Effects of large-scale changes in emissions on nutrient concentrations in Estonian rivers in the Lake Peipsi drainage basin

Arvo Iitala,*, Per Stålнacke, Johannes Deelstra, Enn Loigu, Margus Pihlak

*Institute of Environmental Engineering, Tallinn Technical University, Ehitajate tee 5, 19086 Tallinn, Estonia
bNIVA—Norwegian Institute for Water Research, P.O. Box 173, Kjelsås, N-0411 Oslo, Norway
cJordforsk-Norwegian Centre for Soil and Environmental Research, F. A. Dahl’s vei 20, N-1432 Ås, Norway
dInstitute of Mathematical Statistics, Tartu University, J. Liivi 2-513, 50409 Tartu, Estonia

Received 30 November 2003; revised 1 May 2004; accepted 1 July 2004

Abstract

The fall of the Iron Curtain resulted in dramatic changes in Eastern Europe, including substantial reductions in the use of fertilisers and livestock production, as well as a marked decrease in water consumption by both the general population and industries. This situation has created a unique opportunity to study the way that rivers have responded to these changes. Here, the impact of these reductions on concentrations of nutrients (N and P) at 22 sampling sites on Estonian rivers are examined. There were statistically significant downward trends (one-sided test at the 5% level) in total nitrogen (TN) concentrations at 20 of the 22 sites. These decreases in TN relate to: (i) substantial reductions in the use of organic and inorganic fertilisers, (ii) reduction of cultivated and ploughed areas and increased proportions of grassland and abandoned land and (iii) improvements in farm management practices. For total phosphorus (TP), significant downward trends were detected at only two sites, and there were also two upward trends. The TP trends can be mainly explained by changes in phosphorus discharges from municipal sewage treatment plants. Fifteen downward trends and one statistically significant upward trend were found for the TN:TP ratio. The general decline in this ratio has likely been conducive to blue-green algae blooms in the recipient, Lake Peipsi.

Keywords: Land use; Nitrogen; TN:TP ratio; Phosphorus; Trend analysis; Water quality; Estonia

1. Introduction

Many field studies have shown that losses of nitrogen in surface runoff are correlated with the rates and methods of fertiliser application, the proportion of land that is cultivated, and the prevailing farm management practices (Kauppi, 1979; Loigu and Velner, 1985; Rekolainen, 1989; Keeney and DeLuca, 1993; Zablocki and Pienkovski, 1999; Mander et al., 1998, 2000; Tumas, 2000; Kutra et al., 2002). The studies mainly dealt with the possible impact of increased emissions of nutrients on the water quality. During the last 10–15 years considerable changes in agricultural practice and waste water treatment took
place in Eastern Europe, but only a few river-basin scale studies examined the impact on rivers exerted by the less extensive land-use and decreases in fertiliser application combined with the improved performance of wastewater treatment plants (WWTP). The results are widely varying and both lack of or weak responses in rivers (Berankova and Ungerman, 1996; Procházková et al., 1996; Tonderski, 1997; Stálnacke et al., 2003; Povilaitis et al., 2003) as well as strong downward trends for nutrient concentrations have been reported (Pekarova and Pekar, 1996; Oláh and Oláh, 1996; Hussain et al., in press; Povilaitis et al., 2003).

An unprecedented decrease in the use of fertilisers and livestock production in Estonia that has been greater than in most other Eastern European countries (Fertilizer Yearbook, 2002), as well as the implementation of more effective waste water treatment technologies in municipalities and industries has created a unique opportunity to study the way that rivers have responded to these changes.

Inorganic fertilisers were widely used in Estonian agriculture during the Soviet period (i.e. before 1991), and application reached a peak of 270,000 tons (300 kg ha\(^{-1}\)) annually in 1987–1988 (Agriculture in Estonia, 1997). However, comprehensive economic, technical and social changes took place in Estonia after the country regained its independence. For example, the use of fertilisers has decreased considerably over the last 15 years, and the levels observed in 2001 constituted only about 11% (29,700 tons) of the peak in 1987–1988 that correspond to applications of less than 100 kg ha\(^{-1}\) for mineral fertilisers (63 kg N ha\(^{-1}\) and 13 kg P\(_2\)O\(_5\) ha\(^{-1}\)) and less than 30 tons ha\(^{-1}\) for organic fertilisers (Agriculture, 2001, 2002). Furthermore, the number of livestock units decreased from 800,000 (0.82 LU ha\(^{-1}\) of arable land) in 1988 to less than 390,000 (0.34 LU ha\(^{-1}\) of arable land) in 1994, and the level today is approximately the same as in 1994 (Agriculture, 2001, 2002). Slaughtering of livestock reduced correspondingly the amount of manure.

Point source emissions of N and P to surface waters in Estonia have also decreased as a result of the economic recession in the early 1990s. This was due to a combination with modernisation of industrial production and the construction of new and improvement of existing wastewater treatment plants (WWTPs) in major towns (Vassiljev et al., 2001).

Studies carried out in some smaller agricultural watersheds in Estonia have shown relatively low levels of N and P, as compared to the concentrations found in, for example, the Nordic countries (Loigu and Iital, 2000; Iital and Loigu, 2001; Vagstad et al., 2001, Iital et al., 2002). The low levels of N and P detected in Estonia might be explained by the following: (i) decreased rates of fertiliser application; (ii) lower livestock density; (iii) differences in land use (more natural and cultural grasslands); (iv) hydrological conditions that entail longer water residence time and higher buffering capacity, and substantial retention of these substances within catchments. The majority of the field drainage ditches used today were established in the 1970s and 1980s, and maintenance of the main ditches in these land improvement systems has been insufficient in recent years. Due to this situation, many watercourses are now overgrown with bushes and macrophytes, which has enhanced the retention potential, denitrification and biological uptake.

This study, carried out in the Lake Peipsi drainage basin that makes up 36% of the Estonian territory, investigates the effects of large-scale changes in emissions on nutrient concentrations and how long it will take to detect the response of a river system to changes in land use or agricultural practices. The time series of nitrogen and phosphorus concentrations measured in rivers are statistically evaluated and special attention was paid to natural variation in runoff–concentration relationship. That kind of information can help environmental authorities and decision and policy makers establish realistic goals. Such knowledge can also be highly useful in the implementation of river basin management plans within the EU Water Framework Directive and in selection of adequate measures to achieve good ecological and chemical status of all water bodies by 2015.

2. Study area, data base and methods

2.1. Study area

The Lake Peipsi catchment, including the surface of the lake itself, has an area of 47,800 km\(^2\), of which 16,323 km\(^2\) is in Estonia and the rest in Russia and Latvia. The northern part of this drainage basin has a
sedimentary cover consisting of Ordovician and Silurian limestones; the southern part is characterised by sandy-silty and clayey Devonian deposits, which are overlaid by quaternary deposits that are usually less than 5 m thick, and are thickest (often > 100 m) in the uplands. The topography of the catchment is relatively flat, with maximum elevations of about 30–100 m above sea level. The glaciolacustrine or till-covered plain of the Estonian part of the Peipsi catchment is higher in the south-west and north-west due to the presence of the Pandivere (166 m), Haanja (318 m), Otepää (217 m), and Sakala (146 m) uplands. Most rivers that flow into Lake Peipsi have their sources in these elevated areas. Lake Peipsi drainage area is a sub-catchment of the basin of the Gulf of Finland and the Baltic Sea, and Lake Peipsi is connected with the basin of the Gulf of Finland and the Baltic Sea via the Narva River. The mean air temperature in the Peipsi catchment is 14–15 °C in June and −4 to 4.5 °C in December, and the mean annual precipitation is 600–650 mm (Jaagus and Tarand, 1988). Forests predominate land cover in the north of the catchment (up to 60–70%), but coverage decreases southwards (about 30–40%). The proportion of mires is higher in the drainage areas of rivers in the northern part of the region. Agriculture in the Lake Peipsi catchment includes animal husbandry and the production of arable crops, mainly cereals.

2.2. Sampling strategy and analytical methods

Statistical analysis was undertaken to discern trends in time series of total nitrogen (TN) and total phosphorus (TP) concentrations and TN:TP ratios for 22 sampling sites on 17 rivers and streams in Estonia. A monthly time resolution was used for data from 18 of the sampling sites, and a bimonthly resolution for the remaining four sites (i.e. Põltsamaa-Rutikvere, Võhandu-Himmiste, Pedja-Törve, and Öhne-Rooba; Fig. 1). To analyse total nitrogen, samples were digested with peroxodisulphate, after which the concentrations of nitrate were determined. Total phosphorus was analysed by using the peroxodisulphate digestion procedure to convert the various forms of phosphorus into dissolved orthophosphate. The time series covered at least the period 1986–2001 for 14 of the sites, whereas only 1991 (or 1992) to 2001 was investigated for the other eight sites (Table 2). Both small and large sub-catchments (ranging in size from 108 to 47,815 km²) were studied in all parts of the Estonian portion of the Lake Peipsi basin (Table 1). The drainage areas of the Narva (site No. 19) and Piusa (site No. 9) Rivers

Fig. 1. Map showing the sampling sites.
also include territory within the Russian Federation (69 and 34%, respectively).

### 2.3. Statistical methods

The statistical properties of water quality data (nutrient concentrations) are usually not normally distributed, and they often exhibit a seasonal pattern because they are influenced by water discharge (Gilliom and Helsel, 1986). Here, a recently modified version of the seasonal Mann–Kendall test (Libslander and Grimvall, 2002), referred to as the partial Mann–Kendall (PMK) test, which has been adapted to account for the influence of confounding (i.e., meteorological or hydrological) variables was used with water discharge as such a variable. The univariate Mann–Kendall statistic for a time series \( \{Z_k, k = 1,2,\ldots,n\} \) of data is defined as

\[
T = \sum_{j<i} \text{sgn}(Z_i - Z_j)
\]

where

\[
\text{sgn}(x) = \begin{cases} 
1, & \text{if } x > 0 \\
0, & \text{if } x = 0 \\
-1, & \text{if } x > 0
\end{cases}
\]

If there are no ties between the observations, and there is no trend in the time series, the test statistic is asymptotically normally distributed with

\[
E(T) = 0 \quad \text{and} \quad \text{Var}(T) = n(n-1)(2n+5)/18
\]

If the response variable is measured during several \( \omega \) seasons, the seasonal Mann–Kendall test is computed by first separating the data into \( \omega \) subseries, each of which represents a season. In this way

\[
T_j = \sum_{k<i} \text{sgn}(Z_{kj} - Z_{kj}) \quad j = 1, \ldots, \omega
\]

is the Mann–Kendall statistic for season \( j \), which is summed over all seasons to obtain the seasonal statistics.

### Table 1

Main characteristics of the rivers monitored in the Lake Peipsi drainage basin

<table>
<thead>
<tr>
<th>Site no.</th>
<th>River</th>
<th>Name of sampling site</th>
<th>Catchment area (km²)</th>
<th>Population density (inhab/km²)</th>
<th>Land type</th>
<th>Forest (%)</th>
<th>Wetlands, other natural (%)</th>
<th>Agricultural (%)</th>
<th>Arable (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alajõgi</td>
<td>Alajõe HS</td>
<td>140</td>
<td>2.7</td>
<td>67.2</td>
<td>17.5</td>
<td>14.9</td>
<td>14.2</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>Ahja</td>
<td>Kiidjärve</td>
<td>336</td>
<td>10.9</td>
<td>44.9</td>
<td>3.2</td>
<td>51.3</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pölltsamaa</td>
<td>Rutikvere</td>
<td>861</td>
<td>15.8</td>
<td>45.5</td>
<td>10.0</td>
<td>42.4</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Rannapungerja</td>
<td>Roostaja</td>
<td>214</td>
<td>5.0</td>
<td>59.5</td>
<td>17.5</td>
<td>21.1</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Emajõgi</td>
<td>Rannu-Jõesuu HS</td>
<td>3,374</td>
<td>16.2</td>
<td>42.4</td>
<td>6.0</td>
<td>41.9</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Võhandu</td>
<td>Räpina</td>
<td>1,144</td>
<td>29.8</td>
<td>43.4</td>
<td>6.4</td>
<td>47.1</td>
<td>9.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Võhandu</td>
<td>Himmite HS</td>
<td>848</td>
<td>32.9</td>
<td>45.0</td>
<td>4.2</td>
<td>47.4</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Tänassilma</td>
<td>Oiu</td>
<td>454</td>
<td>31.9</td>
<td>46.2</td>
<td>10.3</td>
<td>42.7</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Piusa</td>
<td>Korela</td>
<td>523</td>
<td>9.5</td>
<td>48.9</td>
<td>4.5</td>
<td>45.7</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Avijõgi</td>
<td>Mulgi HS</td>
<td>366</td>
<td>8.2</td>
<td>66.2</td>
<td>7.0</td>
<td>26.1</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Tagajõgi</td>
<td>Tudulimna</td>
<td>252</td>
<td>2.8</td>
<td>72.7</td>
<td>20.5</td>
<td>6.4</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Kääpa</td>
<td>Kose</td>
<td>282</td>
<td>5.1</td>
<td>60.5</td>
<td>10.5</td>
<td>27.9</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Tarvastu</td>
<td>Põdraoja</td>
<td>108</td>
<td>16.4</td>
<td>41.8</td>
<td>0.9</td>
<td>56.3</td>
<td>30.9</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Pedja</td>
<td>Jõgeva SAJ</td>
<td>665</td>
<td>7.5</td>
<td>57.5</td>
<td>7.7</td>
<td>33.9</td>
<td>19.9</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Pedja</td>
<td>Tõrve HS</td>
<td>776</td>
<td>15.7</td>
<td>55.8</td>
<td>7.9</td>
<td>34.8</td>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Väike-Emajõgi</td>
<td>Pikassila</td>
<td>1,270</td>
<td>24.1</td>
<td>48.7</td>
<td>4.0</td>
<td>44.5</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Emajõgi</td>
<td>Tartu HS</td>
<td>7,828</td>
<td>9.4</td>
<td>45.8</td>
<td>10.4</td>
<td>41.6</td>
<td>21.3</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Emajõgi</td>
<td>Kavastu</td>
<td>8,539</td>
<td>21.9</td>
<td>44.0</td>
<td>9.5</td>
<td>43.6</td>
<td>20.9</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Narva</td>
<td>Vasknarva HS</td>
<td>47,815</td>
<td>6.9</td>
<td>47.0</td>
<td>9.6</td>
<td>39.3</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Öhne</td>
<td>Suislepa</td>
<td>557</td>
<td>14.3</td>
<td>49.3</td>
<td>9.5</td>
<td>38.9</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Öhne</td>
<td>Roobe</td>
<td>266</td>
<td>5.4</td>
<td>56.1</td>
<td>14.2</td>
<td>27.6</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Porijõgi</td>
<td>Reola HS</td>
<td>241</td>
<td>12.9</td>
<td>41.8</td>
<td>2.5</td>
<td>55.0</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>
The Mann–Kendall statistic (MK-Stat) is the function of $S$, and this statistic has a standard normal distribution. The conditional mean of the test statistic is

$$E(T_0^r | T_0^j) = \frac{\text{Var}(T_0^r) T}{\text{Var}(T_j)}$$

and variance

$$\text{Var}(T_0^r | T_0^j) = \text{Var}(T_0^r) - \frac{\text{Var}(T_0^j)^2}{\text{Var}(T)}$$

where $T_0^r$ is a statistic for the response variable, $T_0^j$ is a statistic for the explanatory variable, $\text{Var}(T_0^r)$ and $\text{Var}(T_0^j)$, respectively, denote the variance of $T_0^r$ and $T_0^j$, and $\text{Var}(T_0^r)$ is the covariance between the test statistic of the response variable and the covariate. If there is only one response (nutrient concentrations) and one explanatory variable (water discharge), the distribution of the test statistic will be asymptotically normal.

3. Results

The trends in average annual water discharge at the studied sampling sites during the monitored period show rather remarkable variability. According to the data from the Estonian Meteorological and Hydrological Institute, the average annual discharge increased in the Avijoõgi and Tagajoõgi Rivers, but decreased slightly in the Alajoõgi, Kääpää, Tarvastu, Põltsamaa, Võhandu, Emajoõgi, and Pedja Rivers (Fig. 2). For some rivers (the Õhne, Vääke-Emajoõgi, Narva, and Ahja), no trends in long-term mean annual discharge were detected.

The proportion of agricultural land (arable land and permanent natural grasslands) in the sub-catchments is still relatively high today, in most cases at least 40%. However, the share of arable land (temporary crops, temporary meadows, land temporarily in fallow and abandoned land) is generally rather small (Table 1), and the mean TN concentrations in the rivers were strongly correlated to the fraction of arable land in the catchment (Fig. 3). The population densities were highest (more than 30 inhabitants km$^{-2}$) in the drainage areas of the Võhandu and Tänassilma Rivers (Table 1) and were fairly low (less than 3 inhabitants per km$^2$) in the northern part of the

Lake Peipsi drainage basin, more precisely in the drainage areas of the Alajoõgi and Tagajoõgi Rivers, which are also characterised by large forested and wetland areas (>85%).

TN concentrations in the rivers showed downward trends at almost all sites (Table 2). Very rapid decrease in TN levels occurred as early as the beginning of the 1990s at some of the locations (e.g. Võhandu-Räpina, Avijõgi-Mulgi, Ahja-Kiidjärve, and Põltsamaa-Rutikvere; Figs. 4 and 5). Significant downward trends in TN were also observed in some of the sub-catchments dominated by forests and wetlands. At almost all sites there was the occurrence of pronounced seasonal fluctuation in TN, with the lowest levels in the summer period and the highest concentrations from late autumn to spring. The PMK test revealed statistically significant ($p < 0.05$; one-sided test) downward trends in TN at 20 of the 22 sampling stations (Table 2), and the level of significance was high ($p < 2\%$) at 18 of these 20 sites. No significant upward trends were observed at any of the sampling locations.
For TP, the results of the PMK test were statistically significant for data from four sites (Table 2): two downward trends (Tänassilma and Tarvastu) and two upward trends (Alajögi, Öhne-Suislepa).

Analysing the TN:TP mass ratios, 15 statistically significant downward trends and one upward trend was detected. Six of the 18 rivers showed no trends in TN:TP mass ratios, and five of those six (i.e. the Ahja, Põltsamaa, Tarvastu, Pedja-Tõrve, and Narva) exhibited significant downward trend in TN concentrations.

4. Discussion

Several studies conducted in the last decade have examined the impact on rivers exerted by the rapid changes in land-use and decreases in fertiliser application in Eastern Europe. Notably, a review prepared by Stålnacke et al. (2004) showed that widely varying results have been reported for the different areas that have been studied. For example, lack of (or only weak) responses in rivers (i.e. no downward trends) have been reported for N and P concentrations by Berankova and Ungerman (1996), Procházková et al. (1996) and Tonderski (1997), and for nitrogen levels by Stålnacke et al. (2003) and Povilaitis et al. (2003). Furthermore, downward trends in Eastern European rivers have been observed for nutrients by Pekarova and Pekar (1996), Oláh and Oláh (1996) and Hussian et al. (2004), and for phosphorus in particular by Stålnacke et al. (2003) and Povilaitis et al. (2003).

In Estonia, studies of this kind have previously been performed chiefly in single, smaller catchments. Loigu and Vassiljev (1997) noted a clear downward trend in nitrate concentrations in the rivers of the small and intensively cultivated Kurna catchment (23.2 km², 68% arable land) during the period 1987–1996. This trend was particularly conspicuous for the peak concentrations, and the cited authors stated that

### Table 2

<table>
<thead>
<tr>
<th>Station Sampling site</th>
<th>Total N</th>
<th>MK-Stat</th>
<th>p-value*</th>
<th>Total P</th>
<th>MK-Stat</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Years monitored</td>
<td></td>
<td></td>
<td>Years monitored</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Alajögi-Alajõe</td>
<td>1984–2001</td>
<td>-1.85</td>
<td><strong>0.032</strong></td>
<td>1984–2001</td>
<td>2.20</td>
<td><strong>0.014</strong></td>
</tr>
<tr>
<td>2 Ahja-Kiidjärve</td>
<td>1985–2001</td>
<td>-3.85</td>
<td><strong>&lt;0.001</strong></td>
<td>1981–2001</td>
<td>-1.20</td>
<td>0.114</td>
</tr>
<tr>
<td>3 Põltsamaa-Ruikvere</td>
<td>1986–2001</td>
<td>-3.71</td>
<td><strong>&lt;0.001</strong></td>
<td>1986–2001</td>
<td>-1.34</td>
<td>0.091</td>
</tr>
<tr>
<td>4 Rannapungerja-Roostoja</td>
<td>1992–2001</td>
<td>0.06</td>
<td>0.475</td>
<td>1992–2001</td>
<td>-1.41</td>
<td>0.079</td>
</tr>
<tr>
<td>5 Emajõgi-Jöesuu</td>
<td>1987–2001</td>
<td>-3.43</td>
<td><strong>&lt;0.001</strong></td>
<td>1987–2001</td>
<td>0.87</td>
<td>0.193</td>
</tr>
<tr>
<td>6 Võhandu-Räpina</td>
<td>1986–2001</td>
<td>-3.92</td>
<td><strong>&lt;0.001</strong></td>
<td>1986–2001</td>
<td>-0.74</td>
<td>0.231</td>
</tr>
<tr>
<td>7 Võhandu-Himmiste</td>
<td>1991–2001</td>
<td>-2.76</td>
<td>0.003</td>
<td>1986–2001</td>
<td>-1.30</td>
<td>0.098</td>
</tr>
<tr>
<td>8 Tänassilma-Oiu</td>
<td>1986–2001</td>
<td>-3.59</td>
<td><strong>&lt;0.001</strong></td>
<td>1986–2001</td>
<td>-3.75</td>
<td><strong>&lt;0.001</strong></td>
</tr>
<tr>
<td>9 Pusa-Korela</td>
<td>1992–2001</td>
<td>-2.35</td>
<td><strong>0.009</strong></td>
<td>1992–2001</td>
<td>-0.29</td>
<td>0.386</td>
</tr>
<tr>
<td>10 Avijõgi-Mulgi</td>
<td>1992–2001</td>
<td>-2.25</td>
<td><strong>0.012</strong></td>
<td>1992–2001</td>
<td>-1.31</td>
<td>0.094</td>
</tr>
<tr>
<td>11 Tagajõgi-Tudalinna</td>
<td>1992–2001</td>
<td>-2.26</td>
<td><strong>0.012</strong></td>
<td>1992–2001</td>
<td>0.27</td>
<td>0.393</td>
</tr>
<tr>
<td>12 Kääpa-Kose</td>
<td>1986–2001</td>
<td>-2.30</td>
<td>0.011</td>
<td>1986–2001</td>
<td>-0.07</td>
<td>0.472</td>
</tr>
<tr>
<td>13 Tarvastu-Põdrajoja</td>
<td>1986–2001</td>
<td>-3.35</td>
<td><strong>&lt;0.001</strong></td>
<td>1986–2001</td>
<td>-2.61</td>
<td><strong>0.005</strong></td>
</tr>
<tr>
<td>14 Pedja-Jõevesa</td>
<td>1986–2001</td>
<td>-0.01</td>
<td>0.495</td>
<td>1987–2001</td>
<td>-0.83</td>
<td>0.202</td>
</tr>
<tr>
<td>15 Pedja-Tõrve</td>
<td>1986–2001</td>
<td>-2.51</td>
<td><strong>0.006</strong></td>
<td>1987–2001</td>
<td>-0.51</td>
<td>0.304</td>
</tr>
<tr>
<td>16 Väike-Emajõgi-Pikasilla</td>
<td>1986–2001</td>
<td>-3.79</td>
<td><strong>&lt;0.001</strong></td>
<td>1986–2001</td>
<td>-0.27</td>
<td>0.393</td>
</tr>
<tr>
<td>17 Emajõgi-Tartu</td>
<td>1984–2001</td>
<td>-2.06</td>
<td>0.020</td>
<td>1982–2001</td>
<td>1.02</td>
<td>0.154</td>
</tr>
<tr>
<td>18 Emajõgi-Kavastu</td>
<td>1986–2001</td>
<td>-1.75</td>
<td>0.040</td>
<td>1986–2001</td>
<td>-0.86</td>
<td>0.196</td>
</tr>
<tr>
<td>19 Narva-Vasknarva</td>
<td>1992–2001</td>
<td>-1.87</td>
<td>0.031</td>
<td>1992–2001</td>
<td>1.05</td>
<td>0.146</td>
</tr>
<tr>
<td>20 Öhne-Suislepa</td>
<td>1986–2001</td>
<td>-3.58</td>
<td><strong>&lt;0.001</strong></td>
<td>1986–2001</td>
<td>2.31</td>
<td><strong>0.010</strong></td>
</tr>
<tr>
<td>21 Öhne-Reoobe</td>
<td>1991–2001</td>
<td>-2.36</td>
<td><strong>0.009</strong></td>
<td>1986–2001</td>
<td>1.29</td>
<td>0.099</td>
</tr>
<tr>
<td>22 Porijõgi-Reola</td>
<td>1992–2001</td>
<td>-2.99</td>
<td><strong>0.001</strong></td>
<td>1992–2001</td>
<td>0.04</td>
<td>0.485</td>
</tr>
</tbody>
</table>

* The p-value is significant if < 0.05. Bold type indicates results that are statistically significant at the 0.05 level (one-sided test).
it could be explained by the decreased application of fertilisers and agricultural production in the catchment. Similarly, Mander et al. (2000) found downward nitrogen and phosphorus trends in another small (258 km$^2$) agricultural catchment in Estonia.

The results of these earlier investigations conducted in Estonia are confirmed by the findings of our comprehensive study, which represent both small and large sub-catchments of the entire Estonian part of the Lake Peipsi drainage area. Our most notable observations are as follows: (i) the decrease in TN concentrations was rapid, occurring as early as the beginning of the 1990s at many of the sites (Fig. 1);

Fig. 4. Time series of total nitrogen concentrations in rivers in the Lake Peipsi basin.

\[ y = 11084e^{-0.0003x} \]
\[ R^2 = 0.4077 \]

Fig. 5. Variation in concentrations of total nitrogen (TN) at the Võhandu-Räpina sampling station in 1986–2001.
(ii) there was also a decrease in TN concentrations at sites with catchments dominated by forests; (iii) there was very little evidence of downward trends in TP concentrations; (iv) there was a decline in the amplitude and total variability of the nitrogen series between the 1980s and the early/mid 1990s, after which, the pattern of amplitude and variability of the TN concentrations was rather stable. These interesting findings require more detailed discussion.

It is widely accepted that nutrient concentrations in streams and rivers may respond differently to changes in physical–geographical conditions, agricultural production, rates of fertiliser application, and intensity of land use. Plot experiments carried out in small watersheds in Estonia during the late 1990s have shown that substantial amounts of nitrogen can be lost via the root zone after the harvesting of crops, resulting in nitrate concentrations as high as 60 mg N l\(^{-1}\) in soil–water (Loigu and Itäl, 2000; Tamm, 2001). At the same time, the nitrate concentrations in groundwater and small agricultural streams are low, only about 2–4 mg N l\(^{-1}\). Stålnacke et al. (1999) pointed out that denitrification, presumably in smaller streams and channels, plays an important role in nitrogen reduction in the Baltic countries. The pH in stream water is usually high (≥ 8) during summer, which promotes the volatilisation of ammonia. In addition, the water residence times in Estonian river catchments are much longer than in many other areas with similar geographical conditions (Deelstra, et al., 1998). All of the cited studies clearly indicate that a plot-field catchment system has a considerable potential for nitrogen retention. Assuming that the retention was also high in the 1980s, when the levels of fertiliser application and agricultural intensity were greatest, the rapid decline in TN concentrations that occurred in Estonia during the early 1990s is somewhat surprising. In Latvia, where there was a similar drop in fertiliser use and the hydro-meteorological conditions are similar to those in Estonia, only weak downward trends in dissolved inorganic nitrogen were reported for the same time period (Stålnacke et al., 2003). This can, in part, be explained by the larger size of the river catchments studied in Latvia and by differences in hydro-geological conditions (i.e. possible nitrogen retention in groundwater systems). In our study, the downward trends in TN in forested catchments (e.g. Tagajõgi, Alajõgi, and Avijõgi) were probably caused primarily by the same factors that induced the downward trends in other catchments: namely, insufficient maintenance of main ditches during the past decade, resulting in overgrowth of bushes and macrophytes, which in turn enhances the retention potential (i.e. denitrification and biological uptake).

The improvement of agricultural management practices in Estonia during the 1990s has led to more sustainable use of inorganic and organic fertilisers. This change has resulted in a remarkable decrease in the maximum concentrations of nitrogen in rivers (Loigu and Vassiljev, 1997), because, for example, during the Soviet period mineral fertilisers and manure were applied also to frozen or snow covered soil. According to FAO Statistics (Fertilizer Yearbook, 2002), the decline in the use of fertilisers, especially nitrogenous fertilisers, has been much greater in Estonia (Fig. 6) than in most other Eastern European countries. Considering the area of arable land (crop fields and cultural grasslands) in Estonia, about 34% was unused in 2001 (Agriculture, 2001, 2002), and the share of wintergreen area was quite remarkable, being as high as 80% in some small agricultural catchments. Moreover, it is possible that the particular hydro-geological conditions influence the rate at which nutrient concentrations in streams and rivers respond to changes in land use and nutrient emissions. The Estonian bedrock consists largely of Silurian and Ordovician limestone. Hence, there can be rapid exchange of water between upper and lower water tables through existing cracks. Many rivers, especially in the Pandivere Upland, are fed by groundwater that is rich in nitrate-nitrogen. After the fall of the Soviet Union, the nitrate content in groundwater aquifers decreased substantially (Tamm, 2003). Several field studies have shown that

![Fig. 6. Consumption of mineral fertilisers in Estonia in 1990–2001.](image)
at locations where oxygen present at very low concentrations and where for example organic carbon is available significant denitrification has been found. Gambrell et al. (1975) concluded that losses of nitrate-nitrogen in undisturbed, poorly drained soils with relatively high water tables are lower compared to naturally well-drained soils, mainly as a result of denitrification. McMahon and Böhlke (1996) studied naturally well-drained soils, mainly as a result of relatively high water tables are lower compared to nitrogen in undisturbed, poorly drained soils with decrease in NO₃ concentrations. Gilliam and Skaggs found that denitrification accounted for 15–30% of the decrease in NO₃ concentrations. McMahon and Böhlke (1996) studied denitrification capacity in Nebraska’s South Platte River aquifer which is affected by irrigation, and found that denitrification accounted for 15–30% of the decrease in NO₃ concentrations. Gilliam and Skaggs (1986) and Evans et al. (1992) have shown that water table management can reduce NO₃−N in drainage water by over 60%. This decrease was at least partly caused by an increase in denitrification. Due to insufficiently maintained amelioration systems, the groundwater level rose in Estonia in 1990s and the soil is maintained at saturated or almost saturated conditions for longer time periods leading to anaerobic environments in soils, possible increase in denitrification rates and to lower TN concentrations in open streams. The significant downward trend in TN concentrations at site No. 19 (Narva-Vasknarva), which actually describes the quality of the water in Lake Peipsi, was probably caused by the marked decrease in nitrogen loads (Blinova, 2001) transported to the lake during the last decade. Seasonal trends were also investigated here, but the overall picture provided by our results was not clear on many occasions, probably due to the low TN concentrations. However, at some of the sites with a high proportion of agricultural or arable land (i.e. Tänassilma, Võhandu-Räpina, Piusa, and Porijõgi), significant downward trends were more pronounced during autumn (September to November) and winter (December to February). Seasonal trends were not as significant at the other sites with a high share of arable land (e.g. Põltsamaa, Tarvastu, and Pedja-Tõrve). Significant trends in TN concentrations were not detected in the upstream part of the Pedja River (Pedja-Jõgeva sampling site), which is an area that is generally not directly affected by human activities.

The present statistical trend analysis clearly indicated that the concentrations of TP in most rivers were fairly stable throughout the periods studied. Moreover, other investigators (Loigu, 1993; Haraldsen et al., 2001) have found that the amount of P in the topsoil in Estonia is still at the same level as in the late 1980s, even though there had been a substantial decrease in the rate of application of P fertilisers. The soil has a large capacity to absorb phosphorus, but release of that element can occur after a time lag of several years (Vagstad et al., 2001). A clear downward trend in TP levels was observed in only two rivers, both draining into Lake Võrtsjärv. This can probably be explained by more efficient treatment of municipal wastewater, a decrease in the number of inhabitants in rural areas, and, in particular, less intensive agriculture. In addition, the two rivers that showed downward trends in phosphorus have relatively small catchments, which is probably the reason that responses to the decrease in loads of this element were more readily detected. Despite the improved performance of WWTPs the overall phosphorus load to the rivers is still fairly high. The reason for this is that the number of households and industries connected to the sewerage systems in larger municipalities has grown, which has increased the amount of nutrient-laden wastewater delivered to the treatment plants. Furthermore, rises in the price of drinking water and wastewater treatment have led to a substantial drop in the overall consumption of potable water by the general population, which has resulted in increased concentrations of nutrients in both the wastewaters delivered to WWTPs and the effluents released from those facilities. A typical example of this can be seen in the city of Tartu, which represents the largest single source of pollution in the study area. The efficiency of phosphorus removal is about 80% at the sewage treatment plant in Tartu. However, due to high levels of this element in inlet waters (on average 12.5 mg P l⁻¹ in 2002), the concentrations in the effluent have exceeded the maximum permissible level of 1 mg P l⁻¹ (Fig. 7). In some sub-catchments with high relative point source emissions, evidence of decreased phosphorus concentrations was found, and this was particularly noticeable during high-flow periods due to a dilution effect. For instance, in the Tänassilma River (site No. 8), the observed downward trend in TP was most likely related to the decline in the amount of wastewater delivered to the WWTPs (Fig. 8). Considering the 0.9 percentile of TP concentrations, there was a decrease from 0.18 mg l⁻¹ in the early 1990s to 0.11 mg l⁻¹ in 2001. Only the Tänassilma and Tarvastu Rivers exhibited downward trends in concentrations of both...
TN and TP. However, the Tänassilma was also the only river in which an upward trend in the TN:TP mass ratio was detected. These findings indicate that the TP concentrations have decreased more than the corresponding TN concentrations. It is assumed that phosphorus compounds limit primary production and therefore also control the trophic level in surface waters (Järvekülg, 1993). Consequently, a low N:P ratio may increase the probability of nitrogen limitation in surface waters. In our study, a decline in the N:P ratios was noted at 15 of the 22 sites we investigated (Table 3, Fig. 9). Moreover, other researchers (Nöges et al., 2002) have observed downward trends in N:P ratios and more intensive cyanobacteria blooms in Lake Peipsi in the 1990s, and the latter phenomenon was particularly pronounced in 2001 and 2002. Given that cyanobacteria can directly utilise molecular nitrogen, reducing phosphorus emissions will no doubt improve the quality of surface water in the Lake Peipsi catchment. On the other hand, the economic recovery that is expected in Estonia in coming decades will probably also lead to more intensive agriculture (e.g. a larger proportion of cultivated land and a higher rate of fertiliser application) and consequently increase the losses of nutrients to waters, especially with respect to nitrogen (Mourad et al., 2003).

5. Conclusions

- Twenty statistically significant downward trends in TN (one-sided test at the 5% level) were found from a total of 22 sites on rivers in Estonia, and it is obvious that the rivers have responded to the following: (i) a dramatic decrease in the use of organic and inorganic fertilisers and livestock numbers; (ii) increased proportions of grassland

Fig. 7. Concentration of total phosphorus (TP) in the effluent water discharged from the wastewater treatment plant in Tartu in 2001 and 2002.

Fig. 8. Time series of phosphorus concentrations in the Tänassilma River in 1992–2002.
and abandoned land at the expense of cultivated and ploughed areas; (iii) better farm management practices.

- There were significant downward trends for TP at only two sampling sites, and there were also upward trends at two sites. The trends in TP can be explained by changes in phosphorus emissions from the municipalities.

- Considering TN:TP ratios, 15 downward trends and one statistically significant upward trend were observed for the TN:TP ratio. The general decline in the TN:TP ratios has promoted blue-green algae blooms in the recipient, Lake Peipsi. Consequently, it is imperative that decision makers and managers focus much more attention on removal of phosphorus.

- The rivers in Estonia and Latvia show remarkable differences in TN trends, even though the changes in agricultural practices have been similar in the two countries. This may be partly due to differences in the sizes of the river catchments and varying hydrogeological conditions, although further studies are needed to confirm that assumption.

### Acknowledgements

We thank the Estonian Environment Information Centre for providing the data. The study was performed within the EC-funded project MANTRA-East (Contract No. EVK1-CT-2000-00076). We are also grateful to Patricia Ödman for revision of the English text.

### References


