# NITROGEN RETENTION IN A RIVER SYSTEM UNDER CONSIDERATION OF THE RIVER MORPHOLOGY AND OCCURRENCE OF LAKES

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## ABSTRACT
Two different approaches for the calculation of water surface areas were applied to determine riverine nitrogen retention in four European catchments. The retention rate was calculated sequentially as the mean value for the total catchment, on a sub-catchment scale, or considering the distribution of water surface area within a sub-catchment. For the latter measure, nitrogen retention in larger lakes was calculated separately. Using total nitrogen emissions modelled with MONERIS and HBV-N, a nitrogen river loading was estimated and compared with measured loads. In general, the more detailed consideration of the proportion of water area within a sub-catchment delivered a reduction of the deviation between calculated and measured loads, with increasing regression coefficients. This was particularly the case for catchments with high proportions of surface water in the sub-catchments. In contrast, for a catchment lacking any large lakes, incorporation of the sub-catchment characteristics in the analysis did not result in an improvement of the estimated nitrogen load.

**Keywords: emissions, hydraulic load, nitrogen, retention, water surface area.**

## INTRODUCTION
The retention of nutrients in river systems is highly variable owing to considerable variability in residence time and hydrological conditions that change from the upper to the lower part of a river. Suitable approaches to describe the changing conditions of a river system are as important as reliable and sufficient input data.

The retention of nitrogen differs considerably between rivers and lakes. Thus, it may be hypothesised that the occurrence of lakes and their characteristics, as well as character of main river and tributaries, have a major influence on the retention processes of a catchment. In general, denitrification can be assumed to be the dominant process resulting in the loss of nitrogen from riverine systems, and sedimentation is of only minor importance for nitrogen retention. Denitrification takes place mainly in the top few millimetres of the sediment surface. Consequently, a strong correlation between nitrogen retention and the sediment surface area can be expected, suggesting that sediment surface area could be important for the retention calculation.
The purpose of the work presented in this paper was, therefore, to examine the effects of various methods for the estimation of water surface area on the calculated retention of nitrogen. The occurrence and the location of lakes were also taken into account. In addition, a distinction was made between the main river course (directly located between monitoring stations) and its tributaries on a sub-catchment scale. A simple empirical relationship, describing retention as dependent on water surface area and runoff was used to estimate retention in four European study catchments. Retention in larger lakes was calculated following the Vollenweider (1969) approach.

Study catchments with either a high proportion of lakes, or without any larger lakes, were chosen to investigate the different behaviour and retention rates. The catchments of the River Warnow (GER) and Lough Mask (IRE) represent large lake areas, Rönneå (SWE) is mostly dominated by rivers and River Neckar (GER) has no large lakes in its catchment.

## METHODS
Four European study catchments comprising differing proportions of water surface area (WSA) were chosen for the retention calculations. The Irish catchment (Fig. 1), is located in the central western part of the island, contains the highest WSA (Table 1). and, at 859 $km^2$, is the smallest of the four catchments examined in this study (Table 1). It also has the highest specific runoff (49 $l\ s^{-1}\ km^{-2}$), and contains the lowest population density (22 inh. $km^{-2}$). With a surface area of 82 $km^2$, Lough Mask ($Z_{max}$ 58 m) gathers all, or almost all (there is some uncertainty as to whether some water discharged as ground water to the south of the catchment without flowing through the lake) water originating from the catchment and dominates the entire hydrology and nutrient balance. Mountains to the west and grassland plains to the east of Lough Mask characterize the topology of the catchment.

The Rönneå catchment (Fig. 1), situated in the southwest of Sweden, comprises 1900 $km^2$ and discharges into Skälderviken bay. The catchment is divided into 7 sub-catchments ranging from 150 $km^2$ to 550 $km^2$. The Rönneå catchment is dominated by agriculture and forest and contains only a few smaller lakes, mostly located upstream (Fig. 1).

The catchment of River Neckar (13,957 $km^2$) is the largest of the four study catchments (Table 1). The river originates in the hilly Schwarzwald in southwestern Germany and discharges into the River Rhine. This catchment also contains the highest population density (375 inh.$\cdot$ $km^{-2}$) and, owing to intensive anthropogenic impacts, the highest specific emissions

(26.3 kg N $ha^{-1} \cdot yr^{-1}$) of all study catchments. Owing to the lack of any larger lakes, the catchment has the smallest proportion of surface waters (0.1%, Table 1).

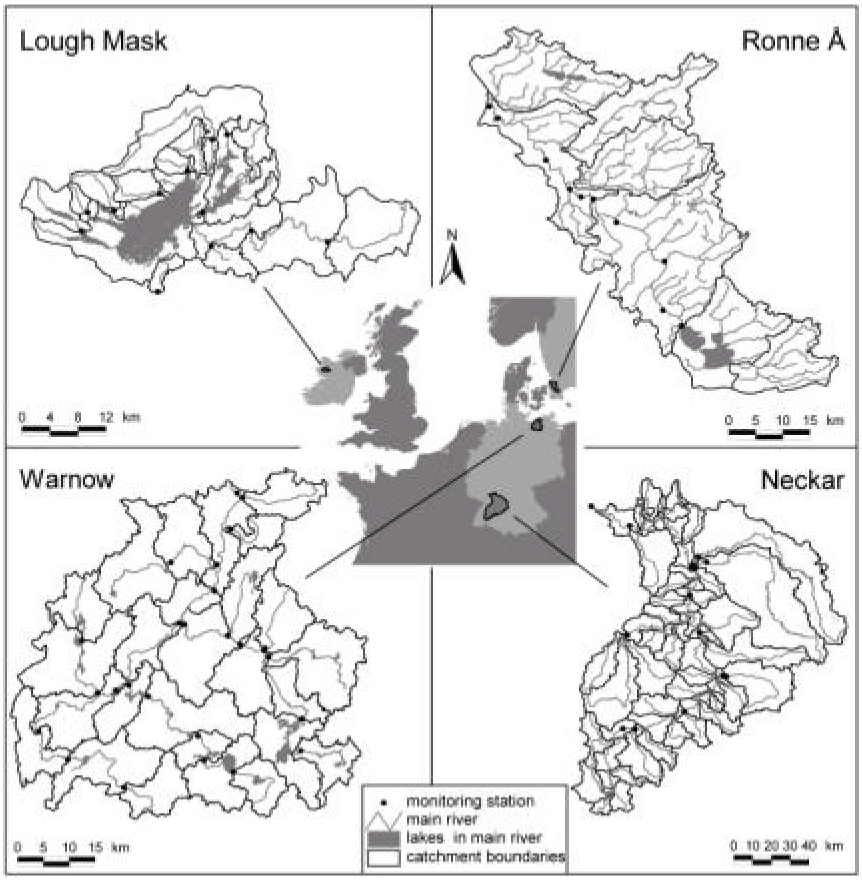


*Figure. 1: Location of the four study catchments and the distribution of the sub-catchments and lakes within each catchment.*

The last of the four catchments, River Warnow, contains a lowland river typical for the northeast of Germany. It is used intensively for agriculture (71%). Gentle slopes, sandy soils and an annual precipitation of 600 mm/yr results in considerably lower specific runoff (4.3 l $s^{-1}$ $km^{-2}$) than the other catchments (Table 1). Many of the waterways are modified or canalised.

**Table 1: Site characteristics and nitrogen load of the four study catchments.**

| | | Lough Mask | Rönneå | Neckar | Warnow |
|---|---|---|---|---|---|
| Study period | | 06.01-05.02 | 93-97 | 93-97 | 95-98 |
| Catchment area | [km²] | 859 | 1,897 | 13,957 | 3,067 |
| Catchment area range | [km²] | 1-118 | 153-558 | 2.4-1,954 | 51-210 |
| No. of sub-catchments | | 33 | 7 | 74 | 26 |
| Specific runoff | [$l \cdot s^{-1} \cdot km^{-2}$] | 49.0 | 12.3 | 11.8 | 4.3 |
| Specific TN load | [$kg\ N \cdot ha^{-1} \cdot yr^{-1}$] | 10.8 | 8.5 | 18.5[3)] | 5.6 |
| Mean population density | [$inh. \cdot km^{-2}$] | 22 | 52 | 375 | 57 |
| Land-use data by CORINE | | | | | |
| Urban area | [%] | 0.26 | 3.2 | 11.9 | 2.8 |
| Agricultural | [%] | 43.3 | 32.2 | 53.4 | 70.8 |
| Forest | [%] | 2.9 | 46.5 | 37.9 | 22.1 |
| Water surface area | [%] | 12.4 | 3.0 | 0.1 | 3.6 |

*[1)] Calculated with MONERIS; [2)] calculated with HBV-N; [3)] DIN load.*

The nutrient emission model MONERIS (Behrendt *et al*., 2002) was applied to all four catchments. The model considers six diffuse pathways (direct atmospheric deposition, surface runoff, erosion, tile drainages, groundwater, urban areas) and emissions from point sources. It was developed and applied for medium to large scaled catchments (Behrendt *et al*., 2000; Behrendt *et al*., 2002), but has also be shown to deliver reliable results in catchments down to 50 km² (Venohr, unpublished data.). MONERIS utilises both GIS analyses and data from statistical reports. For the application of the model, the approaches and constants were not modified. Depending on catchment characteristics some free model parameters had to be adapted.

$$L = E \cdot \frac{1}{1+R_L} = E \cdot \frac{1}{1+a \cdot HL^b} \qquad (1)$$

$$WSA_{MO} = WSA_C + a \cdot A_{catch}{}^b \cdot slope^c \qquad (2)$$

$$RW = a \cdot A_{catch}{}^b \cdot q^c \qquad (3)$$

where,
- L = measured load [$t \cdot yr^{-1}$]
- E = calculated Emissions [$t \cdot yr^{-1}$]
- HL = hydraulic load (runoff/WSA) [$m \cdot yr^{-1}$]
- WSA = water surface area [m²] (MO = MONERIS, C = CORINE)
- $A_{catch}$ = catchment area [km²]
- $R_L$ = load weighted retention coefficient [-]
- RW = river width [m]
- q = specific runoff [$l \cdot s^{-1} \cdot km^{-2}$].

The process-based, semi-distributed HBV-N model (Arheimer and Brandt, 1998) was applied to the Rönneå catchment. The hydrological part (*i.e.* HBV-96, Lindström et al., 1997) includes routines for accumulation and melt of snow, accounting for soil moisture, and lake routing and runoff response. In the N routine, leakage concentrations are assigned to the water percolating from the unsaturated zone of the soil to the response reservoir of the hydrological HBV model. Nitrogen concentrations are applied to water originating from areas with differing land-uses. Emissions from point sources, such as rural households, industries, and wastewater treatment plants are included. Atmospheric deposition is added to lake surfaces, while deposition on land is implicitly included in soil leaching. The model simulates residence, transformation and transport of N in groundwater, rivers and lakes and calculations are made step-wise for each of these compartments. A number of free parameters, which are calibrated against observed time-series of water runoff and nitrogen concentrations (Pettersoon et al., 2001), are included in the model. The equations used to account for the nitrogen turnover processes are based on empirical relations between physical parameters and concentration dynamics. The retention routine included in the HBV-N modelled has not been used for these calculations. The model application in Rönneå was based on the TRK database (Ejhed and Brandt, 2003).

A general nutrient balance was used to describe the sum of all nitrogen retention and loss processes (in the following only referred to as retention): Load (L) = Emission (E) – Retention and Loss (R). By dividing both sides of the equation by the river load, the ratio between the river load and total nutrient emissions can be described by the load-weighted retention coefficient $R_L$. Behrendt and Opitz (2000) used an exponential equation to calculate $R_L$ (Eq.1). The parameters *a* and *b* were determined for TN (Table 2, parameter set 1) and DIN (Table 2, parameter set 2) (Behrendt *et al*., 2002). The same approach was used for the calculation of nitrogen retention in lakes (Table 2, parameter set 3). The parameters have been derived and agreed on by the retention group of the EU-Project EUROHARP (www.euroharp.org).

**Table 2: Parameters used for retention approaches.**

| Parameter set | *a* | *b* |
|---|---|---|
| 1 (TN rivers) | 1.9 | -0.49 |
| 2 (DIN rivers) | 5.9 | -0.75 |
| 3 (TN-lakes) | 7.279 | -1 |

The two essential processes, sedimentation and denitrification, are related strongly to the surface area of sediments (Behrendt *et al*., 2002). For the purpose of this study, differences between the water surface area and the sediment surface area on river- and lakebeds was assumed to be negligible.
In the current study, two methods were used to estimate WSA. The first was developed for MONERIS (Behrendt et al., 2002) to estimate the total water surface area connected to the river system on a sub-catchment scale ($WSA_{MO}$) from the 100 m land cover grid CORINE ($WSA_C$). At this scale, small rivers and lakes are often not included. Behrendt *et al.* (2002) developed an approach to derive the total proportion of surface waters by comparing the area proportion from the CORINE map with those from municipal statistics. This approach does not, however, differentiate between the main river, tributaries or lakes within a sub-catchment.

The second approach, developed for this study, does differentiate between the water surface area of the main river (river stretch between two monitoring stations) and the area of all rivers in a sub-catchment. Accessory lake areas were taken from detailed digital maps and were added to the river surface area. In a first step, the river width was calculated as dependent on the total catchment area and specific runoff (Eq. 3, Table 3). In order to calibrate the parameters *a*, *b* and c for calculation of the main river (MR) width, the measured width from several river stretches in the Lough Mask catchment and information on width of the Phison river (Billen, 1993) were used. Data from the River Warnow was used for the calibration of the parameters *a, b* and *c* (Eq.3; Table 3) to estimate the mean width of all river stretches (ARS). The river flow length was taken from digital maps and distinctions were made between the main river (MR; river stretch between two monitoring stations), and all river stretches within a sub-catchment (ARS).

**Table 3: Parameters used for the estimation ofwater surface area ($WSA_{MO}$) and the mean river width for the main river (MR) and the all river stretches (ARS).**

| | *a* | *b* | *c* |
|---|---|---|---|
| $WSA_{MO}$ | 0.0052 | 1.087 | -0.0278 |
| MR | 0.386 | 0.479 | 0.364 |
| ARS | 0.195 | 0.479 | 0.364 |

The water surface area of the main river ($WSA_{MR}$) could, therefore, be calculated directly on a sub-catchment scale. The water surface area for all river stretches ($WSA_{ARS}$) had to be calculated for the entire catchment first, and then for the sub-catchments by subtracting the surface area of the head waters from those of the entire catchment.

The hydraulic load (HL) was calculated in 3 ways; for methods 1 & 2, retention was calculated for the entire catchment (*i.e.* average retention rate for entire catchment). These calculations were done for both, $WSA_{MO}$ and $WSA_{ARS}$. Method 3 determines HL for each sub-catchment based on $WSA_{MO}$. Here, the retention in the main river was assumed to be negligible compared with the retention in the tributaries of a sub-catchment. Method 3 calculates nitrogen retention separately for main rivers and tributaries, using $WSA_{MR}$ and $WSA_{ARS}$. In sub-catchments with lakes dominating the water surface area of the main river, parameter set 3 was used (Eq. 1, Table 2).

**Results and Discussion**

The mean differences between the measured and the calculated river width in the main river was 20.5% for Lough Mask. Assuming a specific runoff of 10 $l \cdot s^{-1} \cdot km^{-2}$ for the Phison river (Billen, 1993), a mean deviation of 6.4% was calculated. The deviations increase for higher and lower specific runoff, but all calculations showed a very good correlation with the measured river width ($r^2$= 0.99, n = 8). The mean width of all river stretches showed slightly higher deviations (25.2%), with a much smaller $r^2$ of 0.37 (n = 8). The reason for these uncertainties stem from the limited data available on the width of smaller tributaries.

Additionally, surface water hydrology in the catchment of river Warnow is influenced considerably by human impacts. Comparison of the total water surface area calculated by $WSA_{MO}$ and $WSA_{ARS}$ also shows quite high deviations in the four study catchments (Table 4). In the single sub-catchment, especially in smaller catchments of Lough Mask and River Neckar tremendous deviations up to several 100-percent were found. For water surface areas smaller than 1 km² the differences grow rapidly (Fig. 2). This might be caused by the spatial resolution (100 m) of the CORINE land-use map, and inherent uncertainties of the area of small water bodies. Owing to missing information on the real water surface area, no final conclusions could be made about the uncertainties of these calculations.

**Table 4: Deviation between the water surface areas $WSA_{MO}$ and $WSA_{ARS}$ for the total catchment (TC) and the median of the deviations in the single sub-catchments (SC).**

| | Deviation [%] | |
|---|---|---|
| | WSA-TC | WSA-SC |
| Lough Mask | 1.68 | 86.8 |
| Rönneå | 12.6 | 15.4 |
| Warnow | 59.5 | 24.2 |
| Neckar | 47.1 | 53.9 |

Table 5 shows the catchment area specific nutrient emissions modelled with MONERIS and HBV-N. A large deviation between the measured load at the catchment outlet and the emissions estimated with the models can be found. Thus, it can be assumed both, that the retention in the catchments is of an important magnitude and that it might vary considerably between the different catchments.

**Table 5: Mean modelled emissions, based on the models MONERIS and HBV-N and the mean deviation to the measured load (at the catchment outlet, Table 1).**

| | | MONERIS | | HBV-N | |
|---|---|---|---|---|---|
| | | Emissions [kg· $ha^{-1}$· $yr^{-1}$] | Deviation [%] | Emissions [kg· $ha^{-1}$· $yr^{-1}$] | Deviation [%] |
| Lough Mask | TN | 15.2 | 31.8 | | |
| Rönneå | TN | 14.0 | 88.7 | 12.0 | 56.0 |
| Warnow | TN | 12.4 | 133.1 | | |
| Neckar | DIN | 26.3 | 37.0[1)] | | |

[1)] Deviation between TN emissions and DIN river load.

The four differing methods used to calculate riverine nitrogen retention have been applied successively to the study catchments. As assumed, great differences in the retention rates were found (Tab. 6). Interestingly, the different methods did not lead, either to an increase or decrease of the calculated retention rates. Neither was a change of retention in catchments with proportionally high lake areas nor with no big lakes found. To evaluate which of the methods delivered more reliable results, the measured and the calculated load were compared. Comparison of emissions calculated with the HBV-N model and MONERIS, to the application of the revised methodology reduced, in almost all cases, the mean deviation from the measured loads and increased the $r^2$ values (Table 7).

**Table 6: Mean retention rate of the sub-catchments calculated for TN and DIN using the four methods.**

| | | Mean calculated retention rate [%] | | | |
|---|---|---|---|---|---|
| | | | Methods | | |
| | | 1 | 2 | 3 | 4 |
| Lough Mask | TN | 20.5 | 16.4 | 20.0 | 18.9 |
| | DIN | 22.6 | 17.1 | 21.4 | 18.1 |
| Rönneå | TN | 36.6 | 35.5 | 40.9 | 40.8 |
| Warnow | TN | 47.1 | 49.8 | 47.4 | 55.9 |
| | DIN | 63.7 | 65.9 | 62.4 | 66.1 |
| Neckar | DIN | 24.9 | 17.0 | 26.5 | 18.4 |

The strongest improvement was found for the River Warnow with its many lakes, distributed all over the catchment. For the Irish catchment, dominated by Lough Mask, the deviation was not reduced, but the results of the 4$^{th}$ method delivered the strongest correlation with the measured load. Even for Rönneå, with the few upstream lakes, a stronger correlation was found. This change of the results was very similar and achieved for both emissions models HBV-N and MONERIS. Interestingly, however, inclusion of the conditions in the sub-catchment (methods 3 & 4) did not work well for River Neckar, because of small differences in retention rates within the different sub-catchments due to a homogeneous distribution of the WSA. In addition, the error in the calculated nutrient emissions and the measured river load reduces with increasing catchment size (Behrendt *et al*., 2002). Owing to the uncertainties in the nutrient emissions and the load, for small sub-catchments with a homogeneous WSA distribution, the detailed calculation of retention rates on a sub-catchment scale did not, in the present case, reduce the error in the calculated load.

In the Lough Mask catchment the calculated DIN load showed extraordinary high deviations from the measured DIN load. Surface waters in the Lough Mask catchment contain a high concentration of organic nitrogen in the form of humic substances, leading to relatively low DIN concentrations. The mean ratio of 2.9 between TN and DIN concentration in Lough Mask is almost double that of the River Warnow (1.5).

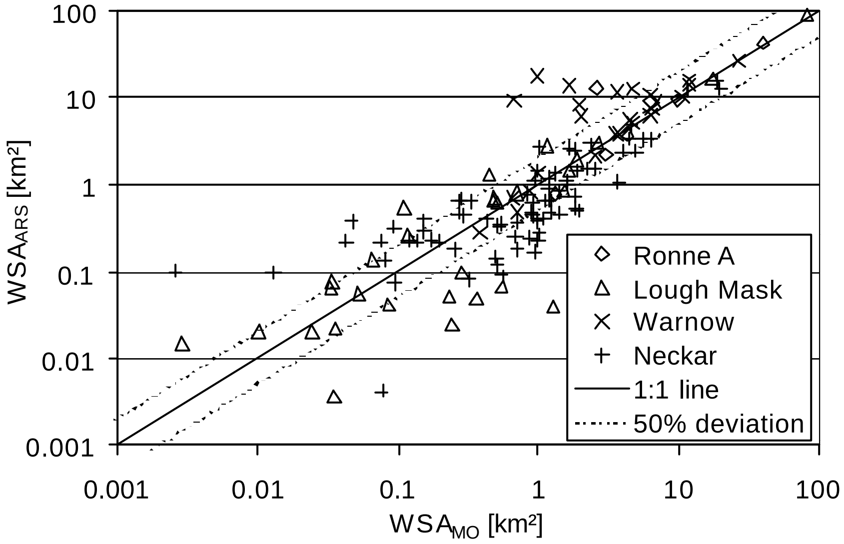


*Figure. 2: Correlation between the water surface area $WSA_{MO}$ and $WSA_{ARS}$ for the sub-catchments of the 4 study areas.*

**Table 7: Mean deviation and the regression coefficient r² (in brackets) between the measured and calculated TN and DIN load.**

| | | Mean deviation [%] | | | |
|---|---|---|---|---|---|
| | | Methods | | | |
| | | 1 | 2 | 3 | 4 |
| Lough Mask | TN | 23.0 (0.63) | 23.8 (0.64) | 25.9 (0.58) | 23.1 (0.74) |
| | DIN | 126.0 (0.55) | 119.6 (0.64) | 131.7 (0.54) | 116.5 (0.64) |
| Rönneå | TN | 27.9 (0.73) | 28.5 (0.76) | 28.0 (0.78) | 27.2 (0.82) |
| | TN[1)] | 22.5 (0.63) | 24.2 (0.54) | 27.8 (0.68) | 22.5 (0.67) |
| Warnow | TN | 31.1 (0.35) | 30.5 (0.44) | 29.0 (0.47) | 22.8 (0.70) |
| | DIN | 37.5 (0.60) | 34.0 (0.70) | 37.3 (0.63) | 31.0 (0.72) |
| Neckar | DIN | 12.5 (0.59) | 17.8 (0.55) | 12.8 (0.57) | 17.2 (0.53) |

[1)] Emissions calculated with HBV-N.

## CONCLUSIONS

The direct comparison of the 1st and 2nd method led to a slight increase of the deviation between measured and calculated for Lough Mask (TN), Rönneå (HBV-N & MONERIS) and Neckar. This increased deviation suggests a better estimate of the water surface area being obtained by the method developed by Behrendt *et al.* (2002) than by the new method presented in this paper. In general, a distinction between the water surface area in the main river and the tributaries resulted in an improvement of the calculated nutrient loads, especially for the catchments with a high proportion of lakes. The less homogenous was the WSA in the sub-catchments, the greater the improvement in results.

For the River Neckar catchment, including no big lakes, the distinction between main river and tributaries did not lead to an improvement of the results. Here, one aspect, to be taken into account is the increase of uncertainties in calculating the discharge per sub-catchment. Runoff measurements may often have high errors. By subtracting the runoff of the upstream sub-catchments from the runoff of the total catchment these errors can be increased. The improvement in the calculation of the nutrient retention on a sub-catchment scale is, in this case, simultaneously reduced by uncertainties in the runoff or water surface area calculation for each sub-catchment.

In future studies, a further development of the new water surface area approach and calibration with more data from other catchments would be useful. The combination of this method with more comprehensive retention approaches, *e.g.* the combined approach by Venohr and Behrendt *et al.* (2002) is promising.

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