The effect of phosphorus on nitrogen retention in lakes

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Abstract

A hypothesis has been presented that nitrogen retention in lakes has become less efficient at the same time as phosphorus concentrations have decreased due to high phosphorus reduction in wastewater treatment. This might have led to higher loading of nitrogen into the Baltic Sea where nitrogen is considered to be the minimum nutrient. The hypothesis was tested using the mass balance modelling approach. Oligotrophic, mesotrophic and moderately eutrophic lakes situated in Finland and Sweden were used in the study. The combined approach of the classical mass balance model of Vollenweider and the statistical sedimentation model of Bachmann was used. At first the model was tested for nitrogen without any impact of phosphorus and it was concluded that this modelling approach is reasonable to study the hypothesis. If phosphorus concentration or retention affects nitrogen retention a better fit for the model of nitrogen retention can be gained when a function of phosphorus input or concentration is included in the nitrogen model of Bachmann. The results indicate that inclusion of phosphorus does not improve the fit of the model and thus it can be concluded that phosphorus can only be a minor factor in regulating nitrogen retention, at least in lakes which are not hypereutrophic.
Keywords: nitrogen, phosphorus, retention, lakes, mass balance, models.

1 Introduction

In the process of eutrophication phosphorus and nitrogen are the most important nutrients and regulating factors. In lacustrine environments phosphorus loading is usually the main factor regulating eutrophication whereas in marine environments nitrogen is more important. In brackish waters such as the Baltic Sea both of these nutrients may be limiting algal growth. However, it has been

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found that nitrogen is the most important limiting nutrient in the Baltic Sea [1] and therefore particular attention has been paid to reduction of nitrogen loading into the Baltic Sea.

Because the impact of phosphorus on the trophic status is so clear wastewaters are treated so effectively that the reduction percentage of phosphorus is higher than 90, up to 98. Today agricultural contribution to nutrient loading from the catchments is dominating compared to domestic wastewaters from cities and other communities. Fortunately, the whole nutrient flow from the catchment does not enter the Baltic Sea because the percentage of lakes in the drainage basins is great at least in Finland, Sweden and part of Russia, and the detention times of the lakes are relatively long. Thus retention of phosphorus and nitrogen reduces nutrient flows to great extent.

In Sweden, Stålnacke *et al.* [2] found that an upward trend in nitrogen flows has taken place in the mid and late 1970s, i.e. at the end of the period during which phosphorus removal had been introduced at practically all municipal wastewater treatment plants in Sweden. Because phosphorus is the main limiting factor in algal growth it can be assumed that the lakes became less eutrophic along with the reduction of phosphorus loading. Thus Stålnacke *et al.* [2] presented a hypothesis that nitrogen retention has decreased along with the reduced phosphorus loading and degree of eutrophy. A similar hypothesis was earlier presented by Ahl [3] for Lake Vänern.

Retention of a substance can be defined as the difference between input and output of the substance. In this study long-term average values, referring to steady state modelling, are only considered. For phosphorus, retention is thus the same as net sedimentation, i.e. the difference between gross sedimentation and the release from the sediment. For nitrogen, the situation is more complicated because in addition to sedimentation and release from the sediment also denitrification and nitrogen fixation must be included. Thus retention of nitrogen is the same as the sum of net sedimentation and denitrification subtracted by nitrogen fixation.

In this study the effect of phosphorus on nitrogen retention in lakes was studied using mass balance modelling approach. The central idea was to find out if the fit of nitrogen balance model can be improved by adding variables related to phosphorus balance into the equation describing nitrogen balance. The study was part of the NUTRIBA project within the Baltic Sea Research Programme of the Academy of Finland (BIREME).

2 The modelling approach

As the starting point the classical first order CSTR mass balance model of Vollenweider [4, 5] was used. At steady state the basic equation can be given as

$$I - Qc - \sigma c V = 0 \qquad (1)$$

where
I = input (M T^{-1})

Q = discharge (L^3 T^{-1})
σ = first order retention coefficient (T^{-1})
c = concentration in the lake ($M\ L^{-3}$)
V = volume of the lake (L^3)

According to the CSTR principle water quality is uniform in the lake and thus the second term on the left-hand side of eqn. (1) represents the output through the outlet of the lake. When long-term average values are considered this description is justified. The third term represents retention.

It was already found by Vollenweider [4, 5] that σ is not a universal constant but varies from lake to lake. Canfield and Bachmann [6] have presented a statistical model by means of which the first order reaction coefficient can be calculated for phosphorus. Bachmann [7] has presented a similar model for nitrogen:

$$\sigma = a_n \left(\frac{I}{V} \right)^b \tag{2}$$

where
σ = first order retention coefficient for nitrogen (a^{-1})
I = input of nitrogen ($mg\ a^{-1}$)
V = volume of the lake (m^3)
a_n = 0.0159
b = 0.594

Concentration of nitrogen (c) can be calculated from eqn. (1) as follows:

$$c = \frac{I}{Q + \sigma V} \tag{3}$$

Only total input into the lake, discharge and volume of the lake are needed. The value of σ is received from eqn. (2).

The "empirical" value of σ can be calculated from eqn. (3) on the basis of input, discharge, volume and concentration:

$$\sigma = \frac{I - Qc}{c\,V} \tag{4}$$

If the retention model described the retention process completely the σ values calculated by eqn. (4) would be equal to the values calculated by eqn. (2). In this case the values of the parameter a_n would be constant and not varying with lakes.

If retention of nitrogen is dependent on phosphorus it can be assumed that the predicting capacity on the nitrogen retention model can be improved by including a function of phosphorus into the model. Then necessarily coefficient

a_n in eqn (2) would be dependent on phosphorus retention. Phosphorus retention is according to Canfield and Bachmann [6] and many other authors [7–10] dependent on phosphorus input into the lake and it can also be described as a function of phosphorus concentration in the lake [4, 5, 11, 12]. Two possibilities to take into account the impact of phosphorus were studied:

$$a_n = f\left(\frac{I_p}{V}\right) \tag{5}$$

$$a_n = f(c_p) \tag{6}$$

where
I_p = total input of phosphorus (mg a^{-1})
V = volume of the lake (m^3)
c_p = phosphorus concentration in the lake (mg m^{-3})

If reasonable functions of eqns. (5) and (6) can be formed their inclusion into eqn. (2), applied together with eqn. (3), will improve the predicting capacity of the nitrogen balance model and thus prove that retention of nitrogen is dependent on phosphorus. The values of the coefficient a_n are calculated by dividing the coefficient σ from eqn. (4) by the power function of I/V:

$$a_n = \frac{\sigma}{\left(\frac{I}{V}\right)^b} \tag{7}$$

where b = 0.594.

3 Material and methods

Two data sets were used. One set consists of Finnish lakes situated in the catchment of the river Kokemäenjoki in South-West Finland (table 1). The other data set which consists of Swedish lakes and is based on different sources and has been described by Persson [13]. Discharges were calculated by dividing the watershed areas by runoff values. Average concentrations for nitrogen and phosphorus were calculated according to the CSTR description as the ratio of substance output and discharge. Frisk *et al.* [10] noticed that the predictability of mass balance models for phosphorus is poor in highly eutrophic lakes. Even though main attention is paid to nitrogen modelling in this study it is also important that phosphorus modelling procedure is valid in the lakes of the study. Therefore lakes with phosphorus concentration higher than 50 mg m^{-3} were omitted from the data.

The models described in chapter 2 were applied using the Finnish and the Swedish data sets separately and also using both of the data sets together.

Table 1: The data of the lakes in the drainage basin of the river Kokemäenjoki. V = volume of the lake (10^6 m^3), Q = discharge (m^3 s^{-1}), I = total nitrogen input (10^9 mg a^{-1}), I_p = total phosphorus input (10^9 mg a^{-1}), c = nitrogen concentration (mg m^{-3}), c_p = phosphorus concentration (mg m^{-3}).

Lake	V	Q	I	I_p	c	c_p
Kuohijärvi	347	6.20	106	3.5	385	5.7
Kukkia-itä	97	6.66	125	2.6	358	9.1
Kukkia-länsi	163	7.54	107	3.0	329	9.6
Pyhäjärvi	104	2.89	112	2.9	577	12
Parkanonjärvi	35	6.94	233	10	853	31
Koveslahti	50	3.37	128	5.8	841	38
Heittolanlahti	21	12.11	319	13	700	31
Kelminselkä	64	4.56	247	9.9	1245	42
Viljakkalanselkä	45	0.49	27	1.0	713	21
Kyrösjärvi1	700	25.74	731	29	799	24
Kyrösjärvi2	116	26.27	681	21	777	22
Iso-Roine	247	13.14	189	4.9	391	11.8
Hauhonselkä	89	2.26	102	4.0	692	26.8
Ilmoilanselkä	89	18.42	264	8.0	434	17
Uuraslahti	7	0.69	34	1.4	1227	50
Nerkoojärvi	56	1.10	44	1.9	590	21

4 Results

The correspondence between observed and calculated nitrogen concentrations was good in the Finnish data set with a correlation coefficient of 0.939 ($p<0.0001$) (fig. 1). The correspondence was not as good in the Swedish data set but, however, the correlation coefficient was 0.624 ($p<0.001$) (fig. 1). In the whole data the correlation coefficient was 0.646 ($p<0.0001$).

In some lakes there were considerable differences between observed and calculated nitrogen concentrations. It was studied if the fit of the model could be improved by including phosphorus concentration or input in the model. The fit of the model could be improved if coefficient a_n in eqn. (2) could be described as dependent on phosphorus. In Finnish lakes a_n is almost constant (fig. 2) which indicates the fact that the basic model for nitrogen can be well used without phosphorus. a_n does not seem to be dependent on phosphorus concentration. In Swedish lakes the situation is a little different because there is more variation (fig. 2). However, there is no clear dependence between phosphorus concentration and a_n and thus no reasonable function $f(c_p)$ can be formed. Eqn, (5) cannot improve the fit of the model. The non-significant correlation coefficients are r=-0.309 (p=0.244) for Finnish lakes, r=0.097 (p=0.593) for Swedish lakes and r=0.070 (p=0.633) for the whole data.

Table 2: The data of the Swedish lakes [13]. V = volume of the lake (10^6 m^3), Q = discharge (m^3 s^{-1}), I = total nitrogen input (10^9 mg a^{-1}), I_p = total phosphorus input (10^9 mg a^{-1}), c = nitrogen concentration (mg m^{-3}), c_p = phosphorus concentration (mg m^{-3}).

Lake	V	Q	I	I_p	c	c_p
Magnusjaure+N	0.03	0.0010	0.041	0.0001	400	4
Gårdsjön	1.5	0.0169	0.732	0.0062	400	5
Vättern	74000	36.02	3192	74	740	7
Stugsjön	0.02	0.0009	0.013	0.0006	197	7
Aspen	79.6	11.14	613	10	956	10
Örträsket	160	17.39	200	7.0	300	11
Kalvsjön	44.9	3.73	115	4.0	500	12
Fegen	181.7	1.32	63	2.4	420	14
Mjörn	850	8.43	854	30	950	14
Bolmen	1070	13.12	4399	11	522	14
Ivösjön	558.29	7.97	379	6.8	800	14
Botjärn	0.32	0.0235	0.36	0.011	420	14
Boren 2	170	51.50	493	11	440	15
Väsman	410	9.19	185	7.7	480	15
Vidöstern	211.23	10.22	538	14	553	17
Erken	214	0.94	47	1.4	770	18
Södra Barken	63	17.53	333	12	529	18
Åsunden	293	4.48	350	5.3	1130	20
Boren 1	170	51.50	652	50	450	26
Mälaren C	8450	94.78	6905	290	400	29
Roxen	748	105.86	3201	75	700	30
Hymenjaure+P	0.03	0.0017	0.005	0.006	200	30
Hornborgasjön	25	4.68	644	7.6	1600	30
Oppmannasjön	49.65	0.73	103	1.1	1000	32
Gåran	0.23	0.21	10	0.26	810	40
Gunillajaure+N+P	0.14	0.0016	0.13	0.01	130	40
Glan	470	119.03	3546	135	650	45
V. Storsjön	181.5	9.25	204	9.0	470	45
Ö. Storsjön	89.35	17.10	455	18	700	45
Hjälmaren	2893	26.72	2657	67	798	46
Mälaren A	210	69.14	3607	154	600	48
Ralången	13.41	4.76	170	3.7	1200	50
Tåkern	35	2.75	207	7.2	2000	50

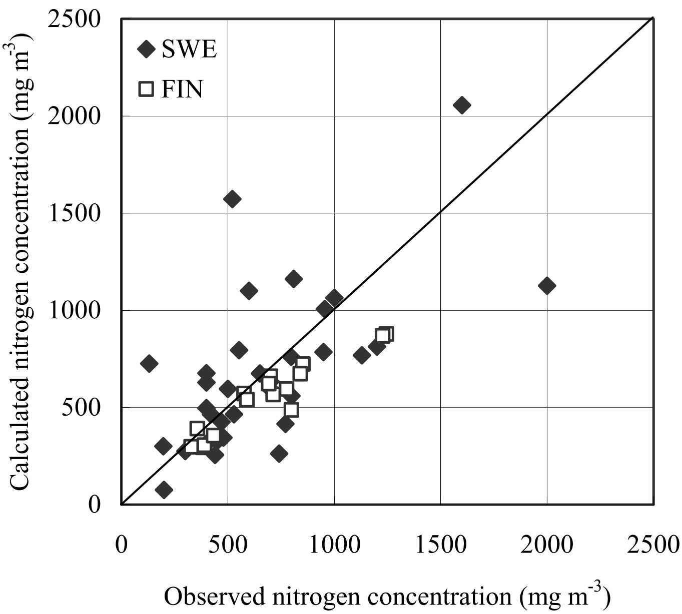

Figure 1: Observed and calculated (eqns. 3 and 2) nitrogen concentrations. □ = Finnish lakes, ♦ = Swedish lakes.

The situation is still worse when a_n is plotted against I/V. There is no clear dependence in the Finnish nor the Swedish data sets (fig. 3). The non-significant correlation coefficients are r=-0.108 (p=0.692) for Finnish lakes, r=0.162 (p=0.369) for Swedish lakes and r=0.148 (p=0.310) for the whole data.

Thus inclusion of phosphorus does not improve the predicting capacity of the nitrogen balance model and nitrogen retention does not seem to be dependent on phosphorus in the data sets of the study which represent a large variety of lakes from oligotrophy to moderate eutrophy.

5 Discussion

The idea that nitrogen retention is dependent on phosphorus in lakes could be theoretically expected. In lakes in which phosphorus concentrations are high also primary production is high. Thus also sedimentation of phytoplankton and nutrients is high. Nitrogen retention may be found to be dependent on phosphorus input or concentration in many cases because phosphorus and nitrogen loadings are often strongly correlated. In the data of this study the correlation coefficient between nitrogen loading and phosphorus loading is = 0.884 ($p<0.0001$) and nitrogen retention and phosphorus retention = 0.775 ($p<0.0001$). These correlation coefficients would be still much higher if one lake were omitted from the data. Thus it is clear that nitrogen retention can be at least to a certain extent predicted by means on phosphorus loading but it does not prove that phosphorus *per se* is a key factor in this process.

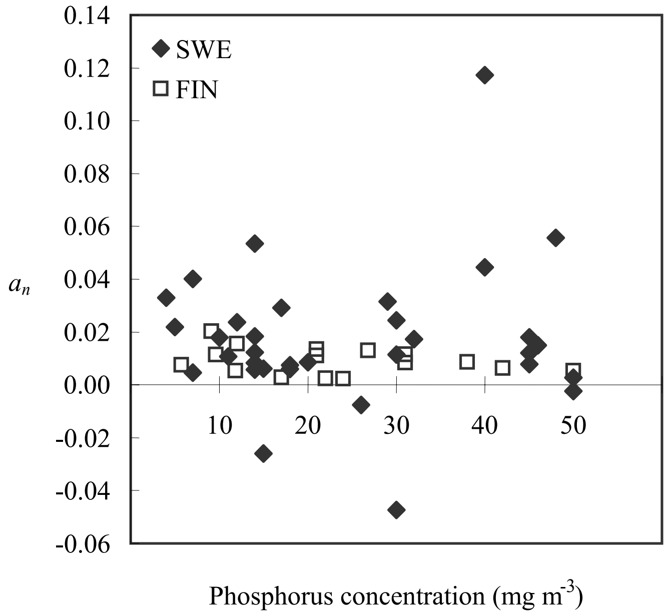

Figure 2: The dependence of sedimentation constant a_n on phosphorus concentration. □ = Finnish lakes, ♦ = Swedish lakes.

In this study highly eutrophic lakes with total phosphorus concentration higher than 50 mg m^{-3} were not considered. It is possible that in hypereutrophic lakes reduction of phosphorus loading decreases retention of nitrogen. Retention percentage of phosphorus is low in this kind of lakes and the generally applied statistical phosphorus retention formulae do not give reliable results [10]. The large lakes in the catchment of the Baltic Sea which cause most of the nutrient retention are usually oligotrophic or mesotrophic or only moderately eutrophic and the main interest of this study was in this kind of lakes in which no direct impact on phosphorus on nitrogen retention was found.

The retention mechanisms are different for nitrogen than for phosphorus. For nitrogen, sedimentation is not necessarily the most important factor but denitrification may dominate. On the other hand nitrogen fixation reduces retention because it is not included in the input term. Nitrogen fixation is particularly high in lakes with low nitrogen/phosphorus ratio, due to nitrogen fixing cyanobacteria. In some lakes the retention constant a_n is negative which could indicate effective nitrogen fixation. The nitrogen/phosphorus ratio varied in these lakes between 7 and 29 while the mean value of the whole data was 36. Denitrification is in principle an anaerobic process. However, total anoxia is not required but local low redox potential is sufficient. In highly eutrophic lakes contribution of denitrification to nitrogen retention is high. In Lake Enäjärvi Kettunen [14] found it to be about 90%. Also Persson [13] reported high shares of denitrification in nitrogen retention in large Swedish lakes.

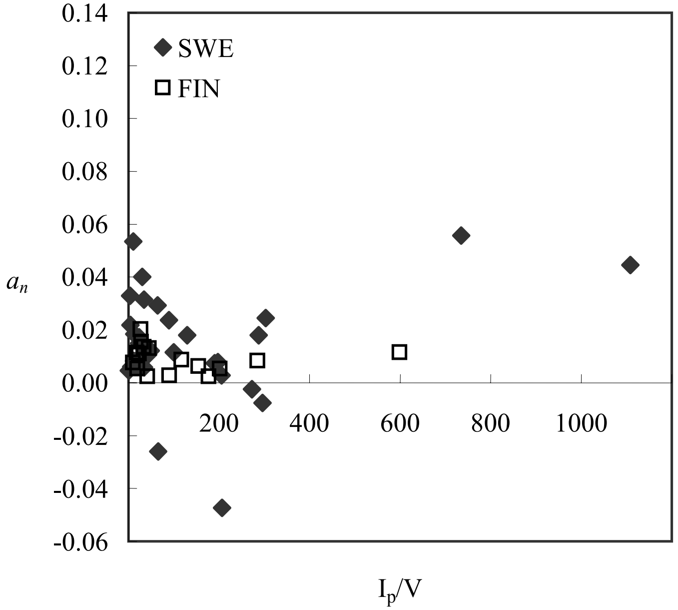

Figure 3: The dependence of sedimentation constant a_n on the ratio of phosphorus input and the volume of the lake (I_p/V). □ = Finnish lakes, ♦ = Swedish lakes.

As a concluding remark it can be stated that no indication was found about the impact of phosphorus input or concentration on nitrogen retention in lakes. So it seems that the water protection strategy with efficient phosphorus removal has not led to higher nitrogen loading to the Baltic Sea.

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