Source apportionment of nitrogen in Estonian rivers

Katrin Kaur, Anatoli Vassiljev, Ivar Annus and Per Stålnacke

ABSTRACT

The statistical model MESAW (Matrix Equations for Source Apportionment on Watershed) was used to estimate the diffuse unit-area source emission coefficients of nitrogen in Estonian rivers. The input data included monitored riverine loads, point sources and land use categories from a total of 50 rivers/catchment areas. Two independent studies were conducted: the estimation of emission coefficients for the whole of Estonia and for a smaller study area near Tallinn. The results from both cases showed that drained peat soils were the highest diffuse source contributor in unit-area loads. The results show that the unit-area loads from drained peat soils were up to 2.3 times higher than from arable land. Moreover, a comparison of emission coefficients for the whole of Estonia and for the Tallinn catchment area indicated that coefficients can vary significantly between sources and single years. Additional detailed studies and monitoring are needed to support these conclusions.

Key words | diffuse sources, drained peat soils, emission coefficient, MESAW, nutrients, water quality

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INTRODUCTION

One of the major environmental management goals in the Baltic Sea region, and thus also in Estonia, is the reduction of riverine nutrient loads. However, recent data analyses of Estonian rivers indicate that nitrogen concentrations have increased in some rivers (Iital *et al.* 2010) despite the decrease in fertilizer use (Vassiljev & Blinova 2012). An increase in nitrogen concentrations has even been detected in watersheds with very low human activity (Iital *et al.* 2010). Hoffmann *et al.* (2000) assumed that the increase in nutrient pollution could also be caused by wide-scale melioration. Some authors (Heikkinen 1994; Kløve 2001; Kløve *et al.* 2010) have reported that drainage of peat soils leads to decomposition of peat and increases the flux of nutrients to watercourses. The drainage of peatlands results in peat oxidation and significantly changes their physical and chemical properties (Litaor *et al.* 2008; Verhoeven & Setter 2010). This can result in high nitrate-nitrogen concentrations in the pore water of drained peatlands that is caused by the aeration of peat and subsequent mineralization and nitrification of organic N (Tiemeyer *et al.* 2007). Vassiljev & Blinova (2012) and Vassiljev (2015) have observed an increase in nitrogen concentrations in some Estonian river basins with a high percentage of drained peat soils. Mineralization of nitrogen from peat soils is regarded as another possible source of nutrients in Europe (Eurostat 2011). To illustrate the problem, the correlation between the concentration of total nitrogen and water runoff is shown for the Leivajõgi River and the Hatu River for 2014–2015 (Figure 1). Both of the watersheds have a relatively high percentage of drained peat soils (Leivajõgi 45.1% and Hatu 44.1%) and there is a low level of human activity in the catchment areas. The Leivajõgi is situated about 20 km south-east of a large city (Tallinn, ~450,000 inhabitants) and the Hatu River is surrounded by natural areas. High concentrations of nitrogen in the Leivajõgi can be seen as a result of diffuse pollution from roads and other human activity arising from its proximity to a large city. However, Figure 1 shows that the concentrations of total nitrogen increase with the increase in water flow in both rivers at the same rate. This clearly indicates that there are other, larger sources than the influence of a large city.

The main objective of this paper was to quantify the emission coefficients of various land cover types and drained peat soils. This paper uses the results obtained in

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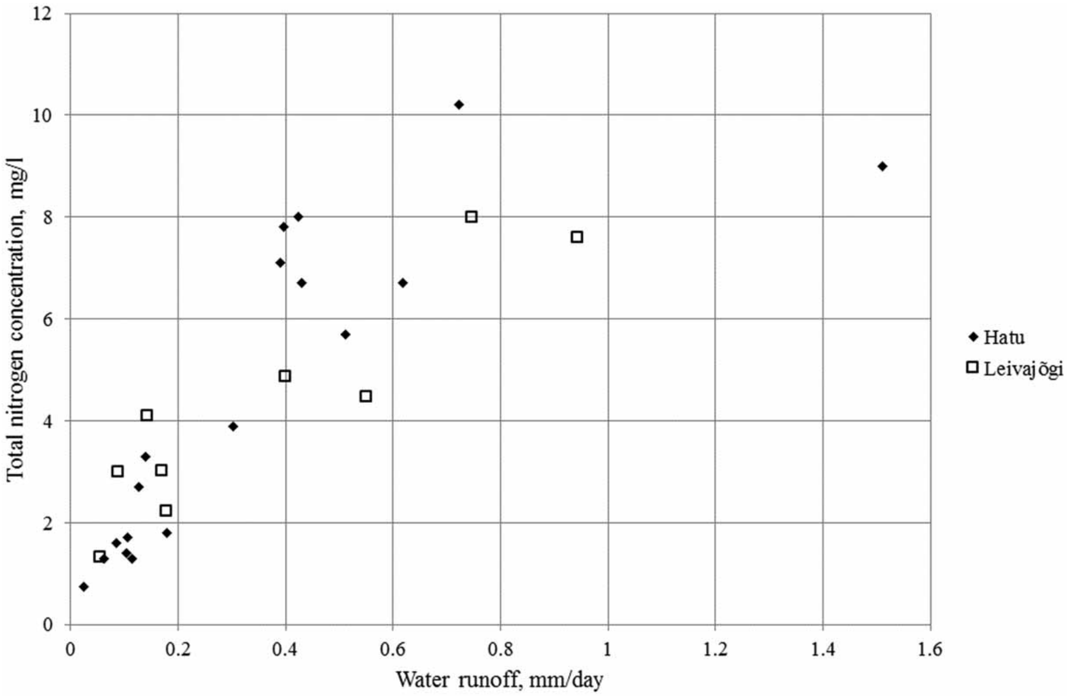

Figure 1 | Correlation between total nitrogen concentration and daily runoff for two rivers with a high percentage of drained peat soils.

Vassiljev *et al.* (2016) but with a significant increase in the amount of data and the time period analyzed. Moreover, the data analysis in this study is more comprehensive.

CASE STUDIES AND METHODOLOGY

In the current study, a statistical approach was used to estimate the nitrogen emission coefficients from various diffuse source categories. Emission coefficients were estimated for the whole territory of Estonia and, for comparison purposes, also for the drinking water catchment area of Tallinn city where there is a high density of water quality monitoring sites (Figure 2).

The statistical model MESAW (Matrix Equations for Source Apportionment on Watershed) was used for source apportionment and retention estimates of nitrogen (Grimvall & Stålnacke 1996). This model has been shown to be expedient for source apportionment, especially for areas with a high density of water quality monitoring sites (Lidèn *et al.* 1998; Vassiljev *et al.* 2008; Stålnacke *et al.* 2015). The model approach uses non-linear regression for simultaneous estimation of source strength (i.e. export/

Figure 2 | Map of Estonia and location of Tallinn catchment area.

emission coefficients to surface waters) for the different land use or soil categories and retention coefficients for pollutants in a river basin or lake. The basic principles and major steps in the procedure include: (1) estimation of mean annual riverine N loads for years 2005, 2006, 2007, 2008, 2011, 2012 and 2013 at each water quality monitoring site, (2) subdivision of the entire drainage basin into subbasins according to the upstream area of the water quality monitoring site, (3) derivation of statistics on land use, lake area, point source emissions and other relevant data for each sub-basin, (4) application of a general non-linear regression expression with the loads at each sub-basin as the dependent/response variable and sub-basin characteristics as covariates/explanatory variables. In the MESAW model, the load at the outlet of an arbitrary sub-basin can be estimated using the following general expression (Equation (1)):

$$L_i = \sum_{j=1}^{n} (1 - R_{j,i})L_j + (1 - R)S_i + (1 - R)P_i + (1 - R)D_i + \varepsilon_i, \tag{1}$$

where L_i = load at the outlet of sub-basin i; L_j = load at the outlet of nearest upstream sub-basin j; $R_{j,i}$ = retention on the way from the outlet of sub-basin j to the outlet of sub-basin i; n = number of sub-basins located to the nearest upstream; S_i = total losses from soil to water in sub-basin i; P_i = point source discharges to waters in sub-basin i; D_i = atmospheric deposition on surface waters in sub-basin i; R = retention in sub-basin i; ε_i = statistical error term.

The load at each sub-basin can be divided into contributions from the sources located in sub-basins further upstream (the first term in Equation (1)) and contributions from the sources located within the sub-basin under consideration (the S_i, P_i and D_i terms). It should be taken into account that for some sub-basins n can be equal to zero (e.g. the uppermost sub-basin or separate basin without any upstream sub-basin). In this case, Equation (1) will be used without the first term. The parameterization of the model is flexible and can be study-area specific. The model is fitted by minimizing the sum of squares for the difference in the observed and estimated loads. In this study, P_i and D_i were assumed to be known and S_i was assumed to be a simple function of land use according to $S_i = (\beta_1 a_{1i} + \beta_2 a_{2i} + \beta_3 a_{3i})$. Coefficients a_{1i}, a_{2i} and a_{3i} denote the area of arable land (excluding arable land on drained peat soil, ~5% of total arable land), other land (named natural areas) that included forests, pastures, natural grasslands, bogs (excluding areas on drained peat soils) and drained peat soils (including all land types located on drained peat soils) in the sub-basin i, and β_1, β_2 and β_3 are unknown export coefficients (i.e. emission coefficients, unit-area loads) for the three land use categories calculated by MESAW.

Nutrients are normally retained temporarily or permanently in watercourses. In the model, retention is expressed as a summary expression for all hydrological and biogeochemical processes that may retain nutrients. In MESAW it can be parameterized by any empirical function. In this study, the retention is subdivided into retention in lakes and riverine retention (i.e. instream retention). It was assumed that retention in lakes is a function of the lake area divided by the drainage area, and riverine retention a function of the drainage area.

Both types of retention can be expressed through the following equation:

$$R_i = 1 - \frac{1}{1 + \lambda_1 \times \text{drainage area}_i} \times \frac{1}{1 + \lambda_2 \times (\text{lake area}_i / \text{drainage area}_i)}, \tag{2}$$

where λ_1 and λ_2 denote a non-negative parameter and R_i denotes the retention in the ith basin. The first part of the function reflects the instream retention whereas the second part reflects the retention in lakes and reservoirs.

Retention from an arbitrary sub-basin m to the river mouth ($R_{m,\ mouth}$) can be derived from:

$$R_{m,mouth} = 1 - \prod_{j=1}^{k} (1 - R_j), \tag{3}$$

where $R_{m,mouth}$ = retention from the outlet of the sub-watershed m on the way to the mouth of the whole river; k = number of sub-basins downstream of sub-basin m; R_j = values of retention within the different sub-basins downstream of sub-basin m.

In case 1 (whole of Estonia), the hydro-chemical parameters were collected from 50 sites in the annual state monitoring program by the Estonian Environmental Agency (EEA). The data collected over a seven-year period from 2005 to 2013 were used in this study. In addition, the EEA measured water runoff at 46 locations that, for some measurement points, did not coincide with the hydro-chemical monitoring sites. In case 2, the hydro-chemical parameters were collected from 12 sites, 11 of them sampled by AS Tallinna Vesi with nitrogen concentration measurements varying from 12 to 52 times per year and one sampled by the EEA (six to 12 times per year). The chemical analysis of water samples was performed in accredited laboratories.

The percentage of peat soils in the watersheds was estimated on the basis of a digital soil map obtained from the Estonian Land Board. The digital CORINE land cover map was used to derive land use statistics for each sub-basin. In the model, the emission coefficients were calculated for arable land excluding peat soils, areas with drained peat soils and other land use categories excluding peat soils categorized as natural areas (including forests, pastures, natural grasslands and bogs). Characteristics of the sub-basins for case 1 and case 2 are presented in Tables 1 and 2.

RESULTS AND DISCUSSION

One challenge of estimating emission coefficients (expressed as unit-area losses) for a whole country is the differences in flow rates (e.g. specific runoff) between the studied sites. Another problem is that the difference in the water runoff between the sites varies between different years, as shown in Figure 3. The Keila River is located in N Estonia and the Võhandu River in SE Estonia. The figure shows that the runoff is almost the same for some years, while it differs significantly for other years (e.g. years 2004 and 2012). In the model, the load at the outlet sub-basin L was calculated as the sum of daily loads. The daily loads, on the other hand, were calculated by multiplying concentrations with discharge. If the discharges are very different in different rivers across Estonia, the calculated loads will differ significantly, not, however, because of land use or soil type but because of the variation in water flow. It was found necessary to adjust riverine loads in the MESAW model for each year under investigation in order to make the results comparable. Firstly, the average annual runoff was calculated using the flow rates of all the rivers in Estonia. Secondly, the flow rate coefficients for each river were calculated by dividing the average runoff by the river's runoff. Finally, the corrected loads were calculated by multiplying loads by the flow rate coefficients. In these procedures, it was assumed that the correlation between the emissions and the runoff is linear.

As an example, Figure 4 shows the dependency between emission and runoff for the Võhandu River (SE Estonia) and the Keila River (N Estonia). The distance between the river mouths is 280 km. It can be seen that the correlation between the two variables is more or less linear. Thus, this rough method was regarded as a suitable means of obtaining a good estimate of the riverine loads for MESAW.

Another problem is the low sampling frequency. In this study, load was calculated using interpolated concentration values between actual measurements. This can lead to significant errors if, for example, all the samples are taken during low water flow. If concentrations increase with flow, the load estimated using the concentrations measured during low water flow will then be lower than the actual load. Figure 5 shows the measured daily discharge and total nitrogen concentration in the Leivajõgi River for 2013. The state monitoring sampling rate changed after 2010 from 12 to six times per year. The result can be seen in Figure 5: in 2013 all samples were collected during low flow discharge. This means that the actual loads in 2013 must be greater than those estimated using interpolated concentration values. The dependency between the concentrations and discharge for 2011–2013 is shown in Figure 6. As a consequence, the load calculations based on interpolated concentrations were underestimated more than twice in 2013. Thus, they had to be corrected before being used as input in MESAW. When no data were available for concentrations in the case of large discharges (e.g. 2013), a regression from other years (e.g. 2011 and 2012) was used to estimate flow-weighted nutrient fluxes.

MESAW was used for calculations in two case studies. First, the diffuse source emission coefficients of total nitrogen were estimated for seven single years (2005, 2006, 2007, 2008, 2011, 2012 and 2013) for the whole of Estonia (Table 3). Years were selected with different average runoff to cover the whole range of runoff from minimal to maximal values. In 2009 and 2010 runoff at most of the sampling points was in the range covered by other selected years. Also the number of sampling points in those years was smaller than in 2011–2013. Therefore data from 2009 and 2010 were not considered in this study.

All the estimated coefficients for all years were statistically significant ($p < 0.05$). The highest unit-area loads for total nitrogen loads in all years were from drained peat soils. The results are somewhat contradictory to official assessments (Estonian Ministry of Environment 2015), which have shown that the highest unit-area loads come from arable land.

Table 1 | Land cover in basins/sub-basins in case 1

		Land cover (km^2)			
River basin	**Monitoring point**	**Arable (km^2)**	**Drained peat (km^2)**	**Other land (km^2)**	**Lakes (km^2)**
Võhandu	Outflow from lake Vagula	223	64	274	12
Võhandu	Himmiste	348	105	376	14
Võhandu	Downstream from Räpina	451	119	553	16
Väike Emajõgi	Tõlliste	338	141	447	9.5
Väike Emajõgi	Pikasilla bridge	385	181	599	9.8
Õhne	Downstream from Suislepa	167	68	317	5.2
Õhne	Upstream from Tõrva, Roobe	57	34	161	4.7
Tarvastu	Upstream from Põdraoja	46	10	35	0.0
Tänassilma	Oiu	173	60	214	1.1
Emajõgi	Rannu-Jõesuu	1,082	455	1,465	275
Emajõgi	Tartu	2,590	1,365	3,460	308
Emajõgi	Kavastu	2,918	1,455	3,743	315
Pedja	Jõgeva Sordiaretusjaam	182	163	318	0.3
Pedja	Tõrve	223	176	371	1.1
Põltsamaa	Rutikvere	285	159	414	3.8
Porijõgi	Reola	116	39	81	1.0
Ahja	Kiidjärve	134	41	158	0.4
Ahja	Lääniste	380	92	456	1.9
Kääpa	Outflow from Kose reservoir	70	50	142	2.8
Avijõgi	Mulgi	88	37	264	0.0
Rannapungerja	Iisaku-Avinurme road, Roostoja	39	33	157	0.0
Tagajõgi	Tudulinna	19	10	212	0.3
Alajõgi	Griini (Alajõe)	16	29	109	0.3
Pühajõgi	River mouth	60	38	121	0.4
Purtse	River mouth (Tallinn-Narva mnt)	163	96	552	0.6
Kunda	Lavi springs	59	58	200	0.2
Kunda	River mouth	141	78	313	0.4
Seljajõgi	River mouth	217	35	164	0.0
Loobu	Vihasoo	110	36	168	0.0
Valgejõgi	Loksa pedestrian bridge	104	60	286	1.9
Pudisoo	Pudisoo	24	9.1	103	0.0
Jägala	Linnamäe	393	323	845	5.4
Leivajõgi	Pajupea	16	35	28	0.0
Vääna	River mouth	120	43	150	1.6
Keila	Keila	245	93	300	0.0
Keila	River mouth	273	102	307	0.0
Vihterpalu	Vihterpalu	71	117	293	0.0
Kasari	Kasari bridge	829	393	1,422	2.1
Velise	Valgu	28	25	89	0.0
Pärnu	Tahkuse	644	334	1,090	0.7

(*continued*)

Table 1 | continued

		Land cover (km^2)			
River basin	**Monitoring point**	**Arable (km^2)**	**Drained peat (km^2)**	**Other land (km^2)**	**Lakes (km^2)**
Pärnu	Oore	1,543	728	2,861	6.5
Vodja	Vodja	24	3.5	24	0.0
Navesti	Aesoo	298	190	553	0.0
Saarjõgi	Kaansoo	34	26	127	0.0
Halliste	Riisa	545	74	1,249	5.8
Reiu	Downstream from Lähkma	91	56	385	0.0
Sauga	Nurme weir	147	74	323	0.9
Pirita	Lükati	223	180	399	5.8
Mustajõgi	Mustajõe	27	59	286	2.1
Rannapungerja	Bridge on Mustvee road	71	49	472	0.3

Table 2 | Land cover in basins/sub-basins in case 2

		Land cover (km^2)			
River basin	**Monitoring point**	**Arable (km^2)**	**Drained peat (km^2)**	**Other land (km^2)**	**Lakes (km^2)**
Jägala	Sael	144	102	213	0.1
Pirita	Ardu	2.6	12	37	0.0
Pirita	Paunküla	5.5	23	59	4.9
Pirita	Ravila	23	34	84	0.2
Pirita	Kose-Uuemõisa	38	40	111	0.0
Pirita	Saula	95	73	201	0.2
Pirita	Vaida	126	125	346	1.3
Jägala	Kaunissaare	188	180	465	4.9
Raudoja	Veehoidla	0.1	1.0	21	0.6
Kuivajõgi	Kose-Uuemõisa	52	31	80	0.5
Kurna	Oja	7.9	8.4	19	0.0

In the next step of the analysis, the MESAW model was applied to a smaller area (Tallinn's drinking water catchment area) with better temporal resolution in its sampling frequency. The modelling results of source apportionment in the Tallinn catchment area are presented in Table 4.

All the coefficients for all years were statistically significant ($p < 0.05$). Similar to the analysis above for the whole of Estonia, the results for the Tallinn catchment area showed that the unit-area losses for drained peat soils are significantly higher than for arable land (except 2008). It is notable that the emission coefficients for all land types are much higher in the Tallinn catchment area than for the whole of Estonia (Tables 3 and 4). This is most likely to be due, in part, to the difference in the sampling frequency but it is even more likely to be due to the spatial scale issue. Table 3 contains average values for the whole of Estonia (relatively large area with significant differences in emission coefficients) while Table 4 contains average values for a smaller catchment area in Northern Estonia.

Previous studies have shown that the emission coefficients from arable land can vary by up to a factor of 25 in different countries (Wickham & Wade 2002) and, according to some studies, even by up to a factor of 8 in Estonia (Deelstra *et al.* 2014). Vassiljev *et al.* (2008) studied the emission coefficients for the whole of Estonia during 1995–2005 and found that the coefficient of nitrogen from arable land was 12.3 kg/ha compared to 15.2 kg/ha obtained in this study. Stålnacke *et al.* (2015) estimated emissions from cultivated areas in the Baltic Sea drainage basin to be 14.3 kg/ha. Emissions from drained peat areas were not estimated. Studies conducted in SE Estonia (Povilaitis *et al.* 2012) resulted in somewhat lower export coefficients compared to the average values defined for the whole of Estonia. This corresponds well with the findings in this study that show that the export coefficients in the study area (N Estonia) are higher than the average values. This indicates that the sources of nitrogen loads should be defined at the catchment area level rather than at the country level to ensure accurate estimations. The spatial issue is further illustrated in Figure 4 where the emission in SE Estonia is much

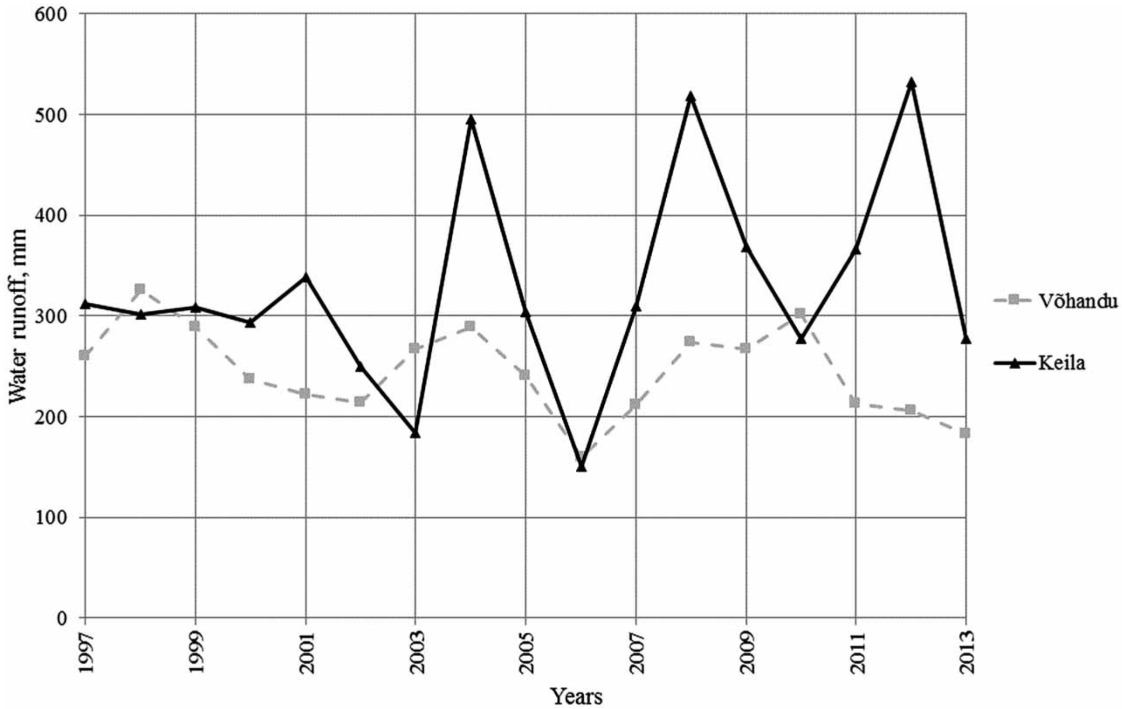

Figure 3 | Annual water runoff in the Võhandu River (SE Estonia) and the Keila River (N Estonia) in 1997–2013.

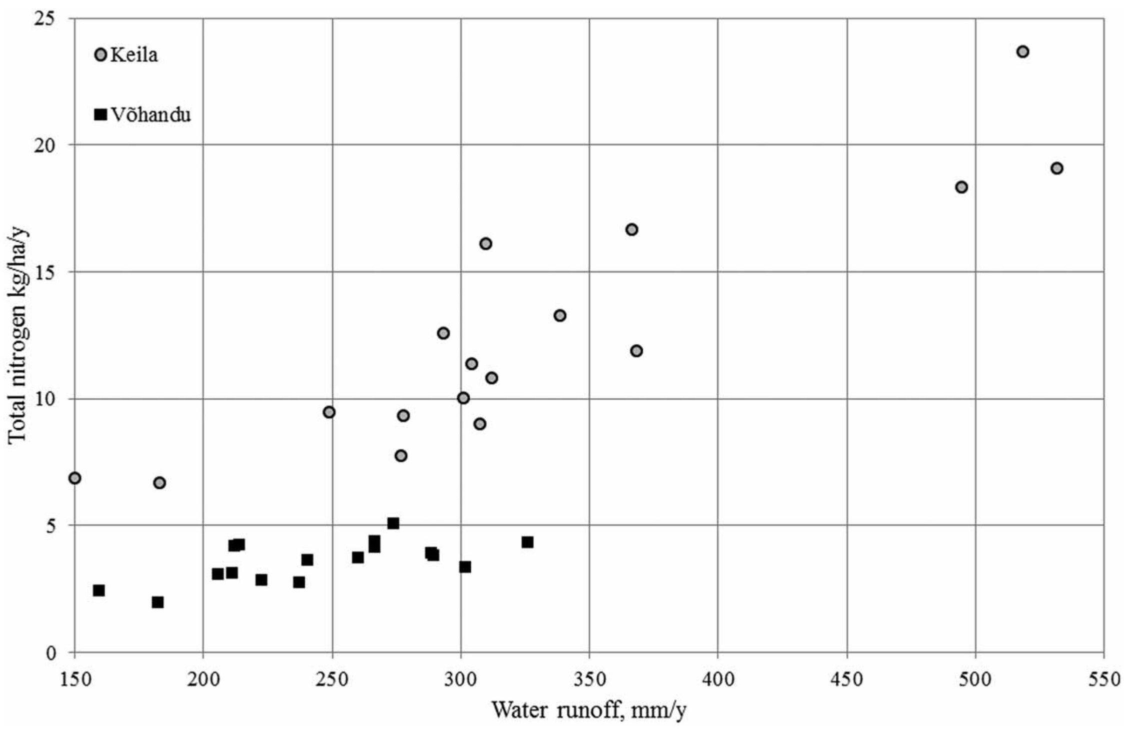

Figure 4 | Dependence between annual total nitrogen emission and water runoff (Keila and Võhandu, 1997–2013).

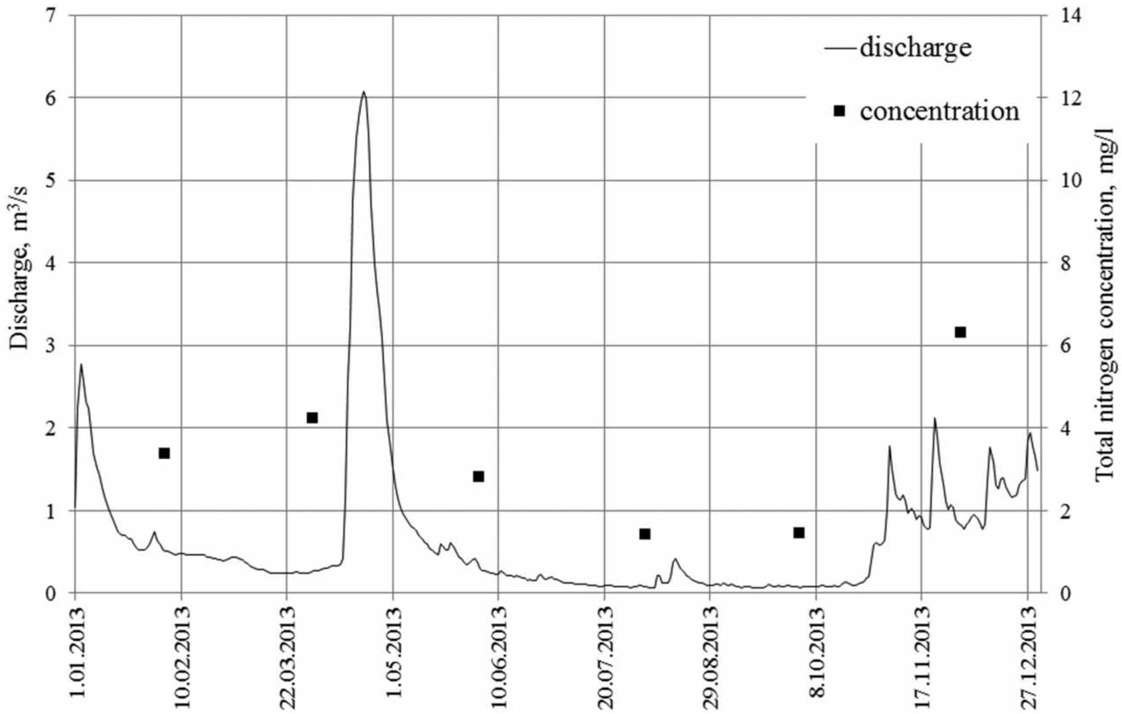

Figure 5 | Measured discharge and concentrations of total nitrogen in the Leivajõgi River in 2013.

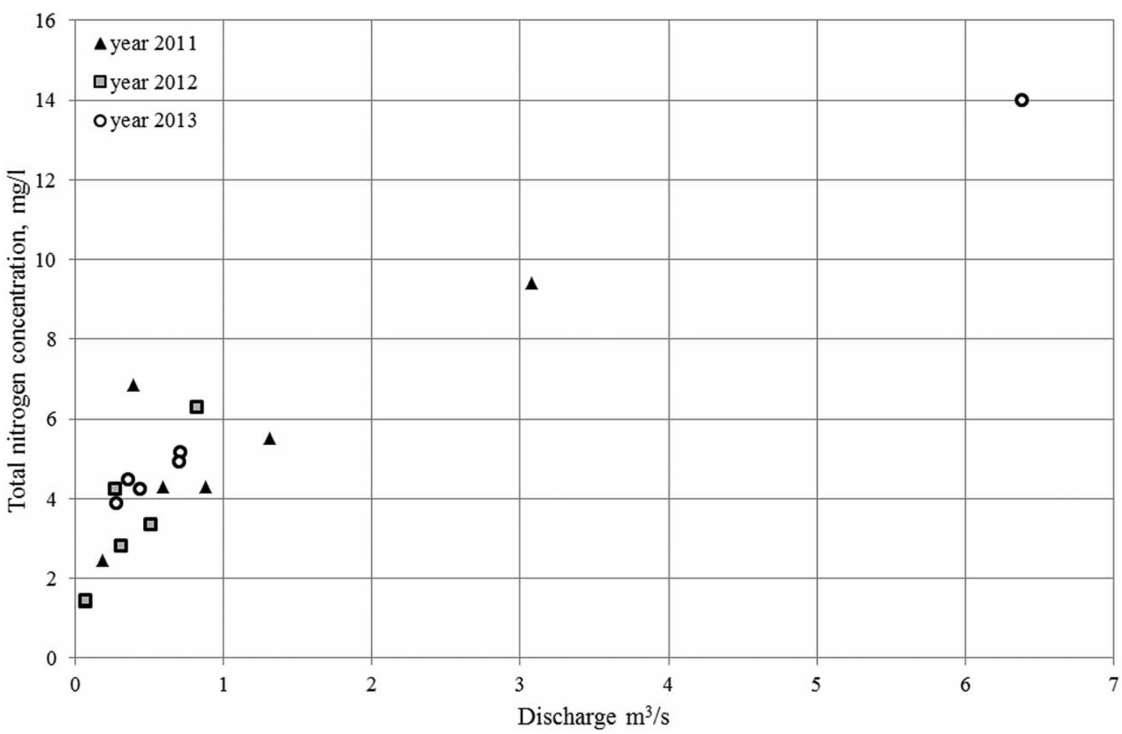

Figure 6 | Correlation between the measured discharge and concentrations of total nitrogen in the Leivajõgi River.

Table 3 | Results of estimated total nitrogen emission coefficients of the three land cover classes for the whole of Estonia

Year	Arable, kg/ha	Standard error	Natural areas, kg/ha	Standard error	Drained peat areas, kg/ha	Standard error	Average water runoff, mm
2005	10.7	2.0	1.5	0.5	24.4	3.8	285
2006	8.4	1.5	0.8	0.4	10.7	3.1	160
2007	16.8	2.3	1.2	0.3	19.1	4.7	245
2008	19.9	4.2	2.8	1.3	33.6	8.0	409
2011	17.9	2.9	2.2	0.7	32.7	6.1	338
2012	21.8	3.2	2.7	1.2	25.8	6.2	392
2013	11.5	2.6	1.2	0.5	23.2	5.4	253

Table 4 | Results of estimated total nitrogen emission coefficients of the three land cover classes for the Tallinn catchment area

Year	Arable, kg/ha	Standard error	Natural areas, kg/ha	Standard error	Drained peat areas, kg/ha	Standard error	Average water runoff, mm
2005	22.1	6.8	2.8	1.7	24.8	9.3	263
2006	15.1	6.5	1.0	0.8	21.9	8.7	137
2007	25.4	9.0	1.6	1.1	32.6	10.1	249
2008	43.6	13.9	3.4	2.8	42.2	17.6	382
2011	20.4	6.0	2.8	1.6	34.3	8.3	312
2012	32.8	7.8	4.5	2.4	38.5	10.3	423
2013	12.1	5.1	1.9	1.6	28.2	10.4	225

lower than that in N Estonia. For example, the measured water runoff in 2010 was practically the same (Figure 2) in both watersheds. Land use and strength of point sources (kg/km^2) in 2010 are relatively similar (Table 5). However, nitrogen emission was 2.4 times higher in the Keila River watershed (N Estonia) than in the Võhandu River watershed (SE Estonia). This could be caused by different relief, different depth of groundwater table, etc. Evidently, the average emission coefficients for the whole of Estonia will be lower than for N Estonia when SE Estonian rivers are included in the estimation of emission coefficients. Moreover, it is likely that there is more intensive agriculture and some additional sources of pollution (e.g. higher air deposition due to more intensive road transport) in the study area close to Tallinn. From the results, it is evident that an extensive study is required to quantify more precise source emissions of nitrogen in Estonia.

Table 5 | Land use and point sources in the Võhandu River and the Keila River in 2010

River-Location	Arable, %	Drained peat areas, %	Other areas (not arable and not peat), %	Point sources, kg/km^2
Võhandu-Räpina	40.1	10.6	49.3	16.0
Keila-Keila	38.4	14.6	47.0	10.0

Emission coefficients from drained peat areas have not been studied in Estonia. A field study in Northern Germany (Scholz & Trepel 2004) revealed that the nitrate concentrations in drained peatlands in an unnatural state can be 5–60 times higher than in natural peatlands. The high emission coefficients of drained peat soils obtained in this study can be explained by the high percentage of peatlands in an unnatural state in Estonia, with only 5.5% of peatlands in a near-natural state (Paal & Leibak 2011).

From the modelling results of case study 2 (Tallinn catchment area) it can be seen that the loads from arable land in 2011, 2012 and 2013 are substantially lower at the same water runoff than in 2005, 2006, 2007 and 2008 (Figure 7). This may be related to the last financial crisis when the use of fertilizer decreased in Estonia during the same period (Statistics Estonia 2015). Annual changes in temperature also have an effect on nutrient concentrations. In Tiemeyer *et al.* (2007) it was found that in some years NO3–N concentrations were low (or zero) at the beginning

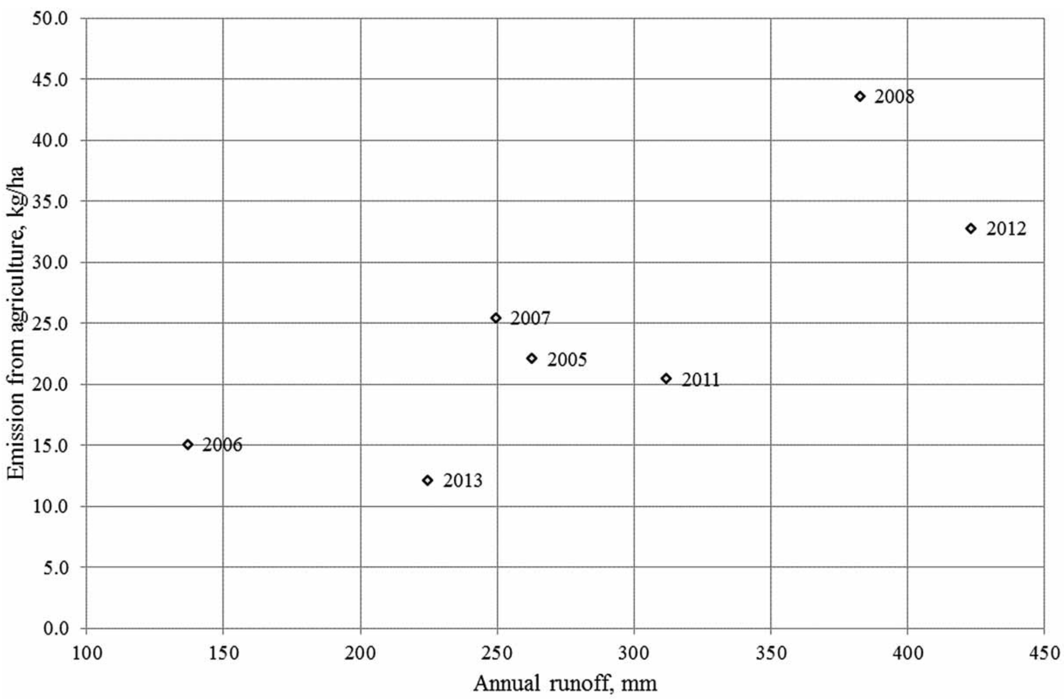

Figure 7 | Emission of nitrogen from agricultural areas vs annual runoff in the Tallinn catchment area.

of the discharge season, while low flow rates at the end of the discharge season (April) coincided with comparatively high NO3–N concentrations. This was explained by different climate conditions during the study period as the net release of nitrogen from peat soils increases with increasing temperature (Koerselman *et al.* 1993). Additional studies are needed to determine the relationship between temperature and changes in emission coefficients.

The export coefficients in MESAW are estimated by correlating observed and calculated loads. For example, Figure 8 presents the comparison between the modelled and measured loads in the Tallinn catchment area for 2012. The correlation between the observed and modelled loads is linear, indicating that the calculated results are reliable.

Calculations of the retention showed that coefficients λ_1 and λ_2 were different for different years and varied between 0.0008 and 0.0025 for λ_1 and between 2.5 and 6.7 for λ_2. This means, for instance, that retention varies from 7 to 20% in different years in rivers with a sub-basin area of 100 km^2 (Equation (2)). For example, if the lake area divided by the drainage area equals 0.168 (corresponds to the Võrtsjärv sub-basin), the retention in different years varies from 30 to 53%. The variation in retention may be explained by different weather conditions.

According to official assessments (Estonian Ministry of Environment 2015), the highest unit-area loads come from arable land. At the same time, Estonia is one of the most peatland-rich countries in the world with almost 22% of the country covered in peatlands in various conditions (Orru 1992), of which 5.5% of the peatlands are in a near-natural state (Paal & Leibak 2011). The rest of the peatlands are affected by drainage for forestry, agriculture and peat extraction (Karofeld *et al.* 2016). Therefore, it is necessary to study the nutrient inflow to the waterbodies from peatlands more thoroughly.

A comparison of emission coefficients for Estonia and the Tallinn catchment area indicated that the coefficients can vary significantly, even in a relatively small country. Therefore, it is suggested that the sources of nitrogen loads should be defined at the catchment area level rather than at the country level. The current study showed that average unit-area losses from drained peat soils can be estimated with a sufficient degree of accuracy and precision. However,

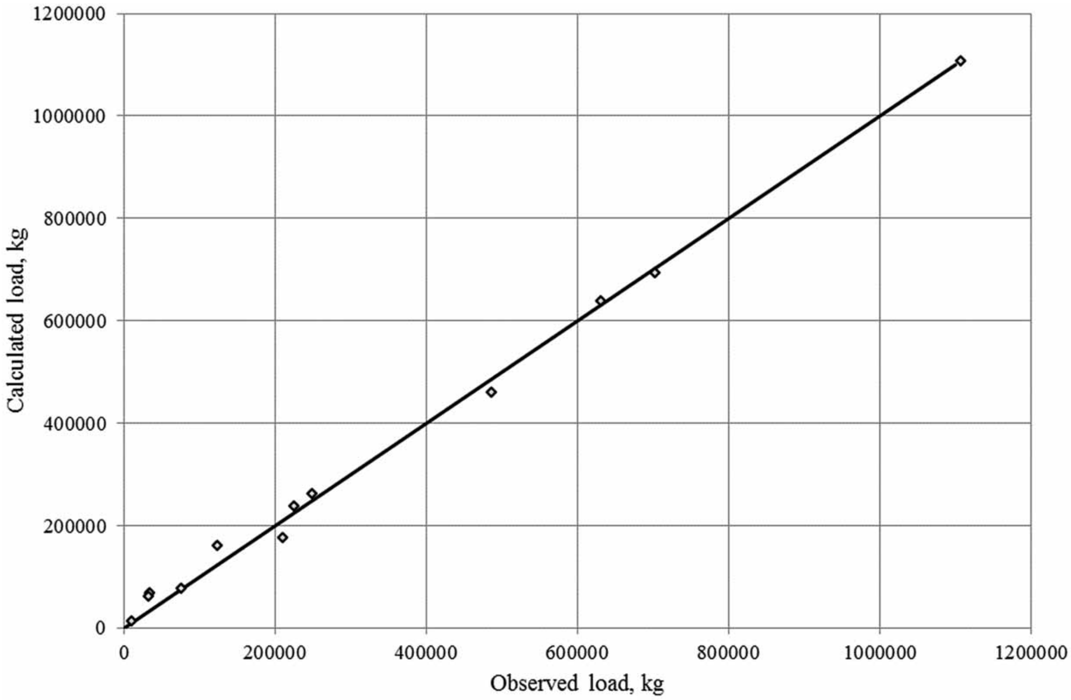

Figure 8 | Calculated vs observed nitrogen loads for the Tallinn catchment area (2012).

the processes are far more complex at smaller spatial scales. For example, the mineralization of nitrogen depends on the peat type and characteristics, soil moisture, depth, drainage types and construction time, so the emission coefficients in different spatial locations could differ. It is suggested that drained peatlands should be a particular concern and that additional and more detailed monitoring and field studies are needed.

Effective restoration strategies are required to reduce nutrient inflows to the waterbodies from drained peatlands. These do not depend solely on the restoration technique adopted but on how well integrated the catchment management schemes are and how well the interacting mechanisms are understood. Much more work is required to examine the hydrological and hydro-chemical processes surrounding artificial drainage and peatland restoration (Holden *et al.* 2004).

CONCLUSIONS

The MESAW model enabled estimation of statistically significant ($p < 0.05$) diffuse emission coefficients in two case studies for arable land, drained peat soils and other land. The study showed that unit-area losses from drained peat soils can be up to 2.3 times higher than from arable land. This is somewhat different from official assessments, which have shown that the highest unit-area loads result from arable lands. Drained peat soils must be recognized as an additional source of nitrogen. This study showed that it is a significant source in Estonia where the percentage of unnatural peatlands is high (~20% of total area of Estonia). Therefore it would be necessary to reconsider the nutrient reduction strategies in Estonia.

Unit-area losses from drained peat soils were estimated to vary between 11 and 34 kg/ha in the whole of Estonia and 22–42 kg/ha in the study area around Tallinn city. This indicates that the emission coefficients in different spatial locations could differ because of a number of different factors. Therefore it is suggested that the sources of nitrogen loads should be defined at the catchment area level rather than at the country level because the emission coefficients can vary significantly even in a small country like Estonia.

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