Temporal and spatial variability of nitrogen flow from small forested basins

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Abstract Studies of spatial and temporal variability of different nitrate fractions were performed. They were based on 10 to 20 year time series from eight Finnish and twelve Swedish catchments, ranging in size from 0.3 to 42 km². The analyses included trend analyses of concentrations, multiple regression analyses of the influence of catchment characteristics, forestry activities and deposition on nitrogen loads, and investigation of the influence of seasonal variability and hydrological dynamics on concentrations. The trend tests indicated that there may be an increase in NO₃-N from certain types of forested areas, although negative trends were found for the Swedish catchments, where the time series started later. Significant differences were found for concentrations of nitrogen during different combinations of flow and season. However, the relations were different for different catchments, especially concerning NO₃-N. Considerable differences in nitrogen loads were found between catchments, and different combinations of explaining variables were selected for different fractions of nitrogen.

INTRODUCTION

In recent years, studies of time series of water quality data from forested catchments have indicated upward trends in nitrogen concentrations (Fleischer et al., 1989, Grimvall et al., 1991). This would be of particular importance for the Northern part of the Baltic Sea, where the drainage basin is dominated by forest. In some cases, the increases could be explained by changes in water flow, i.e. where it has been wetter towards the end of the study period. Other possible explaining factors are forestry activities (e.g. Vitousek et al., 1979) or effects due to elevated inputs of atmospheric nitrogen (e.g. Gundersen & Rasmussen, 1990).

In a joint Finnish-Swedish project, called "The Gulf of Bothnia Year", the environmental status of the Gulf of Bothnia is being studied. One sub-project aims to detect and explain temporal and spatial variability in nitrogen concentrations and loads from forests.

The results from the study are based on analyses of data from eight Finnish and twelve Swedish forested catchments, ranging in size from 0.3 to 42 km². The time series of concentrations of different nitrogen fractions varied between 10 and 20 years. Results will be presented in four papers, which will all be submitted to international journals.
during 1993. Preliminary titles of the papers are as follows:
1: Influence of catchment characteristics, forestry activities and deposition on nitrogen load from small forested catchments.
2: Increasing nitrogen loss from forested areas in Sweden and Finland? — Trend analyses and transport estimations.
3: Seasonal variability and the influence of hydrological dynamics on nitrogen concentrations from small forested catchments.
4: Temporal variations of nitrogen loads and concentrations in small forested catchments.

This paper includes a summary of the findings from papers 1 to 3. The fourth paper includes an analysis of why concentrations and loads in different catchments fluctuate over time due to the temporal variability of hydrological and climatological factors, forestry activities and N deposition. Methods and some preliminary results from that study have been presented by Andersson et al. (1993).

### SPATIAL VARIATIONS OF NITROGEN LOADS

Often, variability of nitrogen loads between different catchments is studied by considering differences of only one relevant factor, e.g. land use. In this study, it was hypothesized that the variability of loads of different fractions of nitrogen could only be explained by the combined effect of hydrological, climatological, physiographic, forest management and deposition factors. Multiple regression methods were used to explain the spatial variability of average loads (1979-1988) as a function of these factors. Loads for the 20 included catchments were calculated by linearly interpolating observed concentrations to estimate daily concentrations and then multiplying with daily flow values.

The independent variables used included relief, mean slope, stream density, percentage of area with fine soils, organic soils and bare rock, annual precipitation and air temperature, atmospheric wet deposition of nitrogen, average monthly minimum and maximum runoff, the ratio between maximum and minimum runoff as an index of peakiness and percentage of area fertilized, clear-cut or drained during the actual period.

The average nitrogen load varied considerably between the 20 studied catchments, for $\text{NO}_3\text{--N}$ from 2 to 133 kg km$^{-2}$ year$^{-1}$ and for organic N from 112 to 441 kg km$^{-2}$ year$^{-1}$ (Fig. 1). In general, the catchments located in southern Finland and Sweden had the highest loads of $\text{NO}_3\text{--N}$, whereas a general geographical pattern was harder to distinguish for the other fractions of nitrogen. The following focuses on hydrologically related variables found to explain part of the spatial variability.

For nitrate N, the strongest correlation was found with high air temperature and/or high N deposition. These two factors were strongly interrelated. In addition, a high percentage of clear-cutting, and a low extent of organic soils promoted high loads. A link between high concentrations and high stream density was also found. The effect of clear-cutting was mainly due to increased runoff volume. The positive correlation with high stream density can be explained by shorter transit times and it might be assumed that a larger part of the atmospheric N deposition reaches the stream without transformations. The negative correlation with percentage of organic soils can partly be explained by denitrification, promoted by the soils often being saturated.

For ammonium N, high loads were mainly correlated to forestry activities and other
Fig. 1 Average loads (1979-1988) and trends in different nitrogen fractions. For eight of the Swedish catchments, only nitrate nitrogen was available. For Murtopuro and Koivopuro, pre- (1979-1982) and post- (1983-1988) treatment loads are given. For Kullarna and Snipätno average loads from 1981-1988 are shown.
variables that are affected by such activities. Correlations were found with a high percentage of drainage or the related parameters of high stream density, high percentage of organic soils, and low maximum runoff, or with clear-cutting and the related parameter annual runoff. In addition, air temperature seemed to be an important factor. The effects of clear-cutting on water volumes, and thus on loads (discussed earlier) was also observed for ammonium N. In addition, the study supported the observation that drainage of organic soils increases mineralization in the aerated soil profiles and thus increases both concentrations and outflow of ammonium.

The most important factors explaining the spatial variability of organic N loads was found to be forestry activities in the form of drainage and also clear-cutting. In addition, high runoff peakiness and high air temperature promoted high loads. Runoff peakiness was shown to be important both for concentrations and loads, indicating that a more peaky flow increases the mobility of organic N. This could be an effect related to erosion in the discharge areas. Also for organic N, an effect of clear-cutting, caused by increased runoff volumes, was indicated.

A conclusion from the study is that there was a considerable variation in nitrogen loads between the catchments and different combinations of variables had to be used for different fractions of nitrogen. It was also concluded that the effect of forestry activities on spatial variability of nitrogen loads was large, but only when catchments with a relatively large percentage of treated area, were included in the analyses. In some cases the effects of forestry activities could have considerable influence on temporal variability of loads from a catchment, although other variables, e.g. physiographic or climatological, were of overriding importance in a regional comparison of catchments.

**Trends in time series of concentrations**

Previous analyses of Swedish river water quality time series have been based on rather simple regression models, assuming independency between the observed concentrations. However, in time series of water quality, seasonality and serial correlation between concentrations are commonly observed. In such cases, non-parametric trend tests give a more correct test of actual trends in the series (Hirsch & Slack, 1984). For analyses of the present data set, a few different methods were evaluated. Trend tests were performed on time series of concentrations ranging over a maximum of 18 years. For the Swedish catchments, when restricting the analyses to periods without change of laboratories, periods with a length of 9 to 13 years were available. Very intensively managed catchments, i.e. Koivupuro, Murtopuro, Lower Kullarna and Sniptjörn, were excluded from the trend analysis.

Upward trends in NO$_3$-N concentrations during the period 1971-1988 were detected in 3 out of 6 catchments with the non-parametric test (Table 1). For the Swedish NO$_3$-N series the analysed period started between 1977 and 1981. In all except one of those catchments, the test variable had a negative sign, and in four of them the downward trend was significant (Table 1). For Teeressuonoja and Huhtisuonoja, it has been hypothesized that the trends might be due to increased nitrogen deposition (Lepistö and Seuna, 1990; Lepistö et al., 1991). No general relations between the geographical distribution of nitrogen deposition or forestry activities and trends in NO$_3$-N concentrations could, however be detected. For organic N, an upward trend was found in one out
Table 1 Test statistics (z ratios) calculated for forested catchments and different nitrogen fractions, using Hirsch & Slack method with flow-adjusted concentration data.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Period</th>
<th>NO₃-N</th>
<th>NH₄-N</th>
<th>Organic N</th>
<th>Total N</th>
</tr>
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<tr>
<td>Sweden</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Huluböcken</td>
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<td>1.08</td>
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<td>Döntersta</td>
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<td>1.05</td>
<td>1.56</td>
<td>1.14</td>
</tr>
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<td>Nolsjn</td>
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<td>-2.48*</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Stormyra</td>
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<tr>
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<tr>
<td>Upper Kularma</td>
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<td>0.64</td>
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<td>Lilla Tivsjn</td>
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<td></td>
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<td></td>
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<tr>
<td>Norrsjn</td>
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<td></td>
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<td>Vuoddasböcken</td>
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<td>-3.27**</td>
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<td>1978-1990</td>
<td>-2.14*</td>
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<tr>
<td>Finland</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Teeressuonoja</td>
<td>1971-1988¹</td>
<td>3.57***</td>
<td>-1.30</td>
<td>1.29</td>
<td>3.13**</td>
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<td>Paunulanpuro</td>
<td>1971-1988¹</td>
<td>-0.15</td>
<td>1.24</td>
<td>-1.18</td>
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<td>Huhtisuoanoja</td>
<td>1971-1988¹</td>
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<td></td>
<td>-2.00*</td>
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<td>Pahkajoja</td>
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<td>-0.47</td>
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<td>Myllypuro</td>
<td>1971-1988¹</td>
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<td>-2.38*</td>
<td>1.18</td>
<td>2.23*</td>
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<td>Võõõ-Askanjoki</td>
<td>1971-1988¹</td>
<td>2.19*</td>
<td></td>
<td>2.39*</td>
<td>2.13*</td>
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</tbody>
</table>

¹ For NH₄-N the time period is 1973-1988
Levels of significance: * 0.01 < p < 0.05; ** 0.001 < p < 0.01; *** p < 0.001

of eight catchments (Table 1).

For all N fractions, flow adjustment affected the results considerably in some of the catchments, whereas in others it had no effect. In several of the catchments, no simple relation between flow and concentration could be observed. This indicates that a simple flow adjustment based on monthly mean concentrations and flows is not sufficient to detect the effect of hydrological variations on concentration and load in these small catchments with quick responses.

In summary, the results from the trend tests suggest that there may be an increase in NO₃-N from certain types of forested areas. The trends cannot easily be explained by increasing nitrogen deposition or increasing water flow. This is not surprising, since the effect of both those factors could be expected to vary between catchments. Further analysis of geophysical characteristics and hydrological dynamics will probably help in interpreting the results. In a study of trend tests for water quality data, it was concluded that a 17 year series with a sampling frequency of six per year was needed to bring the error probability down to 0.1 (Berryman et al., 1988). In the Swedish series, 10 to 13 years must be considered a short period. However, the negative sign in nine out of ten catchments, suggests that the results may reflect actual changes during the 1980s.

No support for the suggested increase in organic N loss from forested land could be gained from the present set of data. However, it must be remembered that data on organic N was limited to 8 catchments, of which 2 had only 11 to 12 years of data.

SEASONALITY AND LINKS BETWEEN FLOW DYNAMICS AND CONCENTRATIONS

One part of this project is to find links between seasonality, flow dynamics and nitrogen
concentrations. Such relations can be used to improve load estimates and to establish if such trends can be explained by variability in flow dynamics.

For some of the catchments a logarithmic regression model could be used to explain relations between concentrations and flow, but in general the relationships were more complex. Since the concentrations showed a very skewed distribution, a non-parametric test (Wilcoxon test) was used to examine if concentrations were significantly different during different conditions, hypothesized to influence concentrations. The following conditions were compared: (a) high and low flow; (b) increase and no increase of flow; (c) low flows during summer and the rest of the year; and (d) high flows during the first and second part of the year. Low flow was defined such that 50% of the days were included and high flows included 25% of days. If the average flow during the actual day and the antecedent two days was higher than the average flow during the preceding three to five days the flow was considered as increasing. June-August were considered as summer months. Different combinations of these conditions were also investigated.

Differences between NO$_3$-N concentrations during low and high flows were found for most of the catchments. Concentrations were generally lower at high flows, which can be explained by dilution. In four catchments, however, concentrations were higher during high flows. After analyses of catchment characteristics, this seemed to be related to larger nitrate pools due to higher mineralization rates in these areas. For most catchments, samples taken during increasing flow showed higher concentrations of NO$_3$-N. This was especially pronounced during spring, which can be explained by mineralization during winter and accumulation of atmospheric deposition in the snowpack, causing high concentrations during the initial phase of the spring flow. For some catchments, a relationship between high concentrations and flow increase was only found during high flow (Fig. 2), whereas for others increases during low flow were linked to high concentrations. We have not yet found a distinction between these two groups of catchments from our data of catchment characteristics. NO$_3$-N concentrations showed rather strong seasonality. Low flow concentrations during summer were lower

![Fig. 2 Medians of NO$_3$-N concentrations during high flow, divided in samples taken during days with increasing flow and days without an increase in flow. Only values from catchments where the differences were significant at the 1-10% level by the Wilcoxon test are shown.](image-url)
than during the other parts of the year, which can be explained by high uptake by vegetation as well as high denitrification rates during summer. During high flow, catchments in Northern and Eastern Finland had higher concentrations during the autumn, whereas catchments in Central and Southern Sweden showed higher concentrations during high flows in spring. This could probably be explained by climatological differences as mineralization rates and spring flow volumes vary between these two regions.

For NH$_4$-N, almost all the catchments showed differences between high and low flow. The majority had higher concentrations during low flow, which indicates dilution during high flows. However, four catchments had higher concentrations during high flows. Two of these were drained and clear-cut to a much larger extent than the others. Several studies have shown that clear-cutting and drainage increase mineralization (Vitousek et al., 1979) and that drainage shortens transit times. Clear cutting also reduces the ammonium N uptake of plants. Flow increase did normally not influence NH$_4$-N concentrations. A clear link between NH$_4$-N concentrations and seasonality was found. Low flow concentrations were lowest during summer and high flow concentrations were higher during spring than autumn. This was probably due to lack of ammonium uptake by plants during the non-growing seasons.

Concentrations of organic N were higher at high flow than low flow (Fig 3). This was probably due to more intensive erosion during high flow periods, both in the stream bed itself as the erosive forces are stronger and in surrounding discharge areas where saturated surface flow may occur, which also increases the erosion rate. During flow increases, some catchments had higher concentrations, indicating that accumulated organic matter is being washed out. For most of these areas, only increases during high flow affected the concentrations significantly. Probably, the erosive forces are not strong enough to wash out the material during low flows. The only sign of seasonality in the organic N concentration data was that all catchments except one had higher organic N concentrations during summer. This can be explained by high quantities of organic matter in and along streams during the growing season.
It can be concluded that significant differences in the concentrations of nitrogen during various combinations of flows and seasons exist. However, the relations were different for different catchments, especially concerning NO$_3$-N. This means that no general model can be applied to all catchments. Catchment characteristics must be considered, since they have a large influence on the relations between nitrogen concentrations and various combinations of stream flow and seasons.

The influence of water flow paths was demonstrated by the links found between flow increase events and nitrogen concentrations. Further studies of such links can be made by using a hydrological model.

For one of the included catchments, Topmodel (Sivapalan et al., 1987) has been used to calculate discharge, soil moisture deficits, groundwater levels, extensions of saturated areas and partitioning of discharge into surface runoff and pre-event water. The catchment (Döntersta) has shallow till and clay soils, with a carr in the lower part.

From the preliminary results, the proportion of surface runoff seemed to be the most important hydrological factor for the NO$_3$-N concentrations upstream of the carr, showing a negative correlation during summer and a positive correlation during the rest of the year. At the outlet, the increase of the saturated area seemed to be the most important factor for high NO$_3$-N concentration, whereas low concentrations were found in the end of flow recessions.

High proportions of surface runoff are mainly found when the total discharge is low. A high proportion of surface runoff in the total discharge will increase concentrations if there is a surface pool of accumulated NO$_3$-N, but otherwise will cause a dilution and lowering of concentrations. Upstream of the carr, where till soils dominated, pools could be expected to be significantly smaller. A high proportion of surface runoff caused high concentrations as long as a pool existed whereas increasing discharge areas seemed to cause a dilution effect. Andersson and Sundblad (1991) carried out similar analyses on organic N.

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REFERENCES


