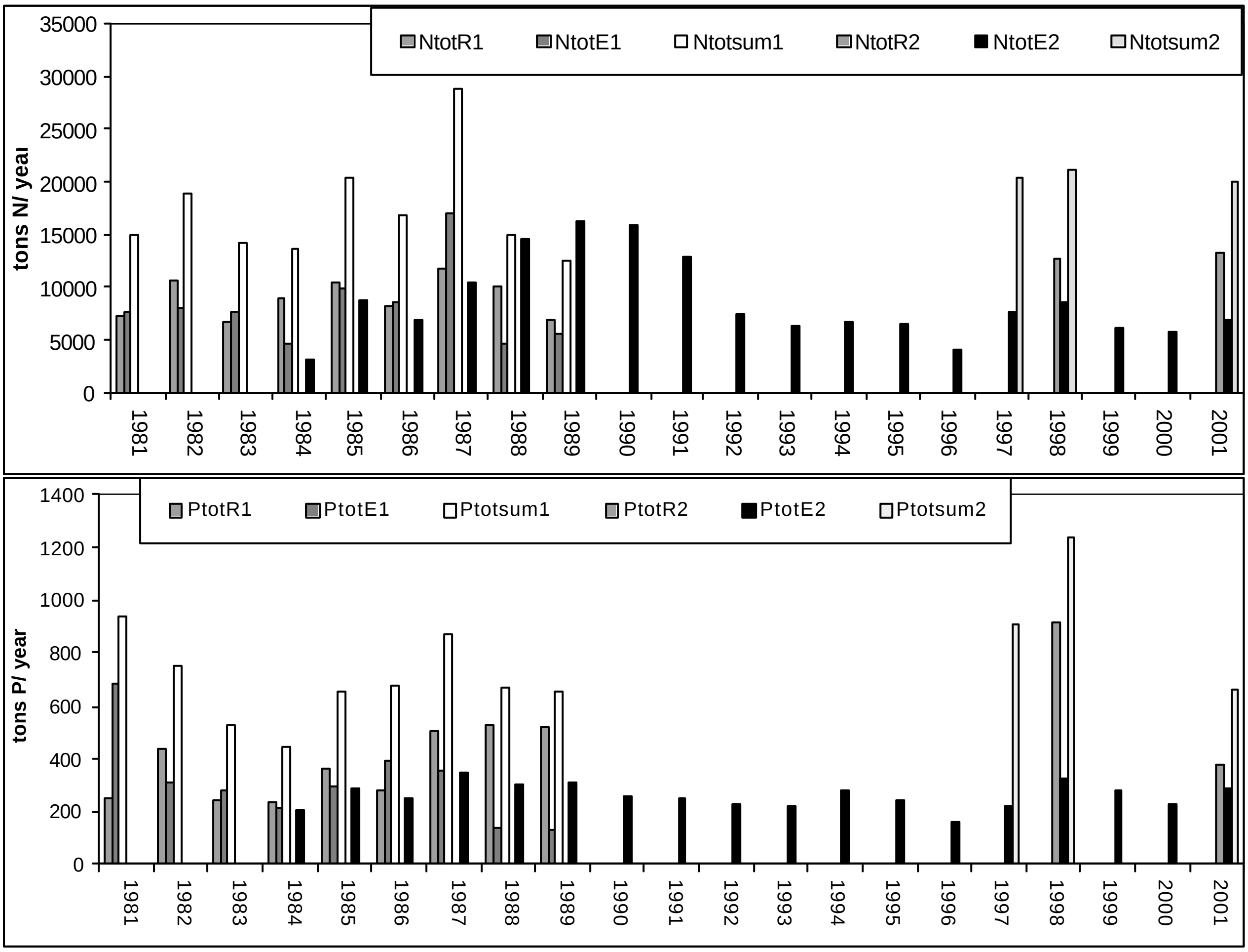

Figure 5. Results of all available loading calculations of Lake Peipsi. R1, E1 and sum1 – calculated by I. Nedogarko; sum1 for 1997 - average for 1995-1997 from Stalnacke et al. *(2002); E2 – calculated by I. Blinova, Ü. Leisk and I. Tõnno; R2 and sum2 for 1998 from Nõges* et al. *(2003); R2 and sum2 for 2001 – calculated by T. Nõges on the basis of measured TN and TP concentrations and discharges of the R. Velikaya obtained from B. Skakalski, and assuming the same proportion of the R. Velikaya in total Russian loading as estimated by Nõges* et al. *(2003)*

Changes of nutrient concentrations in L. Peipsi

No clear trends of TN and TP concentrations can be noticed in Lake Peipsi *s.s.* in recent years. TN declined slightly in the 1990s while TP has remained quite stable (Fig. 6). This is in good accordance with changes in Estonian TN loadings that also declined substantially in the 1990s (Fig. 5). Stability of in-lake TP concentration couples to the TP loading pattern. In lakes Pihkva and Lämmijärv a certain increase in both TN and TP concentrations can be noticed in last years which could indicate somewhat increased loading from Russian side. In L. Lämmijärv the increasing trend of TP concentration is statistically significant (r=0.35, P=0.007), deacreasing trend of TN/TP is significant both in L. Peipsi *s.s.* (r=-0.256, P<0.001) and L. Lämmijärv (r=-0.35, P=0.007). Both phosphorus concentration and the N/P ratio are crucial for phytoplankton abundance and community composition. At high P level and low N/P ratio bloom forming blue-greens are favoured due to their ability to fix atmospheric N_2 in the conditions of N limitation. In L. Peipsi the TN/TP ratio less than 30 gives the advantage to cyanobacteria (Nõges *et al.*, 2002). To reduce the risk of water blooms it is important to to reduce phosphorus loading to the lake. There may be some delay in the reaction of in-lake P concentration to the reduced loading due to P release from sediments. Recent data on sediment chemistry (A. Kisand, unpublished) show, however, that the pool of labile phosphorus in L. Peipsi sediments is much smaller than in deeper lakes and also smaller than in shallow lakes of smaller size. It can be assumed that in a very large lake where sediments are frequently stirred up by waves, labile P is washed out from sediments into the water column and does not accumulate as in smaller and deeper lakes. The nutrient budget calculated for 1998 revealed, however, that L. Peipsi was annually retaining 50-70% of the inflowing phosphorus (Nõges *et al.*, 2003). Accumulated phosphorus seems to be firmly binded in sediments by iron and calcium compounds, and assumingly not easily released if sediments remain aerobic and pH is close to neutral. Consequently, the reduction of phosphorus loading is assumed to decrease in-lake P concentration and reduce cyanobacterial dominance and water blooms in L. Peipsi.

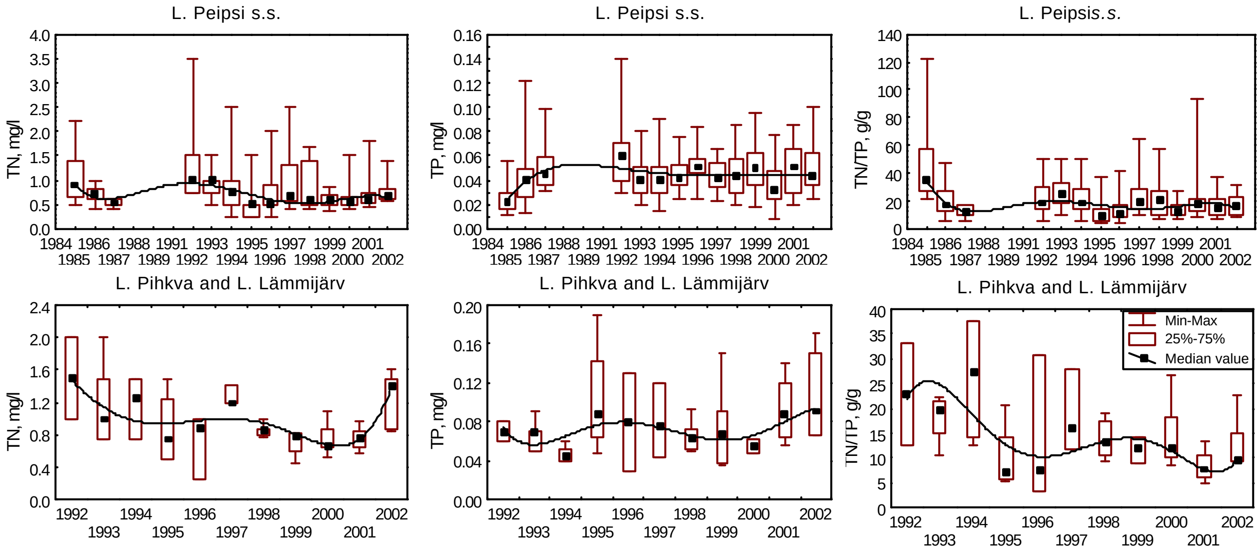

Figure 6. Changes of total nitrogen (TN) and phosphorus (TP) concentration in L. Peipsi in 1984-2002

CONCLUSIONS

The following trends could be distinguished in the watershed and in the ecosystem of Lake Peipsi:

- Since the end of the 1980s, nitrogen loading from Estonian cachment has decreased about 2-fold, a reduction from Russian catchment could also be noticed.
- Phosphorus loading from Estonian side decreased until 1996 and after that started to increase again. High phosphorus loading from Russian catchment occurred, probably, in l995-1998 and, after that, seems to be diminished.
- P concentration has been quite stable in L. Peipsi *s.s.* but incresing in lakes Pihkva and Lämmijärv in the last few years.
- In-lake nitrogen concentration has diminished until the end of the 1990s; an increase can be noticed in last 2 years.
- The N/P ratio in loadings and in the lake has decresed.
- Total amount of phytoplankton has remained at the same level since the 1960s.
- Cyanobacterial blooms have reappeared in recent years and caused summer fish-kills.

Basing on the statements above, it could be concluded that regarding nutrient concentrations, the trophic status of Lake Peipsi has not increased during the last decade. The water blooms resulting in fish-kills are rather caused by the changed N to P ratio in loadings. The destabilisation of Lake Peipsi ecosystem is the result of decreased nitrogen loading in the conditions of non-changed, or even increased phosphorus loading. The most important measure to achieve the further improvement of water quality would be the reduction of phosphorus loading from both Estonian and Russian catchment.

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