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Modelling Nitrogen Transport and Retention in the Catchments of Southern Sweden

The Baltic Sea is suffering from eutrophication and attempts are being made to reduce nutrient loads. This article focuses on nitrogen transport from southern Sweden (145 000 km^2), and presents a model approach (HBV-N) that has been used in the national decision-making process for best management practices. Calculations of nitrogen leaching, retention in the freshwater system, net transport to the sea, and source apportionment are presented for the period 1985–1994. Input data were handled in GIS, including results from SOIL-N and MATCH. Daily simulations were made in 3725 subbasins with calibration against measured time series at 722 sites. Diffuse source pollution was normally retained by 10–25% before entering the river network. Lakes normally reduced nitrogen transport by 30–40 kg ha^{-1} yr^{-1} of lake area. On average, 45% of the annual gross load was reduced during transport, but temporal and spatial variations were great. 75 000 tonnes N yr^{-1} reached the sea.

INTRODUCTION

Eutrophication of fresh- and marine waters due to increased input of nutrients is a problem in many parts of the world, and large efforts are needed to reduce the emissions to improve the situation (1, 2). To control eutrophication efficiently, we need to know the nutrient sources and their net contribution to the load. Several large-scale studies in various countries have therefore focused on nutrient input to eutrophied waters from different sources (3–6). The riverine nutrient load may then be estimated by using, e. g. land-use information and leakage coefficients (7, 8), river monitoring (9, 10), statistically based models (11, 12) or dynamic modelling (13–15).

The Baltic Sea in northern Europe is a brackish waterbody where eutrophication is considered a serious problem by the surrounding countries. The prevalent opinion is that the problem is caused by high nitrogen and phosphorus loads, which may have increased by about four and eight times, respectively, during the last 100 years (16). Sweden has, among other countries, signed international agreements which aim to reduce the nitrogen load on the sea by 50% between 1985 and 1995 (e.g. the Helsinki Commission and the North Sea Conference/Paris Commission). A national project was started in 1995 at the Swedish Environmental Protection Agency (Swedish EPA) to investigate the effects of the Swedish commitments: Has the goal for nitrogen reduction been reached and what further measures should be taken to improve the situation? Several Swedish scientists from different disciplines and institutions were brought into the project to contribute knowledge and to develop tools for the investigation.

Anthropogenic nitrogen emissions to the Baltic Sea come from rivers, atmospheric deposition, and coastal point sources. The riverine load represents more than 60% of the total load to the sea (10). In each river, the nitrogen transport reflects specific land-use activities and point sources within the river basin as well as the hydrological and meteorological conditions, and biogeochemical processes in soil, sediment and surface waters. To determine the impact of different sources, and to reduce the nitrogen load in the most cost-effective way, it is important to have knowledge not only about emissions, but also about the flow paths and turnover processes that may affect the load during transport to the sea. To obtain a complete picture based on measurements only would be difficult and expensive; consequently, some kind of model must be applied. Such a model tool for water-quality simulations may be used in environmental management and planning, e.g., for estimations of source distribution, anthropogenic influence, and various future scenarios.

The Swedish Meteorological and Hydrological Institute (SMHI) was asked to develop a model for calculations of the water-related nitrogen transformation occurring during transport from the sources to the sea, and to apply the model to southern Sweden (Fig. 1). The emission database at the Swedish EPA and leakage from various types of fields, estimated at the Swedish University of Agricultural Sciences (17), was to be used as input to the model. This article describes the model and its application to southern Sweden. Daily simulations for the 10-year period (1985–1994) were made in 75 river basins, and in the coastal zones in between the basins. Some major results and their reliability in comparison to measurements and previous investigations are shown. The results are unique for high spatial resolution over such a large area; 145 000 km^2 of which 115 000 km^2 subdivided into 3725 subbasins are modelled continuously.

THE HBV-N MODEL

The hydrological HBV model (18, 19) has been successively equipped with a nitrogen routine at SMHI (20–22). The HBV model is conceptual with physically-logical algorithms, and is semidistributed. It has a statistical approach to describe variations within subbasins. It uses data of daily precipitation and temperature, and monthly evapotranspiration from climate stations to provide daily estimates of areal precipitation, snow accumulation and melt, soil moisture, groundwater level, and runoff from every subbasin, and routing through lakes. The model includes free parameters that are calibrated against measured time-series of water discharge. In the present nitrogen routine (23), calculations are made from the root zone to determine transport in groundwater, rivers and lakes within subbasins, which are coupled into larger river systems. Since most of Sweden has a rather thin till-soil layer, the groundwater divides are assumed to follow the catchment boundaries.

Figure 2 illustrates the system described by the HBV-N model. In the nitrogen routine, root zone concentrations are assigned for

Figure 1. The area studied in the south of Sweden covers 145 000 km^2 and 75 rivers discharging to the sea.

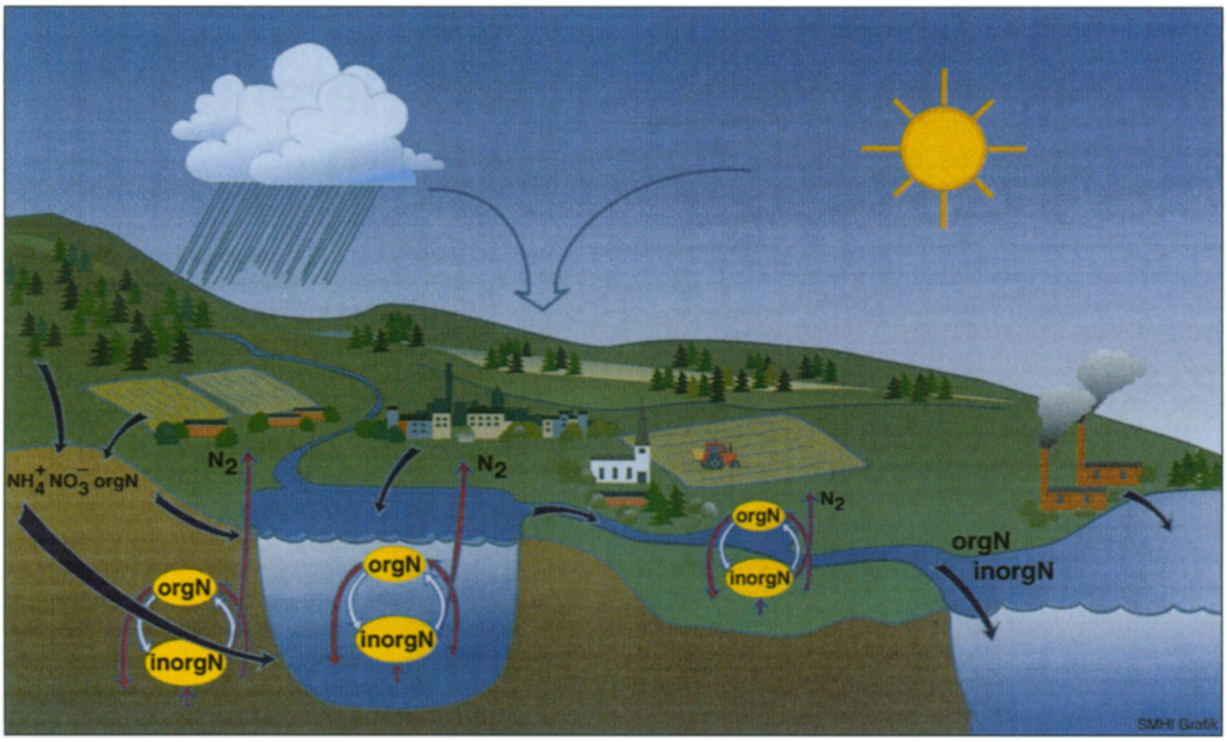

Figure 2. Illustration of the system modelled by the HBV-N model. The nitrogen transport simulations are based on the water discharge received by the hydrological HBV model, mixing of water with different concentrations, and simple functions describing the net influence from various biogeochemical processes affecting the nitrogen load during the residence time in discharge areas, rivers and lakes.

various land-use categories (i.e. arable land, forest, pasture and other land; See section on Studied Area and Database) to the water percolating from the unsaturated zone to the groundwater. This soil leakage is mixed with emissions from rural households and atmospheric deposition on water surfaces. The runoff from the subbasin is mixed with the water from upper subbasins, emissions from industries, and effluent from municipal treatment plants. In addition, when lakes are involved, lake water will contribute with atmospheric deposition. If there is no lake in the subbasin, the water and nitrogen sources are simply mixed and flow into the lower basin.

In addition to the mixing of water with different nitrogen concentrations, empirically-based relations between physical parameters and concentration dynamics reflects the turnover processes that may affect the nitrogen load during residence in groundwater, rivers, and lakes. The present version of the nitrogen model has separate routines for simulations of inorganic and organic nitrogen concentrations, and the calculations are made numerically on a daily time-step for each subbasin. Based on continuity, the nitrogen concentration in each water volume can be calculated:

$$\frac{d(cv)}{dt} = \sum \{c_{in}v_{in}\} + D + P - \Phi - cv_{out} \qquad \text{Eq. 1}$$

where

- c = concentration of nitrogen fraction
- v = water volume of groundwater, river or lake
- $_{in}$ = inflow (e.g. for groundwater: soil leakage from various land uses; for lakes: upstream rivers and local discharge)
- $_{out}$ = outflow to river, lake or downstream subbasin
- D = atmospheric deposition on water surfaces
- P = emissions from point sources
- Φ = relationship that describes the net effect of several biogeochemical processes in the water system

Φ differs between the nitrogen fractions and between the routines for groundwater, rivers and lakes, and is mainly based on temperature and inorganic nitrogen concentration (Table 1).

The net flux of inorganic nitrogen is considered to be a sink, dominated by the processes of vegetation take-up and denitrification. The growing season is very much related to temperature, which is also crucial for the denitrification rate along with the inorganic nitrogen concentration (24, 25). For groundwater, these processes can be related to the near-stream interface zones between groundwater and surface water, which play a critical role in determining the amount of nitrogen entering the stream channel (26). For lakes, the choice of retention expression was guided by the assumption that denitrification is the major sink, and that this process mainly takes place at the sediment surface (25). Hence, the area of the waterbody rather than the volume, was included.

The groundwater expression in Table 1 for seasonal concentration variation of organic nitrogen is based on empirical studies of time-series in Scandinavian forest streams, which show higher concentrations during the growing season (27, 28). This may be a result of biological production within the watercourses and their surrounding area. In each water storage, biological production is assumed to be related to temperature, and to the average inorganic nitrogen available during winter and, thus, as an indicator of trophic status of the basin or water. This production is considered to be connected to the subbasin area for groundwater discharge, which means that the production becomes more significant during summer base-flow, while for rivers and lakes it is related to water volume. Additionally, concentrations in lakes decrease more rapidly during the autumn, which can not be explained by dilution only. This is probably due to sedimentation and mineralization processes. Therefore, the nitrogen-transformation expression for lakes describes both a source of organic material and a sink. At temperatures below zero, the HBV-N model does not account for biological or chemical processes.

Short time variations in concentrations may appear with flow increase due to changed flow paths, wash-out of accumulated inorganic nitrogen in snowpack or pre-event water, and/or short-circuiting in the near-stream zone (26, 28, 29). This is simulated by accumulation of soil leakage in a small reservoir without, nitrogen removal that discharges the inorganic nitrogen at high flow and flow increase. This procedure requires another two free parameters, *par(4)* and *par(5)* (23), and is not considered in catchments where only low amounts of nitrogen are available for leaching (inorganic nitrogen < 0.39 mg L^{-1}), since dilution is more common during these hydrological circumstances (28). Similarly to the subbasin discharge, all lake water is completely

Table 1. Relations used in the model (Eq. 1) between physical variables and the net outcome from various nitrogen transformation processes affecting the nitrogen load during the residence time in groundwater, rivers and lakes on the way to the sea.

Nitrogen fraction	Water storage	Φ in Eq. 1	Abbreviations	
Inorganic nitrogen	Groundwater	$par(1) \cdot c_i \cdot T_{10} \cdot V_{active}$	par(n)	= free parameter used for calibration
	Rivers	$par(2) \cdot c_i \cdot T_{10} \cdot V$	c_i	= inorganic nitrogen concentration
	Lakes	$par(3) \cdot c_i \cdot T_{10} \cdot A_{lakes}$	c_{iw}	= c_i of the dormant season
			T_{10}	= average of last 10 days air temperature
Organic nitrogen	Groundwater	$-par(6)^{i} \cdot c_{iw} \cdot (T_{10}-T_{20}) \cdot A_{basin}$	T_{20}	= 10 days average temperature preciding T_{10}
	Rivers	$-par(7)^{i} \cdot c_{iw} \cdot (T_{10}-T_{20}) \cdot V$	V	= water volume in storage
	Lakes	$-par(8)^{ii} \cdot c_{iw} \cdot T_{10} \cdot V_{active}$	V_{active}	= water volume effected by turn-over processes
			A_{lakes}	= lake surface area
			A_{basin}	= subbasin area exlusive lakes

^{i}) par(6) and par(7) are 0 when the temperature is falling (T_{10}-T_{20} < 0), i. e. no net organic nitrogen production.
^{ii}) par(8) is positive when the temperature is falling (T_{10}-T_{20} < 0), i. e. net removal of organic nitrogen.

mixed, except for a small reservoir with short residence time, from which the nitrogen is transported without being affected by retention at peak flows (including *par(9)* and *par(10)*).

The HBV-N model is calibrated and validated against measured concentrations. The nitrogen routine includes a total of 10 free parameters, but since each nitrogen fraction is calibrated separately and the procedure should be done step-wise, (*i)* the local discharge; *ii)* the stream; *iii)* the lakes), there are never more than three free parameters to be calibrated at the same time.

To summarize the model approach; the model simulates spatial, seasonal, and event-based variation of nitrogen concentrations in the terrestrial freshwater system. The model is connected to a database which contributes with annual constant input, and further separation into inorganic and organic nitrogen is made according to standards. The database includes, e.g., emissions, land use, soil leakage concentrations, and seasonal atmospheric deposition. In the model, spatial variation in concentration between subbasins is achieved through:

i) differences in gross load, which is the combination of the database and daily simulated water discharge;

ii) differences in simulated local, lake or river retention, which is influenced by spatial variation in temperature, water residence time, peakiness of hydrography, lake area and volume, inorganic nitrogen concentration and calibrated parameters.

In the model, temporal concentration dynamics within each subbasin are achieved through variations in:

i) seasonal atmospheric deposition and daily levels of water inflow from different sources;

ii) simulated local, lake or river retention, which is dependent on fluctuations in temperature, inorganic nitrogen concentration, and water discharge;

iii) variations in water residence time and water discharge, since high flow may involve flushes of inorganic nitrogen not affected by retention.

STUDIED AREA AND DATABASE

The calculations include 145 000 km^2 in southern Sweden, with more than 7 million inhabitants and the largest area of arable land in Sweden. In total, nitrogen transport was simulated in 3725 subbasins with an average area of 35 km^2. Several institutions and authorities contributed with input to the database (Table 2). Daily climatological data were interpolated for each subbasin from nearby meteorological stations. Geographical information was gathered for each subbasin regarding: lake areas and depths; mean altitude; coupling to other subbasins; land use and management; agricultural crops and fertilization; soil type; forest fertility; point sources (treatment plants, rural households and industries); and, if available, measured concentrations from monitoring programs. Most of the data were handled in a GIS at the Swedish EPA, where statistics on administrative units and point sources were coupled to specific subbasins. For instance, crop composition of fields was available for parishes, fertilization levels and strategies for entire counties, and population for municipalities. Since water divides rarely coincide with administrative borders, the data had to be reclassified; it was then considered to be normally distributed and was apportioned or summarized for each subbasin.

Leakage concentrations (23) from arable lands and pastures have been estimated by the Swedish University of Agricultural Sciences (17) using the SOIL-N model (30) for more than 500 types of field and pasture in the region. Of these 7–19 were chosen for each subbasin to represent different crops and fertilization strategies, according to soil type and agricultural region. The leakage concentrations from forests and other land were estimated from monitoring data. Atmospheric deposition on lake surfaces was calculated by the MATCH model (31) at the SMHI.

CALIBRATION

A 1-year warming-up period was used for the hydrological model simulations to adjust the starting conditions. General parameters for the hydrological model had already been obtained through regional calibration (32) against measured flow in a total of 106 sites within the 16 counties of southern Sweden. However, the area north of Lake Vänern did not have such parameters, so the discharge from this region (30 000 km^2) was obtained through interpolation of measurements and extrapolation to catchments with similar characteristics.

The nitrogen model was calibrated against concentrations of inorganic and organic nitrogen, respectively. Calibration was conducted through an iterative procedure where different parameter sets were tested until the best model fit was obtained. The model performance was evaluated statistically according to the explained variance (R^2) defined by Nash and Sutcliffe (33).

$$R^2 = \frac{\sum (\overline{M} - M)^2 - \sum (S - M)^2}{\sum (\overline{M} - M)^2} \qquad \text{Eq.2}$$

where

M = measured values
$\overline{M}$ = average of measured values
S = simulated values

Firstly, the parameters describing local transport and transformation in near-stream zones (i.e. groundwater in Table 1), were optimized for areas without lakes or upstream subbasins. Since there was a lack of data from such subbasins, (southern Sweden includes about 14 500 lakes), southern Sweden was divided into 8 regions and general parameters based on simultaneous calibration of 5–10 subbasins, were assumed to be representative for each region. Secondly, parameters for nitrogen transformation in rivers were calibrated regionally as well,

Table 2. Database of HBV-N indata for the modelling of southern Sweden (Qty = Quantity). The information on land use, soil leakage, rural households and point sources in the study presented was based on conditions during 1985–1987. Daily meteorological and hydrological data were used for the 10-year period (1985–1994).

Indata	Qty. in each subbasin	Qty. in southern Sweden	Background information (Original source[i])
Hydrography:			SVAR—water divides (SMHI)
river basins (>200 km^2)		75	
coastal zones between rivers		62	
subbasins		3725	
Interpolated meteorological data:			Meteorological observations (SMHI)
precipitation stations	4	198	
temperature stations	1	60	
potential evapotranspiration[ii]	1	70	
Land use classes (km^2):			
arable land	6–18	486	9 agricultural regions (SLU/NV), 3 soil types (SNA/NV), 9 crop types (SCB/NV), 2 fertilization regimes SLU/NV)
forest	1	4	Forest cover (UNIP/GRID Arendal), fertility classification (SLU/NV)
pasture	1	27	9 agricultural regions (SLU/NV), 3 soil types (SNA/NV)
other land	1	2	Remaining land (i.e.total area-forest,arable land,pasture,lakes)
lake surface	0–3	14 398	SVAR-lake archive (SMHI)
Root zone concentrations (mg L^{-1}):			
arable land	6–18	486	SOIL-N model simulations (SLU)
forest	1	4	Measurements from small homogenous areas (SMHI, various research areas)
pasture	1	27	SOIL-N model simulations (SLU)
other land	1	2	Based on model experiences (SMHI)
Rural households (kg)	1	1	Population statistics (SCB/NV), average discharge / pers (NV)
Atmospheric deposition on water surface (kg)	0–3	14 398	MATCH model simulations (SMHI) in ~ 400 grids (20x20 km^2), SVAR—lake archive (SMHI)
Lake depths (m)	0–2	3518	SVAR—lake archive (SMHI), regression analysis (SMHI)
Point sources (kg)	0–2	about 700	Averages and measurements of discharge for industry and municipal treatment plants (NV)
Measured time-series			National and regional monitoring programs (PMK, JRK, River basin associations, County boards)
Nitrogen concentrations (1–2 samples / month) (totN, NO_x-N, NH_4-N) (*mg L^{-1}*)	1	722	
Water discharge (daily) (*L s^{-1}*)	1	109	Hydrological stations (SMHI)

[i]) Abbreviations:
JRK = National Programme for Agricultural Environmental Monitoring in Sweden
NV = Swedish Environmental Protection Agency
PMK = National Programme for Environmental Monitoring in Sweden
SCB = Statistics Sweden
SLU = Swedish University of Agricultural Sciences
SMHI = Swedish Meteorological and Hydrological Institute
SNA = Swedish National Atlas
SVAR = Swedish Water Archive
UNIP/GRID = United Nations Environment Program / Global Resource Information Database

[ii]) Based on calculations with the Penman equation, according to Eriksson (41).

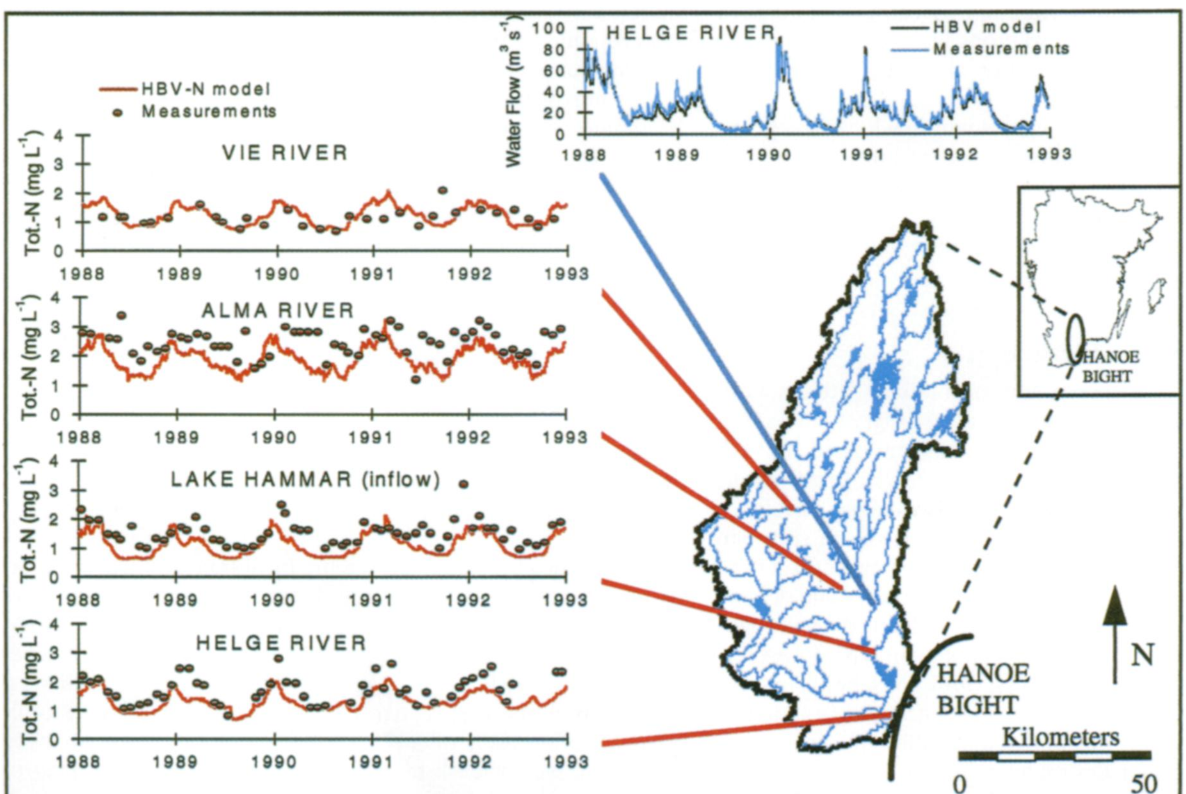

Figure 3. Modelling and measurements of water runoff and nitrogen concentrations in different parts of the Helge river basin. The calibration was done seperately for inorganic and organic nitrogen concentrations at 20 sampling sites simultaneously, giving the best fit for the whole basin.

but based on even fewer subbasins. Finally, the parameters of the lake routine were calibrated for each of the 75 river basins and the coastal zones between the basins, against all nitrogen data available. In river basins where no measurements were available for calibration of the lake parameters, parameter settings from nearby catchments with similar characteristics were used. To conclude, at most, 3 free parameters in the model were calibrated at the same time.

Due to the regional calibration, the model parameters describe the best fit for all subbasins in a region or drainage basin (Fig. 3). The parameter setting is then assumed to be robust enough to describe the discharge from unmeasured basins, although a single subbasin may show better results if calibrated seperately. The calibration procedure was partly done automatically using R^2 as the optimization criteria, but visual inspections, (especially of the concentration dynamics from unmeasured subbasins), were also used to judge the goodness-of-fit. In total, 722 sampling sites and about 38 300 measurements of each nitrogen fraction were used in the calibration.

NITROGEN TRANSPORT AND RETENTION

The emissions of nitrogen through root-zone leakage and point sources (gross load) were compared to the simulated discharge to the sea after nitrogen transformation in the freshwater system (net load). For the studied period, 1985–1994, the average total gross load from southern Sweden was estimated to be 136 000 t yr^{-1} (t = tonnes), while the corresponding net nitrogen transport to the coastal sea was estimated at 75 000 t yr^{-1}. Consequently, the average total nitrogen reduction was 61 000 t yr^{-1}. This reduction can be separated into two components; local retention and downstream retention. Local retention is the result of transformation processes affecting concentrations of groundwater discharge (i.e. in groundwater-surface water interface zones), whereas downstream retention is caused by biogeochemical processes in rivers and lakes, in all downstream subbasins passed on the way to the sea. According to the model description, local retention only affects diffuse sources (i.e. soil leakage, rural households and atmospheric deposition), while downstream retention affects all emissions entering the freshwater system. Normally, local retention reduced the non-point sources by 10–25% before their entrance to the river system (Fig. 4A).

Figure 4 shows that there was wide spatial variation in nitrogen reduction in southern Sweden. The nitrogen retention in lakes dominated, while river retention was small. Since the lakes were efficient nitrogen traps, the load from areas upstream of large lake systems was greatly reduced. The zone near the coast with few lakes and short residence time showed little or no load reduction.

The reduction capacity within the river basins also varied between years (Fig. 5) due to hydrological and meteorological conditions. Accord-

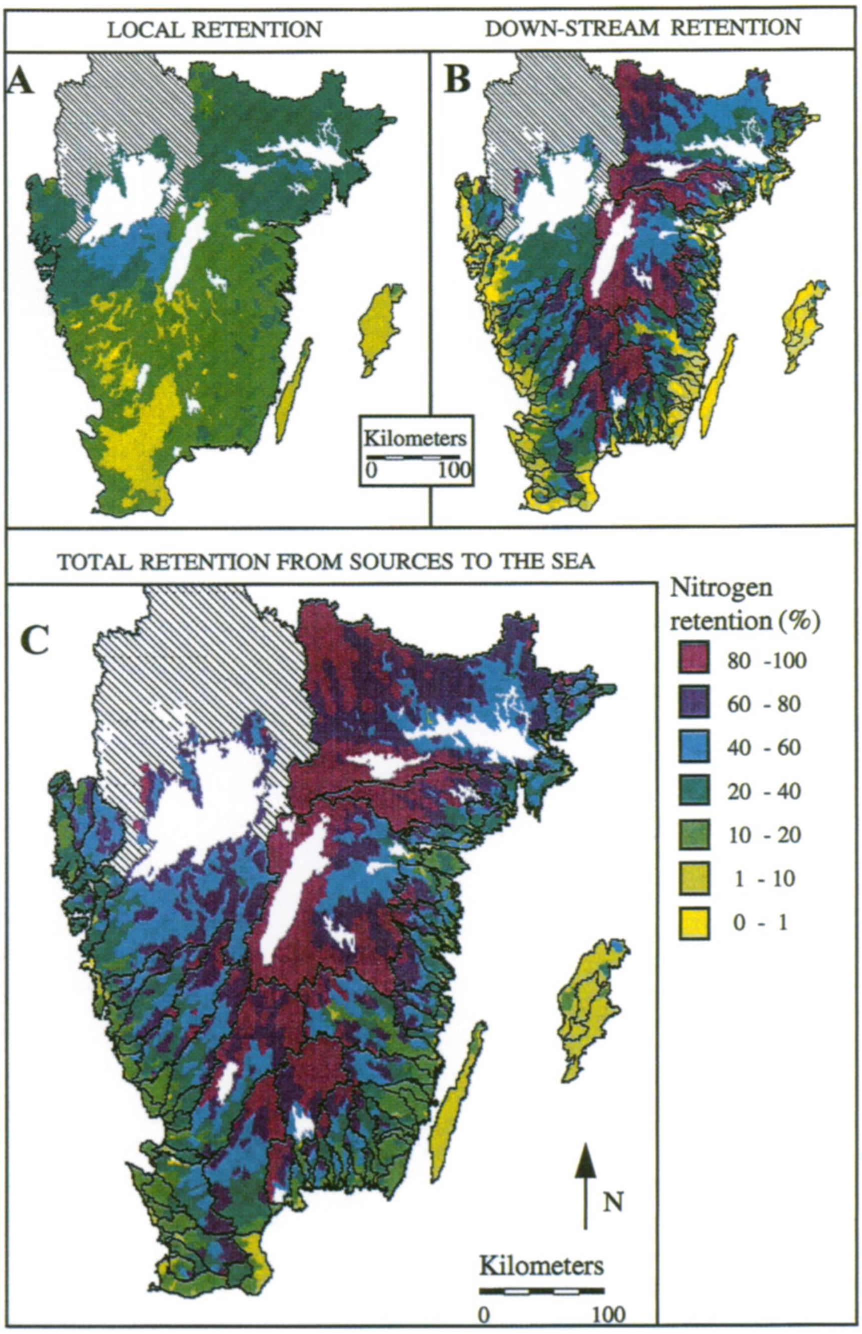

Figure 4. Annual average of nitrogen retention in A: the local discharge (e. g. in discharge areas, riparian zones and open ditches); B: downstream river segments and lakes; C: total retention during transport from the sources to the sea. The grey area north of Lake Vänern was not included in the detailed spatial analysis of retention.

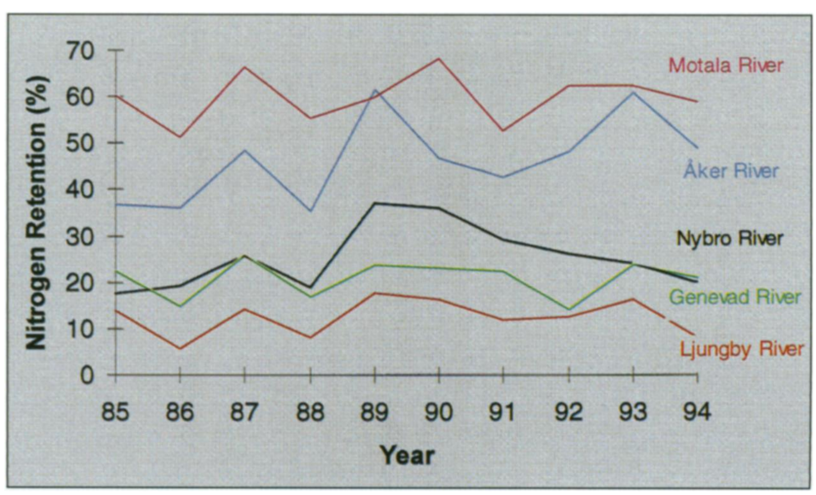

Figure 5. Ten years nitrogen retention (percent) as an annual average for all emissions within five different river basins.

ing to the simulations, most of the lakes in the region reduced the nitrogen load by 30–40 kg ha^{-1} yr^{-1}, but since a few of them were very efficient, the average reduction was 106 kg ha^{-1} yr^{-1} (Fig. 6).

As can be seen in Figure 7, the geographical pattern of land-based nitrogen emissions drastically changed, if the transport to ground- and surface water was not the focus, but the focus was instead on the sea load. Some inland regions with high emissions due to intensive farming or dense population were difficult to distinguish after nitrogen transformations in the freshwater system. This was particularly obvious for areas draining to the eastern coast, and inland cities like Jönköping, Örebro and Växjö. In other regions, the emissions remained unaffected due to the short residence time of the water, especially near the coast and in the western and southern parts.

Figure 8 illustrates the total source apportionment for southern Sweden as an annual average with the emissions of 1985/87 and meteorological and hydrological conditions of the ten year period. When comparing the contribution from various sources, soil leakage from arable land was the largest single source corresponding to 45% of the total nitrogen load. The total for nitrogen reduction during transport to the sea was highest for diffuse sources and lowest for point sources, since the latter two were more frequently represented in coastal areas and consequently less disposed to retention processes in the freshwater system.

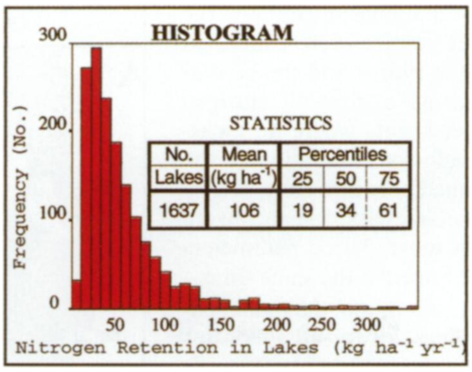

Figure 6. The distribution presented as annual average of modelled nitrogen retention among the studied lakes located in 1637 subbasins in southern Sweden.

VALIDATION AND UNCERTAINTY

The modelled water discharge, nitrogen concentrations, and nitrogen transport were compared to measurements when such were available. Most measurement stations were used in the regional calibration of water discharge or local, river and lake retention, and could thereby influence the results. However, in the few independent stations that could be used for validation, the model performance showed almost the same variation in accuracy as for the stations used for calibration. In general, the dynamics of water discharge and inorganic nitrogen concentrations corresponded well with the measured time-series, while the model did not pick up the variations in organic nitrogen concentrations from mixed basins. This was mostly caused by management practices on arable lands, which were not included in the model expressions.

For water discharge on the east coast and in the far south, the model both underestimated and overestimated the discharge, up to 20% for single stations, with an average of +1%. On the west coast, (excluding the Göta River), on the other hand, the water discharge was generally underestimated by 10%. This is probably due to the automatic interpolation of meteorological data, which did not consider the strong precipitation gradient in the western part of the area studied.

The simulations of nitrogen concentration were based on constant leakage levels and simulated transport/transformation fluxes (Eq. 1). In Figure 9, two examples are given of incorrect leakage levels caused by errors in the database. The arable land in the Marsta river basin was underestimated by 13%, when the data on administrative units were transmitted into hydrological units. Moreover, the soil type was classified as clay till, while field studies show that clayey sand actually dominates the catchment. In Sweden, the leakage from clay till is lower than for clayey

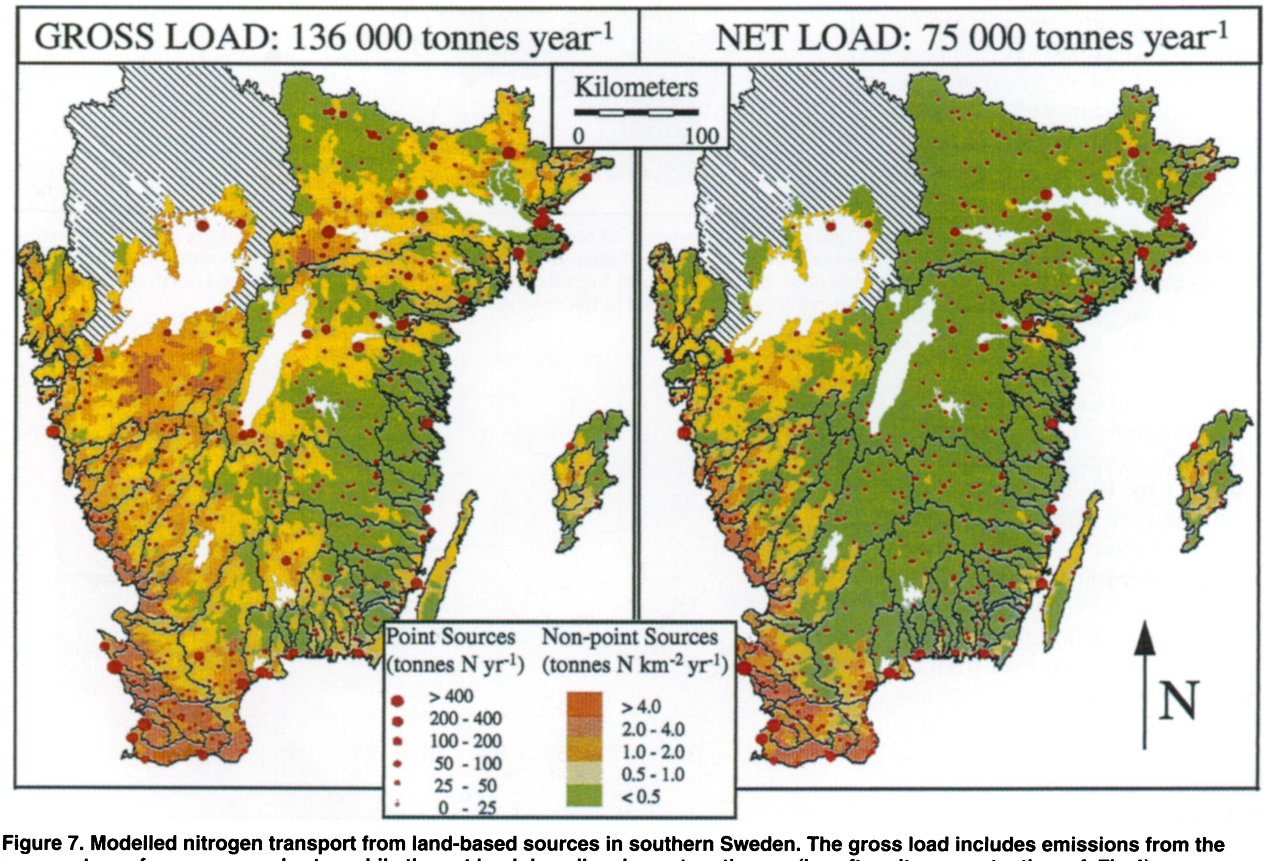

Figure 7. Modelled nitrogen transport from land-based sources in southern Sweden. The gross load includes emissions from the sources to surface- or groundwater, while the net load describes impact on the sea (i.e. after nitrogen retention, cf. Fig 4).

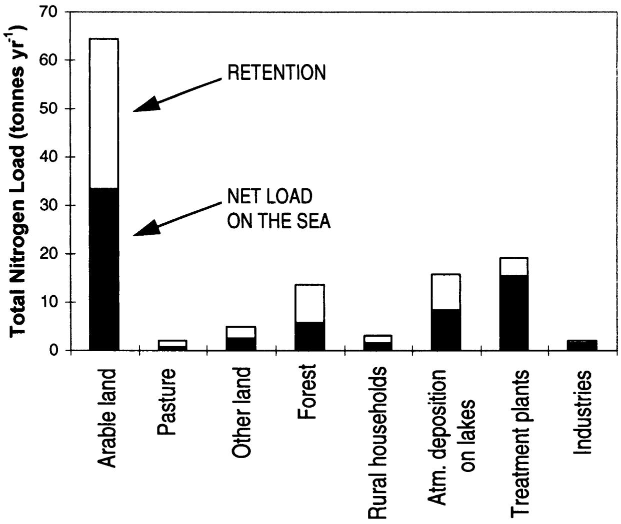

Figure 8. Total nitrogen load on the sea from various land-based sources. The bars describe the gross load, and are divided into retention during the residence time in the freshwater system and the net transport to the sea.

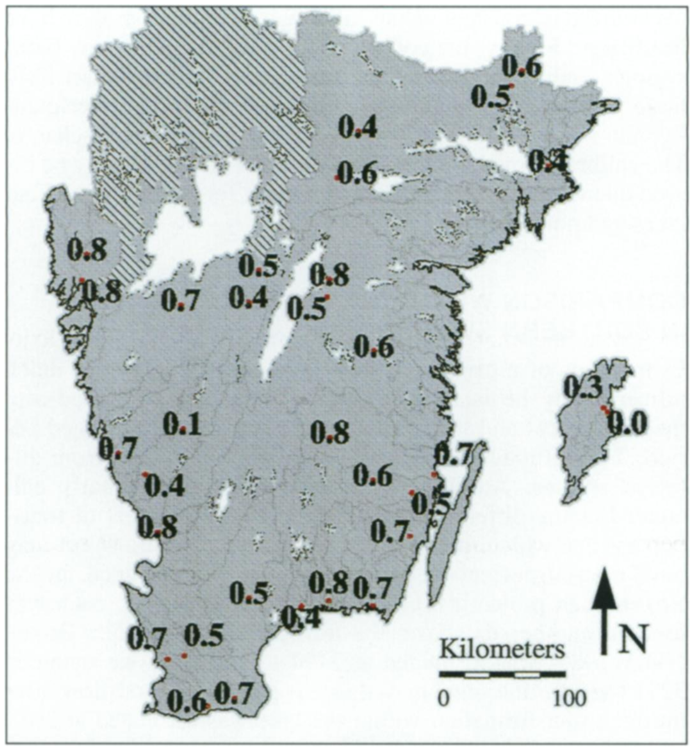

Figure 10. Explained variance (R^2) of modelled nitrogen transport in 32 sites (red dots) where both concentrations and water runoff are measured. The R^2 for both large and small catchments are shown in the Figure. The measurements cover 23% of the total discharge.

sand (21), and consequently both these errors in the database will lead to underestimations of the concentrations, which is also shown in the Figure. For the Åsaka river basin, the soil type is correct, but arable land is underestimated once again. Nevertheless, the concentrations are overestimated. This may be due to incorrectly estimated ley-area in crop composition, which is also held on administrative units, or the SOIL-N data for normal leakage not being representative for the catchment in question.

Occasionally, these types of over- and underestimations were found, and therefore there was a risk that the reduction simulated by HBV-N would compensate for errors in the database instead of describing the biogeochemical processes controlling nitrogen fluxes. This would be reflected in unrealistic time series of nearby catchments with the same parameter settings. Therefore, the dynamics were carefully controlled on a visual basis. When comparing median annual differences between simulated and linear-interpolated concentrations, most measurement stations overestimated or underestimated the concentrations by 10%, but a difference of more than 30% was also frequent (23).

The model performance of nitrogen transport was estimated statistically in 32 sites where both water discharge and nitrogen concentrations were measured (Fig. 10). Both small and large rivers were considered, representing 23% of the total nitrogen discharge to the sea. An average of 60% of the variance was explained by the model (i.e. $R^2 = 0.6$). The best results were found among catchments draining to the east coast, i.e. the Baltic Proper, and for the Nissan river basin on the west coast. Some high R^2 values in the Skagerrak basin were the result of compensation from underestimated water runoff (see above) and overestimated nitrogen concentrations. The weak results on the large island of Gotland were due to underestimation of both water discharge and nitrogen concentrations.

The source of errors and uncertainty may be difficult to quantify. Qualitatively, however, they may be referred to indata availability for the region (23). Key data were only available for administrative units and had to be reclassified for catchments, which may introduce large errors as illustrated in the examples in Figure 9. In some subbasins, the land class "other land" was large, up to 50% of the subbasin area, which complicated the assignment of leakage concentrations. For arable land, the leakage concentrations were obtained from regional estimations by the one-dimensional SOIL-N model for 10 years of monocultures with constant fertilization (17), which may not always be representative of single subbasins. Constant annual soil leakage may also have influenced local retention to include some vegetation take-up and not only near-stream reduction. Moreover, the relation between inorganic and organic nitrogen in the emissions was

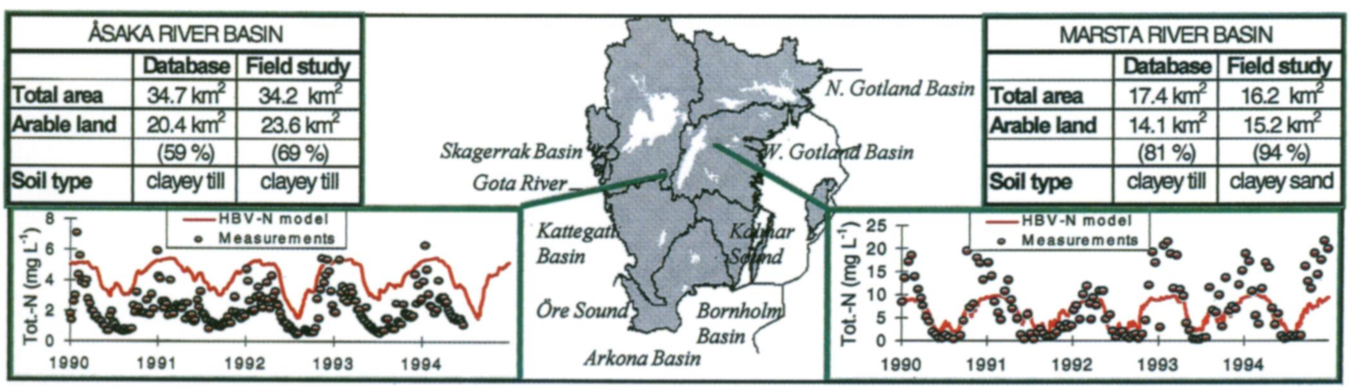

Figure 9. Modelled and measured nitrogen concentrations in two small rivers where the model overestimates and underestimates, respectively, the concentrations. The Tables show the discrepancy between the database of the project and field studies in the catchments.

generalized to constant values, although the variations may have been large. Finally, the concentration measurements may be of various quality and often they are collected downstream from large point sources which may influence the local water quality, and not be truly representative of the total water discharge. The calibrated model parameters for local discharge may be biased due to the few time-series measured for subbasins without lakes and point sources.

COMPARISON WITH OTHER STUDIES IN SOUTHERN SWEDEN

Estimations of nitrogen transport and retention are very much influenced by the database quality and resolution combined with meteorological and hydrological conditions for the studied period. Thus, it may be difficult to compare the results from different studies. Additionally, the retention is normally calculated as the difference between two large numbers of transport events, which means that a small change in transport may have a strong effect on the estimations. For instance, in the Roxen-Glan project (34) when a similar model approach was used in another database, the nitrogen load on Lake Roxen (1985–1989) was estimated at 3194 t yr^{-1}, while we obtained 3291 t yr^{-1} for the same period in this project. The outflow after nitrogen transformation within the lake was estimated at 2689 and 2406 t yr^{-1}, respectively. The numbers are fairly close, but still the difference in estimated retention is rather large (cf. 16% to 27%), which shows the sensitivity of this type of retention calculation.

Nevertheless, we compare the results with some other investigations. No large-scale calculations with the precision of the present study have been made for southern Sweden, although, single lakes or catchments have been investigated. Tirén (35) reported values of denitrification between 0 and 500 kg N ha^{-1} yr^{-1} for 35 Swedish and Danish lakes according to measurements and budget calculations. Half of the lakes were in the interval 0–50 kg N ha^{-1} yr^{-1}. Denitrification is assumed to be the major sink in our model approach, and in the present study half of the estimated lake retentions were between 19–61 kg N ha^{-1} yr^{-1}, which shows good correspondence between the investigations. Some results of percentual nitrogen reduction in specific lakes are shown in Table 3. The largest discrepancy in results is found for Lake Vättern. A more detailed modelling of water circulation is probably necessary for more correct estimates in the large lakes.

One rare example of distributed calculations of retention in river basins is the study of the Lagan catchment made by Grimvall and Stålnacke (36). It is based on a statistical approach, but the results from their study show very good agreement with our estimates of lake and river retention, both regarding the maximum retention of 80% for some subbasins, and the general retention pattern. Grimvall and Stålnacke also calculated net leakage on the subbasin level for the period 1985–1989. The major part of the transport could be assigned to soil leakage and was at most 2.4–3.6 t N km^{-2} yr^{-1} for subbasins, where we also found between 2 and 4 t N km^{-2} yr^{-1}. Upstream of Lake Bolmen we estimated the net transport to be 0.5 t N km^{-2} yr^{-1}, and Grimvall and Stålnacke, with one exception, found up to 0.6 t N km^{-2} yr^{-1}.

Although these results for southern Sweden are unique, due to their spatial resolution, they may be generalized for larger regions when compared with other studies. Coefficients are commonly used for estimations of load from nonpoint sources. General coefficients for some sources in 5 regions were estimated and compared with the ones presented by Löfgren and Olsson (37) (Table 4, cf. the regions in the map in Fig. 9). Discrepancy in coefficients may be a result of different land-use databases and different study periods, but also of different model approaches. The numbers differ mainly regarding leakage from arable land and pastures in the catchments of Kattegatt and Göta River, from the forest in the Öresund catchment and for atmospheric deposition on lakes in the Göta river basin (i.e. Lake Vänern). The comparison of flow weighted average concentrations in discharging water showed good agreement (Table 4).

Table 5 shows various estimations of nitrogen transport from southern Sweden to the marine basins. The results are of the same order of magnitude but vary slightly due to differences in databases, model approaches, and weather conditions during the study periods.

DISCUSSION

The model approach demanded correct indata for estimation of nitrogen emissions to ground- and surface water. Information

Table 3. Estimated annual nitrogen retention in some large lakes of southern Sweden. Discrepancies between the results from different studies may be caused by differences in databases, model approaches and weather conditions during the studied periods.

Lake	Present study:	Earlier studies in southern Sweden:		
	Retention	Retention	Study period	Source ref.
Vänern	30%	25–40%	1970–1989	42
		30–40%	1982–1992	43
		43%	1990–1992	43
Vättern	80%	55%	1971–1973	44
Mälaren	40%	55%	1981–1985	45
Bolmen	45%	60%	1980–1984	46
Ringsjön	60%	45–60%	1984–1988	47
		57%	1985	48

Table 4. Generalized export coefficients for gross transport from various land use in regions draining to different marine basins (cf. map in Fig. 9), and average concentrations in discharging water. The Table shows the results from the present study as well as the results from an earlier study in the region.

	Löfgren and Olsson (37), Olsson and Löfgren (49) study period: 1982–1987				Present study (1998) study period: 1985–1994			
	Export coefficients (kg km^{-2} $year^{-1}$)			Riverine	Export coefficients (kg km^{-2} $year^{-1}$)			Riverine
Discharge to marine basin	arable land and pasture	forest[i]	atm.dep.[ii]	concentration (mg L^{-1})	arable land and pasture	forest[i]	atm.dep.[ii]	concentration (mg L^{-1})
Baltic Proper	1636	130	625	1.4	2021	154	744	1.7
Öresund	3965	247	1081	6.5	3524	526	1306	8.6
Kattegatt	2280	241	1094	1.2[iii]	4373	289	1430	1.1[iii]
Göta River	994	189	625	–	3155[iv]	192[iv]	1234[iv]	–
Skagerrak	2906	164	846	0.9	3304	143	750	1.5

[i]) Including contribution from forest management and disturbance
[ii]) Atmospheric deposition on water sufaces
[iii]) Kattegatt including the Göta River
[iv]) Excluding the unspecified area north of the lake Vänern

Table 5. Estimated transport from southern Sweden to the surrounding sea and its marine basins (cf. map in Fig. 9). The Table shows the results from several large-scale studies that have been made in the region.

Author (study period)	Nitrogen load (tonnes yr^{-1}) from land draining to: Baltic Proper	Öresund	Kattegatt	Göta River	Skagerrak	Total
Larsson et al. (16) (1977–1983)	28 000	9400				
Rosenberg et al. (50) (1982–1987)	44 300		37 000			
Swedish Ministry of Environment (51) (1985–1990)	35 800	44 800			2900	83 500
Löfgren and Olsson (37), Olsson and Löfgren (49) (1982–1987)	35 600	8300	18 200	18 300	2900	83 300
Lindahl et al. (52) (1985–1990)	31 900	8600	14 600	17 600	3700	76 400
HELCOM (53) (1990)	33 200	6200	33 900			
Statistics Sweden (54–57) (average for 1987, 1990, 1992 and 1995)	35 200	7900	36 400		3600	83 100
Stålnacke[i] (1985–1994)	33 650	41 100				
Present study (1998) 1985–1994, annual emission values from 1985–87	29 900	7000	15 400	17 000	5700	75 000[ii]

[i]) Unpublished material, including coastal point sources from 1987 by Statistics Sweden (1989)
[ii]) About 4900 tonnes yr^{-1} in coastal point sources are missing in the database compared to Statistics Sweden (54).

about land use, soil type, fertilization, crop rotation, etc. is crucial for detailed estimations of nitrogen leakage and retention. It can be concluded that the quality of the database was not good enough for correct simulations in any of the 3725 subbasins. In other applications of HBV-N, leakage concentrations have been calibrated against measurements (22, 38) which may provide a solution in some cases. However, in such applications it is difficult to relate the leakage to specific land-use practices. In the modelling of southern Sweden, a further goal was to make scenarios for changes in land use and farming practices, which demanded strong coupling to the database. Most important for large-scale retention is the size and location of the lakes in the region, and even though leakage numbers for single subbasins may not be correct, the large-scale pattern should be rather reliable. The study has certainly led to improved support to decision makers compared to earlier studies where retention was often assigned a constant value, e.g. 50% of all inland emissions (39).

Measures to reduce nitrogen transport should be taken where they are most cost effective and be related to the environmental problem in question. From our results, it can be seen that measures to reduce leakage from arable land in the southwest has four times higher effect on the load to the sea than the same measures in the region draining to the northern Gotland basin. This is due to high retention of leakage from arable land in the lake Mälaren region. To make the measures as cost effective as possible, similar comparisons between various strategies should be made in every river basin where it is planned to reduce nitrogen loads. A more detailed management proposal, based on the results presented in this and the article by Johnsson and Hoffman in this Ambio issue (17), has been developed at the Swedish EPA, including remedial measures, policy instruments, and prioritization of measures (40).

The present model approach is applicable in regions other than southern Sweden. However, the model does not consider nitrogen influence from deep ground aquifers, since these are rare in Sweden where soils are rather thin. The importance of lake retention in Sweden is mainly due to the large number of lakes. In other types of landscape, e.g. flat lowlands where water residence time in rivers is significant, riverine retention becomes more important. Lidén et al. developed the HBV-N riverine retention equation to better describe such a catchment in Estonia (38). Further model development at SMHI includes incorporation of a phosphorus routine. The model will then be suitable for restoration programs for single lakes, to explore where in the drainage basin measures should be taken. Careful analyses and problem definition within the aquatic environment must, of course, precede the discussion of catchment measures. In addition, descriptions of nutrient interactions and storage in soil and sediments will be considered so that the model becomes predictive, and realistic scenarios for nutrient transport may be made regarding climate change, human impact and environmental management in the future.

CONCLUSIONS

The model approach shows that:
– There is a need for information about land use, management, and soil type on the subbasin level for correct nitrogen transport simulations on the local scale in Sweden.
– Monitoring programs should be designed not only for point-source control, but also for diffuse leakage estimation and model calibration purposes.
– Further model development is needed for more precise results and scenario estimations. The influence from other substances on the nitrogen cycle must be considered (e.g. phosphorus), as well as the historical impact on storage and release in soil and sediments.
The modelled retention shows that:
– The average retention for the 10-yr climatic period 1985–1994 is 61 000 t yr^{-1}, i.e. 45% on average for the entire region.
– The diffuse leakage from soil and rural households was normally reduced by 10–25% in groundwater-surface water interface zones. Lakes were the most effective nitrogen traps and normally reduced the nitrogen by 30–40 kg ha^{-1} yr^{-1} of lake area.
– Some areas in southern Sweden have no retention at all, while the emissions from others are completely consumed on the way to the sea. Retention during transport from sources to the sea is dependent on the character of downstream subbasins (especially the residence time in lakes).
– The annual retention in a catchment may vary by 30% between different years.

– The retention in southern Sweden is low in zones near the coast. However, in catchments with low lake percentages, this zone may sometimes reach far up in the river basin.

The modelled nitrogen transport and source distribution shows that:

– The average gross load from southern Sweden is 136 000 t yr^{-1}, and the net transport is 75 000 t yr^{-1} (considering the climatic period 1985–1994 and the emissions from 1985).

– The soil leakage contribution is higher on the west coast due to high water discharge and few lakes, i.e. short residence time.

– The contribution from arable land is as an average of 45% and from municipal treatment plants 21%. The contributions from forests, pastures and other lands including the region upstream of Lake Vänern were in total 19%. Atmospheric deposition on lakes contributed 11%, and industry and rural households 1–2% each.

– Regarding the leakage from arable land to the marine basin N. Gotland (map in Fig. 9), only 25% reached the sea, due to the large lake system in the river basin. The corresponding net transport from arable land in the southernmost county is 80%.

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