Overview of water quality problems in Estonia with the focus on drained peat areas as a source of nitrogen

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Abstract The eutrophication caused by enlarged loads of nutrients from watersheds remains one of the most important problems for surface waters in Estonia. The changes in the agricultural sector of the Estonian economy at the beginning of 1990s led to a drastic decrease in application of mineral fertilizers and also in livestock population. Nevertheless, very little evidence was found that these changes noticeably influenced concentrations of nutrients in rivers. This fact confirms the opinion of some researchers that the impact of agriculture on the pollution of surface water by nutrients was overestimated. Intensive pollution of surface water may be caused by wide-scale soil amelioration. Currently, about one third of the Estonian territory is drained and most of this area is covered by peat soils. Intensively managed peat soils can act as a source of nutrients. In this study, the potential contribution of the nitrogen leached from the peat soils to nitrogen load coming from watersheds was estimated. Data on long-term monitoring, field investigations and modelling have been analysed. The results showed that drained peat soils must be regarded as a noticeable diffuse source of nitrogen in Estonia.

Key words water; rivers; nitrogen; drained peat soils; eutrophication

INTRODUCTION

According to the Water Framework Directive (2000), the 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; Vassiljev & Blinova, 2012). In many rivers, the concentrations of nutrients exceed the upper values for good status established in Estonia (3 mg/L for total nitrogen and 0.08 mg/L for total phosphorus (Classes, 2009). Nitrogen concentrations in some rivers exceed the limits by 5-fold. However, often it is impossible to explain such high nitrogen concentrations in river water by known pollution sources on the watershed. This fact impedes elaboration of effective water protection measures.

According to current opinion, the drastic increase of nutrient concentration in Estonian surface waters during the late 1970s was caused mostly by (1) effluent discharge (point sources), and (2) intensive use of commercial fertilizers in agriculture (diffuse pollution). Therefore, primary attention was focused on the measures for reduction of nutrient loads from the above-mentioned sources. The reconstruction of old sewage treatment plants and opening of new ones significantly decreased nutrient pollution loads from point sources during the last decades. The changes in the agricultural sector of the Estonian economy at the beginning of 1990s led to a drastic decrease in application of mineral fertilizers (Fig. 1) and also in livestock population. Nevertheless, little evidence was found that decrease of nitrogen loads from these sources noticeably affected the concentrations of nutrients in rivers (Stålnacke *et al*., 2004; Vassiljev *et al*., 2008). The nutrient runoff from some watersheds remained at undesirably 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).

The intensively managed peat soils are generally considered as a source of nutrients because the indigenous peat can contain considerable amounts of nutrients available for leaching (Rakovskiy & Pigulevskaya, 1978; Heathwaite, 1991). The drainage, which is a common practice for reducing moisture and improving aeration conditions in soil, especially in swamp areas, shortens the residence time of water in the soil. As a result, the anaerobic conditions are replaced by aerobic ones, which in turn lead to accelerated decomposition of organic matter. Bozkurt *et al.* (2001) showed that the depletion rate of partially saturated peat (4500 $g/m^2/year$) is much higher

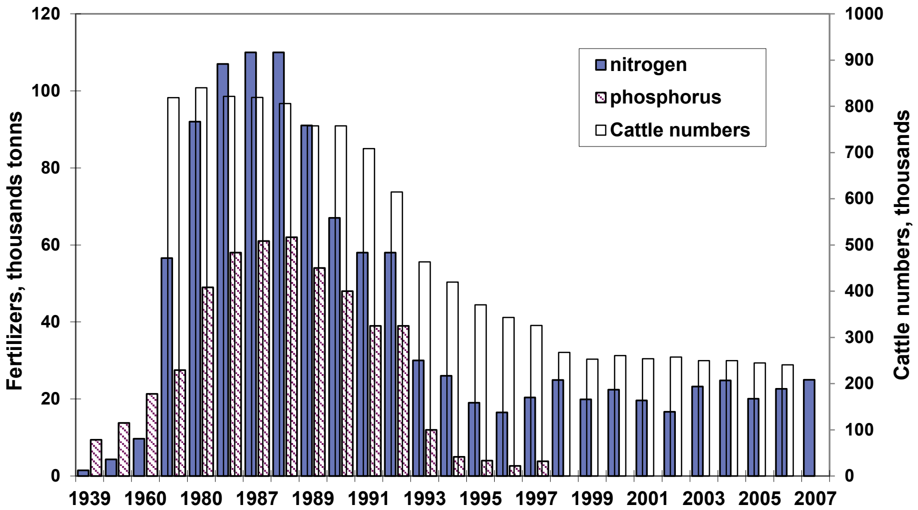

Fig. 1 Dynamics of mineral fertilizer use and cattle numbers in Estonia (Statistics Estonia http://www.stat.ee).

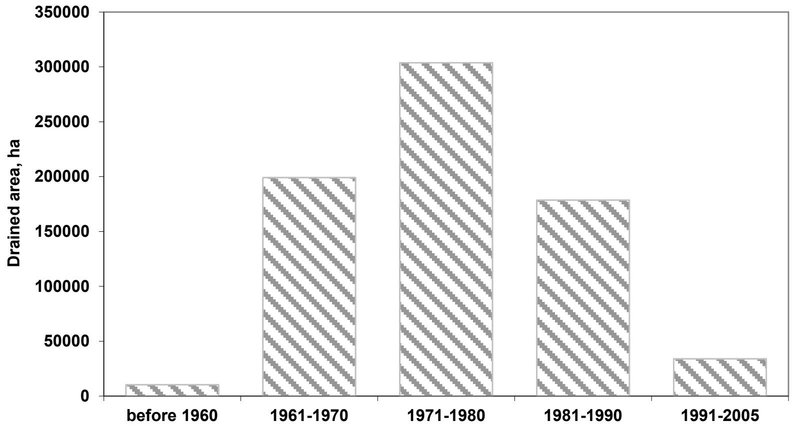

Fig. 2 Areas drained in Estonia (Estonian Ministry of Agriculture 2007).

than that of 100% saturated peat (8 and 12 g/m^2/year). 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 soil amelioration, which was conducted at the same time. Other authors also show significant increases of nutrient runoff from drained areas after drainage of forests and peatlands (Lundin & Bergquist, 1990; Prévost *et al*., 1999).

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 (Fig. 2). As the intensive application of mineral fertilizers in agriculture started approximately at the same time (Figs 1 and 2), the increased leaching of nitrogen from drained peat soils was masked by nitrogen runoff from the fertilized agricultural lands.

The objective of the current study was to evaluate the contribution of the nitrogen leaching from the peat soils to nitrogen load coming from the watersheds.

MATERIALS AND METHODS

According to official statistics, the drastic decrease of the use of mineral fertilizers and number of cattle was marked in Estonia at the beginning of the 1990s (Fig. 1). Therefore, the temporal change in nitrate concentrations (total nitrogen measured after the year 1991) in rivers were evaluated for the period 1988–1998 in order to study dependence on agricultural activity.

Analysis of the time variation of the concentrations using regression analysis is probably the simplest and most commonly used method for trend evaluation. This method uses the simultaneous empirical relationship between concentration, runoff and time (Grimvall *et al.*, 1991) in the following general form:

$$c = a + b_1Q + b_2 * t + .. + b_{n+1}t^n$$

where: c = concentration, Q = water discharge, t = time, n = maximal power of the polynomial and $a, b_1, b_2 ... b_{n+1}$ are the coefficients estimated by regression analysis.

A preliminary study showed that powers higher than 1 for terms with t do not improve the model. Moreover, it was also shown that dependences of concentration on water flow are often nonlinear. So, the following general regression function was used in the final analysis:

$$c = a + b_1t + b_2Q + b_3Q^2$$

Three variants have been used in our study:

1. linear dependence on time $c = a + b_1t$ (1)
2. linear dependence on time, linear dependence on flow $c = a + b_1t + b_2Q$ (2)
3. linear dependence on time, nonlinear dependence on flow $c = a + b_1t + b_2Q + b_3Q^2$ (3)

The simplest variant (1) describes the dependence of concentration on time only. Concentrations in rivers often depend on water flow. Variants (2) and (3) take into account this dependence (so-called flow adjusted trends).

The modelling was also used to investigate the influence of soil fertilization on nitrogen concentration in the rivers. The SOILN model (Johnsson *et al.*, 1987) was developed in Sweden for simulating nitrogen fate in soil. It allows simulation of nitrogen leaching from a field depending on the level of fertilization. The model uses results of the hydrological models MACRO (Jarvis, 1994) or SOIL (Jansson, 1991) as input data. The driving input data for these hydrological models include daily meteorological information: precipitation, air temperature, wind speed, vapour pressure and solar radiation. The soil profile in the MACRO model is divided into two separate but interacting pore regions, the macropores and micropores, each characterized by the conductivity, vertical flow rate and degree of saturation. The SOIL model does not simulate water exchange between macropores and micropores. The version of the SOILN model, which works with the MACRO model, simulates nitrogen exchange between macropores and micropores (Larsson & Jarvis, 1999).

It was shown that the use of the combination of MACRO and SOILN models (Vassiljev, 2006) in the case of clay soils simulate the fate of nitrogen better than the combination of SOIL and SOILN (Forsman & Grimvall, 2003). Therefore, calculations of the dependence of nitrogen leaching on the level of fertilization were performed using MACRO and SOILN models in the current study.

As the SOILN for the MACRO model did not work correctly, for calculations of nitrogen leaching from watersheds with a high percentage of drained peat soils, the SOIL and SOILN models were used as well. To adjust the SOIL and SOILN models to the watershed scale, some procedures proposed by Vassiljev *et al.* (2004) were used.

The data for long-term state monitoring (hydrochemical and hydrological) were used in the study. Additional measurements were performed for investigation of the influence of drained peat soils on water quality. Namely, nutrient concentrations and water discharge were measured four times per year in 18 additional streams with relatively high percentages of drained peat soils in their catchment areas. On the basis of water discharge, the runoff depth was calculated for each investigated watershed (the water runoff from the drainage basin divided by its area and expressed in mm during the given period of time). The runoff depth was then used in data analysis to compare 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: ISO 11905 for total nitrogen, and ISO 10304 for nitrate.

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 18 investigated sub-basins.

RESULTS AND DISCUSSIONS

Trends

The analysis of nitrogen concentration trends in rivers using equations (1)–(3) revealed that the drastic decrease of mineral fertilizers use in agriculture from the beginning of 1990s (Fig. 1) did not lead to a decrease of nitrogen concentration in most of the investigated rivers (Table 1).

Table 1 Trends in nitrate concentrations in 12 Estonian rivers for the period 1988–1998.

River	Equation used:			Land use (%)		
	(1)	(2)	(3)	Forest	Arable	Natural
Ahja	0[a]	0	0	43	11	5
Avijõgi	0	0	0	58	13	14
Kääpa	0	0	0	58	15	13
Kasari	0	0	0	49	22	16
Keila	0	0	0	39	22	14
Kunda	0	0	0	49	17	13
Leivajõgi	pp[b]	pp	pp	51	11	13
Loobu	0	0	0	45	19	11
Õhne	nn[c]	nn	nn	52	13	18
Pedja	0	0	0	50	22	13
Seljajõgi	0	0	0	24	35	5
V. Emajõgi	0	0	0	46	13	6

[a] 0 – absence of trend ($p > 0.05$)
[b] pp – positive trend ($p < 0.05$)
[c] nn – negative trend ($p < 0.05$)

Iital *et al*. (2009) obtained similar results for 53 Estonian rivers, which were analysed for the period 1992–2006. According to that investigation, 31 rivers did not show any statistically significant trend in nitrogen concentration, 18 rivers showed a negative trend, and 4 rivers showed a positive trend. The authors also revealed positive trends in some rivers with low human impact.

The absence of an obvious dependence between nitrogen concentrations in rivers and application of mineral fertilizers in the watershed may be explained using modelling of nitrogen leaching. Forsman & Grimvall (2003) performed calculations by the SOIL and the SOILN models for sandy soils with different levels of fertilization and showed that leaching of nitrogen from soil increases only if the level of fertilization is higher than 80 kg/ha/year. Our calculations using the MACRO and SOILN models showed that for clay soil leaching of nitrogen increases if the level of fertilization is higher than 110 kg/ha/year. The highest annual application of nitrogen fertilizers in Estonia recorded in 1986–1988 was 112 kg/ha/year (Fig. 1), which only slightly exceeds the simulated threshold values of 80–110 kg/ha/year. This may explain why for only for a small number of Estonian rivers a negative trend in nitrogen concentration was revealed in our study.

Even more strange is the positive trend for rivers with low human impact (e.g. Leivajõgi, Table 1). The increase of nitrogen concentrations with increase of runoff (Fig. 3) indicates that significant diffuse sources of nitrogen exist on the watersheds.

Impact of the peat soils

As mentioned above, the drained peat soils may be an additional diffuse source of nitrogen leaching from watersheds. This assumption is confirmed by the data obtained by Tiemeyer *et al.* (2007) indicating very high (up to 30 mg/L) concentrations of nitrate nitrogen in water from drained peat soils. High leaching of nitrogen from drained peat soil was also shown by van Beek *et* *al.* (2007). The wash-off of nitrogen from the drained peat soils noticeably exceeds that from the mineral soils due to the higher nitrogen content and higher rate of mineralization than in the mineral soils (Mališauskas & Kutra, 2008). Several authors reported significant leaching losses from the drained peat soils irrespective of fertilization, i.e. a peat soil itself may contribute to the formation of nutrient load coming from a watershed (Heathwaite, 1990; Nilsson & Lundin, 1996; Van Beek *et al.*, 2004).

Eighteen additional watersheds with different percentage of peat soils were sampled to test the hypothesis that the drained peat soils may act as a source of nitrogen. The analysis of data revealed that in the investigated rivers nitrogen concentrations rise with the increase of runoff.

As the total nitrogen concentrations in river water depend on water runoff (Fig. 3), and the watershed areas are notably differ (4–474 km^2), the concentrations in the investigated rivers should be compared at the same depth of runoff to analyse the influence of peat soils on nitrogen concentrations in the rivers. The nitrogen concentrations recorded in investigated rivers at a runoff depth of 1.5–2.1 mm/day have been selected to analyse the relation between the total nitrogen concentrations in rivers and peat soils percentage in the watersheds (Fig. 4).

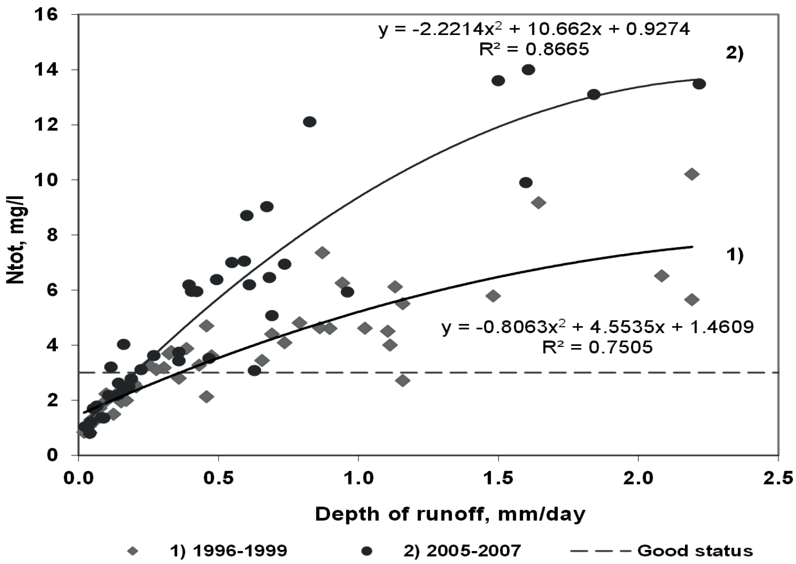

Fig. 3 The dependence of total nitrogen (Ntot) concentrations on the depth of runoff (River Leivajõgi, 1996–1999 and 2005–2007).

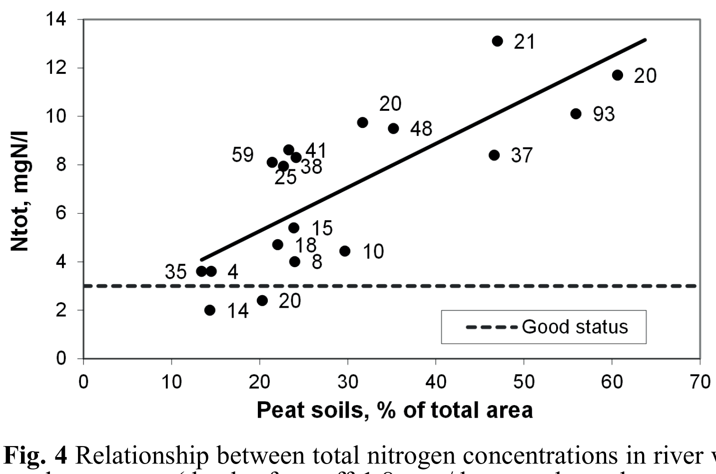

Fig. 4 Relationship between total nitrogen concentrations in river water and peat soils percentage in the catchment area (depth of runoff 1.8 mm/day, numbers show percentage of arable land). *F* statistic is 22.95 with significance *F* = 0.000238.

One can see that the total nitrogen concentrations increase with the percentage of peat soils quite rapidly (Fig. 4). As follows from Fig. 4, the concentrations of total nitrogen in rivers exceed the limit of a good status, 3 mg/L (Classes, 2009), if peat soils cover more than 20% of the watershed area (at least for a runoff depth of about 1.8 mm). The numbers in Fig. 4 indicating percentage of arable land, show that the increase in concentrations is rather independent of the arable land percentage. The spread of points in Fig. 3 is quite high as many other factors influence nitrogen leaching, e.g. content of nitrogen in peat soil, thickness of drained soil, density of drains, degree of organic matter decomposition, age of drainage system, and influence of other nitrogen sources.

Quantification of the contribution of each individual factor is complex as the relationships between sources and nitrogen transport to surface water are still poorly understood (Van Beek, 2007). Being used for agricultural purposes, different types of peat soil decompose at different rates. The botanical origin of peat and the degree of peat decomposition determine its chemical composition and the rate of organic matter decay. For example, it is known that peat produced by vascular plant species always decays faster than *Sphagnum* peat (Efimov, 1980; Bambalov, 1984; Bragazza *et al.,* 2007). The degradation of the half of the organic matter may take from 5 to 50 years (Bozkurt *et al*., 2001; Tomin & Korshunova 2006). It means that this source of nitrogen may act for several decades.

All these factors need more detailed investigation. However, the results obtained show that in Estonia drained peat soils must be considered as an important and notable diffuse source of nitrogen in addition to agricultural activities, which affects surface water quality and must be taken into account when evaluating diffuse pollution sources. It was shown in our previous study (Vassiljev & Blinova, 2012) that export of nitrogen from drained peat soils is on average 1.5-fold higher than export from agricultural lands in Estonia. However, export coefficients may vary depending on many factors as mentioned above. Additional investigations are needed to quantify leaching of nutrients from different types of peat soils.

Modelling of nitrogen leaching from drained peat soil

In light of the high influence of drained peat soils on water quality, an attempt to model the nitrogen leaching was made for one of the investigated watersheds with a large area of peat soil. The SOIL and SOILN models were used in this case. Both models are field-scale tools and additional procedures have to be used for their application at the watershed scale (Vassiljev *et al*., 2004; Vassiljev, 2006). These procedures include calculations for different fields, an optimization procedure to estimate the contribution of each field to the total flow and influence of the river system, and calculations of water flow and concentrations at the outlet of the watershed. These procedures were described in detail in Vassiljev *et al*. (2004).

The calculations for the River Leivajõgi were performed for the period 2000–2003. Soil parameters from a database prepared for the SOIL model were used. This database contains soil parameters for almost 300 different soils and the most suitable soil was selected from this database. Figure 5 presents a comparison of the measured and simulated water discharge at the outlet of the watershed. The Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) of the model are 0.57 and –0.73, respectively.

The modelling of nitrogen concentration was performed using the SOILN model. The content of nitrogen in drained peat soil was assumed to be 5000 g-N per cubic metre. The fertilization rate was 0 kg ha^{-1} $year^{-1}$. Figure 6 shows the comparison of the observed and simulated concentrations. One can see that the observed and simulated values coincide quite well. The Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) of the model are 0.34 and 9.9, respectively.

The results of the modelling show that it is possible to model the influence of the drained peat soils on water quality at the watershed scale. However, this approach should be also tested by modelling of the watersheds with different land use. It is necessary to investigate the behaviour of the drained peat soils in a longer perspective (several decades), but for that additional efforts are needed to prepare data.

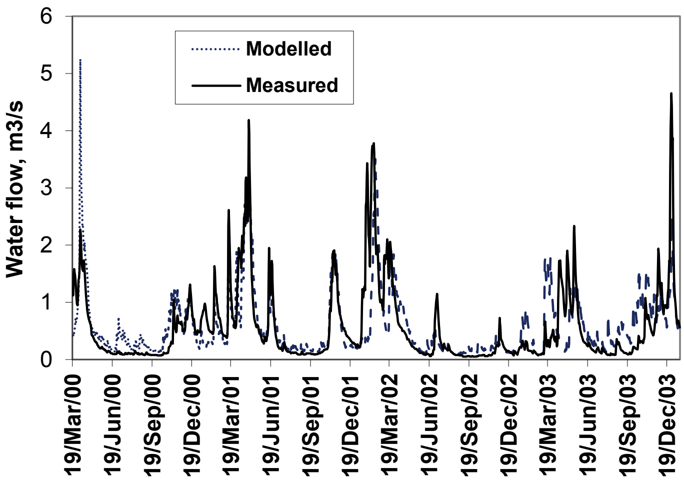

Fig. 5 Discharge simulated and observed in the River Leivajõgi.

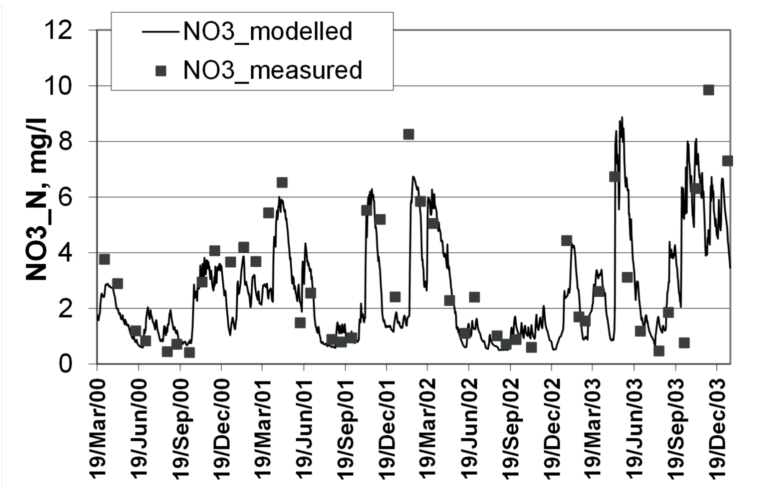

Fig. 6 Simulated and observed nitrate concentrations in the River Leivajõgi.

Our measurements performed on the watershed with a high percentage of drained peat soils also revealed that the construction of a dam led to an increase of nitrogen concentrations in the river, but the question is how long this increase will continue? Unfortunately it is impossible to model human activities such as the construction of a dam, in the SOIL and the SOILN models. The further development of these models is needed to investigate these processes in more detail.

CONCLUSIONS

- The obtained results show that the drained peat soils must be regarded as a noticeable diffuse source of nitrogen in Estonia.
- The leaching of nitrogen from drained peat soils can be modelled by SOIL and SOILN models at the watershed scale. This provides a possibility to simulate nitrogen leaching from the drained peat soils in a longer perspective (for several decades).
- Unfortunately, it is not possible yet to simulate the influence of dams on nitrogen fluxes in a watershed with the chosen models. Simulation of the impact of dams needs additional modules to be included in the SOIL and the SOILN models.

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