Nitrogen Leaching in Small Agricultural Catchments

Modelling and monitoring for assessing state, trends and effects of counter-measures

Katarina Kyllmar
Department of Soil Sciences
Uppsala

Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2004

Acta Universitatis Agriculturae Sueciae
Agraria 485

ISSN 1401-6249
ISBN 91-576-6761-6

Tryck: SLU Service/Repro, Uppsala 2004

Abstract

Kyllmar, K. 2004. *Nitrogen Leaching in Small Agricultural Catchments - Modelling and monitoring for assessing state, trends and effects of counter-measures*. Doctoral thesis. ISSN 1401-6249, ISBN 91-576-6761-6.

Nitrogen (N) leaching from arable land to the aquatic environment is considered a serious problem.

Small agricultural monitoring catchments in Sweden were used for the application and testing of model-based methods for quantification of N leaching from arable fields, and for analysis of measured data. The physically-based modelling system SOILNDB was used in two different approaches for quantification of N leaching; by direct simulations using monitored field data and by producing field N leaching coefficients (field-NLCs) on the basis of agricultural statistics, *etc*. The field-NLCs were then used to calculate N losses from the fields.

Measured N loads at the stream outlets varied widely between the 27 catchments, from 2 to 41 kg ha^{-1} yr^{-1}. They were correlated to climate, soil texture, proportion of arable land and crops grown in the catchments. Significant downward trends in N loads were revealed for seven catchments. In one monitoring catchment, direct simulations for individual fields resulted in a mean N leaching for the fields of 44 kg ha^{-1} yr^{-1}, whereas measured N load in the stream was 40 kg ha^{-1} yr^{-1}. The difference could be attributed to dilution by water from non-agricultural land with typically lower N concentration. Calculation of field N leaching using field-NLCs for nine monitoring catchments also showed a satisfactory agreement with measurements in the streams when contributions from other sources and uncertainties in groundwater flows were considered. The two applications also showed that N leaching varied greatly between individual fields.

The potential effects of several counter-measures to reduce N leaching were estimated (using field-NLCs) to be between 34 and 54% for the nine individual monitoring catchments. The measures comprised changes in crop combinations (crop and following crop), application time of manure and adjusted mineral fertilizer dose, and introduction of catch crop. The potential to reduce N leaching was also estimated for a medium-sized catchment. This reduction was relatively low (21%), partly due to the restricted possibility of introducing catch crops into the crop rotations.

In water quality management planning, methods for quantification of N leaching from arable land should cover these large spatial variations in N leaching so that areas with a large impact on the recipient can be identified and the most effective combinations of measures to reduce N leaching can be determined.

Keywords: nitrogen, leaching, arable field, agriculture, catchment, monitoring, SOILNDB model, coefficient method, field-NLC, trend, scenario, crop rotation, catch crop

Author's address: Katarina Kyllmar, Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Water Quality Management, P.O. Box 7072, SE-750 07 Uppsala, Sweden. E-mail: Katarina.Kyllmar@mv.slu.se.

Contents

Appendix

Papers I-IV

The present thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Kyllmar, K., Carlsson, C., Gustafson, A. & Johnsson, H. Nutrient discharge from small agricultural catchments in Sweden. Characterisation and trends. Submitted to *Agriculture, Ecosystems and Environment*.

II. Kyllmar, K., Larsson, M.H. & Johnsson, H. Simulation of N leaching from a small agricultural catchment with the field scale model SOILNDB. Accepted by *Agriculture, Ecosystems and Environment*.

III. Kyllmar, K., Mårtensson, K. & Johnsson, H. Model-based coefficient method for calculation of N leaching from agricultural fields applied to small catchments and the effects of leaching reducing measures. Accepted by *Journal of Hydrology*.

IV. Larsson, M.H., Kyllmar, K., Jonasson, L. & Johnsson, H. Estimating reduction of nitrogen leaching from arable land and the related costs. Submitted to *Ambio*.

Introduction

Diffuse nitrogen (N) pollution from agricultural land is the major source of N load to surface waters and groundwater in many regions (Kronvang *et al.,* 1996; Stålnacke*,* 1996; EC, 2002) and since emissions from point sources such as wastewater treatment plants and industries have been reduced during recent decades, the relative contribution from agricultural land has increased (Behrendt *et al.,* 2002). In Sweden, the diffuse N pollution from agricultural land, which occupies only 7.6% of the land area, contributed 40% of the land-based net load to the sea during 1995 to 1999 (Brandt & Ejhed, 2002).

One of the national environmental goals in Sweden is to reduce the anthropogenic waterborne N transport to the sea by 30% between 1995 and 2010 (Swedish EPA, 2003). With the implementation in the EU member states of the Water Framework Directive (WFD) (EC, 2000), water management plans will be set up for river basin districts, with the aim that all water should maintain or reach good status by 2015. These water management plans will include *inter alia* (i) background descriptions that include identification and estimation of sources of anthropogenic impacts on surface waters; (ii) classification of waters in relation to environmental quality targets; (iii) action plans including counter-measures and associated costs for these; and (iv) evaluation of status and effects of measures on water quality.

Models can be helpful tools for quantification of diffuse losses (Thorsen, Feyen & Styczen*,* 1996; Grizzetti *et al.,* 2003) and can be used for producing background information to the water management plans, since diffuse N losses from all arable land cannot be monitored and quantification of the effects of different measures is difficult without models. Water management in the EU is further regulated by the Nitrate Directive (ND), which requires each member state to identify nitrate vulnerable zones where action programmes with measures concerning agricultural practices must be implemented (EC, 1991). Small agricultural monitoring catchments, which have been established in most countries in the Nordic-Baltic region (Vagstad *et al.,* 2001), may act as indicators of pressure from the entire agricultural area on surface waters and groundwater. In these catchments, monitoring combined with modelling can be used for further clarification of the relationship between crop management and water pollution.

Objectives of thesis

The objectives of this thesis were to: (i) further develop model-based methods for calculations of N losses from arable fields; (ii) apply and test these methods by using data from small agricultural monitoring catchments; (iii) evaluate how the methods can be used with respect to resolution in input data; and (iv) to calculate the effect on N losses of some measures intended to reduce N leaching.

Background

Modelling N flows at catchment scale

The catchment scale ranges from small catchments that are discharged through small streams to large river basins that cover thousands of square kilometres and may extend beyond national borders. Within an agricultural catchment, diffuse N pollution from arable land is the dominant source of N load in the stream, whereas in a large river basin, arable land is one of several significant sources of N pollution in water. Other sources are *e.g.* forests and urban areas, as well as point sources such as waste water treatment plants and industries.

A common approach for analysing the flows within a somewhat larger catchment is to quantify the losses from diffuse sources and point sources and to use them as inputs to hydrological models and retention equations. Catchment models such as these can treat the input sources either spatially lumped or distributed. In a lumped model no spatial variation occurs and all parameters and variables are assumed to cover the characteristics of the entire catchment area. In a distributed model the catchment is divided into sub-catchments or into grid-cells and within each sub-unit the properties, *e.g.* land use, are assumed to be uniform. N flow from each sub-unit is then routed through surface water, shallow subsurface water and deep groundwater within the catchment. The N passing through surface water and shallow subsurface water reaches the stream relatively quickly, whereas N passing through deep groundwater is mixed with old groundwater and delayed before reaching the catchment stream outlet. Furthermore, some N is removed by retention processes occurring in the water bodies.

Models and methods for quantification of N losses from arable land at the catchment scale are further discussed here, whereas methods for estimation of point sources, hydrological models and retention equations are not dealt with, since they are beyond the scope of this thesis. Catchment models have been reviewed or compared by *e.g.* Behrendt *et al.* (2001), Schoumans & Silgram (2003) and Wolf, Rötter & Oenema (2004). Hydrological models have been reviewed by *e.g.* Singh (1995).

Quantification of N losses from arable land

N leaching models

Leaching of N from arable land can be calculated with models that range in complexity from static empirical models to dynamic physically-based models.

Empirical models or regression equations are described by *e.g.* Simmelsgaard & Djurhuus (1998) and Simmelsgaard *et al.* (2000) (the N-LES model). Empirical models are derived from analysis of data (*e.g.* plot experiments) and appropriate fitting procedures. The results produced are typically long-term annual averages of different combinations of crops, field management and site-specific properties.

Since the models are developed on the basis of a certain set of measurements, the applicability to areas with other conditions may be restricted.

Physically-based models mainly describe the hydrological, chemical and biological processes occurring in the soil-water-plant system by equations derived from scientific theory, *e.g*. the Richard's equation for unsaturated and saturated sub-surface flow. These physically-based models are mostly one-dimensional and simulate the N leaching from the root zone as one of several N flows in the soil-water-plant system (*e.g*. mineralisation, denitrification and plant uptake). The dynamic approach produces N leaching values with high temporal resolution (*e.g.* daily values) and the leaching from different field management systems, climates and soil types can be described. These leaching models require large data inputs. However, detailed scenarios can be calculated. Such models include ANIMO (Groenendijk & Kroes, 1999), DAISY (Hansen *et al.,* 1990), LEACHN (Hutson & Wagenet, 1991), and SOIL/SOILN (Jansson & Halldin, 1979; Johnsson *et al.,* 1987), which is included in the modelling tool SOILNDB (Johnsson *et al.,* 2002).

Intermediate between empirical and physically-based models are models that reproduce general structures and processes based on simplified equations. These models are not intended to provide precise process descriptions. Some intermediate N leaching models include CREAMS (Knisel, 1980), EPIC (Jones *et al*., 1991) and SLIM (Addiscott & Whitmore, 1991).

N leaching models have been reviewed or compared by several authors, *e.g.* Vereecken *et al.* (1991), de Willigen (1991), Diekkrüger *et al.* (1995), Thorsen, Feyen & Styczen (1996), Wu & McGechan (1998) and Moreels *et al.* (2003).

Methods for quantification of N losses

For large areas, where detailed site-specific data are seldom available, other approaches have been used for calculation of N losses from arable land. The simplest methods for estimation of diffuse pollution of N from arable land are lumped source apportionment calculations. N losses from arable land (including retention losses) are obtained in this approach by subtracting estimated losses from point sources from the total measured load in the catchment stream outlet. Since the diffuse sources are treated spatially lumped, no critical areas can be identified, and only long-term changes in total loads can be determined. Equations for source apportionment calculations have been compared by *e.g*. Behrendt (1999).

The spatial distribution of N losses from agricultural land has been calculated on the basis of information on N surpluses at the soil surface, soil characteristics and climate by *e.g.* de Wit (2001) and Behrendt *et al*. (2002). In the modelling chain STONE (Wolf *et al.,* 2003), the N losses from arable land are simulated for each sub-unit with the physically based model ANIMO and on information of crops, fertilizer use, livestock numbers *etc*.

At the small agricultural catchment scale, N leaching models and detailed field management data have been used to calculate N losses from arable land, which have been compared to measured N transport in the catchment stream outlets. Examples are Jørgensen *et al*. (2002) who used the N-LES model, Deelstra, Bechmann & Kværnø (2002) who used a Norwegian version of the SOIL/SOILN model and Hoffmann & Johnsson (2003) who used the SOILNDB modelling tool.

Another method is to produce N leaching coefficients that represent different land uses. The coefficients are expressed either as losses (kg N ha^{-1}) or as concentrations (mg N l^{-1}). In the latter approach, the magnitude of the losses of N is obtained from the water discharge levels used. The coefficients can be applied to land areas on the basis of information on distribution of land use properties (*e.g.* type of land use, crop distribution on arable land *etc.*).

N leaching coefficients can be produced by (i) compilation of data from measurements in field experiments and in small sub-catchments under various agro-environmental conditions (*e.g.* climate, soils, crops, agricultural management), or by (ii) models using agricultural statistics as input data. A coefficient method where measured data were compiled is described by Johnes (1996).

Model-based N leaching coefficients representing crops or farm types have been produced using different types of models. Input data have consisted of agricultural statistics on crop distribution, livestock production and consumption or use of fertilizers, together with complementary information from advisory services concerning agricultural practices. The empirical model N-LES was used by Jørgensen *et al*. (2002) to determine the N leaching from crops on a number of typical farms in two small agricultural catchments. The N leaching rates from these crops were then applied to a much larger catchment on the basis of the distribution of crops and farm types in the area. Empirical equations were also used for determination of farm type leaching in an integrated economic and agricultural N pollution modelling framework for large scale calculations of N losses (Schou, Skop & Jensen 1998). The modelling framework MAGPIE (Lord & Anthony, 2000) where the leaching model SLIM is included, was used for producing coefficients for different crops. In catchment and national load calculations the coefficients were adjusted for spatial variations in soil and climate.

The physically-based model DAISY has been used for producing leaching coefficients for representative farm rotations. These coefficients were applied to arable land in a medium-sized catchment according to areal distribution of crops, farm types and soil types (Styczen & Storm, 1993; Refsgaard *et al.,* 1999). The same approach was used by Vinten & Dunn (2001) for a Nitrate Vulnerable Zone by scaling up N leaching simulated with the physically-based ANIMO for typical farm rotations (Trabada-Crende & Vinten, 1998). Another physically-based model, SOIL/SOILN integrated in the modelling tool SOILNDB (Johnsson *et al.,* 2002), was used for producing N leaching coefficients for a variety of agro-environmental conditions (*i.e.* crop, fertilization regime, soil type and climate) (Johnsson & Hoffmann, 1997). The coefficients were normalised for weather variations and in a later version (Johnsson & Mårtensson, 2002) the influence of crop rotations on each crop was also included. In regional and national load calculations the coefficients have been used for determination of losses from agricultural land (Brandt & Ejhed, 2002; Sonesten, Wallin & Kvarnäs, 2004).

Classification of methods for calculation of N losses into typical categories is not straightforward since intermediates of different methods exist. Coefficients calculated with models can be produced with more or less detailed input data and with various complexities in the models. The possibility to describe various N leaching situations then differs, as does the scale at which they can be applied. One single coefficient can be applied for a whole sub-catchment and the source apportionment method can be used within a sub-catchment, resulting in the same resolution for both approaches.

Scenario analysis

Many scenarios discussed in the literature for the medium-sized to large catchment scale concern changes in land use and in N surplus on arable land. Land use changes such as converting arable land into permanent grassland or forest, *e.g.* Kronvang *et al*. (1999), van Herpe *et al*. (2002) and Zakrisson, Ekstrand & Huang (2004), are radical scenarios (except for marginal areas) that are secondary effects of political decisions rather than active measures by the farmers. Reducing N surpluses on arable land, described by *e.g.* Müller-Wohlfeil *et al*. (2002) and Wolf *et al*. (2003), is on the contrary highly adequate in countries with intensive animal production such as the Netherlands, where the mean annual N surplus is high, *e.g.* 295 kg N ha^{-1} in 1995 (Wolf, Rötter & Oenema, 2004).

In Sweden, excessive application of N is probably not a general problem even if too high application rates may occur on individual fields. In 1999 the mean annual rate of mineral N application (in fertilizer and in manure) was approximately 100 kg ha^{-1} and the export of N with crops was approximately 90 kg ha^{-1} (Johnsson & Mårtensson, 2002). Apart from eliminating possible overdoses, there are a variety of measures that can be implemented by the farmer. By using crop rotation data, scenario analysis of the effects of crop management practices is considerably facilitated.

For the small catchment scale, scenarios are described by *e.g.* Vinten & Dunn (2001) who analysed the effects of reduced proportion of vegetables in exchange for cereals and grass, reduced fertilizer doses and removal of crop residues from fields with vegetables. Johnes & Heathwaite (1997) calculated the effects of measures such as reducing fertilizer doses, growing catch crops, reallocating crop management with high risk for N leaching to areas with large distance to the surface drainage network and converting all arable land to grassland. Deelstra, Bechmann & Kværnø (2002) calculated the effects of optimal fertilizer dose, catch crops and irrigation. However, descriptions of detailed scenario analysis of measures in crop management systems for the medium-sized and large catchment scale are scarce.

Materials and Methods

Agricultural monitoring catchments

General

The catchments (Paper I) used in this thesis for evaluations and applications are included in the Swedish Monitoring Programme for Agricultural Land. The catchments are small (from 1.8 to 54 km^2) and most of them are dominated by arable land (Table 1). Water quality and nutrient loads were measured in the stream outlets and activities in the catchments influencing water quality were

Table 1. *Characterisation of monitoring catchments*

Catch-ment	LR†	Area (ha)	Arable land (%)	Dominant soil texture class of arable land	Measurements in stream outlet (mean annual values): Water discharge (mm)	N conc. ($mg\ l^{-1}$)	N load ($kg\ ha^{-1}$)
M42	1a	902	95	sandy loam, loam	284	8.3	24
M37	1a	867	95	clay loam	330	7.2	24
M36	1a	791	79	sandy loam, clay	286	8.9	26
N34	1b	1460	92	sandy loam	335	11.2	41
N33	1b	650	93	sandy loam, loam	277	9.2	26
M41	2a	1228	67	sandy loam	380	8.8	34
M39	2a	683	90	sandy loam, loam	366	10.5	38
M40	2b	177	80	loamy sand	188	12.3	23
K31	2b	750	34	sandy loam	237	3.6	9
I28	3	490	90	sandy loam	170	9.3	16
F26	7a	175	78 ≡	sandy loam	455	4.7	21
O15	9	600	37	clay loam	449	2.3	10
E24	4	564	68	clay	153	4.2	6
E21	4	1681	89	sandy loam	142	10.7	15
O18	5a	776	91	clay loam	351	5.6	20
O17	5a	975	60 ≡	sandy loam	292	3.9	12
O14	5a	1000	70	silt loam	326	5.6	18
S13	5b	3521	39	sandy loam	321	3.1	10
T10	6	720	70	sandy loam/peat	434	8.1	35
T9	6	2500	45	clay	301	2.3	7
U8	6	470	62	clay	280	3.5	10
C6	6	3290	57	clay loam	237	3.3	8
AB5	6	2100	52	clay loam	193	4.3	8
AB4	6	917 ‼	47	loam	215	4.9	12
W3	13	5373	37	silt loam	299	1.7	5
X2	14	900	60	silt loam	254	2.6	7
AC1	15	3279	16	loamy sand	213	1.1	2

† Leaching region
‼ Monitoring area within catchment
≡ Arable land and pasture

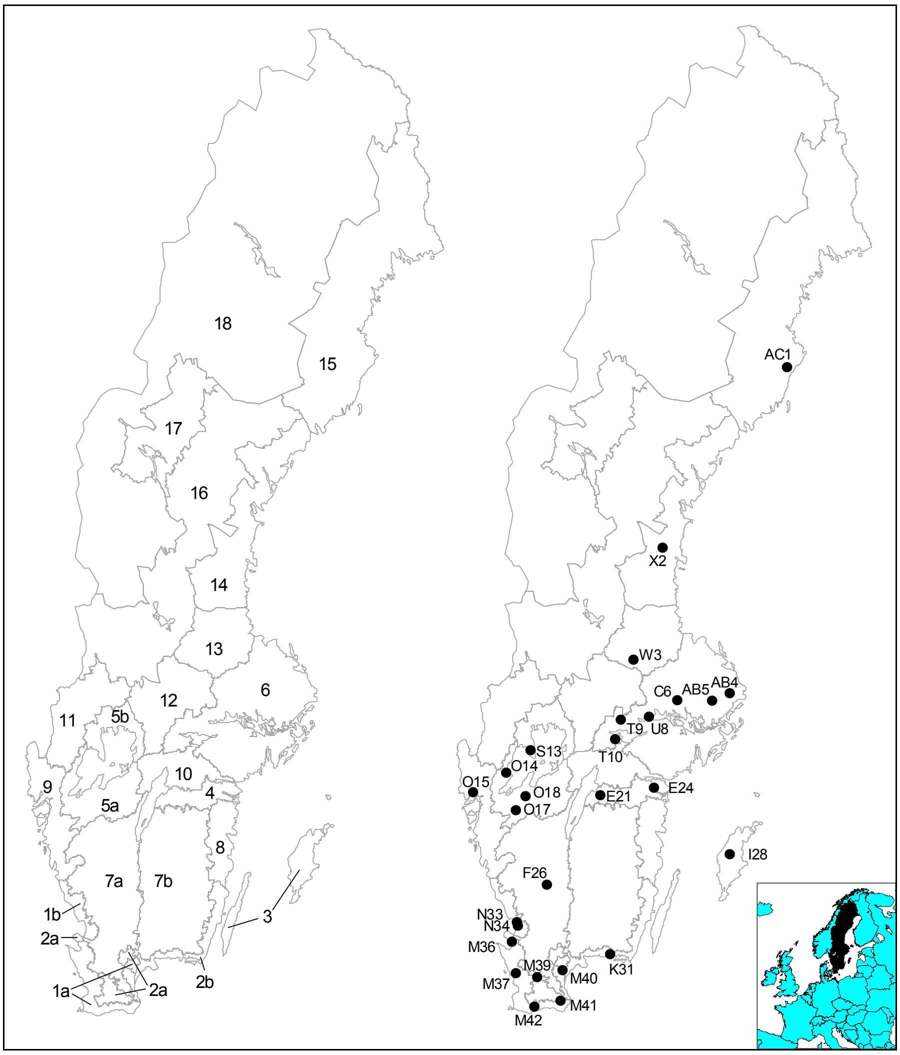

Figure 1. Sweden with (a) leaching regions and (b) monitoring catchments.

surveyed. Information concerning annual agricultural management on field level such as crops grown, crop yields, amounts of manure and fertilizer applied, timing for fertilization and timing for soil cultivation was then collected. The monitoring started between 1988 and 1993 in all catchments except one, and in 2002, the programme consisted of 27 catchments (Fig. 1b) representing the main agricultural areas in Sweden.

Estimated net losses from arable land

The N load in the stream originating from arable land was estimated through source apportionment. Contributions of N from point sources and land use other than arable land were estimated based on surveys and subtracted from the total stream load. The remaining load was assumed to be the net load from arable land (*i.e.* gross load with retention losses removed). The net load was subsequently divided by the area of arable land to obtain area-specific net losses (kg ha^{-1}). The net losses were used for comparison of measured data with model-calculated field N losses.

Trend analysis

Time series of monthly transport of nitrate N in the streams were normalised using a semiparametric regression model where temporal variations attributed to water flow were removed and suppressed (Stålnacke *et al.,* 1999; Stålnacke & Grimvall, 2001). The flow-normalised time series were tested for trends using the Seasonal Mann-Kendall Test (Hirsch & Slack, 1984).

Methods for calculation of N leaching from arable fields

The modelling system SOILNDB

SOILNDB is a one-dimensional management-orientated modelling system for quantification of N leaching from arable land (Johnsson *et al.,* 2002). SOILNDB (Fig. 2) links input data and data from parameter databases to automatic parameterisation procedures for two physically-based research models: the water and heat model SOIL (Jansson & Halldin, 1979) and the nitrogen model SOILN (Johnsson *et al.,* 1987). The major processes determining transformations and

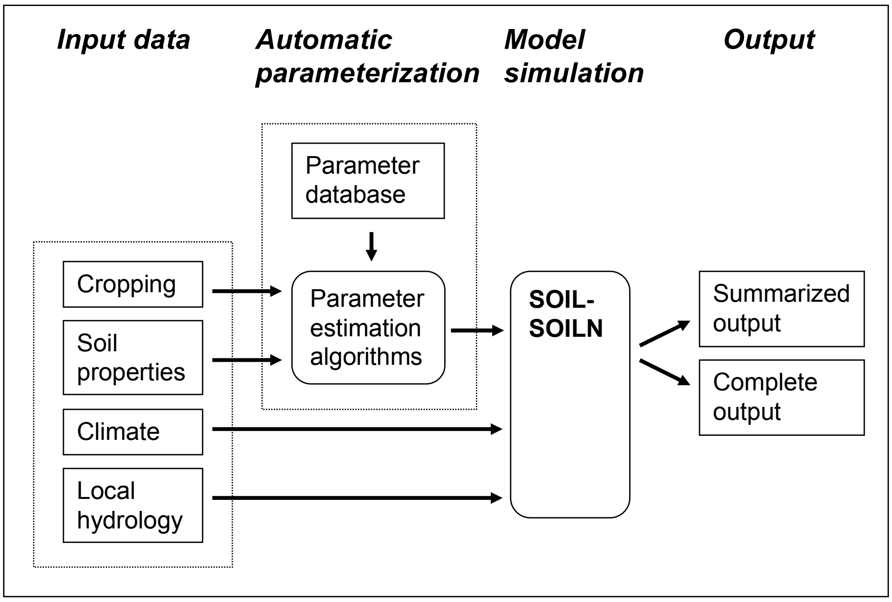

Figure 2. Schematic description of the SOILNDB modelling system.

transport of N in arable soils, such as decomposition and mineralisation of litter and faeces, mineralisation of humus, denitrification, plant uptake and leaching, are included. With SOILNDB, the time-consuming process of parameterisation, administrating model runs and presenting model results is reduced, allowing a large number of calculations for various agro-environmental conditions to be made efficiently. The underlying SOIL and SOILN models have been used in many applications, mainly at field scale (see review by Hoffmann, 1999) and the values in the parameter database originate from these previous applications and to some extent from literature surveys (Johnsson *et al.,* 2002; Johnsson & Mårtensson, 2002; Hoffmann & Johnsson, 2003; Larsson & Johnsson, 2003).

Simulation of field N leaching

N leaching from each field in a mainly tile-drained agricultural monitoring catchment (N34) was simulated for a four year period using SOILNDB (Paper II). A new version of the model (Larsson & Johnsson, 2003) was tested in which leaching can be divided between flow to tile drains and groundwater. Input data for the simulations had high resolution and comprised soil texture classes and time series of annual crop and field management data (*i.e.* amounts of manure and fertilizer applied, harvested yields and timing for sowing, harvest, soil cultivation and fertilizations) for each of the 317 fields in the catchment.

Simulated N leaching and water discharge for the fields (daily and annual values) were area-weighted to catchment mean values and compared to measurements in the stream, *i.e.* N and water as catchment discharge as well as source apportionment calculated net loss of N from arable land. The ability of the model to simulate water discharge and N leaching was evaluated using a statistical model efficiency (EF) method (Nash & Sutcliff, 1970).

Calculation of field N leaching using model-based coefficients

Field N leaching coefficients (field-NLCs)

SOILNDB was also used for producing field N leaching coefficients (field-NLCs) for application and calculation of N leaching from arable land (Papers III & IV). The method is a further development of the so-called TRK-method for obtaining standard N leaching coefficients (NLCs) for agricultural land in Sweden (Johnsson & Mårtensson, 2002). In TRK, Sweden was divided into 22 leaching regions (Fig. 1a) that were assumed to be relatively homogeneous with respect to farming and climate. Here (Papers III & IV), field-NLCs were produced for four of these leaching regions (1a-b, 2a-b).

Input data for producing field-NLCs comprised soil characteristics for a number of soil texture classes; climate series with 20 years of daily values representing each of the four leaching regions; and crop management data (*e.g.* crop areas, standard yields, amounts of fertilizer and manure applied) on these regions based on agricultural statistics for the year 1999 (Statistics Sweden 1999, 2000a, 2000b).

Using a randomised procedure, crop sequences (*i.e.* crop rotations) of 60 000 years were produced for each region, where the occurrence of each crop in the crop sequence was proportional to its areal representation in the actual region. Limitations in possible crop combinations were then taken into consideration. The crop sequences were combined with the climate data by repeating the 20-year climate periods 3 000 times so that each crop occurred at different places in the climate periods and before and after different crops in the sequences. N leaching using SOILNDB was then simulated on these crop sequences for each soil type in the four leaching regions.

Mean values of annual N leaching (representing the period 1 July of the crop year to 30 June the following year) were calculated on the simulated outcomes for each combination of main crop, following crop and fertilization regime for each of these crops (*i.e.* manure applied in autumn or in spring or only fertilizer applied). In this way leaching coefficients normalised for weather variations for each leaching region and soil type were achieved. Confidence intervals (95%) were calculated for each coefficient on simulated outcomes of N leaching. In total, 2690 coefficients were produced and stored in a database. The field-NLCs differ from the NLCs for national load calculations in that they include 35 crop combinations (Table 2) (instead of only 12 crops) and three fertilization regimes (instead of two).

Table 2. *Crop groups for actual year and following year*

	Crop group
Actual year	
	Winter cereals
	Winter oilseeds
	Spring cereals and spring oilseeds
	Potatoes
	Sugar beet
	Ley
	Green fallow in crop rotation
Following year	
	Winter cereals
	Winter oilseeds
	Spring sown crops
	Ley
	Green fallow in crop rotation

Application in small agricultural monitoring catchments

The field-NLCs were used for calculation of N leaching from the fields in nine small agricultural monitoring catchments in southernmost Sweden (K31, M36-37, M39-42, N33-34) (Paper III; Fig. 1b). Each field was given a coefficient on the basis of field information concerning crops and fertilizations during a two-year period and soil texture class. The area-weighted mean of N leaching from all fields in each catchment respectively was calculated and compared to long-term averages of measured N.

Application in a medium-sized catchment

The field-NLCs were also used for N leaching calculations for a medium-sized catchment, Rönne å river (1 900 km^2), in southernmost Sweden (Paper IV). The arable land in the catchment is located in three leaching regions (1a, 2a and 7a), but coefficients for only one of the leaching regions (2a) were used for all arable land in the entire catchment. Leaching region 2a constitutes an intermediate of the two others concerning climate, crops and crop management.

Information was available in 64 sub-catchments on crops, number of animals and soil texture classes. Since there was no information concerning crop rotations, field-NLCs for the same main crop were aggregated. The influence of following crops on N leaching was then averaged according to areal crop distribution in the region.

In each sub-catchment, N leaching losses were calculated with the aggregated field-NLCs according to distribution of soil texture classes, crops and the estimated percentage of area receiving manure (based on the number of animals). Area-weighted average annual losses of N from each sub-catchment were converted to N concentrations using the mean water discharge in the sub-catchments. These N concentrations constituted input to the hydrological model HBV-N, which also includes retention equations. The results of this coupling are described by Arheimer *et al.* (2005).

Measures to reduce N leaching

The potential effects on N leaching of a number of leaching reduction measures were calculated on the basis of existing crop management in the nine monitoring catchments and in the medium-sized catchment. The measures were chosen to be practically feasible in existing production, *i.e.* crop distribution, amounts of manure applied and total yields were assumed to be unchanged. The measures were:

- *A* application of manure in spring instead of autumn, which included an adjusted dose of fertilizer in spring
- *B* late termination (ploughing-in) of ley in autumn
- *C* catch crop in spring cereals and in spring oilseeds
- *D* catch crop in winter cereals, winter oilseeds, spring cereals and spring oilseeds
- *E* increased area of catch crops in spring cereals and spring oilseeds by substituting winter cereals and winter oilseeds with corresponding spring crops. To maintain production levels with this measure, the area of fallow was decreased in exchange for spring sown cereals and oilseeds.

In the nine small catchments (Paper III) all measures were assumed to be implemented in all possible fields with the best potential effect, whereas in the application on the medium-sized catchment (Paper IV) we accounted for only 70% of the potential reducing effect for the catch crop measures.

Results

N losses in agricultural catchments

Spatial variations among agricultural catchments

The measured mean annual N load in stream outlets of the 27 agricultural monitoring catchments (Paper I) varied from 2 to 41 kg ha^{-1} (Table 1). Estimated net losses from arable land were somewhat higher, ranging from 8 to 48 kg ha^{-1}. The largest losses of N were observed in catchments with high N concentrations in discharge water and medium to high water discharge levels. Catchments with high N concentrations often had a high percentage of arable land and were characterised by several factors that increase losses of N, such as sandy soils or peat soils, a large proportion of annual crops or intensively cultivated crops (*e.g.* potato) and high livestock density in combination with low percentage of ley. Most of these catchments with high N concentrations are situated in the southern part of Sweden were the winters are mild. Since temperature is a key factor governing mineralisation of organic matter and crop residues in the soil, mild winters increase the risk for N leaching from the root zone to drainage systems and to groundwater. No correlation was found between N balances at catchment scale and net losses of N from arable land.

Spatial variations within catchments

Monitoring catchments

The N leaching from the fields, calculated with field-NLCs, varied greatly between the fields in the nine monitoring catchments (Paper III). As an example for catchment N34, the N leaching from the fields (in a number of 317) ranged from 6 to 118 kg ha^{-1}. Direct simulations with SOILNDB in N34 (Paper II) resulted in mean N leaching for the simulated period ranging from 3 to 126 kg ha^{-1}. During a single year (for example 1999) simulated N leaching ranged from 4 to 188 kg ha^{-1}. For the same year, when the fields were sorted according to N leaching rates and divided into 50 groups with approximately equal area, the leaching varied between 5 and 163 kg ha^{-1} (Fig. 3).

The variations between the fields can be explained by field to field variations in soil texture classes, crop rotations, actual crops in the particular year, yields, amounts of N applied and variations in other field management operations. The lowest leaching rates were calculated for fields with green fallow or ley. Elevated leaching was obtained for some of the potato fields and for some fields with high levels of applied N in relation to the harvested yields, which included some fields with leys that were terminated and ploughed in during the actual year. On average, application of manure resulted in larger simulated leaching than when only mineral fertilizer was applied.

The differences in N leaching variations between the methods can be attributed to the use of weather-normalised values with field-NLC calculations, whereas weather variations occur between the years in the direct simulations. Furthermore,

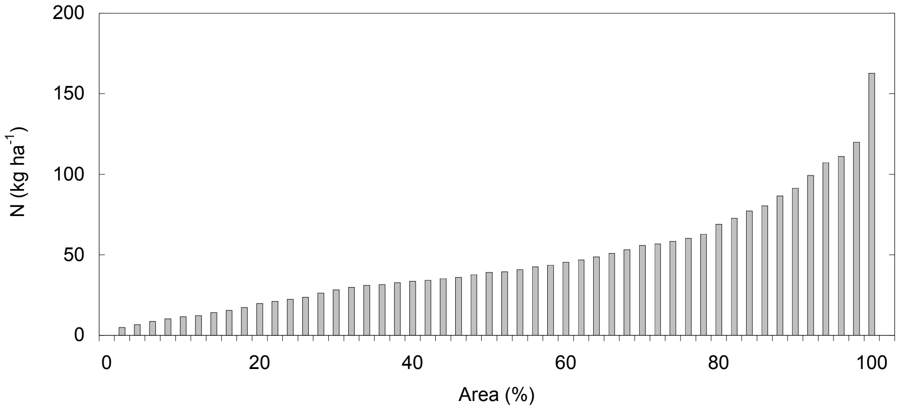

Figure 3. Distribution of simulated field N leaching for catchment N34 as annual accumulated values for 1999/2000 where each bar represents 2% of the total area of the simulated fields.

variations in the agricultural practices were probably not covered to the same extent using field-NLCs.

Medium-sized catchment

Within the medium-sized catchment (Paper IV), the sub-catchments with highest N concentrations in discharge water, >10 mg l^{-1}, (comprising 22% of the arable land) were located in areas dominated by arable land close to the river. In these areas cereals covered approximately 60% of arable land, followed by ley, fallow and sugar beet. The soils in these areas were characterised as loamy or clayey. The lowest leaching concentrations from arable land (<5 mg l^{-1}) were obtained in sub-catchments dominated by forest and with sandy loam soils. In these areas, ley was the dominant crop (covering 85% of arable land), while spring cereals covered the remaining area.

Temporal variations and trends

Temporal variations in N losses due to seasonality and weather conditions were large, both in the measurements and in direct SOILNDB simulations (while N leaching calculated with field-NLCs is normalised for weather variations). For catchment N34 the daily, monthly and annual range in N losses as catchment mean values were 0-2, 0-14 and 26-65 kg ha^{-1} respectively for measurements, whereas they were 0-9, 0-19 and 19-81 kg ha^{-1} respectively for simulations. Simulated N leaching from the root zone varied more than measured N discharge in the stream due to the dampening effect of the surface water and groundwater bodies.

When flow-normalised time series of monthly transport of nitrate N in the streams in 24 monitoring catchments were evaluated for trends (Paper I), significantly downward trends were found for seven catchments (M36-37, N33, E21, O14-17 and W3) whereas an upward trend was revealed in one catchment (M41). Additionally, in the majority of the catchments with no significant trends for nitrate N, tendencies for downward trends were noted. Significant downward trends in catchment M36 (Fig. 4) and O14 correlated to smaller amounts of applied manure especially during autumn and to smaller proportions of area with spring cereals and spring rape. Leaching of N is typically higher from spring cereals than from winter cereals (*e.g.* 52 and 38 kg ha^{-1} yr^{-1}, respectively, with coefficients for leaching region 1a and sandy loam soils). Two catchments with downward trends had increasing water discharge during the study period, which may have given a false trend in flow-normalised transport, whereas for the three remaining catchments with downward trends the number of surveyed years was too few for evaluation of causes.

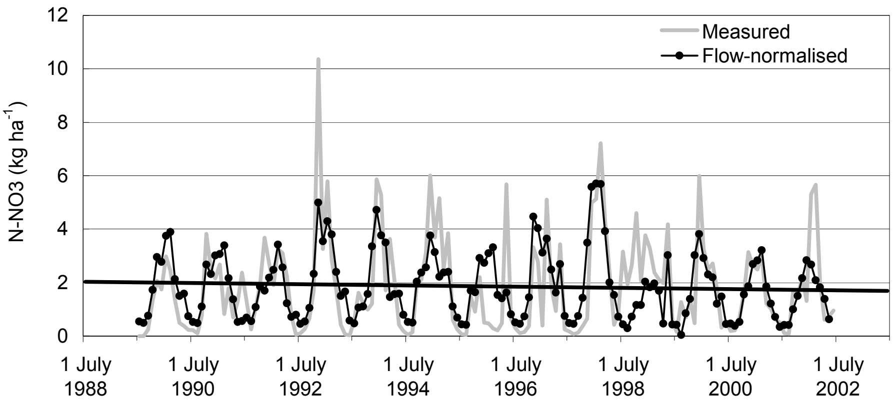

Figure 4. Monthly transport values of N (measured and flow-normalised) for catchment M36. Trend line on flow-normalised values included.

Potential to reduce N leaching from arable land

Small monitoring catchments

Calculation of the effects of measures for reduction of N leaching in the nine small catchments showed that a potential exists to decrease N leaching without drastically changing agricultural practices (Fig. 5). However, the measures gave different effects in the catchments since crop rotations and crop management practices varied considerably between the catchments. When all measures except measure *E* were combined in each catchment, N leaching was reduced by between 24 and 37% for the individual catchments. This decrease in N leaching was not as large as the sum of the separate measures tested, solely because they were not fully additive. When measure *E* was also included (increased area of catch crop by substituting winter cereals and winter rape with corresponding spring crops), the calculated decrease in N leaching increased to between 34 and 54% (Fig. 6).

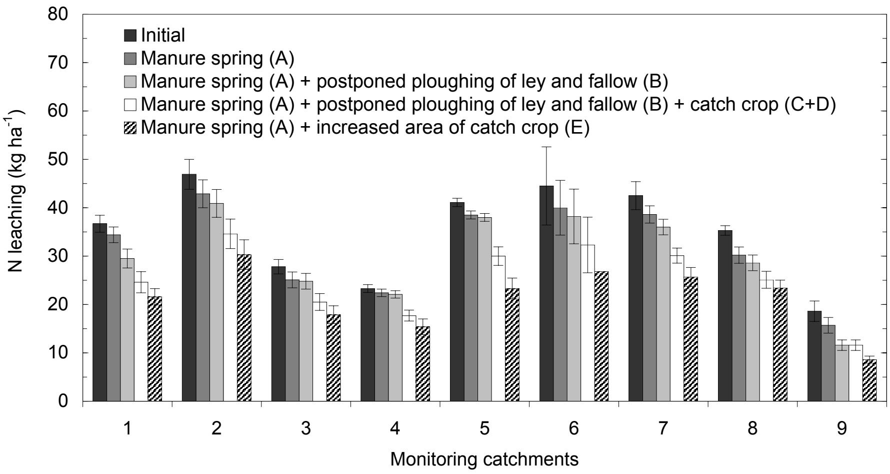

Figure 5. Annual N leaching from the root zone calculated with field-NLCs, including confidence intervals (95%), before and after application of measures for nine catchments in southern Sweden.

Medium-sized catchment

When the potential effects of measures were calculated for the 64 sub-catchments within the medium-sized catchment (Paper IV), the number of sub-catchments with N concentrations higher than 10 mg l^{-1} decreased from 11 to 5 for measure *C* (catch crop in spring cereals and spring rape) whereas the number decreased to zero when all measures were combined. At the same time the number of sub-catchments with concentrations lower than 5 mg l^{-1} increased from 10 to 23. This corresponds to a total reduction in N losses from arable land of 21%.

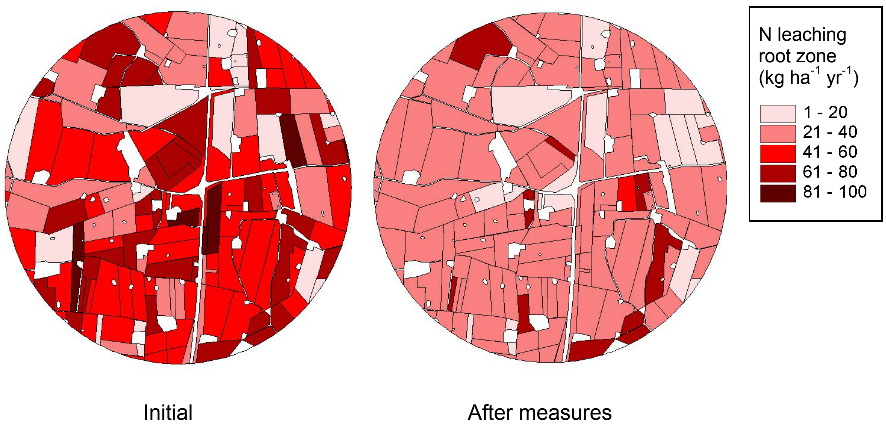

Figure 6. Potential changes in N leaching of field measures calculated with field-NLCs for one monitoring catchment.

Discussion

Uncertainties in input data

Model parameterisation

When physically-based models such as SOILNDB are used there are a considerable number of parameter values to be chosen, each of them including uncertainties. Some parameters in SOILNDB that significantly affect N leaching have been examined by Johnsson *et al.* (2002) and by Larsson & Johnsson (2003), while uncertainties in model structure or parameter selection in the underlying SOIL/SOILN models have been studied for example by Bergström & Johnsson (1988), Larocque & Banton (1994), Lewan (1996), Torstensson & Johnsson (1996) and Larsson & Jarvis (1999). It was indicated that the N leaching rate is sensitive to parameters related to (i) mineralisation of litter and faeces; (ii) plant uptake and N content in harvested products; and (iii) soil organic matter content and denitrification rate.

At the catchment scale, suitable information for adjusting parameters is seldom available and standard values must then be used for most parameters, as in the applications presented in this thesis. Uncertainties in the modelling results can instead be related to input data such as climate, soils and crop management.

Climate data

Meteorological measurements and especially measurements of precipitation are connected to uncertainties. Wind drift may have a large influence on measured amounts, as may adhesion and evaporation. Hoffmann (1999) tested the influence on N leaching rates simulated by SOILNDB of a 10% change in precipitation and found that N leaching rates changed by approximately 25%. The reason for this large increase in N leaching is that the evaporation was nearly unchanged and almost all of the additional precipitation was accounted for as discharge. In addition, a selected meteorological station may not be representative of either a small catchment or a whole region (as assumed for the field-NLCs). This may be the explanation for the somewhat overestimated water discharge revealed when the field-NLCs were used for N leaching calculations for catchments N33 and N34 (Paper III).

Soil texture and soil organic matter content

Determination of the correct soil texture class for a specific area is of great importance for the simulated N leaching rate. For example, when comparing field-NLCs for different soil texture classes but with the same climate, crop combination and fertilization regime, N leaching rates decreased with clay content (60, 52, 43, 30 and 18 kg N ha^{-1} yr^{-1} for loamy sand, sandy loam, loam, clay loam and clay respectively).

N mineralisation is regulated by the amount of soil organic matter (SOM), which is an input to SOILNDB. Since the SOM content influences both the crop uptake and the leaching significantly, it is important to estimate it with care. At the catchment scale, reliable measurements of SOM content are seldom accessible, but if yields and nitrogen flow rates in the stream are available, the SOM may be estimated by calibration.

Local hydrology

Using the new option in SOILNDB (*i.e.* to divide outflow of water from the soil profile between groundwater and tile-drains, instead of assuming that all drainage occurs as free drainage from the root zone at the soil profile depth of 1.5 m), may influence the results. When comparing simulations with free drainage with flow to both tile drains and groundwater (but otherwise using the same parameterisation) for catchment N34, the free drainage simulations resulted in higher water discharge (18%) than with tile drains. With free drainage most of the water that leaves the root zone is discharged whereas with tile drains water can be accumulated under the tile drains until the level of these is reached (except for the amount that is routed to groundwater outflow at the bottom of the profile). More saturated conditions with tile drains resulted in increased evapotranspiration, which in turn resulted in decreased water discharge. When more water was distributed to groundwater by increasing the parameter governing the potential groundwater flow, the water discharge dynamics became smoother and approached the free drainage water flow pattern (Fig. 7). The best fit with dynamics in measured stream water flow was obtained by setting the potential daily groundwater flow to 1 mm day^{-1}, which resulted in a flow to groundwater of 27% of total water flow during the four year period.

To compare the effect on N leaching of the two drainage options, the precipitation was adjusted for the free drainage simulations to achieve the same discharge as with outflow to tile-drains and groundwater. This resulted in higher simulated N leaching with free drainage (11%) compared to flow to tile drains and

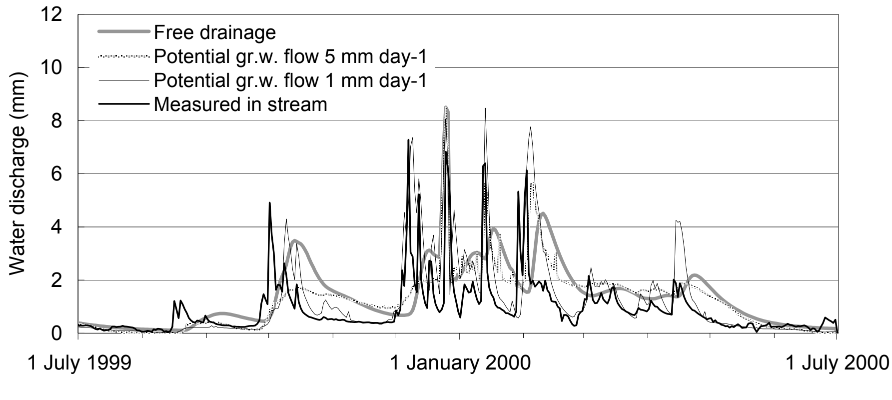

Figure 7. Daily water discharge for catchment N34. Measured in stream outlet, simulated with free drainage and simulated with potential groundwater flow set to 1 and 5 mm day^{-1} respectively.

groundwater. The reason for this was a lower plant uptake with the free drainage simulations resulting in more mineral N available for leaching. In addition, with free drainage the net mineralisation was somewhat lower due to drier conditions in the soil profile.

Crop management data

The surveys on crops and crop management on the fields in the monitoring catchments are associated with many uncertainties. Not all farmers are willing to give information, which results in surveys not covering all arable land in a catchment. Uncertainties also arise in transfer of collected information into databases, since several people could be involved in data management.

Not all farmers keep notes of their field activities and hence they can only give estimates concerning timings of different field activities, yields and amounts of fertilizer and manure applied. Even if notes are kept, some information is especially difficult to determine for the farmer, *e.g.* amounts of manure applied and ley harvests. Furthermore, information on N content in manure and in harvested ley is often very limited. When the yields of ley recorded by the farmers in catchment N34 were compared to both agricultural statistics for the region and to estimates of ley yields in the area produced by the local extension service (Halling, 2000), it was found that the farmers in the catchment probably underestimated their yields by more than 25%. Simulations in which these yields of ley were increased by 25% (Paper II) resulted in 8% lower mean N leaching for the whole catchment than when the recorded yields of ley were used. A sensitivity analysis was also made of the influence on N leaching of changes (±10%) in yields in all crops in N34 during a two-year period (since the yields in these years were uncertain). With lower yields, this resulted in a 9% increase in mean N leaching for the four year period and with higher yields in a 7% decrease. However, in a whole catchment yields may be underestimated on some fields and overestimated on others, so the error in N leaching is probably considerably lower than indicated by the sensitivity analysis described above.

Comparison of modelling and monitoring results

Water discharge from fields and in stream

Catchment N34, which has more than 90% arable land, can be characterised as a large tile-drained field with a short time-lag between discharge from the fields and outflow from the catchment. This was indicated by a relatively high model efficiency value (0.68) when accumulated bi-weekly water discharge for simulations from fields was compared to measurements in the stream. However, the simulated water discharge was somewhat underestimated during dry periods and overestimated during wet periods compared to the measurements. This could be explained by an accumulation of water in groundwater bodies during wet periods whereas a release of groundwater occurs continuously and contribute to a base flow in the stream during the whole year. Those groundwater fluctuations are, however, outside the boundaries of SOILNDB.

Discrepancies in three of nine catchments regarding water discharges calculated with field-NLCs and measured in stream outlets (Fig. 8) may have several explanations. In very small catchments, the discharge water that bypasses the tile drains to groundwater may not reach the stream until downstream of the catchment stream outlet. This is probably the case for catchments M40 and N33. Contribution of deep-flow groundwater to the stream from outside the catchment is probably the explanation to the relatively low N concentrations in stream water in catchment M42. These kinds of local hydrological variations with both downward and upward seepage occurring within the same area are typical for the undulating agricultural landscape in Sweden. These variations also render it difficult to determine the location of water dividers and as a result the area-specific water discharge. Climate data used for producing the coefficients may also be unrepresentative as indicated for catchments N33 and N34, where the mean precipitation was lower at the meteorological station close to the catchments than the regional mean. Consequently, if differences between discharge from fields calculated with field-NLCs and discharge measured in stream could be explained by groundwater inflow or outflow in the actual catchment, the coefficient-calculated discharge may be representative for arable land in that catchment.

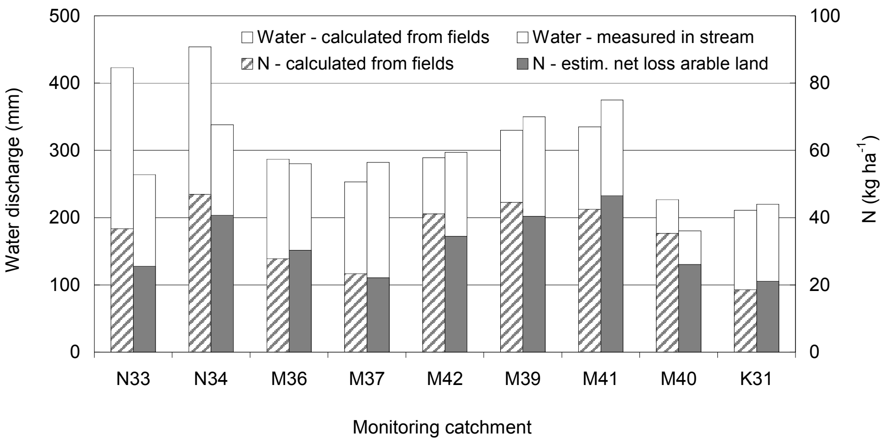

Figure 8. Annual water discharge and N leaching for nine monitoring catchments calculated with field-NLCs and long-term catchment averages of water discharge measured in stream and of estimated net loss of N from arable land.

N leaching from fields and N load in stream

For catchment N34, the N discharge calculated with field-NLCs (produced with simulations using the free drainage option) can be compared with direct simulations with free drainage (Fig. 9). Lower relative N discharge rate with field-NLCs (when water discharge differences are taken into consideration) than with direct simulations can possibly be explained by lower N delivery from the soil organic matter with the field-NLC calculations and by differences in agricultural practices.

When comparing annual field N leaching for catchment N34 obtained from simulations (with divided outflow) with source apportionment-based net loss of N from arable land, there was no strong evidence of retention of N occurring between field and stream (Paper II). This was also indicated for the nine monitoring catchments when field-NLC calculated N losses were compared with net loss of N from arable land and water discharge discrepancies were taken into consideration. Since most of the transport takes place during winter when the biological activity is low, the retention in open ditches and ponds is probably low. The retention in groundwater (*i.e.* denitrification) is probably also low. In Denmark, where nitrate reduction is assumed to occur in monitoring catchments with sandy soils and a predominance of flow to groundwater (Postma *et al*., 1991; Andersen *et al*., 2001), the bedrock and the sedimentary deposits have different origins. Furthermore, in the Swedish, mainly tile-drained monitoring catchments, most of the water flow that bypasses the tile drains and reaches the stream via the groundwater seems to be shallow, as indicated in N34.

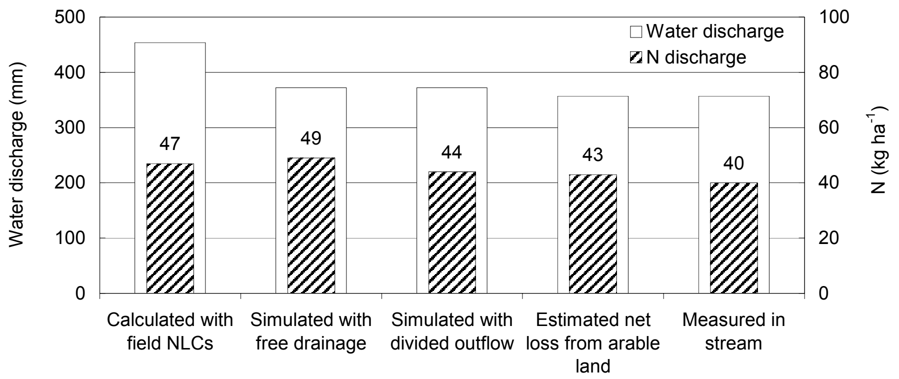

Figure 9. Annual N leaching for catchment N34 determined with different methods. Calculated values with field-NLCs are weather-normalised, whereas simulations and measurements represent four year averages.

Moreover, dilution of N in the shallow subsurface flows due to mixing with old groundwater did not seem to occur to any large extent. The N concentration in the old shallow groundwater is probably almost the same as that in the infiltrating water due to the long-term impact of agriculture on the uppermost groundwater body, which was indicated for catchment N34 by measurements in some shallow wells (unpublished data). However, outflow of deep groundwater may have influenced water quality in the stream in catchment M42. An initial test of SOILNDB for catchment M42 indicated that retention or dilution in groundwater occurred, whereas the retention of N in tile drain discharge was assumed to be small (Hoffmann & Johnsson, 2003). Arheimer & Brandt (1998), who used the HBV-N model to calculate the transport and retention of N from arable land in southern Sweden, concluded that coastal areas without lakes and with short residence times have no or little retention whereas the average retention from agricultural land was 45%.

Trends of N loads in the streams

The downward trends in N loads revealed in the monitoring catchments (Paper I) are supported by decreasing trends in some rivers dominated by agricultural land in southern Sweden (Sandsten, 2003; Grimvall & Nordgaard, 2004). In large rivers dominated by forest, no downward trends were found (County Administrative Board of Halland, 2004).

In Norway, where significant downward trends in N loads were revealed in four of eight agricultural monitoring catchments (Vandsemb *et al.,* 2003), fertilization significantly decreased in one catchment whereas in another, a catch crop was grown on 40% of the arable land during the last three years of the monitoring period. Danish agricultural catchments also showed decreasing trends (Grant *et al.,* 2003), which were correlated to lower area-specific inputs of N and less spreading of manure in autumn, which was replaced by spreading in spring. Furthermore, in Denmark the N concentrations have decreased in rivers dominated by arable land whereas no changes have been seen in water from less disturbed land (Andersen *et al.,* 2003). However in Latvia, where application of manure and artificial fertilizer has decreased dramatically since the late 1980s, there were only downward trends in three out of 12 rivers (Stålnacke *et al.,* 2003). This was mainly explained by mineralisation of large pools of organic N, long transit time in soil water and groundwater, and large retention in first-order streams.

Measures for reduction of N leaching

The possibility of calculating effects of crop combinations (*i.e.* crop and following crop) is of considerable value since changes in crop rotation constitute a potential for reducing N leaching. As an example, by postponing ploughing-in of ley and green fallow as a result of changing the following crop from winter cereals to spring cereals (and changing from spring cereals to winter cereals on other fields), the potential reduction in N leaching was between 1 and 27% for the monitoring catchments (Paper III) depending on the percentage of ley and green fallow. However, catch crops, which are known to reduce N leaching by up to 50% (Aronsson, 2000), could if applied to both spring and winter forms of cereals and oilseeds only be applied to approximately 34% of arable land in the nine monitoring catchments (Paper III) and to 24% in the medium-sized catchment (Paper IV) due to limitations in the crop sequences, *i.e.* the following crop must be spring sown. By also applying the measure in which winter forms of cereals and oilseeds were substituted with corresponding spring forms and the area of fallow was decreased, the potential area for growing catch crops on arable land increased to 60% for the nine monitoring catchments and to 38% for the medium-sized catchment. The larger potential area for catch crops in the monitoring catchments than in the medium-sized catchment was due to the smaller proportion of ley and fallow in the former (21% compared to 46%).

Overdoses of applied N are known to increase the risk for elevated N leaching (Bergström & Brink, 1986; Gustafsson, Fleischer & Joelsson, 2000). However, Kyllmar, Johnsson & Mårtensson (2002) found by analysing field management data for seven of the monitoring catchments (for 1996) that identifying the crops that are given excessive amounts of N in relation to N in yield is not straightforward, since other factors may have a significant influence (*e.g.* soil texture and organic matter content, field management history, *etc*.). In addition, uncertainties in data collected by surveys do occur.

In a sensitivity analysis (Kyllmar, Johnsson & Mårtensson, 2002), coefficients were produced for winter wheat for different rates of applied N and yields on the basis of data from the Rural Economy and Agricultural Societies (1999). The relationship between applied N and yield became almost linear at least up to an annual fertilization rate of 250 kg ha^{-1} and a yield of 12 tonnes ha^{-1}. Similarly, no increase in simulated N leaching was revealed. However, the crop growing figures should be used with care since ideal conditions may have occurred. In the seven monitoring catchments, only one field with winter wheat received over 210 kg N ha^{-1}. A further evaluation of the relationship between applied N and yield for various crops under site-specific conditions is needed.

In the County of Skåne, where six of the monitoring catchments are situated, the national environmental quality goal for reducing anthropogenic waterborne N load to the sea (from the level in 1995) is a reduction from 30 to 25% (County Administrative Board of Skåne, 2003). For the agricultural sector, the regional goal is that emissions of N to water should decrease by 12% by 2010. If the calculated effects for the monitoring catchments of all measures except increased proportion of catch crops (Paper III) are adjusted for natural background leaching (*e.g.* 5 kg ha^{-1} yr^{-1} for sandy loam in leaching region 1a) the anthropogenic reduction (at the root zone) can be between 26 and 39% altogether, if the best possible effect is assumed on all possible area. This indicates that there may be opportunities to reach the goal with implementation of these measures. The revealed trends in the monitoring catchments indicate that the measures already introduced have reduced the N leaching. Regulations concerning *e.g.* spreading of manure have existed in various forms since the beginning of the 1990s, whereas subsidies for *e.g.* catch crops and ploughing in spring have been introduced more recently. Many farmers are also familiar with several measures to reduce N leaching through the project Focus on Nutrients (www.greppa.nu, 01/07/04) which is an advisory campaign in farm nutrient management. The project is a co-operation between the Swedish Board of Agriculture, the County Administrative Boards and the Federation of Swedish Farmers, and in 2004 approximately 50% of arable land in the County of Skåne was cultivated by farmers associated with the project.

Further possible measures and alternative crop management practices that need new coefficients to be produced are *e.g.* (i) incorporation of cereal straw into the soil, which could give a reduction in N leaching of 1-2% during a three year period after incorporation (Johnsson, 1991) due to an increase in the C/N ratio; (ii) changed timing of soil cultivation (ploughing) where *e.g*. late ploughing in autumn causes lower N leaching than early ploughing due to later incorporation of organic matter in the soil and hence lower mineralisation; (iii) different types of catch crop; and (iv) decreased dose of applied manure by assuming that more fields are receiving manure but at longer intervals. Possible measures that may be calculated with present coefficients are *e.g*. spreading of manure in crops with a long growing season and high N uptake (*e.g*. winter cereals and ley) and when possible, locating crops with high N leaching risk (*e.g*. potato, rape and spring cereals) on soils with a higher clay content.

Appropriate use of the N leaching calculation methods

Direct simulations with SOILNDB

Two typical approaches to using direct simulations with SOILNDB in a monitoring catchment can be defined. One is to use detailed crop management data for each specific field within a catchment for simulation of N leaching for each of these fields (Paper II). With this approach, a thorough evaluation of the temporal and spatial variation in N leaching within a catchment can be performed. Another approach may be to generalise crop management data for a catchment as a basis for simulations. This approach can be suitable for catchments where crop management information is unavailable for some years.

N leaching coefficients

Coefficients based on monitoring data

Field-NLCs can be produced on the basis of crop management data for a specific monitoring catchment. If different sets of coefficients are produced for separate periods in the monitoring period they can be used for determination of normalised annual leaching for the actual crop management during these periods and possible trends in N leaching in the catchment due to changes in crop management can then be detected. However, these catchment-specific field-NLCs are only applicable on the same dataset as they were produced on, since crop distribution and crop management vary among the monitoring catchments.

Coefficients based on regional data

Leaching coefficients based on regional agricultural statistics (and complementary information from advisory services) can be applied to small monitoring catchments for N leaching calculations. The application that was made using this approach (Paper III) showed that even though the coefficients represent average situations and all variations in field management cannot be fully covered, the resolution was sufficiently accurate in the load calculations. The coefficients are easy to apply on accessible data in small monitoring catchments and the potential effects of possible measures are easy to determine.

At the medium-sized to large catchment scale, where detailed field information is almost always lacking, the field-NLCs can be used with another approach than in the monitoring catchments (Paper IV). For calculations of N load, the coefficients must be merged so that the following crops are included in the main crop since crop rotations are unknown for specific fields. Following crops can then be merged using the crop distribution either in the catchment or in the region. However, when calculating the potential effects of measures that concern crop rotations, the original field-NLCs, which include following crop, should be used.

For regional and national load calculations, standard leaching coefficients as described by Johnsson & Mårtensson (2002) that are based on regional agricultural data are most suitable. Since these coefficients are produced using the same data and the same parameterisation as for the field-NLCs, calculation of the effects of measures on the regional and national scale may be possible with the field-NLCs.

Usefulness for water quality management work

The water management plans that will be set up within the implementation of the WFD for river basin districts will require identification and estimation of sources to anthropogenic impact on surface waters. The standard NLCs that have already been used for national load calculations can be appropriate for this purpose. The plans for counter-measures will require more detailed calculations to cover the potential effects on N leaching of possible measures. For this purpose the field-NLCs are suitable even at the large catchment or regional scale, since detailed field information not is necessary for estimations of scenario loads. Finally, both standard NLCs and field-NLCs can be used for evaluating progress towards fulfilling environmental quality targets, *i.e.* the current impact of agriculture on surface waters and groundwater, the effect on water quality of measures taken and the further measures required to meet the targets.

With the detailed field-specific information for the small agricultural monitoring catchments, trends for changes in crop management can be detected earlier than for the larger scale where only agricultural statistics are available. The impact of field management on N leaching may then be analysed by either producing catchment-specific field-NLCs for different intervals in the monitoring period or by using field-NLCs based on agricultural statistics for calculation of N leaching from field management during different periods. Field management factors can then be used as environmental quality indicators and the effect of implemented measures can be estimated.

The daily values of water discharge, N leaching and N concentration that can be produced by SOILNDB are suitable for input to hydrological models with high spatial and temporal resolution or for determination of temporal excess of threshold values in N concentrations in water discharging into groundwater. However, the total amount of N that recharges into groundwater bodies may be more relevant and also where the largest N losses occurs. Detailed knowledge of the magnitude of N losses from various crop management systems is then more significant. In areas classified as nitrate vulnerable zones, according to the ND, this approach is highly valuable.

Conclusions

- N losses from arable land to water varied widely between the 27 monitoring catchments (from 8 to 48 kg ha^{-1} yr^{-1}) due to differences in climate, soil texture and crops grown. The losses also varied greatly between fields. Methods for quantification of N losses from arable land should cover these large spatial variations. Areas with a large impact on the recipient can then be identified and the most effective combinations of measures to reduce N leaching can be determined.
- Using a physically-based N leaching model and detailed monitoring data on crop management, *etc*. facilitates a thorough evaluation of the spatial and temporal variations in N leaching occurring within a catchment. For each field, the N leaching for each unique combination of soil texture, crop rotation, fertilization, timing for tillage, *etc*. can be quantified.
- Calculation of N leaching with coefficients (field-NLCs) is a simple way to take advantage of physically-based simulations of N leaching. The coefficients represent a large variety of combinations of crop management situations, soil texture and climate. Since they are normalised for weather variations, they are suitable for quantification of N loads of prevailing crop management both in monitoring catchments and in areas where only agricultural statistics are available. However, to be able to estimate the effects of additional crop management situations, additional coefficients have to be produced.
- For action plans aiming to reduce N leaching as required by the WFD, the coefficients are useful for calculation of the potential area for implementation of various measures and the potential effect on N leaching of these measures. Since the following crop is also included in the crop coefficient, measures concerning changes in crop rotations can be quantified, *e.g*. the effects of postponing ploughing-in ley and growing catch crops on larger areas.
- Monitoring catchments are useful as indicators of changes in crop management in the agricultural sector. In these small catchments, measures implemented in crop management can be detected earlier than in agricultural statistics. Trends in N loads may also be identified before they become evident in rivers due to less influence from other sources. Detection of trends can be performed either by statistical trend analysis of flow-normalised time series of N loads or by calculation with coefficients of N leaching for prevailing crop management during different periods.
- Estimation using field-NLCs of the effects of a number of leaching reduction measures showed that the potential exists to reduce N leaching without drastically changing agricultural practices. When the best possible effect was assumed, the potential decrease of the measures was between 34 and 54% for the nine individual monitoring catchments. For the medium-sized catchment the reduction was lower (21%) due to a

lower reduction potential assumed for the catch crop measure and to limitations in the crop rotations for growing of catch crop.

- It can be concluded that modelling combined with monitoring in small agricultural catchments is a useful tool for assessing state, trends and effects of counter-measures for water quality management planning aimed at reducing the impact of N leaching from arable land on the aquatic environment.

References

Addiscott, T.M. & Whitmore, A.P. 1991. Simulation of solute leaching in soils of differing permeabilities. *Soil Use and Management 7*, 94-102.

Andersen, H.E., Pedersen, M.L., Jørgensen, O. & Kronvang, B. 2001. Analysis of the hydrology and flow of nitrogen in 17 Danish catchments. *Water Science and Technology 44*, 63-68.

Andersen, J.M., S. Boutrup, S., Svendsen, L.M., Bøgestrand, J., Grant, R., Jensen, J.P., Ellermann, T., Rasmussen, M.B., Jørgensen, L.F. & Laursen, K.D. 2003. *Vandmiljø 2003 Tilstand og udvikling - faglig sammenfatning.* Faglig rapport fra DMU, nr 471. National Environmental Research Institute, Denmark. 50 pp. (In Danish).

Arheimer, B. & Brandt, M. 1998. Modelling nitrogen transport and retention in the catchments of southern Sweden. *AMBIO 27*, 471-480.

Arheimer, B., Löwgren, M., Pers, C. & Rosberg, J. 2005. Integrated catchment modelling of reduced nutrient emissions: impact, potential and costs of various measures and scenarios. *AMBIO*.

Aronsson, H. 2000. *Nitrogen Turnover and Leaching in Cropping Systems with Ryegrass Catch Crops*. Doctoral Thesis Agraria 214. Swedish University of Agricultural Sciences. 32 pp.

Behrendt, H. 1999. A comparison of different methods of source apportionment of nutrients to river basins. *Water Science and Technology 39*, 179-187.

Behrendt, H., Dannowski, R., Deumlich, D., Dolezal, F., Kajewski, I., Kornmilch, M., Korol, R., Mioduszewski, W., Optiz, D., Steidl, J. & Stronska, M. 2001. Nutrient and heavy metal emissions into the river system of Odra - results and comparison of models In: *Annual Report 2001.* Leibniz - Institute of Freshwater Ecology and Inland Fisheries, Germany. 12 pp.

Behrendt, H., Kornmilch, M., Opitz, D., Schmoll, O. & Scholz, G. 2002. Estimation of the nutrient inputs into river systems - experiences from German rivers. *Regional Environmental Change 3*, 107-117.

Bergström, L. & Brink, N. 1986. Effects of differentiated applications of fertilizer N on leaching losses and distribution of organic N in the soil. *Plant and Soil 93*, 333-345.

Bergström, L. & Johnsson, H. 1988. Simulated nitrogen dynamics and nitrate leaching in a perennial grass ley. *Plant and Soil 105*, 273-281.

Brandt, M. & Ejhed, H. 2002. *TRK, Transport - retention - källfördelning, Belastning på havet.* Rapport 5247. Environmental Protection Agency. 117 pp. (In Swedish).

County Administrative Board of Halland. 2004. *Hur mår Halland 2004?* Meddelande 2004:4. Länsstyrelsen i Halland. 44 pp. (In Swedish).

County Adminstrative Board of Skåne. 2003. *Skånes miljömål och handlingsprogram*. Skåne i utveckling 2003:62. Länsstyrelsen i Skåne. 72 pp. (In Swedish).

Deelstra, J., Bechmann, M. & Kværnø, S.H. 2002. SOIL and SOIL-NO at catchment scale - a case study for an agriculture-dominated catchment. *Water Science and Technology 45*, 9-17.

de Willigen, P. 1991. Nitrogen turnover in the soil-crop system; comparison of fourteen simulation models. *Fertilizer Research 27*, 141-149.

de Wit, M.J.M. 2001. Nutrient fluxes at the river basin scale. I: the PolFlow model. *Hydrological Processes 15*, 743-759.

Diekkrüger, B., Söndgerath, D., Kersebaum, K.C. & McVoy, C.W. 1995. Validity of agrosystem models. A comparison of results of different models applied to the same dataset. *Ecological Modelling 81*, 3-29.

EC. 1991. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of water against pollution caused by nitrates from agricultural sources. *Official Journal of the European Communities L 375*, 8 pp.

EC. 2000. Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for the Community action in the field of water policy. *Official Journal of the European Communities L 327*, 72 pp.

EC. 2002. *Implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Synthesis from year 2000.* Member States reports. European Commission, Directorate-General for Environment. 44 pp. ISBN 92-894-4103-8.

Grant, R., Blicher-Mathiesen, G., Pedersen, M.L., Jensen, P.G., Pedersen, M. & Rasmussen, P. 2003. *NOVA 2003. Landovervågningsoplande 2002*. Faglig rapport fra DMU, nr 468. National Environmental Research Institute, Denmark. 131 pp.

Grimvall, A. & Nordgaard, A. 2004. *Sjöar och vattendrag i Skåne - går utvecklingen åt rätt håll? Statistisk utvärdering av vattenkvalitet och provtagningsprogram i Skåne län*. Skåne i utveckling 2004:1. County Administrative Board of Skåne. 55 pp. (In Swedish).

Grizzetti, B., Bouraoui, F., Granlund, K., Rekolainen, S. & Bidoglio, G.F. 2003. Modelling diffuse emission and retention of nutrients in the Vantaanjoki watershed (Finland) using the SWAT model. *Ecological Modelling 169*, 25-38.

Groenendijk, P. & Kroes J.G. 1999. *Modelling the Nitrogen and Phosphorus Leaching to Groundwater and Surface Water with ANIMO* 3.5. Report 144. Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, The Netherlands.136 pp.

Gustafsson, A., Fleischer, S. & Joelsson, A. 2000. A catchment-oriented and cost-effective policy for water protection. *Ecological Engineering 14*, 419-427.

Halling, M. 2000. Vallfröblandningar i intensiva slåttersystem. In: *Försöksrapport 2000. Animaliebältet. Fältförsöksverksamheten i animaliebältet 1999*. Ed. Ekre, E. Hushållningssällskapens Multimedia. (In Swedish).

Hansen, S., Jensen, H.E., Nielsen, N.E. & Svendsen, H. 1990. *DAISY. A Soil Plant Atmosphere System Model.* NPo Research Report No. A10. National Agency of Environmental Protection, Denmark.

Hirsch, R.M. & Slack, J.R. 1984. A nonparametric trend test for seasonal data with serial dependence. *Water Resources Research 20*, 727-732.

Hoffmann, M. 1999. *Assessment of Leaching Loss Estimates and Gross Load of Nitrogen from Arable Land in Sweden.* Doctoral Thesis Agraria 168. Swedish University of Agricultural Sciences. 36 pp.

Hoffmann, M. & Johnsson, H. 2003. Test of a modelling system for estimating nitrogen leaching - A pilot study in a small agricultural catchment. *Environmental Modelling and Assessment 8*, 15-23.

Hutson, J.L. & Wagenet, R.J. 1991. Simulating nitrogen dynamics in soils using a deterministic model. *Soil Use and Management 7*, 74-78.

Jansson, P.-E. & Halldin, S. 1979. Model for annual water and energy flow in a layered soil. In: Conference proceedings: *Comparision of Forest Water and Energy Exchange Models*. Ed. Halldin, S. International Society for Ecological Modelling. Copenhagen. pp. 145-163.

Johnes, P.J. 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. *Journal of Hydrology 183*, 323-349.

Johnes, P.J. & Heathwaite, A.L. 1997. Modelling the impact of land use change on water quality in agricultural catchments. *Hydrological Processes 11*, 269-286.

Johnsson, H. 1991. *Simulation of Nitrogen Losses using the SOILN model*. NPo Research Report No. A20. National Agency of Environmental Protection, Denmark.

Johnsson, H., Bergström, L., Jansson, P.-E. & Paustian, K. 1987. Simulated nitrogen dynamics and losses in a layered agricultural soil. *Agriculture, Ecosystems and Environment 18*, 333-356.
Johnsson, H. & Hoffmann, M. 1997. *Kväveläckage från svensk åkermark - beräkningar av normalutlakning och möjliga åtgärder.* Report 4741. Swedish Environmental Protection Agency. 52 pp. (In Swedish).
Johnsson, H., Larsson, M., Mårtensson, K. & Hoffmann, M. 2002. SOILNDB: A decision support tool for assessing nitrogen leaching losses from arable land. *Environmental Modelling & Software 17*, 505-517.
Johnsson, H. & Mårtensson, K. 2002. *Kväveläckage från svensk åkermark. Beräkningar av normalutlakning för 1995 och 1999.* Rapport 5248. Swedish Environmental Protection Agency. 89 pp. (In Swedish).
Jones, C.A., Dyke, P.T., Williams, J.R., Kiniry, J.R., Benson, V.W. & Griggs, R.H. 1991. EPIC: An operational model for evaluation of agricultural sustainability. *Agricultural Systems 37*, 341-350.
Jørgensen, J.O., Müller-Wohlfeil, D.-I., Kronvang, B., Andersen, H.E., Wiggers, L. & Bidstrup, J. 2002. The impact of land use changes on the future load of nitrogen to a Danish inlet: quantification of leaching from the root zone. In: Proceedings of symposium held at Wageningen October 2000: *Agricultural Effects on Ground and Surface Waters: Research at the Edge of Science and Society*. Eds. Steenvoorden, J., Claesson, F. & Willems, J. IAHS Publication no. 272, 2002. pp. 183-188.
Knisel, W.G. 1980. CREAMS, *A Field Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems*. Conservation Research Report 26. USDA-ARS. 640 pp.
Kronvang, B., Græsbøll, P., Larsen, S.E., Svendsen, L.M. & Andersen, H.E. 1996. Diffuse nutrient losses in Denmark. *Water Science and Technology 33*, 81-88.
Kronvang, B., Svendsen, L.M., Jensen, J.P. & Dørge, J. 1999. Scenario analysis of nutrient management at the river basin scale. *Hydrobiologia 410*, 207-212.
Kyllmar, K., Johnsson, H. & Mårtensson, K. 2002. *Metod för bestämning av jordbrukets kvävebelastning i mindre avrinningsområden samt effekter av läckagereducerande åtgärder. Redovisning av projektet "Gröna fält och blåa hav".* Ekohydrologi 70. Swedish University of Agricultural Sciences, Department of Soil Sciences. 99 pp. (In Swedish).
Larocque, M. & Banton, O. 1994. Determining parameter precision for modeling nitrate leaching: Inorganic fertilization in Nordic climates. *Soil Science Society of America Journal 58*, 396-400.
Larsson, M.H. & Jarvis, N.J. 1999. A dual-pororsity model to quantify macropore flow effects on nitrate leaching. *Journal of Environmental Quality 28*, 1298-1307.
Larsson, M.H. & Johnsson, H. 2003. Simulation of nitrate leaching using a modelling system with automatic parameterization routines. *Soil Use and Management 19*, 172-181.
Lewan, E. 1996. *Evaporation, Discharge and Nitrogen Leaching from a Sandy Soil in Sweden.* Reports and Dissertations 27. Swedish University of Agricultural Sciences, Department of Soil Sciences. 37 pp.
Lord, E.I. & Anthony, S.G. 2000. MAGPIE: A modelling framework for evaluating nitrate losses at national and catchment scales. *Soil Use and Management 16*, 167-174.
Moreels, E., De Neve, S., Hofman, G. & Van Meirvenne, M. 2003. Simulating nitrate leaching in bare fallow soils: a model comparison. *Nutrient Cycling in Agroecosystems 67*, 137-144.
Müller-Wohlfeil, D.-I., Jørgensen, J.O., Kronvang, B. & Wiggers, L. 2002. Linked catchment and scenario analysis of nitrogen leaching and loading: a case study from a Danish catchment-fjord system, Mariager Fjord. *Physics and Chemistry of the Earth 27*, 691-699.
Nash, J.E. & Sutcliff, J.V. 1970. River flow forecasting through conceptual models. Part I - A discussion of principles. *Journal of Hydrology 10*, 282-290.
Postma, D., Boesen, C., Kristiansen, H. & Larsen, F. 1991. Nitrate reduction in an unconfined sandy aquifer: Water chemistry, reduction processes, and geochemical modelling. *Water Resources Research 27*, 2027-2045.

Refsgaard, J.C., Thorsen, M., Jensen, J.B., Kleeschulte, S. and Hansen, S. 1999. Large scale modelling of groundwater contamination from nitrate leaching. *Journal of Hydrology 221*, 117-140.

Rural Economy and Agricultural Societies. 1999. *Skåneförsök 1999*. Meddelande nr 66. Försöksringarna och Hushållningssällskapen i Skåne. (In Swedish).

Sandsten, H. 2003. *Transporter av fosfor och kväve från skånska vattendrag. Tillstånd och trender till 2001.* Skåne i utveckling 2003:30. County Administrative Board of Skåne. 51 pp. (In Swedish).

Schou, J.S., Skop, E. & Jensen, J.D. 1998. *Integrated Economic and Environmental Analysis of Nitrogen Pollution from Agriculture.* Report No. 96. Danish Institute of Agricultural and Fisheries Economics. 99 pp.

Schoumans, O.F. & Silgram, M. 2003. *Review and Literature Evaluation of Quantification Tools for the Assessment of Nutrient Losses at Catchment Scale.* EUROHARP Report 1-2003, NIVA report SNO 4739-2003. Oslo, Norway.

Simmelsgaard, S.E. & Djurhuus, J. 1998. An empirical model for estimating nitrate leaching as affected by crop type and the long-term N fertilizer rate. *Soil Use and Management 14*, 37-43.

Simmelsgaard, S.E., Kristensen, K., Andersen, H.E., Grant, R., Jørgensen, J.O. & Østergaard, H.S. 2000. *Empirisk model til beregning af kvælstofudvaskning fra rodzonen. N-LES Nitrate Leaching EStimator*. DJF rapport Markbrug nr. 32, september 2000. Danish Institute of Agricultural Sciences. 34 pp. (In Danish, with English Summary).

Singh, V.P. Ed. 1995. *Computer Models of Watershed Hydrology*. Water Resources Publications, Colorado. 1030 pp.

Sonesten, L., Wallin, M. & Kvarnäs, H. 2004. *Kväve och fosfor från Vänern och Västerhavet – Transporter, retention och åtgärdsscenarier inom Göta älvs avrinningsområde.* Rapport 2004:33, County Administrative Board of Västra Götaland. Rapport 2004:17, County Administrative Board of Värmland. Rapport 29, 2004, Vänerns Vattenvårdsförbund. (In Swedish).

Stålnacke, P. 1996. *Nutrient Loads to the Baltic Sea*. Doctoral thesis. Linköping Studies in Arts and Science, No 146. Linköping University, Sweden.

Stålnacke, P., Grimvall, A., Sundblad, K. & Wilander, A. 1999. Trends in nitrogen transport in Swedish rivers. *Environmental Monitoring and Assessment 59*, 47-72.

Stålnacke, P. & Grimvall, A. 2001. Semiparametric approaches to flow normalization and source apportionment of substance transport in rivers. *Environmetrics 12*, 233-250.

Stålnacke, P., Grimvall, A., Libiseller, C., Laznik, M. & Kokorite, I. 2003. Trends in nutrient concentrations in Latvian rivers and the response to the dramatic change in agriculture. *Journal of Hydrology 283*, 184-205.

Statistics Sweden. 1999. *Standard Yields for Yield Survey Districts, Counties and the Whole of Sweden in 1999*. Statistiska meddelanden J15 SM 9901, 22 pp. (In Swedish, with English summary).

Statistics Sweden. 2000a. *Use of Fertilizers and Animal Manure in Agriculture in 1998/99.* Statistiska meddelanden Mi 30SM 0002. (In Swedish, with English summary).

Statistics Sweden. 2000b. *Yearbook of Agricultural Statistics 2000*. 216 pp. (In Swedish, with English Summary).

Styczen, M. & Storm, B. 1993. Modeling of N-movements on catchment scale - a tool for analysis and decision making. 1. Model description. 2. A case study. *Fertilizer Research 36*, 1-17.

Swedish EPA. 2003. *Sweden's Environmental Objectives. de Facto 2003.* Swedish Environmental Protection Agency. 63 pp.

Thorsen, M., Feyen, J. & Styczen, M. 1996. Agrochemical modelling. In: *Distributed Hydrological Modelling*. Eds. Abbott, M.B. & Refsgaard, J.C. Kluwer Academic Publishers. pp. 121-141.

Torstensson, G. & Johnsson, H. 1996. *Simulation of Water and Nitrogen Dynamics in a Five Year Leaching Experiment with Varying Fertilisation and Manure Treatments*. Reports and Dissertations 29. Swedish University of Agricultural Sciences, Department of Soil Sciences. 62 pp.

Trabada-Crende, F. & Vinten, A.J.A. 1998. Assessing the effects of land management and catchment hydrology on well water quality in a designated nitrate vulnerable zone. *Agricultural Systems 57*, 523-540.

Vagstad, N., Stålnacke, P., Andersen, H.E., Deelstra, J., Gustafson, A., Ital, A., Jansons, V., Kyllmar, K., Loigu, E., Rekolainen, S., Tumas, R. & Vuorenmaa, J. 2001. *Nutrient Losses from Agriculture in the Nordic and Baltic Countries. Measurements in Small Agricultural Catchments and National Agro-Environmental Statistics.* TemaNord 2001:591. Nordic Council of Ministers, Copenhagen.

Vandsemb, S.M., Bechmann, M., Eggestad, H.O., Øygarden, L. & Deelstra, J. 2003. *Erosion og næringsstofftap fra jordbruksarealer. resultater fra Jord- og vannovervåking i lantbruket (JOVA) 2002/03*. Jordforsk rapport nr 102/03. The Norwegian Centre for Soil and Environmental Research & The Norwegian Crop Research Institute. 48 pp. (In Norwegian).

van Herpe, Y.J.P., Troch, P.A., Quinn, P.F. & Anthony, S. 2002. Modelling hydrological mobilization of nutrient pollutants at the catchment scale. In: *Agriculture, Hydrology and Water Quality*. Eds. Haygarth, P.M. & Jarvis, S.C. CAB International. pp. 243-264.

Vereecken, H., Jansen, E.J., Hack-ten Broeke, M.J.D., Swerts, M., Engelke, R., Fabrewitz, S. & Hansen, S. 1991. Comparison of simulation results of five nitrogen models using different datasets. In: *Soil and Groundwater Research Report II: Nitrate in Soils*. Final report of contracts EV4V-0098-NL and EV4V-00107-C. Commission of the European Communities. pp. 321-338.

Vinten, A.J.A. & Dunn, S.M. 2001. Assessing the effects of land use on temporal change in well water quality in a designated nitrate vulnerable zone. *Science of the Total Environment 265*, 253-268.

Wolf, J., Beusen, A.H.W., Groenendijk, P., Kroon, T., Rötter, R. & van Zeijts, H. 2003. The integrated modeling system STONE for calculating nutrient emissions from agriculture in the Netherlands. *Environmental Modelling & Software 18*, 597-617.

Wolf, J., Rötter, R. and Oenema, O. 2004. Nutrient emission models in environmental policy evaluation at different scales - experience from the Netherlands. *Agriculture, Ecosystems and Environment* (in press).

Wu, L. and McGechan, M.B. 1998. A review of carbon and nitrogen processes in four soil nitrogen dynamics models. *Journal of Agricultural Engineering Research 69*, 279-305.

Zakrisson, J., Ekstrand, S. & Huang, B. 2004. *Kväve och fosformodellering i Svartån och Tyresån*. Rapport B1551. IVL Swedish Environmental Research Institute Ltd. 86 pp. (In Swedish).

Web-site

Focus on Nutrients. Index page. *http://www.greppa.nu*. (Accessed 01-Jul-2004).

Acknowledgements

Many people contributed support, help and inspiration during my work to accomplish this thesis. I am very grateful to all of you. Some of you I would like to mention specially:

First of all, my sincerest gratitude to:

- Assoc. Prof. Holger Johnsson, my supervisor, who introduced me to modelling. My thanks to you, for always being there to provide inspiring support and fruitful discussions. Analysing and solving problems was really a fun part of the thesis work.

- Prof. Arne Gustafson, my assistant supervisor. I really appreciated your enthusiasm, good mood, encouragement and mentoring.
- Dr. Martin Larsson, my assistant supervisor. Many thanks for good co-operation and for your helpfulness and always cheerful mind.

My deepest thanks also go to:

- Colleagues at the Division of Water Quality Management. Special thanks to Carina Carlsson, Kristina Mårtensson and Barbro Ulén for their help and contribution to some of the projects, to Göran Johansson for help with practical things and for support, to Gunnar Torstensson and Hans Bonde for help with development of the multi-functional water sampling box, and to Stefan Ekberg, Anneli Mejbert and Amanuel Tesfamikael for analysing all the water samples. I also appreciate the kind support from the rest of you: Helena Aronsson, Lars Bergström, Inga-Lill Hammarberg, Faruk Djodjic, Jenny Kreuger, Kristian Persson and Mirja Törnquist.
- Hans Johansson at the Division of Hydrotechnics for help with model programming.
- Markus Hoffmann, for inspiration and for sharing my interest in catchment monitoring.
- Adel Shirmohammadi at the University of Maryland for giving me the opportunity to study catchment monitoring in Maryland and for discussions of model applications.
- Arne Joelsson at the County Administrative Board of Halland for inspiring co-operation. Kristian Wennberg and Lars Bengtsson at the County Administrative Boards of Skåne and Blekinge respectively, for fruitful discussions.
- The staff at the Rural Economy and Agricultural Societies in Halland for interviewing the farmers and for help in the field.
- The farmers in the catchments for their courtesy.
- The PhD students and other participants in the VASTRA programme for fruitful and interesting co-operation in multidisciplinary projects.
- Mary McAfee, for improving my English. Ingvar Nilsson, Lisbet Lewan and Olle Andrén, for valuable comments on the manuscript.
- Relatives and friends that provided me with inspiration and support. Even though your names don't appear here, your importance for me is invaluable!

Last, but not least, my special thanks to:

- My father Lennart, my brother Johan and Britt-Marie for love, understanding and encouragement. And not to forget, my beloved little heart of gold, Stella.

This thesis was produced as part of the multidisciplinary Swedish Water Management Research Programme (VASTRA), funded by the Foundation for Strategic Environmental Research (MISTRA) which is gratefully acknowledged. The County Administrative Boards of Skåne, Halland and Blekinge are also appreciated for contribution of funding. Finally, I would also like to thank the Swedish Environmental Protection Agency for funding the Monitoring Programme for Agricultural Land.