The influence of drained peat soils on diffuse nitrogen pollution of surface water

Anatoli Vassiljev and Irina Blinova

ABSTRACT

Eutrophication caused by excess nutrient loads is the main problem for Estonian surface waters. Even after the drastic decrease in the application of mineral fertilizers at the beginning of the 1990s, the concentrations of nitrogen and phosphorus in many rivers remained at undesirable and unexpectedly high levels. The investigation showed that drained peat soils are an important source of nitrogen export to the surface waters. Runoff of nitrogen from drained peat soils is, on average, 1.5-fold higher than from agricultural lands in Estonia.

Key words | diffuse pollution, nutrients, peat soils, river water quality

Anatoli Vassiljev (corresponding author)
Tallinn University of Technology,
Ehitajate tee 5, Tallinn 19086,
Estonia
E-mail: *avasil@staff.ttu.ee*

Irina Blinova
National Institute of Chemical Physics and Biophysics,
Akadeemia tee 23, Tallinn 12618,
Estonia

INTRODUCTION

According to the Water Framework Directive (2000), good status of surface water must be achieved by the year 2015. However, the eutrophication, caused by enlarged loads of nutrients (nitrogen and phosphorus) from watersheds, still remains one of the most important problems for surface waters in Estonia (Iital *et al.* 2010). In many rivers, the concentrations of nutrients exceed the upper hydrochemical limit values of good status established in Estonia (3 mg/L for total nitrogen and 0.08 mg/L for total phosphorus (Classes 2001)). Nitrogen concentrations in some rivers exceed the limit five-fold. It is sometimes impossible to explain such high nitrogen concentrations by known pollution sources. This fact impedes elaboration of the effective water protection measures.

According to current opinion, the drastic increase of surface water pollution by nutrients during the late 1970s was caused, above all, by effluent discharge (point sources) and by intensive use of commercial fertilizer in agriculture (diffuse pollution). As a result, primary attention has been focused on the measures for reducing the nutrient loads from the above-mentioned sources. Reconstruction of old sewage treatment plants and opening new ones has significantly decreased nutrient pollution load from point sources during the last decades. However, it has been estimated that in Estonia diffuse sources play a noticeable role in the formation of the total nutrient load. For example, 60% of the total annual nitrogen load and 40% of the total phosphorus load from the Lake Peipsi watershed (nearly one-third of the territory of Estonia) come from diffuse sources (Vassiljev & Stålnacke 2005). The changes in the agricultural sector of Estonian economy at the beginning of the 1990s led to a drastic decrease in the application of mineral fertilizers (Figure 1) and also in livestock population. Nevertheless, very little evidence that these changes in agricultural practices noticeably affected the concentrations of nutrients in rivers was found (Blinova & Vassiljev 2004; Stålnacke *et al.* 2004; Lepistö *et al.* 2006). The nutrients runoff from some watersheds remained at undesirable and unexpectedly high levels. This fact confirms the opinion that the impact of agriculture (particularly use of mineral fertilizers) on the pollution of surface water by nutrients was overestimated (Thomas *et al.* 1992).

Hoffmann *et al.* (2000) hypothesized that intensive pollution of surface water by nutrients in Sweden and Finland in the 1960s was caused not only by agricultural activity but also by wide-scale melioration, which was conducted at the same time. The significant increase of nutrient runoff from drained areas was also observed after the drainage of forests and peatlands (Lundin & Bergquist 1990; Prévost *et al.* 1999). Peat soils can act as a source as well

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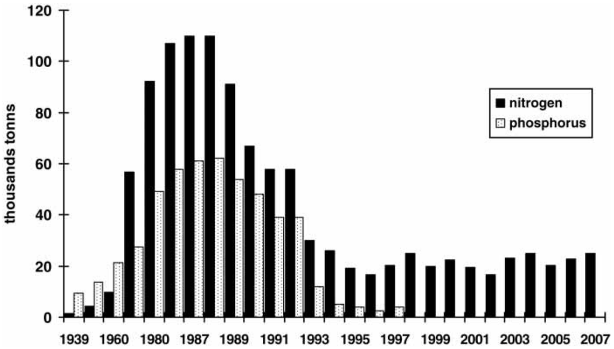

Figure 1 | Use of mineral fertilizers in Estonia.

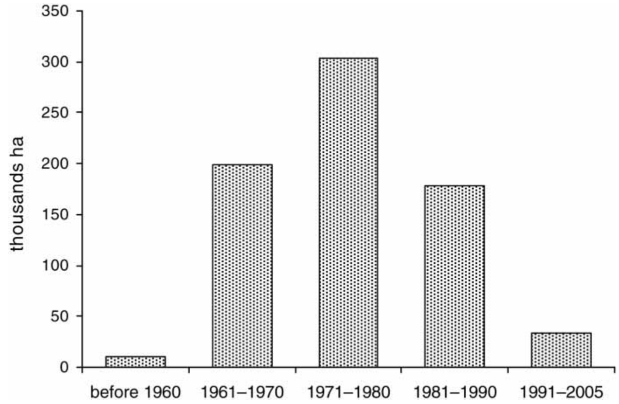

Figure 2 | Dynamics of drainage works in Estonia (Estonian Ministry of Agriculture 2007).

as a sink of nutrients, depending on the peat type and drainage conditions (Peverly 1982; Heathwaite 1991). However, intensively managed peat soils are generally considered as a source of nutrients because the indigenous peat can contain considerable amounts of nutrients, which are available for leaching (Rakovskiy & Pigulevskaya 1978; Heathwaite 1991).

The drainage, which is a common practice for reducing moisture and for improving aeration conditions in soil, especially in swamped areas, shortens the residence time of water in the soil and, as a result, the anaerobic conditions are replaced by aerobic conditions that in turn lead to accelerated decomposition of organic matter. Bozkurt *et al*. (2001) showed that the depletion rate of partially saturated peat (4,500 g/m^2/year) is much higher than that of 100% saturated (8 and 12 g/m^2/year). The degradation of half of the organic matter in a 10 cm partially saturated layer may take between 5 and 50 years (Bozkurt *et al*. 2001; Tomin & Korshunova 2006). As a consequence, the role of drained peat soils may change from a sink to a source of nitrogen and may act as an additional diffuse pollution source over several decades.

Currently, about one-third of the Estonian territory is drained. The intensive land drainage for agriculture and forestry started in the 1950s and has continued up to now with a peak in the 1970s (Figure 2). The intensive application of mineral fertilizers in agriculture started at approximately the same time (Figures 1 and 2). Moreover, a large part of the territory covered by drained peat soils was used as agricultural land. Therefore, the increasing leaching of nitrogen from drainage of peat soils was masked by nitrogen runoff from fertilized agricultural lands.

The objectives of the current study were to test the hypothesis that drained peat soils may be considered as a significant diffuse source of nitrogen pollution and to provide a quantitative estimation of this source.

MATERIALS AND METHODS

Detailed investigations have been performed at the River Leivajõgi watershed which has a high percentage of drained peat soils (Figure 3). This watershed is located 20 km southeast of Tallinn and the total investigated area is 78.5 km^2 (Table 1). To detect the nitrogen sources, the hydrochemical and hydrological parameters were measured in five sampling points in different locations of the river watershed

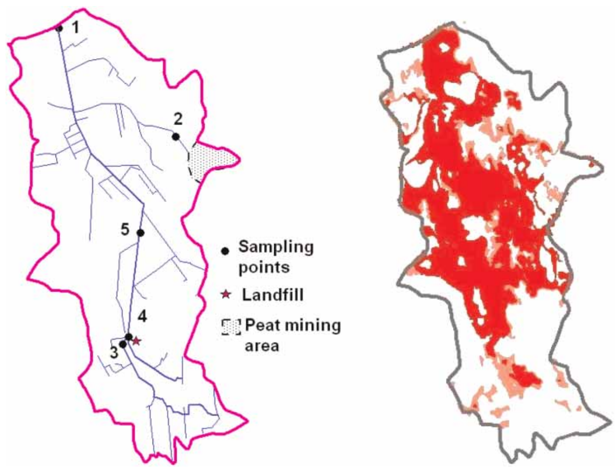

Figure 3 | Location of sampling points (on the left) and drained peat soils (on the right) in the River Leivajõgi basin.

Table 1 | Characteristics of investigated watersheds

Sampling point	Total area (km^2)	Drained peat soils % of total area	Forest	Agricultural land[a]
1	78.5	45.1	58.7	37.9
2	4.4	14.4	57.6	13.9
3	11.6	14.5	94.1	5.9
4	18.1	17.2	80.5	19.4
5	27.2	31.7	63.8	36.3
6	8.6	35.2	37.1	47.8
7	3.9	55.9	7.2	92.8
8	13.4	23.9	65.5	34.5
9	4.7	21.4	35	65
10	8.2	29.7	52.4	10.8
11	15.4	60.6	38	60.4
12	120	22.7	42.8	49.1
13	84.8	23.3	43.3	51.4
14	26.1	20.3	69.2	26.7
15	8.8	24.2	53.7	46.3
16	30.6	46.6	59	39.2
17	12	13.4	51.4	34.6

[a]Agricultural land includes arable lands and pastures.

(Figure 3 left) six times per year during 2005–2007. The nutrient concentrations and water discharge (four times per year) were also measured in twelve additional small streams (numbers 6–17 in Table 1) with a relatively high percentage of drained peat soils in the catchment area.

Water discharge was measured simultaneously with water sampling in all the observation points. The cross-sectional method was used to measure the flow rate for investigated streams, i.e. water discharge was calculated on the basis of the measurements of the cross-sectional area of the stream and the velocity of water in different points of the cross-section. On the basis of measured water discharge, the 'depth of runoff' (total water runoff from a drainage basin divided by its area and expressed in mm during a given period of time) was calculated for each investigated watershed. The depth of runoff has been used in data analysis for convenience in comparing runoff from different drainage basins.

The chemical analysis of water samples was performed in an accredited laboratory specializing in chemical analysis of drinking, surface and sewage water. The following standard analytical methods were used: total nitrogen – ISO 11905, nitrate – ISO 10304.

The data of long-term state monitoring (hydrochemical and hydrological) were also used in the study.

The percentage of peat soils in the watersheds was estimated on the basis of a digital soil map. The digital CORINE land cover map was used to derive land use statistics for each of the 17 investigated sub-basins (Table 1). Agricultural lands (Table 1) include both arable lands and pastures.

According to the WFD guidance (2002), the evaluation of diffuse pollution sources may be carried out with the help of the export coefficients (EC) of nutrients. This simple approach is based on the idea that the nutrient load exported from a catchment is the sum of the losses from individual sources and on the assumption that, for a given climate, specific land-use will yield characteristic quantities of nitrogen and phosphorus to a receiving water body (Robinson *et al.* 2005). The estimation of the EC for drained peat soils has been performed by means of statistical model MESAW (Grimvall & Stålnacke 1996), which was elaborated for source apportionment of the riverine transport of pollutants. This model approach uses non-linear regression for simultaneous estimation of source strength (e.g. EC to surface waters) for different land use or soil categories and retention coefficients for pollutants in a river basin. Software for this model was developed in Estonia by A. Vassiljev and may be downloaded free from www.staff.ttu.ee/~avasil.

RESULTS AND DISCUSSION

Analysis of nitrogen pollution sources at the River Leivajõgi catchment area

It should be mentioned that monitoring of total nitrogen levels in Estonian rivers has only been carried out since 1992. Analysis of long-term trends of nitrogen content in the River Leivajõgi water revealed that there is no relation between the dynamics of nitrogen concentrations in the river and the application of mineral fertilizers. In spite of the fact that the annual application of nitrogen fertilizers during 1996–2007 (Figure 1) remained at the same low level (nearly six-fold smaller than in 1988), the nitrogen content in river water had increased in this period (Figure 4).

The data analysis (point 1 in Figure 3) showed that concentrations of total nitrogen in the River Leivajõgi depend on the depth of water runoff (Figure 5). The division of the data set into three time series (1996–1999, 2000–2004 and 2005–2007) demonstrates that the largest increase of nitrogen concentrations during 1996–2007 was recorded under the higher depth of runoff. For example, concentrations at the same depth of runoff (e.g. 1.5 mm/day) were 6, 8 and 11 mg/L for the time series 1996–1999, 2000–2004 and 2005–2007, respectively. This means that nitrogen concentrations measured during high flow conditions have almost doubled during the years 1996–2007.

The increase of nitrogen concentration along with water runoff indicates the presence of a substantial source of diffuse pollution in the catchment area. The calculations showed that pollution, resulting from agricultural activity and point sources, could not explain such high nitrogen concentrations in the River Leivajõgi water. For example, the nitrogen load calculated using measured concentrations and water flow was 142 tons in the year 2003. However, the nitrogen load calculated for this year as the sum of loads from known nitrogen sources in this basin (agriculture areas, animal husbandry and point sources) was only 40 tons (Vassiljev *et al*. 2008) These calculations point to an additional source of nitrogen in the Leivajõgi basin. Analysis of the existing information revealed three main additional potential diffuse sources (peat mining area, landfill and drained peat soils) in the River Leivajõgi catchment

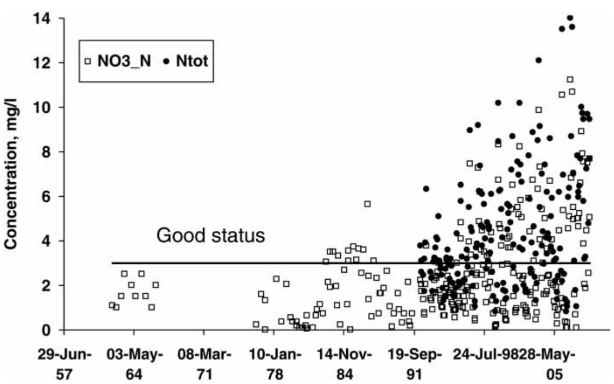

Figure 4 | Measured nitrate nitrogen (NO_3-N) and total nitrogen (N_{tot}) concentrations in the River Leivajõgi (point 1 in Figure 3, data of state monitoring).

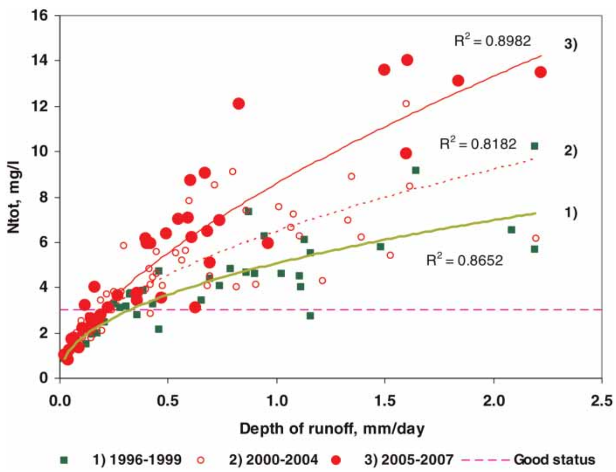

Figure 5 | The dependence of total nitrogen (N_{tot}) concentrations on the depth of runoff (River Leivajõgi, 2005–2007 point 1).

area. To estimate the role of these pollution sources, the water quality was monitored in four additional points (Figure 3).

Sampling points 3 and 4 have been selected to assess influence of the landfill located upstream of the river. Point 2 has been selected to evaluate pollution from peat mining area.

Influence of peat mining area

The average concentration of total nitrogen observed in the river downstream from the peat mining area (point 2 on Figure 3) was 2.2 mg/L and the maximum value was 3.25 mg/L (Table 2). One can see that the nitrogen load from this area cannot be the reason for high concentrations in point 1, where the maximum value of total nitrogen concentration was 15.0 mg/L.

Table 2 | Concentrations of total nitrogen along the River Leivajõgi (Figure 3) in the years 2005–2007

Sampling point	Mean	Max	Min
2	2.2	3.25	1.43
3	2.8	5.3	1.5
4	5.5	8.2	2.5
5	6.7	10.9	2.2
1	7.1	15.0	3.8

Influence of landfill

The concentration values in point 3 characterize the nitrogen load from the watershed with a high percentage of forest and moderate distribution of peat soils (Table 1). Measurements showed that the average total nitrogen concentration in point 3 (2.8 mg/L) was noticeably lower than in points 1 and 5 (Table 2). The higher average total nitrogen concentrations in point 4 (5.5 mg/L) compared with point 3 can be explained by the influence of the landfill (Figure 3). One can see that landfill increases nitrogen concentrations in the tributary of the River Leivajõgi significantly. However, concentrations observed in point 4 were still substantially lower than those in downstream points 1 and 5 (Table 2). Taking into account the relatively small water discharge in point 4, one can say that the diffuse pollution from the landfill does not noticeably affect the water quality in downstream points 5 and 1. Thus, the observation data showed that nitrogen loads from both the peat mining area (point 2) and from the landfill (point 4) do not explain the high concentrations in points 5 and 1 and that some other source of diffuse pollution probably exists in the River Leivajõgi basin.

Influence of drained peat soils

Analysis of the soil map showed that the percentage of peat soils in the sub-basins indicated by points 5 and 1 was much higher than in the sub-basins indicated by points 3 and 4 (Table 1). Thus, it may be supposed that leaching of nitrogen from peat soils is the main reason for the high concentrations in points 5 and 1. This assumption is confirmed by the data obtained by Tiemeyer *et al.* (2007) which indicated high (up to 30 mg/L) concentrations of nitrate nitrogen in the waters from drained peat soils. The authors also noted increased concentrations of nitrate nitrogen along with an increase of water flow. High leaching of nitrogen from drained peat soil was also shown by Van Beek *et al.* (2007). The runoff of nitrogen from drained peat soils noticeably exceeds that from mineral soils due to higher nitrogen content and higher rate of mineralization than in mineral soils (Mališauskas & Kutra 2008). Several authors reported significant leaching losses from drained peat soils irrespective of fertilization, i.e. peat soil itself may also contribute to the formation of nutrient load coming from watersheds (Heathwaite 1990; Nilsson & Lundin 1996; Van Beek *et al.* 2004).

Twelve additional small watersheds with different land use and distribution of peat soils were sampled (Table 1) to test the hypothesis that drained peat soils act as a source of nitrogen.

As the total nitrogen concentrations in river water depend on water runoff (Figure 5), the concentrations in the investigated basins should be compared at the same depth of runoff to define the influence of peat soils on nitrogen concentrations in the rivers. As shown above, concentrations of total nitrogen observed on days with depth of runoff higher than 1.5 mm/day increased much faster in the years 1996–2007 than concentrations observed under lower flow conditions. Therefore, the nitrogen concentrations recorded in investigated rivers at depth of runoff (1.5–2.1 mm/day) have been selected to analyze the relationship between the total nitrogen concentrations in rivers and peat soils proportion in the watersheds (Figure 6).

One can see that the total nitrogen concentrations increase with the percentage of peat soils quite rapidly (Figure 6). The concentrations of total nitrogen in rivers are higher than the limit of good status (3 mg/L) if peat soils cover over 20% of the watershed area. The spread of points in Figure 6 is quite high and depends on many factors: content of nitrogen in peat soil, thickness of drained

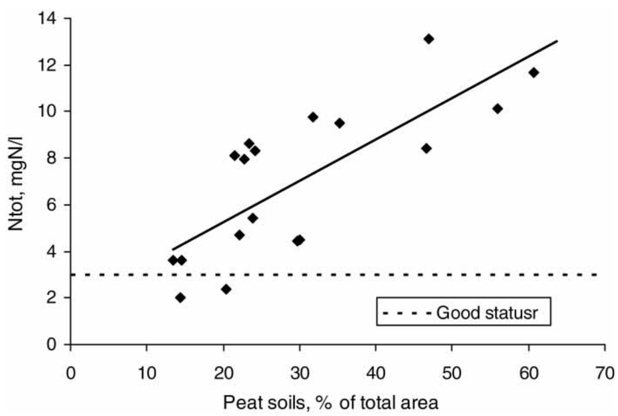

Figure 6 | Relationship between total nitrogen concentrations in river water and peat soils percentage in the catchment area (depth of runoff 1.8 mm/day). *F-statistic* is 22.95 with *significance F* 0.000238.

soil, density of drains, degree of decomposition of organic matters, age of drainage system and influence of other nitrogen sources. Quantification of the contribution of each individual factor is complex because the relations between sources and transport processes to surface water are still poorly understood (Van Beek *et al.* 2007). Being used for agricultural purposes, the different types of peat soils decompose at different rates. The botanical origin of peat and the degree of peat decomposition determine the chemical composition of peat and the rate of decay of organic matter. For example, peat produced by vascular plant species always decays faster than *Sphagnum* peat (Efimov 1980; Bambalov 1984; Bragazza *et al.* 2007). All these factors require more detailed investigation. However, in Estonia, the results obtained show that drained peat soils must be considered as a noticeable diffuse source of nitrogen (in addition to agricultural activities), as it affects the surface water quality and must be taken into account when evaluating diffuse pollution sources.

The quantitative assessment of the nitrogen load originating from drained peat soils has been performed using the statistical model MESAW (see above under Materials and methods), which uses a general non-linear regression expression with loads at each sub-basin as dependent/response variable and sub-basin characteristics and additional sources as explanatory variables. The more sub-basins included in a calculation, the higher reliability of the obtained EC. The MESAW also enables the use of EC obtained from previous investigations or from literature (known coefficients) for some sources. Therefore, EC estimated by Vassiljev *et al.* (2008) for agricultural lands and forests on the basis of the large number of sub-basins have been used in this study. These coefficients and information on nitrogen loads, land-use areas, drained peat soil areas (Table 1) and point sources for each studied sub-basin have been used in our calculations of the EC from drained peat soils. The calculations for the years 2005–2007 showed that drained peat soils produce 10–16 kg/ha per year of nitrogen depending on the depth of annual runoff. Standard errors of the coefficients (1.0–1.5 kg/ha) evaluated by MESAW show high reliability of the EC for drained peat soils.

The export of nitrogen from drained peat soils for the years with depth of runoff in the range 120–210 mm can be evaluated by the following equation:

$$EC = 0.045r + 5.6$$

where EC is the export of nitrogen from drained peat soil (kg/ha per year); r is the depth of annual runoff (mm).

Thus, our calculations show that the export of nitrogen from drained peat soils is higher than the export from agricultural lands (on average 1.5-fold higher). However, coefficients may be higher or lower depending on many factors as mentioned above. Additional investigations are required to quantify leaching of nutrients from different types of peat soils. Moreover, this source of nitrogen is comparable with and even may have a higher impact on, the formation of river water quality than agricultural lands.

CONCLUSIONS

- The obtained results show that drained peat soils must be regarded as a noticeable diffuse source of nitrogen in Estonia.
- According to our estimation, export of total nitrogen from drained peat soils is approximately 1.5-fold (or even more!) higher than from agricultural lands in Estonia.

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