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Contemporary trends of temperature, nutrient loading, and water quality in large Lakes Peipsi and Võrtsjärv, Estonia

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From 1961–2004, surface water temperature in large and shallow Lakes Peipsi and Võrtsjärv in Estonia increased significantly in April and August; respectively 0.37–0.75 and 0.32–0.42 degrees per decade reflecting the changes in air temperature. The average annual amount of precipitation in the catchment increased significantly. Reflecting practices in agriculture and wastewater treatment, nutrient loadings to the lakes increased rapidly in the 1980s and decreased again in the early 1990s. As total nitrogen (TN) loading decreased faster than total phosphorus (TP) loading, the TN/TP ratio in the loadings decreased. Both the increased temperature and low TN/TP ratio favoured the development of cyanobacteria blooms in Lake Peipsi. In Võrtsjärv, where the TN/TP mass ratio is about two times higher than in Peipsi, blooms did not occur. Recently, the TN/TP ratio has shown a tendency of increase in both lakes suggesting a certain reduction of blooms to be expected also in Lake Peipsi. Nutrient dynamics in the lakes followed the changes in loadings, showing the ability of shallow lake ecosystems to react sensitively to changes in catchment management as well as in climate.

Keywords: surface water temperature, nutrients, longterm trends

Introduction

Lake Peipsi (3,555 km^2, mean depth 7.1 m) located on the Estonian-Russian border is the largest international lake in Europe. The volume of water in Peipsi is 25 km^{3}and its mean residence time is about 2 years (Jaani, 2001). The River Narva contains the outflow of Lake Peipsi and runs into the Gulf of Finland. Lake Võrtsjärv (270 km^2, mean depth 2.8 m) is the largest lake belonging entirely to Estonia (Figure 1). The watershed of Lake Võrtsjärv (3,104 km^2) lies within the Lake Peipsi catchment (47,800 km^2). Riverine transport is the major pathway for nutrient input into both lakes. Väike Emajõgi is the largest inflow of Võrtsjärv contributing 41% of its water discharge (Nõges P. et al., 2008); the River Emajõgi is the outflow of Võrtsjärv and the largest river discharging into Peipsi from the Estonian part of its watershed (Nõges T. et al., 2005). The majority of phosphorus and nitrogen compounds (>80%) are carried into Lake Peipsi by the Rivers Velikaya and Emajõgi, the first carrying biologically treated sewage from the Russian town of Pskov (∼200,000 inhabitants) and the latter receiving the effluent of the wastewater treatment plant of the Estonian town of Tartu (∼100,000 inhabitants). The treatment plant has been in operation in Tartu since the end of 1998; previously the untreated wastewater from Tartu was discharged directly to the river.

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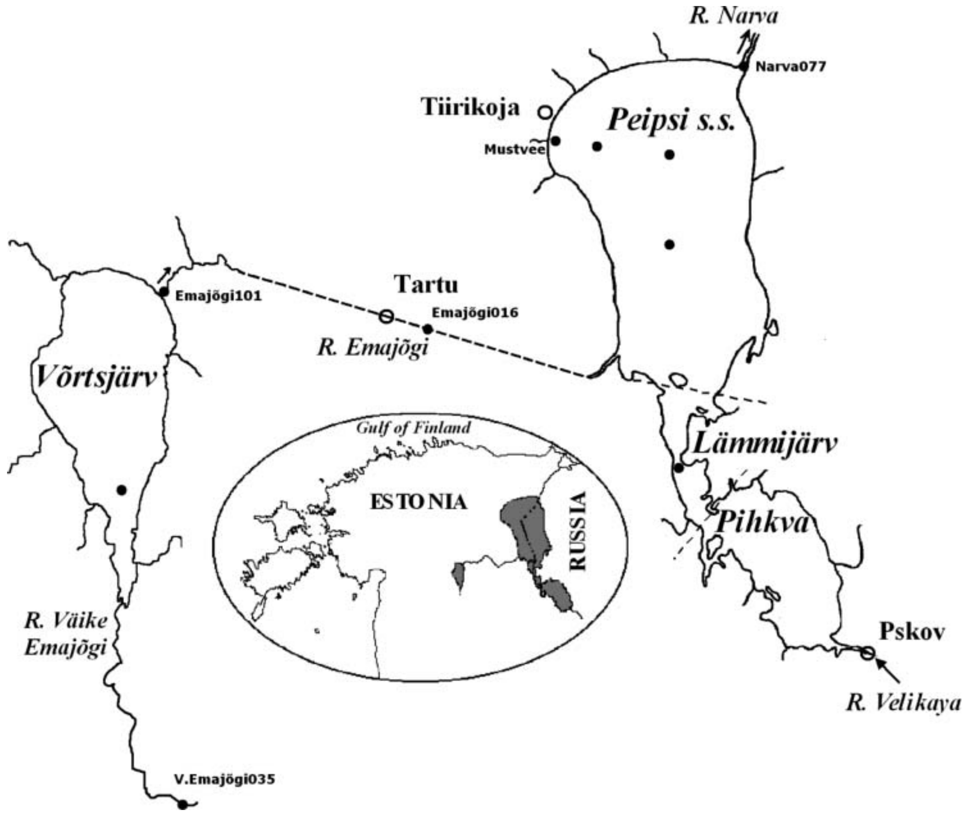

Figure 1. Location map of sampling stations in Lakes Peipsi and Võrtsjärv and their catchment area.

Long-term dynamics in nutrient and organic matter loadings reflect changes in agricultural practices and climate. In the past 40–50 years, European lakes have been subjected to eutrophication caused by the increased supply of nutrients. As a result of decreased loadings since the late 1980s or early 1990s, the ecological status of many lakes has improved considerably (Jeppesen et al., 2005b). The structure of changes in the nutrient supply has been rather different in the Western European countries compared to the countries of the former Soviet Union. In the western countries (e.g. in Denmark), extensive efforts have been made to improve wastewater purification and to reduce phosphorus concentration in the effluent (Kronvang et al., 2005; Jeppesen et al., 2005a). In Eastern Europe (e.g. in the Baltic States), a major nitrogen reduction occurred as a result of the collapse of the Soviet-type agriculture (Järvet, 2001; Blinova, 2001; Juhna and Klavins, 2001). In Estonia the opulent use of fertilizers including swine slurry in the 1970s and 1980s, which lead to high phosphate, ammonium, and organic matter loadings, was replaced by milder and more economic practices in the early 1990s. The knowledge about the nature of climate change and its impacts is far from being complete. The response of lake ecosystems to climate change is complex and often unpredictable as different lake types and ecosystem components may react in individual ways. For instance, increasing water temperature in spring in Estonian inland waters shifted the spawning time of bream (*Abramis brama*) to 10 days earlier, while no shift in the spawning time of roach (*Rutilus rutilus*) has been observed. As a consequence, the difference between spawning times of roach and bream decreased from 22 to 13 days and the difference in average temperatures at the onset of spawning by about 3°C (Nõges P. and Järvet, 2005). Kangur et al. (2007) described a negative effect of high temperature on the abundance of the smelt stock in Lake Peipsi. Climate change may either diminish or magnify the effects of eutrophication.

In the present paper we review the contemporary climatic, hydrological and loading trends observed in Lakes Võrtsjärv, Peipsi and their catchments, and their impact on water quality in these large and shallow lakes.

Material and methods

We analysed long-term trends of air temperature (AT) and precipitation (PR) at two meteorological stations, Tiirikoja and Tartu, located within the catchment of Lake Peipsi (Figure 1). The trend of surface water temperature (SWT) was studied in both Lakes Võrtsjärv and Peipsi; the trends of water discharge (Q), the concentrations of total nitrogen (TN) and total phosphorus (TP), and the TN/TP ratio were studied in the rivers Väike Emajõgi, Emajõgi, and Narva.

AT, SWT and Q were measured by the Estonian Institute of Hydrology and Meteorology according to the guidelines of World Meteorological Organisation (WMO, 1994; 2008). TN and TP were analysed at the accredited laboratory Tartu Environmental Research Centre Ltd according to the methods described by Grasshoff et al. (1983) and corresponding ISO standards. The data were gathered in the state monitoring program of Estonian surface water quality and obtained through the Centre of Information and Technology at Estonian Ministry of Environment.

We analysed the data from the river stations for which the longest time series of nutrient concentrations were available (see Tables 1 and 2 for the length of time series). In the River Väike Emajõgi the station V.Emajõgi035 is situated downstream from the town of Valga, the main polluter of this river. In the River Emajõgi the station Emajõgi101 is situated at the outflow from Lake Võrtsjärv and was assumed to characterise the integrated water quality in this lake; the station Emajõgi016 is situated downstream from the town Tartu, the main polluter of this river. In the River Narva, the station Narva077 is situated at the outflow from Lake Peipsi and was assumed to characterise the integrated water quality in this lake. To characterise nutrient concentrations in Lake Peipsi main basin (Peipsi s.s.; Figure 1) we averaged the data from three pelagic sampling stations; for Lake Võrtsjärv the data from one pelagic sampling station was used (see Figure 1 for location of the sampling stations).

To reveal long-term trends, we analysed the monthly and yearly average values of AT, Q and SWT calculated from the daily measurements, and yearly average values of TN and TP calculated from the monthly measurements. Based on the Kolmogorov-Smirnov test, all indicated data were normally distributed ($p > 0.2$). Changes in a time series can occur either gradually or abruptly (a step change). A non-parametric Mann-Kendall test for gradual trends and a Cumulative deviation test for step changes were applied (Trend C1.0.2 Catchment Modelling toolkit, CRC for Catchment Hydrology), the details of these methods are described by Kundzewicz and Robson (2004).

Results and Discussion

Trends of air temperature and lake surface water temperature

At Tartu and Tiirikoja stations the average annual AT increased by 0.4° per decade in 1961–2004 (Nõges T., 2009), and the increasing trend of AT (Figure 2A) had a step change in 1987 (Table 1). Water temperature and ice cover are most directly affected by climate forcing. The existence of consistent trends has been demonstrated for water temperatures in rivers (Hari et al., 2006) and lakes (Livingstone, 2003; Straile et al., 2003; Arhonditsis et al., 2004; Coats et al., 2006; Dokulil et al., 2006) and for ice phenology (Weyhenmeyer et al., 2005). In the large and shallow Lakes Peipsi and Võrtsjärv, daily SWT was largely dependent on daily AT during ice-free period ($R^2 = 0.86$, $n > 3000$). From 1961–2004, SWT in Peipsi and Võrtsjärv increased significantly in April and August, by 0.37–0.75 and 0.32–0.42 degrees per decade, respectively (Nõges T., 2009). In Võrtsjärv and in the southern part of Peipsi at Mehikoorma, the increasing trend of SWT in August (Figure 2B) had a significant step change in 1989 (Table 1) which did not occur in northern Peipsi at Mustvee (Nõges T., 2009).

Trends and relationships of precipitations and river hydrology

The average annual PR had significant increasing trends at Tartu and Tiirikoja in 1961–2004 (Figure 2C) with a step change in 1976 in Tartu and in 1977 in Tiirikoja (Table 1). On a monthly basis, PR increased significantly for January-February ($p < 0.01$), March ($p < 0.1$), and June ($p < 0.05$). The average annual discharge in the River Väike Emajõgi was significantly positively related to the average annual PR in Tartu (Figure 2D). From 1961–2004, the average annual Q in this river had a significant increasing trend (Figure 3A) with a step

Table 1. Trends of average annual air temperature (AT), precipitations (PR), discharge (Q), concentration of total nitrogen (TN) and phosphorus (TP) and TN/TP ratio, and surface water temperature (SWT) in August in Lakes Võrtsjärv and Peipsi and their watershed.

Parameter	Site	Period	Trend	Trend p	Step year	Step p		Mean	Min	Max	STD
ATyear, °C	Tiirikoja	1961–2004	increasing	<0.01	1987	<0.01	1961–1986	4.29	2.75	6.18	1.01
							1987–2004	5.32	2.56	6.67	1.01
ATyear, °C	Tartu	1961–2004	increasing	<0.01	1987	<0.01	1961–1986	4.72	3.32	6.60	0.94
							1987–2004	5.82	3.20	7.17	0.98
PRyear, mm day^{-1}	Tiirikoja	1961–2004	increasing	<0.01	1977	<0.01	1961–1976	1.44	0.98	1.77	0.22
							1977–2004	1.75	1.23	2.13	0.26
PRyear, mm day^{-1}	Tartu	1961–2004	increasing	<0.01	1976	<0.01	1961–1975	1.45	0.98	1.96	0.25
							1976–2004	1.76	1.25	2.30	0.31
SWTaug, °C	Peipsi Mustvee	1961–2004	increasing	<0.05		NS	1961–1988	17.9	15.2	20.4	1.3
							1989–2004	18.9	15.2	22.2	1.9
SWTaug, °C	Võrtsjärv	1961–2004	increasing	<0.01	1989	<0.05	1961–1988	17.9	15.8	19.8	1.1
							1989–2004	18.9	16.7	21.0	1.2
Qyear, $m^3\ s^{-1}$	V. Emajõgi035	1961–2007	increasing	<0.01	1977	<0.01	1961–1976	6.74	4.66	13.49	2.07
							1977–2007	8.80	4.52	15.05	1.95
TNyear, mg l^{-1}	V. Emajõgi035	1986–2007	decreasing	<0.01	1991	<0.01	1986–1990	3.66	2.68	5.43	1.09
							1991–2007	1.68	1.29	2.50	0.31
TPyear, mg l^{-1}	V. Emajõgi035	1986–2007	decreasing	<0.01		NS	1986–1990	0.091	0.065	0.150	0.034
							1991–2007	0.071	0.056	0.089	0.009
TN/TPyear, mg mg^{-1}	V. Emajõgi035	1986–2007	decreasing	<0.05	1991	<0.01	1986–1990	54.8	47.3	68.9	8.3
							1991–2007	25.1	16.2	46.5	6.6

Table 2. River and lake water chemistry in 1992–2007 in the watershed of Võrtsjärv and Peipsi.

	n	Mean	Min	Max	STD	M-K trend, p
V. Emajõgi035						
TN, mg l^{-1}	189	1.62	0.50	4.60	0.74	decreasing, <0.1
TP, mg l^{-1}	189	0.072	0.032	0.160	0.022	decreasing, <0.01
TN/TP, mg mg^{-1}	189	23.7	3.6	75.0	11.4	NS
Võrtsjärv						
TN, mg l^{-1}	315	1.40	0.34	3.70	0.60	NS
TP, mg l^{-1}	317	0.050	0.010	0.330	0.026	NS
TN/TP, mg mg^{-1}	315	34.3	4.4	142.9	22.4	NS
Emajõgi101						
TN, mg l^{-1}	155	1.31	0.46	5.00	0.63	NS
TP, mg l^{-1}	155	0.046	0.010	0.190	0.027	NS
TN/TP, mg mg^{-1}	155	37.4	2.6	120.0	25.7	NS
Emajõgi016						
TN, mg l^{-1}	192	2.08	0.55	5.60	0.94	NS
TP, mg l^{-1}	192	0.077	0.028	0.220	0.027	decreasing, <0.1
TN/TP, mg mg^{-1}	192	30.6	6.9	132.4	19.1	NS
Peipsi s.s.						
TN, mg l^{-1}	274	0.65	0.25	2.10	0.25	NS
TP, mg l^{-1}	274	0.042	0.008	0.240	0.021	NS
TN/TP, mg mg^{-1}	274	18.2	3.2	51.8	9.0	NS
Narva077						
TN, mg l^{-1}	153	0.62	0.07	1.40	0.26	NS
TP, mg l^{-1}	153	0.038	0.010	0.140	0.024	NS
TN/TP, mg mg^{-1}	152	22.3	2.4	138.0	18.5	NS

change in 1977 (Table 1). On a monthly basis, Q had significant increasing trends for January ($p < 0.05$), February ($p < 0.01$), March ($p < 0.01$), and June ($p < 0.05$).

Trends of river water chemistry

In the River Väike Emajõgi the yearly average concentrations of TN and TP and the TN/TP ratio decreased significantly since 1986 (Figure 3B, C, D). A step change of TN and TN/TP took place in 1991 (Table 1) at the time of the breakdown of the Soviet Union. The application of large amounts of fertilizers in the 1980s was often accompanied by substantial nutrient leakage into water bodies. Compared to the levels at the end of the 1980s, only 5–10% of N-, P- and K-mineral fertilizers and 30% of the manure were applied to the fields at the end of the 1990s (Järvet et al., 2002). In the post-Soviet period, since 1992, the decrease in TN and TP concentrations continued in the River Väike Emajõgi. In the Emajõgi and Narva Rivers as well as in the lakes, the yearly average TN and TP concentrations and the TN/TP ratio did not reveal any significant trend (Table 2). The mean nutrient concentrations in the lakes and their outflows were well coupled.

Trends of riverine nutrient loads

In the 1980s, the riverine loading of nutrients into Lakes Peipsi and Võrtsjärv increased drastically; while in the early 1990s a sharp decrease occurred, primarily in TN loadings. As TN loading decreased faster than TP loading, the TN/TP ratio in the loadings decreased (Nõges T. et al., 2003a, 2005, 2007). Multiple regression analysis showed that the rate of fertilization was the most important factor determining the nitrogen runoff from the catchment of Lake Võrtsjärv (Järvet et al., 2002). Since the end of the 1980s, TP concentrations in the main inflow of Lake Võrtsjärv and TP loadings showed a decreasing trend (Table 1, Figure 4B) while the loadings of TN increased in the 2000s (Figure 4A) resulting in an increased of the TN/TP loading ratio (Figure 4C).

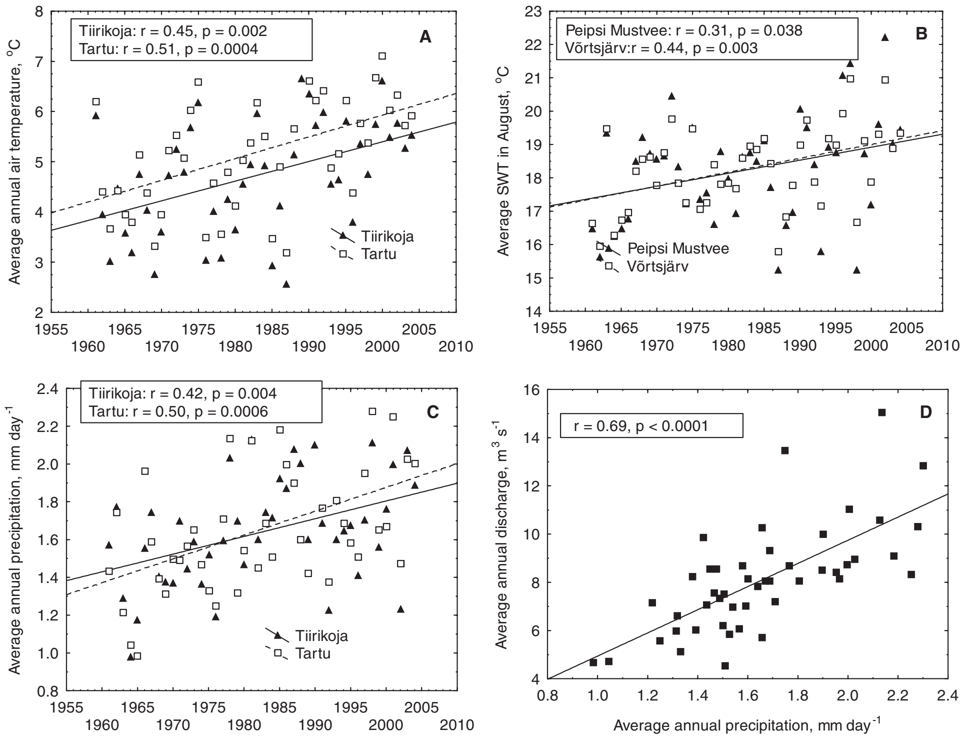

Figure 2. Linear trends of average annual air temperature (A) and precipitations (C) in the meteorological stations Tartu and Tiirikoja, surface water temperature (SWT) in Lakes Võrtsjärv and Peipsi (B) in 1961–2004 ($n = 44$), and the relationship between precipitations in Tartu and the discharge in the River Väike Emajõgi. See site locations on Figure 1 and the results of Mann-Kendall test for trends and a Cumulative deviation test for step changes in Table 1.

In Peipsi, it is more difficult to get an overview of the total nutrient loadings as the data is scarce from a large part of the watershed belonging to Russia. To provide insight, we combined two sets of published data (Figure 4D–F). Nõges T. et al. (2005) analysed all available data on loadings from both the Estonian and the Russian subcatchments and showed that the total loading of TP in 2001 was almost equal to the high loadings at the beginning of the 1980s and that TP loadings from Russia in mid 1990s even exceeded those of the 1980s. Loigu and Leisk (1996) reported that in each of 1985–1989 the annual TN and TP loads into Lake Peipsi were 55,350 and 1,163 tonnes, respectively. According to Nõges T. et al. (2003a), the respective values in 1998 were 23,800 and 1,300 tonnes, and 60% of the total TP loading entered the southernmost basin (Lake Pihkva) from the River Velikaya. Loigu et al. (2008) reported that Peipsi received 15,650 tonnes of TN (Figure 4D) and 712 tonnes of TP (Figure 4E) in 2001–2005.

The information on the loadings from the Russian basin of Peipsi is quite scarce and inaccessible, but as part of this loading reaches the main basin through Lake Lämmijärv, we can indirectly judge the dynamics of Russian loadings based on the situation in Lämmijärv. TP concentration in this basin increased until 2003 (Figure 5E) and a corresponding growth of phosphorus loading from the Russian subcatchment could be supposed. It could be due to the lack of maintenance of efficient wastewater treatments in Pskov and other settlements after the collapse of the Soviet Union (Nõges T. et al., 2007). In the last years, TP concentration started to decrease both in Lämmijärv and Peipsi, indicating some improvement of the situation. This could partly be explained by smaller loads observed in dry years. As our recent studies showed (Nõges P. et al., 2007), both components forming the load (water discharge and concentrations of substances) decreased in dry years. In Võrtsjärv the dynamics of both N and P concentrations (Figure 5G, H) were consistent to the loading history (Figure 4A, B), showing the high sensitivity of large shallow lakes to changes in human activity in the catchment.

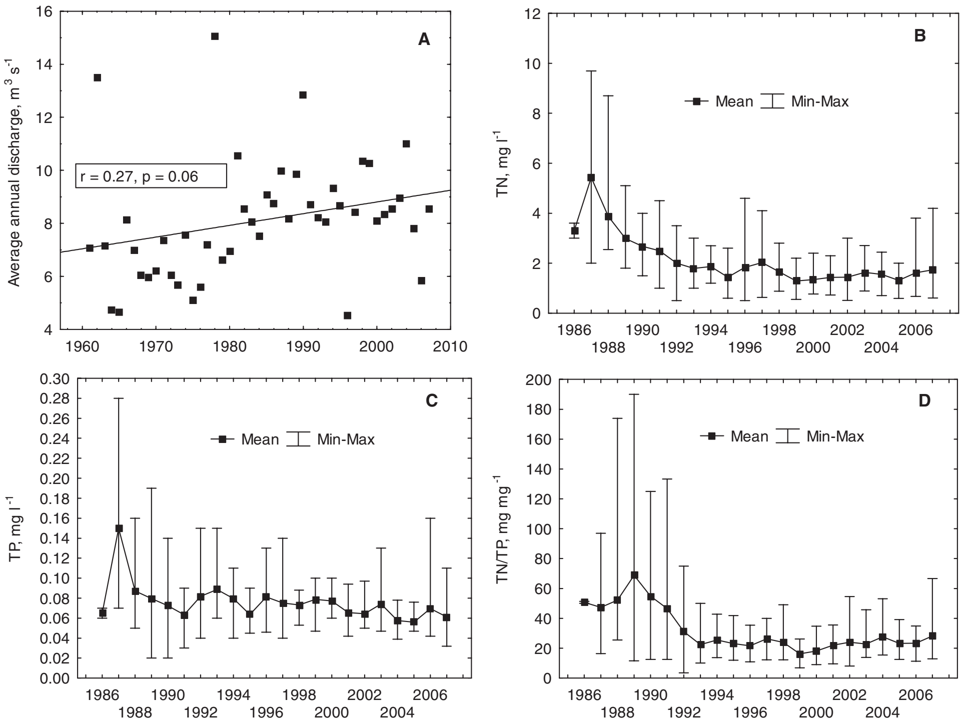

Figure 3. Linear trend of the annual average discharge (A) in 1961–2007 ($n = 47$) and long-term dynamics of the concentrations of total nitrogen (TN) and phosphorus (TP), and TN/TP ratio in 1986–2007 in the River Väike Emajõgi. The results of Mann-Kendall test for trends and a Cumulative deviation test for step changes are presented in Tables 1 and 2.

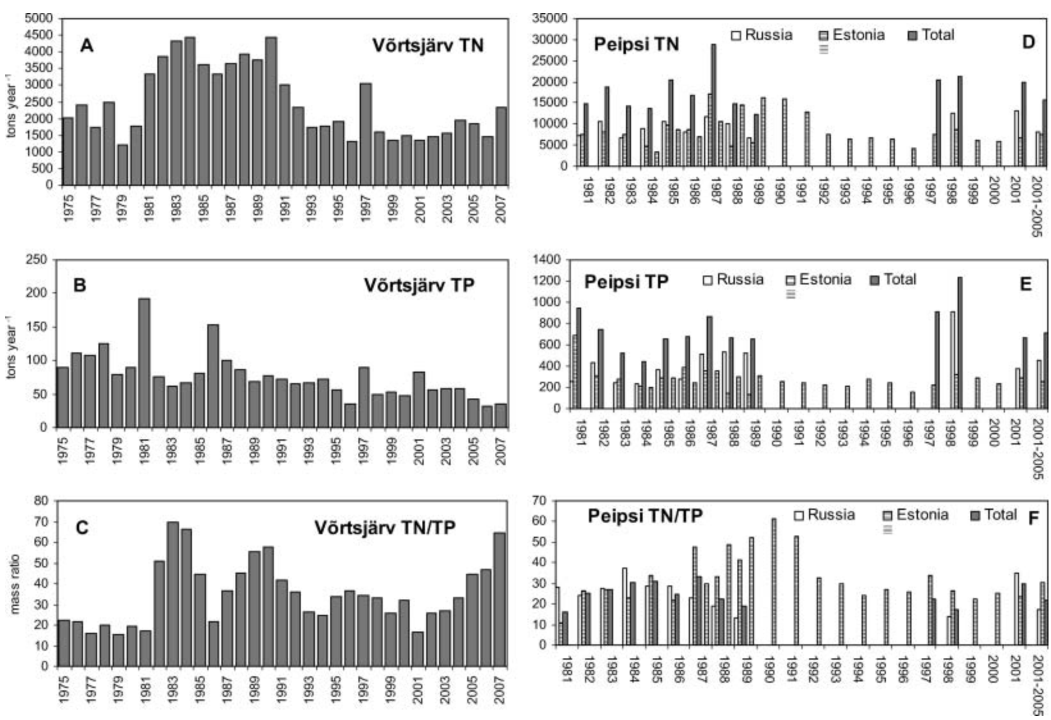

Figure 4. Long-term dynamics of the loading of total nitrogen (TN) and phosphorus (TP) and TN/TP ratio in the loading of Lake Võrtsjärv (A, B, C) and into Lake Peipsi (data from Nõges T. et al., 2005; Loigu et al., 2008).

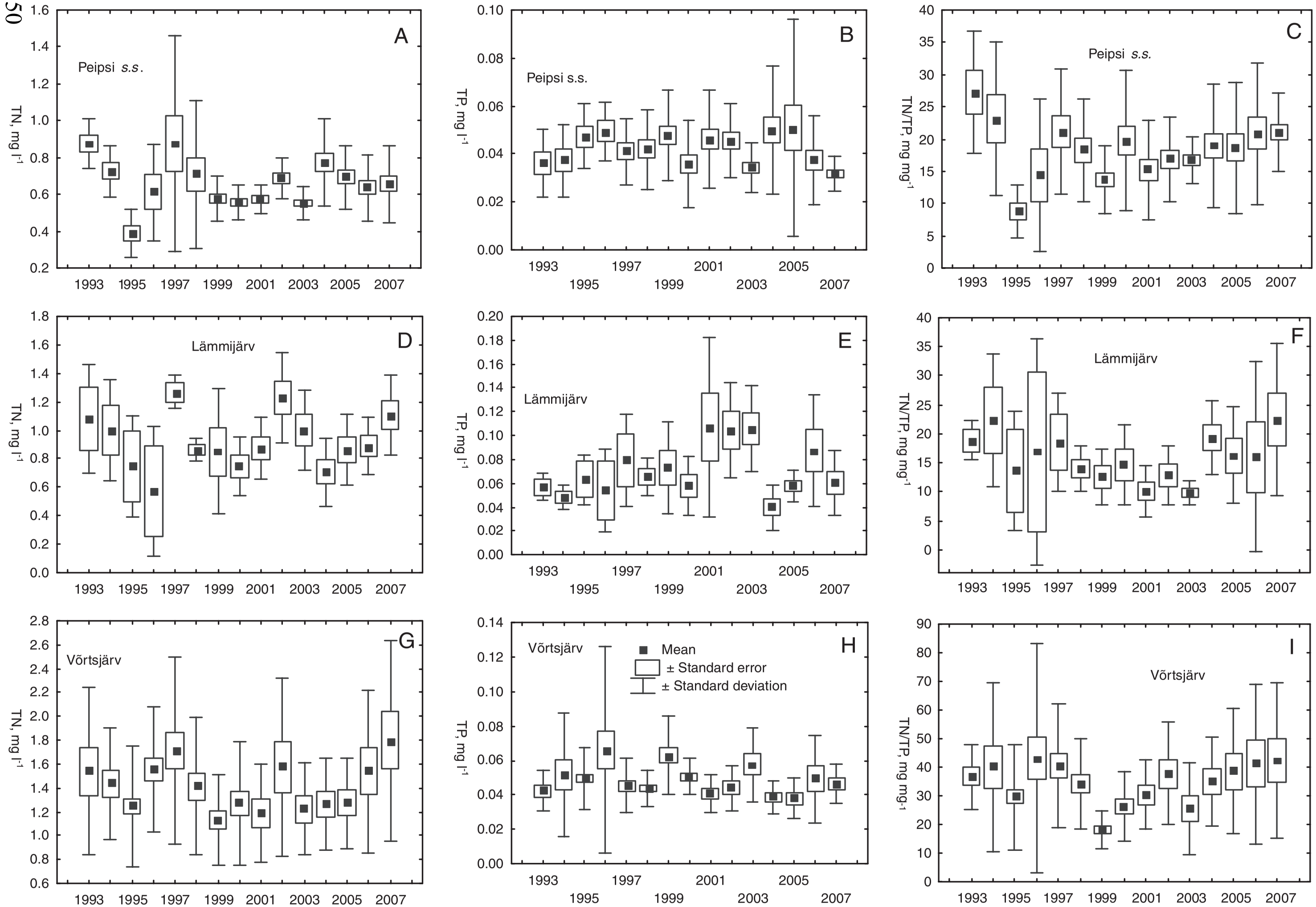

Figure 5. Changes of total nitrogen (TN) and phosphorus (TP) concentration and TN/TP ratio in Lakes Peipsi (A, B, C; average of three sampling stations shown on Figure 1), Lämmijärv (D, E, F) and Võrtsjärv (G, H, I) in post-Soviet period 1993–2007.

Trends of the lake water quality

According to paleolimnological evidence, the eutrophication of Lake Peipsi escalated in the 1970s–1980s (Heinsalu et al., 2007). The eutrophication history was similar for Lake Võrtsjärv (Nõges P. and Järvalt, 2004). Cyanobacterial blooms, a common phenomenon in both lakes in the first half of the 20th century, were caused predominantly by meso-eutrophic species: *Gloeotrichia echinulata* in Peipsi and *Anabaena lemmermannii* in Võrtsjärv (Mühlen and Schneider, 1920; Laugaste et al., 2001). Blooms ceased in the 1980s due to heavy nitrogen loading and intensified again in Peipsi in late 1990s, together with the decrease of the N/P ratio (Nõges et al., 2007). Reappearing cyanobacteria blooms in Peipsi have caused serious summer fish-kills in recent years (Kangur et al., 2005). These fish-kills seem to be a straightforward consequence of reduced nitrogen levels at remaining high phosphorus levels and, thus, the changed N/P ratio. In Võrtsjärv where recurrent winter fish-kills have been observed, the climatic factors affecting the water level are more crucial (Nõges T. et al., 2003b). In Peipsi the N_2-fixing *Gloeotrichia echinulata, Aphanizomenon flos-aquae* and *Anabaena* species prevail in summer phytoplankton. In Võrtsjärv the dominant cyanobacteria *Limnothrix planktonica, L. redekei* and *Planktolyngbya limnetica* are not capable to fix N_2, and the main N_2-fixing taxa *Aphanizomenon skujae* and *Anabaen*a spp. commonly do not dominate. TN/TP mass ratio in Võrtsjärv is about two times higher than in Peipsi (Figure 5C, F, I, Table 2). The critical TN/TP mass ratio in May–October, below which the N_2-fixing cyanobacteria achieved high biomasses, was around 40 in Võrtsjärv and around 30 in Peipsi (Nõges T. et al., 2008). In Võrtsjärv the TN/TP ratio is above this critical value both in the inflows and in the lake while in Peipsi it often drops below this threshold. Recently the TN/TP ratio has shown an increasing tendency in both lakes (Figure 5C, F, I). Increased TN loading (Figure 4A) and in-lake concentrations (Figure 5A, D, G), and decreased or stabilised TP loading (Figure 4B) and in-lake concentrations (Figure 5B, E, H), suggest that a reduction of water-blooms could be expected in Lake Peipsi.

However, both lakes are large and shallow and largely controlled by climatic factors, either directly by increased water temperature or indirectly through the fluctuations of non-regulated water level (Nõges T. et al., 2003b). The consequences of the water level fluctuations on the ecosystem of Lake Võrtsjärv are discussed in detail by P. Nõges et al., in this issue. Temperature dependence of cyanobacteria development and N_2 fixation should be taken into account in the context of global warming, as higher water temperatures support both cyanobacterial growth (Jöhnk et al., 2008; Paerl and Huisman, 2008) and P recycling from sediments (Genkai-Kato and Carpenter, 2005). According to Nõges T. et al. (2008) the temperature dependence of N_2 fixers in Lake Peipsi is the main factor determining the increasing potential share of N_2 fixing species in the phytoplankton community along with increasing water temperature.

Conclusions

Studied lakes Peipsi and Võrtsjärv are largely controlled by climatic factors; either directly by increased water temperature or indirectly through the fluctuations of non-regulated water levels. Changes in air temperature, surface water temperature in both lakes have increased significantly during 1961–2004. Practices in agriculture and wastewater treatments are reflected through nutrient loadings to the lakes, which increased rapidly in the 1980s and decreased again in the early 1990s. As total nitrogen (TN) loading decreased faster than total phosphorus (TP) loading, the TN/TP ratio in the loadings decreased. Both the increased temperature and low TN/TP ratio favoured the development of cyanobacteria blooms in Peipsi. In Võrtsjärv, where the TN/TP mass ratio is about two times higher than that in Peipsi, blooms did not occur. Nutrient dynamics in the lakes followed the changes in loadings, showing the ability of shallow lake ecosystems to react sensitively to changes in catchment management. Recently, the TN/TP ratio has shown a tendency to increase, suggesting a certain reduction in blooms to be expected.

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