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Water Discharge and Leaching of Nitrate

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PREFACE

This thesis is based on experimental results from two former projects, Leaching of plant nutrients to surface and ground water, and The influence of agriculturing on the water quality. Both projects are at present a part of the National Swedish Environmental Monitoring Programme (PMK).

The thesis is a summary of the following six papers:

I Gustafson, A. Nitrate leaching from arable land in Sweden under four cropping systems. (Submitted to Swedish J. agric. Res.)

II Gustafson, A. 1983. Leaching of nitrate from arable land into groundwater in Sweden. Environ. Geology 5(2), 65-71.

III Gustafson, A. Simulation of water discharge rates from a clay till soil over a ten year period. (Accepted for publication in J. Hydrol.)

IV Gustafson, A. Simulation of nitrate leaching from arable land in southern Sweden. (Submitted to Acta Agric. Scand.)

V Gustafson, A. Estimation of groundwater recharge and related losses of nitrate in a tile drained clay till. (Submitted to Environ. Geology.)

VI Jansson P.-E. & Gustafson, A. Simulation of surface runoff and pipe discharge from an agricultural soil in northern Sweden. (Submitted to Nordic Hydrology.)

The papers are referred to in the text by their Roman numerals.

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WATER DISCHARGE AND LEACHING OF NITRATE

Arne Gustafson

Abstract. A network of measuring stations was established for monitoring the leaching of nutrients from arable land to surface water and groundwater. The monitoring activity is a part of the National Swedish Environmental Monitoring Programme.

Data from the network as discharge, groundwater pressure, concentrations of nitrate and recorded agricultural practicies were used.

Mathematical models for water and heat and for nitrogen were used in more penetrating studies of causes of nitrate leaching. The water and heat model generates the necessary driving variables for the nitrogen model. The nitrogen model represents transformations of nitrogen in the soil and transport of nitrogen within and from the soil.

The water and heat model was modified to enable better partitioning between surface runoff and pipe discharge. Good partitioning between these two kinds of flows is of vital importance if the nitrogen model is to calculate accurate nitrate losses.

The results prove that the amount of nitrate in the soil profile and the discharge rate are decisive factors for the amount of nitrate leached. The amount of available nitrate in the soil is regulated by many factors, among which crop type is one. Annual crops contributed more to the amount of nitrate leached than perennial crops owing to the longer time of nitrogen uptake by the perennials.

Ploughing of leys did not increase losses compared to losses from established ley unless the ploughing was undertaken in the middle of the growing period and followed by repeated cultivations under fallow conditions favourable for mineralization and nitrification.

Simulations proved that nitrate content in the soil in the beginning of September and the litter mineralization during September–March largly explained the between-year variation in nitrate leaching under normal discharge conditions. Leaching of nitrate increased above normal and decreased below normal discharge for the same amount of mineral nitrogen available for leaching.

A necessary condition for leaching to groundwater was decreasing groundwater pressure with depth.

With the water and heat model it was possible to calculate the flow to surface water and groundwater separately. The reliability in simulated groundwater recharge was considered by comparison with the difference between stream runoff and drainage discharge.

INTRODUCTION

Historical background

During the 1970s the contribution from the agriculture to the enrichment of nitrates in surface water and groundwater in Sweden was paid increasing attention.

Earlier investigations into losses of nitrate from arable land revealed a situation that was by no means alarming (Wiklander 1959, 1970; Wiklander & Hallgren 1960, 1971). More attention was paid to the question of guidelines for the largest possible amounts of sewage sludge which could be applied to farmland with retained water quality (Brink 1971, 1972). Neither had earlier studies in larger watersheds shown any larger contribution of nitrate from agriculture (Brink & Hallgren 1963; Brink 1965, 1969; Brink & Widell 1967). However in the beginning of the 1970s research dealing with nutrient losses in rivers and streams indicated increasing nitrogen contents in river water, especially in rivers flowing through intensively farmed areas (Ahl & Odén 1972a, 1972b), this was also later confirmed by Andersson (1986). Earlier, after a literature review, Brink & Gustafson (1970) suggested; "Due to the limited available data for evaluating the influence of forestry and agriculture on surface and groundwater bodies, the creation of a network of measuring stations for monitoring long-term leaching of plant nutrients from forest and arable land is of the utmost concern. Such a network should include different pedological and hydrological conditions."

Also in central Europe the question of nitrate enrichment in water bodies became of great importance at that time (Brink 1974).

Establishment of a network

Measuring scale. Assisted by grants it was possible to start building up a network of measuring stations in 1972 (Brink, N., Gustafson, A. & Persson, G. 1978). However, the measuring scale had to be first decided. This is always an important task because the aim and the measuring scale are closely related. When using a scale on stream and river basin level, the investigated area is mostly a mixture of different land use including forest, arable land, and lakes. Also setlements and communities are frequently involved. The evalution of the influence of different individual factors on the waters are, in this case, mostly an impossible task. The stream and river basin level scale provides, however, an integrated result of all water-affecting factors. This is necessary information when, e.g., the total losses to lakes and seas have to be calculated.

If the aim of the investigation is to follow the influence of only cultivation and cropping measures on surface water and groundwater quality, the field scale provides the most suitable choice. On the other hand, if comparisons between individual cultivation and cropping measures are of major interest then a smaller scale with tile-drained plots or lysimeters is more suitable. The lysimeter scale also provides possibilities to look more closly at processes (Bergström 1987).

Since the proposed aim of the network was to follow the influence of agricultural activities both on surface water and groundwater and to relate this influence to actual agricultural practices, the field scale was found to be the most suitable scale.

Initial results and identification of decisive factors for nitrate leaching. In the later part of the 1970s the first more assembled results from the network were published (Brink, Gustafson & Persson 1978, 1979). The conclusion as far as nitrate was concerned showed that especially on sandy soils in southern Sweden very large losses to both surface water and groundwater occurred.

Different decisive factors for this alarming situation were frequently identified by the results from the network (Brink 1978, 1982; Brink & Gustafson 1983; Gustafson 1978, 1982).

The results also suggested proper counter measures and due to the alarming situation further development of suggested counter measures became a question of major concern. This develop could be achieved by continuously increasing the number of tile-drained plot experiments where different decisive factors and counter measures were thoroughly tested, such as, application rates of nitrogen fertilizers and manure (Bergström & Brink 1986; Brink & Joelsson 1978), application time of manure (Brink & Jernlås 1982), importance of irrigation (Jernlås & Klingspor 1983) and growing of catch crops (Gustafson & Torstensson 1984; Kreuger & Brink 1984).

An increased proportion of surface runoff was also concluded to be a factor of importance in reducing the amount of nitrate leached because surface runoff normally has a lower nitrate content than pipe drainage effluent which has leached the soil profile. This could be thoroughly analysed from the results from the Röbäcksdalen station in northern Sweden, where the two flow types were separately collected (Gustafson & Torstensson 1983b).

The regional representativity of the different stations in the network was investigated. It could be concluded that the regional representativity was generally good for individual stations as far as leaching of nitrate was concerned when comparison was made with fields of comparable soil type in the region. During this work, attention was also focussed on the importance of different crops as a decisive factor for the amount of nitrate leached (e.g. Gustafson & Hansson 1979; Gustafson & Hansson 1980; Gustafson & Gustavsson 1982; Gustavsson, Tomassen & Wiksten 1985; Ulén 1982).

Hydrology of the stations

In a special project into the intensity and duration of discharge from arable land, both the drainage water and the groundwater hydrology at all stations were more thoroughly investigated.

The result of the project concluded that events with flow rates exceeding 1.5 l/(s.ha) usually have a duration less than 24 hours. Exceptionally, durations of several days were recorded in connection with intensive snow melting or by contribution of pressure ground water to the pipe drainage system (Gustafson, Gustavsson & Torstensson 1984). The measured flowrates and durations were in accordance with older findings (e.g. Flodkvist 1947; Flodkvist & Gustafsson 1958; Hallgren & Tjernström 1966).

Also the major flowpaths of water were demonstrated in this project. The flowpaths are of the utmost importance when dealing with leaching of nitrate from arable land (Gustafson 1986). As far as groundwater is concerned, the influence of different flowpaths upon leaching of nitrate is thoroughly analysed in this thesis. For drainage water, the portioning between surface runoff and tile drainage is of major importance (Gustafson & Torstensson 1983b).

Use of models

During recent years it has also been asked in Sweden whether models could be used in order to simulate water discharge and nitrate leaching from arable land. Efforts were then made to test existing water models and to develop them for use on arable land. Two most frequently used hydrological models are the HBV model (Bergström 1976) and the SOIL model (Jansson & Halldin 1979). Both models have been proved capable of predicting the rate of water discharge from arable land (Bergström, Brandt & Gustafson 1987; Lundin 1984).

However, only the SOIL model is suitable for simulation water flows in partially frozen soils since the HBV model does not account for temperature and heat in a layered soil structure.

Recently, two nitrogen models with different resolutions and objectives have been developed. One is based on a simplified approach and is connected to the HBV model. It has been successfully tested by simulating nitrate leaching from two fields in southern Sweden (Bergström et al. 1987). The other model, using a somewhat more detailed approach, is connected to the SOIL model. It considers plant uptake, mineralization, immobilization, nitrification, denitrification, and leaching processes in a layered soil structure. The model also defines two pools of organic matter; fast-cycling litter and slow-cycling humus (Johnsson, Bergström, Jansson & Paustian 1987). The later model has been used in the evaluation of field experiments in agricultural research (Johnsson et al. 1987; Jansson, Borg, Lundin & Lindén 1987). A further application is made in this thesis.

This thesis

This thesis can be regarded as part of a continuous process in identifying and increasing knowledge of decisive factors for nitrate leaching from arable land to surface water and groundwater but also as part of a first step to introduce models as tools in the evaluation of results gained.

AIMS OF THE THESIS

The thesis is based on six separate aims;

> To quantify the nitrate impact on drainage water quality under four different cropping systems encompassing both annual and perennial crops and different climatic conditions.
>
> To identify and avaluate factors decisive for groundwater contamination by nitrate from arable land.
>
> To test a water and heat model for simulation of long-term water discharge from arable land to surface water and groundwater, even though only limited data on soil and crops were available.
>
> To test a nitrogen model for simulation of nitrate leaching from arable land.
>
> To estimate groundwater recharge and correspondent nitrate losses from a field where only pipe discharge was measured.
>
> To test a water and heat model for simulation of surface runoff and pipe discharge in a frozen soil.

MATERIALS AND METHODS

All discharge data, piezometer data and leaching data used came from the network of monitoring stations run by the Division of Water Management at the Swedish University of Agricultural Sciences. Data on agricultural practices used were supplied by the hosts of the experimental fields. The Swedish Meteorological and Hydrological Institute (SMHI) supplied the climatic data and stream runoff data.

Measuring techniques and methods of analyses and calculations were described earlier by Brink et al. (1978) and Gustafson & Torstensson (1983a).

Data concerning soil characteristics necessary for the simulations, were collected by the Division of Agricultural Hydrotechnics (Andersson & Wiklert 1977; Wiklert, Andersson & Weidow 1983).

A technical description of the water and heat model used in the discharge simulations is given in Jansson & Halldin (1980) and a description of the extended water and heat model used in paper VI is presented in that paper.

A description of the nitrogen model used is given in Johnsson et al. (1987).

RESULTS AND DISCUSSION

Nitrate leaching under different cropping systems

Results from four different experimental fields were used (I). Crop rotations varied due to production direction and climatic conditions and included cereals, mixed crops, oil plants, sugar beets and leys. Leys were established by re-seeding in all cases. Both grass leys and mixed clover and grass leys occurred.

The crop type was of utmost importance for the leaching magnitude. Grass and clover leys of several years standing and a grass ley of two years standing reduced the mean losses up to four and six times respectively compared to mean losses after cereals under comparable discharge conditions. The much more extended growing period by leys compared to annual crops, followed by nitrogen uptake lowering the amount of nitrate available for leaching even outside the growing season of annual crops, could largly explain these different leaching magnitudes.

It is frequently considered that the ploughing of a ley should drastically increase the leaching of nitrate due to intensive mineralization of crop residues. However, with late ploughing of leys (October–December) the losses were still on the same low level as under established ley conditions, but early ploughing (July) followed by repeated cultivations increased the loss fully three times more than after cereals. If early ploughing (August) was combined with sowing of a winter crop the loss was still less than following cereals.

Also after sugar beets the losses were lower than after cereals and close to the losses after wheat with a re-seed and a grass ley of one year standing. The extended growing period for sugar beets in the autumn compared to cereals played an important role in this context.

The largest mean loss following cereals was recorded in the most southerly site. The milder winter climate with more intensive and extended time for mineralization of crop residues, higher fertilization levels and larger mean discharge rates were all important factors in this context.

It may also be concluded that since perennial crops constitute the major part of crop production in northern Sweden, this contributes keeping the total nitrate losses in this part of the country on a comparably low level.

Leaching of nitrate into groundwater

The landscape can be divided into recharge areas, where the vertical flow component is moving downward, discharge areas, where the vertical flow component is moving upward, and into intermediate areas where the direction of the vertical flow component can reverse from time to time (II).

Using piezometers it was established to which type of area a specific groundwater site belonged. Where the water was moving downward there was a decrease in head with depth, and where it was ascending there was a corresponding increase. Thus, the head was likely to be lower than the water table in an recharge area and higher in a discharge area. As a consequence, there was no possibility of agriculture affecting the deeper groundwater quality in a discharge area; this was only possible in recharge areas. The magnitude of this impact on the groundwater quality was dependent on local conditions such as climate, type of soil, type of crop and fertilizing intensity. It was evident that certain combinations of the mentioned factors gave unduly high nitrate concentrations in the groundwater. The most decisive factor for groundwater contamination is, however, the direction of the vertical flow component. Groundwater contamination is exclusively related to recharge areas.

Simulation of water discharge

Annual drainage discharge. A wide range of humidity conditions occurred during the ten-year investigation period and caused strong fluctuations in yearly discharge (III). Summer conditions was found to be important for achieving a high degree of correspondence between simulated and measured discharge rates. Due to the shortage of discharge during the growing season and the lack of soil moisture measurements, it was not possible directly to test the simulated water uptake. Nevertheless, the simulated discharge was highly sensitive to prevailing evapotranspiration rates, making it possible, indirectly, to test the simulated water uptake. The best agreement between simulated and measured discharge was obtained when the critical tension where the reduction of water uptake begins was put to 1600 cm. An increased duration of the period with a lower surface resistance when growing winter crops also improved the results. Good agreement was obtained between simulated and measured discharge rates for all years except the first.

Daily drainage discharge. When using daily mean values as driving variables, highly accurate values for simulated daily discharge cannot be expected. Nevertheless, the level of correspondence with the measured daily discharge was fairly good. The best fit was achieved during flood conditions, when the ground was unfrozen. Generally, winter conditions were more difficult to simulate. Some peakflows never appeared in the simulations while others occurred with a substantial delay. In addition, the shape of the peaks was frequently distorted.

Groundwater discharge. An interesting finding during the work was the ability to estimate rates of water percolation to the deeper groundwater body. The simulated percolation varied between 21 and 69 mm/yr with a mean value of 46 mm/yr; this was about 18 per cent of the drainage discharge.

Simulation of nitrate leaching

Parameter values necessary for the simulation were derived from measurements and management practices or adapted from other applications (IV). Model outputs could only be tested against measurements of leaching and nitrate content of the soil.

The simulated yearly deposition was the smallest nitrogen source. The dominating mineralization originated in the litter and as a mean for the investigated period the litter mineralization was five times as large as the humus mineralization. The yearly sum of deposition and net mineralization averaged 89 N kg/(ha.yr) and was lower than fertilization, averaging 123 N kg/(ha.yr). Thus, the most important N-source was fertilization. A net immobilization phase took place after ploughing in most years. There was an increased mineralization during years following sugar beets especially in the May-July periods.

Great attention was paid to the crop uptake since this was of vital importance for the final result. The fact that nitrogen availability is the only limiting factor for uptake and that no consideration is paid to other factors varying with time, including such as drought and stress or meteorological elements, made it difficult to get an accurate uptake without changing the potential uptake for different crops and years. The most practical approach was to relate potential uptake to the yield.

The overall seasonal dynamics of simulated nitrate contents of the soil agreed well with other findings (e.g. Bergström 1986; Lindén 1983). The simulated contents agreed well with measurements made on six of eight occasions, which must be considered as confirming that the simulation was reasonable.

The discharge rate and the amount of nitrate in the soil profile are two main factors controlling the magnitude of the leaching. Since both were well described by the simulations, the simulated yearly losses agreed well with measured losses in most years. In the final year the agreement was poor, mainly as a result of model failing in partitioning between surface runoff and dranage discharge. A fairly large portion of surface runoff took place during the spring flood this year while the water and heat model accounted for drainage discharge only. Nitrate concentrations are normally lower in surface runoff than in drainage discharge (Gustafson & Torstensson 1983b). Thus the simulated leaching was apparently overestimated.

The between-year variation in the leaching magnitude during years with "normal" discharge rates could largely be explained by the amount of nitrate remaining in the soil profile in the beginning of September and the litter mineralization during the period September-March. Years with higher or lower discharge rate than the "normal" resulted in increased or decreased nitrate leaching, respectively, compared to the normal for the same amount of mineral nitrogen available for leaching.

Estimation of groundwater recharge

To quantify the groundwater recharge without using expensive and sophisticated methods is not an easy task. An easier and more practical method is to use a simulation model to get at least a good estimate of the recharge. This was the approach used in paper III. The error in simulated recharge might, however, be substantial due to insufficient information about the subsoil.

The reliability of simulated recharge was tested by comparing it with the difference between stream runoff from a nearby stream and tile drainage discharge (V). The area of the stream basin was of such an extent that it was reasonable to assume that the stream runoff also included ground water discharge. Furthermore, the characteristics of the stream basin were similar to those of the experimental field, i.e. the dominating landuse and soil type were the same, as well as dominating crops. In addition, very small differences in precipitation were expected between the areas.

The comparison between simulated recharge and measured difference between stream runoff and tile drainage discharge showed that the simulated groundwater recharge was of the same order of magnitude and can therefore be regarded as a realistic estimate of groundwater flow into deeper horizons of the experimental field.

Using the yearly means of nitrate concentrations in the groundwater and simulated yearly recharge, the losses of nitrate passing the 2.9 m and 5.6 m horizons in the ground did not exceed 3.5 and 1.9 NO_3-N kg/(ha.yr), respectively.

Simulation of snow, frost, surface runoff, and pipe discharge

As documented by the simulations at the Näsbygård field (III), the simulation of partly frozen soil is a difficult task. Especially the partitioning between surface runoff and pipe discharge is tricky. Nevertheless, an important feature in nitrate leaching models must be to account for the lower nitrate concentrations in surface runoff compared with pipe discharge (Gustafson & Torstensson 1983b). For example, the lack of this ability gave poor agreement between measured and simulated nitrate losses in the leaching simulation at Näsbygård (IV). Thus, further improvement of the water and heat model in handling the surface runoff complex is to be desired as far as correct simulation of nitrate losses is concerned.

Some improvements were undertaken, e.g., a special surface water pool was introduced (VI). In order to test the ability of the improved model to predict surface runoff and pipe discharge, adaptations were now made to an experimental field in northern Sweden where surface runoff and pipe discharge were measured separately.

The simulated snow depth and snow density was important for the correct simulation of frost. To get good agreement with observed depths, the snow melting coefficients were adjusted.

When simulated and measured frost depths were compared, the best agreement was obtained for ploughed soil where the frost was deepest. The inclusion of a low thermal conductivity of the uppermost soil as a way of accounting for the grass cover in the ley was not successful in all years.

During a five-year period, the total runoff simulated for the barley system was about 200 mm above the measured sum of 1180 mm. The corresponding simulated runoff for the ley system was about 100 mm less than the observations. A similar tendency was also observed for the simulated pipe discharge but in this case the discharge from the barley system was slightly above the measured sum of 380 mm whereas the ley simulation was considerably below the measurements. Although the model overestimated the total surface runoff for the barley system, the best agreements with regard to the runoff patterns were obtained between the barley simulation and the measured runoff. This was not surprising since annual crops averaged 70 per cent of the field area.

It can be concluded that the model application demonstrated the importance of correct quantification of soil frost if drainage from an agricultural soil is to be estimated. The partitioning between surface runoff and pipe discharge was on the whole correctly simulated but discrepancies between simulation and measurements concerning temporal distribution occurred.

Further research is therefore of importance to improve applicability of the model for winter conditions. If the requirements are restricted to seasonal estimates of the water balance components from arable land, the present stage of knowledge seems satisfactory.

The present study can be considered as a first step towards modelling of nitrate losses from soils strongly influenced by frost. However, a number of problems remain, e.g., on how the solute transport is influenced by freezing and by substantial heterogeneity of water flow-paths.

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NITRATE LEACHING FROM ARABLE LAND IN SWEDEN UNDER FOUR CROPPING SYSTEMS

Arne Gustafson*

Abstract. Long-term nitrate leaching to surface waters was studied using selected systematically drained agricultural fields under different cropping systems and climatic conditions. The discharge rates, including surface runoff together with tile drainage effluent, were measured in subground measuring stations using a Thomson weir technique. Discrete water sampling was performed.

Crop rotations varied due to cropping system and climatic conditions and included cereals, mixed crops, oil plants, sugar beets and leys. Leys were established by reseeding in all cases. The crop type was of utmost importance as regards leaching magnitude. Grass and clover leys of several years standing reduced the mean losses up to four times and a grass ley of two years standing six times compared to the mean losses after cereals under comparable discharge conditions. The much longer growing period in leys followed by nitrogen uptake which lowered the amount of nitrate available for leaching, even outside the growing season of cereals, could largely explain these different leaching magnitudes.

Late ploughing of leys (Oct.-Dec.) gave losses which were still on the same low level as under the ley but early ploughing (July) followed by repeated cultivations increased the loss more than three-fold in comparison with those after cereals. If early ploughing (Aug) was combined with sowing of a winter crop the loss was less than when following cereals.

Also after sugar beets the losses were lower than after cereals and close to the losses after wheat with re-seeding and a grass ley of one year´s standing.

The largest mean loss following cereals was recorded at the southernmost site. The milder winter climate with more intensive and longer times for mineralization of crop residues, higher fertilization levels and larger mean discharge rates were all important factors in this context.

INTRODUCTION

Long-term field measurements show that modern Swedish agriculture has widely contributed to the enrichment of nitrate in both surface- and ground water (Brink, 1982; Brink et al., 1978, 1979; Brink et al., 1986; Gustafson, 1982; Gustafson, 1983).

Thus, creation of accurate countermeasures against nitrate pollution is of the utmost importance for prevention of environmental and health hazards. This requires quantitative understanding of how different combinations of crop management, soils and climatic conditions influence the nitrogen balance.

The main objective of this study was to evaluate the influence of different cropping systems on leaching losses of nitrate.

MATERIAL AND METHODS

The field sites

A network of representative experimental fields was established by the

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Table 1. Crop distribution (%) and mean nitrogen dressing with commercial fertilizers (N kg $ha^{-1}yr^{-1}$) for counties in 1985 and experimental fields during the entire investigation period.

Area	Leys	Cereal Crops	Rem. Crops incl. Fallow	Nitrogen Dressing
Field Vagle	67	33	0	40.8
County Jämtland	75	23	2	25.0
Field Flinkesta	23	69[a]	8	87.5
County Södermanland	22	64	14	99.0
Field Helleberg	18	73	9	108.5
County Skaraborg	21	68	11	103.0
Field Näsbygård	8	61	31	118.4
County Malmöhus	12	57	31	116.0

[a] Included two years of oats and peas mixed.

Division of Water Management at the Swedish University of Agricultural Sciences to gather information on long-term trends in discharge and mass transport of nutrients from arable land in Sweden (Brink et al., 1978, 1979). The measurements were started at Näsbygård and Flinkesta in 1973, in 1975 at Helleberg and in 1977 at Vagle. The measurements are still running at all fields (Brink et al., 1986).

Each field site is drained by a tile drainage system and provided with wells for collecting surface runoff. The field drains were mainly placed at a depth around 1 m.

The pipe drainage and surface runoff rates were quantified together in a measuring station using a Thomson weir. Flow was registered continuously by a water-stage recorder. The locations of the field sites are presented in Figure 1.

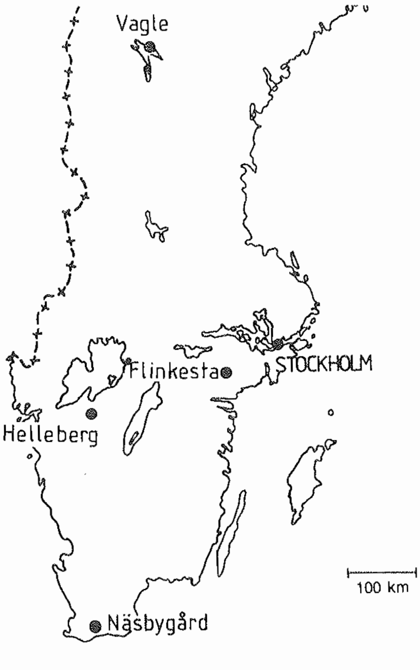

Figure 1. Location of experimental sites.

Table 2. Crop, fertilizers, manure, yield and dates.

	Crop		Fertilizers (kg ha^{-1})				Manure (t ha^{-1})		Harvest (t ha^{-1})		First date of cultiv.
Year	Type	Date	N	P	K	Date	Solid	Date	Amount	Date[a]	
Vagle											
1977	Ley II	-	60	26	49	17 May	0	-	4.3 DM	28 Jun	-
1978	Ley III	-	58	25	47	12 May	0	-	5.3 DM	13 Jun	24 Oct
1979	Barley and oats[b]	31 May	0	0	0	-	30+20[c]	25 May	2.7	24 Sep	None[d]
	Barley and oats[e]	31 May	44	26	0	25 May	20	27 Oct	2.7	24 Sep	None[d]
1980	Barley and oats	14 May	44	26	0	13 May	20	20 Sep	3.2	17 Sep	1 Oct
1981	Barley and re-seed	18 May	27	16	0	17 May	15	16 May	4.0	16 Sep	-
1982	Ley I	-	62	27	51	5 May	0	-	6.0 DM	16 Jul	-
1983	Ley II	-	26+31	44	0	18 May, 6 Jul	20[f]	10 May	8.0 DM	22 Jun	-
1984	Ley III	-	56	25	46	3 May	0	-	4.9 DM	7 Jul	-
1985	Ley IV		0	27	0	19 May	25[f]	20 May	3.4 DM	7 Jul	19 Jul
Flinkesta											
1973	Winter wheat	14 Sep 72	31+31	0	0	30 Apr, 22 May	20	17 Jul 72	4.3	16 Aug	1 Sep
1974	Spring rape	19 Apr	104	24+28	30	18 Apr, 17 Sep	0	-	2.4	16 Sep	18 Sep
1975	Winter wheat	30 Sep 74	78	0	0	28 Apr	0	-	3.8	12 Aug	1 Oct
1976	Barley	11 May	78	0	0	11 May	0	-	3.1	23 Aug	20 Sep
1977	Oats and re-seed	17, 20 May	65	15	0	17 May	0	-	3.1	23 Sep	-
1978	Ley I	-	64+42	28	52	20 Apr, 3 Jul	0	-	5.0 DM	13 Jun	-
1979	Ley II	-	104+42	24	0	27 Apr, 29 Jun	0	-	7.0 DM	20 Jun	-
1980	Ley III	-	91+28	21	0	18 Apr, 4 Jul	0	-	6.9 DM	13 Jun	18 Nov
1981	Barley	5 May	78	18	0	5 May	25	15 Oct	3.8	25 Aug	29 Oct
1982	Oats and peas	7 May	56	16	16	7 May, 16 Sep	10	5 Mar	3.7	20 Aug	14 Sep
1983	Winter wheat	17 Sep 82	98	0	0	23 Apr	0	-	5.4	17 Aug	19 Oct
1984	Oats and peas	29 Apr	78	18	0	29 Apr	25[g]	Oct	5.0	31 Aug	6 Nov
1985	Barley + re-seed	15, 22 May	70	0	0	15 May	25[g]	Mar	3.1	12 Sep	-

[a] First day of harvest or first harvest when growing ley and multiple harvest occurs. [b] 2/3 of the field. [c] Applied on 27 Oct. [d] No ploughing due to frozen ground. [e] Applied to 1/3 of the field. [f] Urine. [g] Applied to half of the field.

Sampling and analyses

Drainage water for chemical analyses was collected every second week when discharge occurred but more frequently during flood conditions. All samples were analysed for nitrate with the colorimetric Cd-reduction method (APHA, 1985). The analytical method was adjusted for an auto-analyser.

Crop, fertilization and management

Regional. The type of crops used varied both due to climatic conditions and cropping system. A comparison of cropping systems between experimental fields and each county, including type of crops used and mean amount of N-commercial fertilizer applied, is presented in Table 1. The figures represent the conditions at the experimental fields during the entire period of investigation and in the counties according to official statistics (Statistiska Meddelanden, 1985). The comparison shows that the experimental fields fairly well reflected the regional crop distribution. This is also a necessary condition if the results are to have regional applicability. It is of special interest to see the magnitude of the change in the area used for ley production going from the northermost county (Jämtland) to the southernmost county (Malmöhus).

Local. Detailed information about crop type, sowing time, rates and timing of nitrogen fertilization and harvest as well as first date of cultivation in the autumn are presented in Tables 2 and 3. All dates and yields were supplied by the farmers.

At Vagle, ley and mixed grain crops totally dominated the plant production. The ley and grain crops were used for cattle feeding in milk production. Sowing usually took place in mid or late May. Both commercial fertilizers and manure were used. Manure application occurred both in the autumn and spring periods. In 1979 the ploughing in of manure, applied in late October, was impossible due to frozen ground. Urine was

Table 3. Crop, fertilizers, manure, yield and dates.

	Crop		Fertilizers (kg ha^{-1})				Harvest (t ha^{-1})		First date of cultiv.
Year	Type	Date	N	P	K	Date	Amount	Date[a]	
Helleberg									
1975	Spring wheat	19 Apr	117	21+21	39+39	18 Apr, 1 Sep	3.0	15 Aug	10 Sep
1976	Oats	27 Apr	104	28	52	27 Apr, 23 Aug	6.5	14 Aug	18 Aug
1977	Winter wheat	15 Sep 76	109	14	26	25 May, 3 Sep	4.4	7 Sep	17 Oct
1978	Oats	18 Apr	104	14	26	17 Apr, 15 Sep	4.8	10 Sep	17 Sep
1979	Winter wheat	3 Oct 78	109	14	26	18 May, 8 Oct	5.0	10 Sep	25 Oct
1980	Oats	7 May	101	14	26	27 May, 10 Oct	4.8	23 Sep	15 Oct
1981	Barley + re-seed	21 Apr	78	18	33	18 May, 1 Sep	4.0	17 Aug	-
1982	Grass for seed	-	31+54	0	0	15 Mar, 20 Apr	1.0	24 Jul	-
1983	Grass for seed	-	90+31	40	40	18 Apr, 1, 7 Aug	0.7	23 Jul	27 Jul
1984	Winter rape	9 Aug 83	43+107	0	0	13 Mar, 30 Apr	3.1	16 Aug	19 Aug
1985	Winter wheat	7 Sep 84	115	0	0	17 May	6.0	3 Sep	20 Oct
Näsbygård									
1973	Spring wheat	22 Mar	112	0	0	26 Mar	4.1	29 Aug	8 Oct
1974	Barley	9 Mar	79	64	64	14 Mar, 20 Sep	5.1	15 Aug	20 Aug
1975	Sugarbeets	25 Apr	135	0	0	21 Apr	38.5	15 Oct	27 Oct
1976	Spring wheat	17 Apr	112	0	0	20 Apr	4.2	26 Aug	7 Sep
1977	Barley	6 May	78	56	104	23 May, 5 Sep	4.2	18 Aug	20 Aug
1978	Sugarbeets	11 Apr	140	0	0	11 Apr	45.8	15 Oct	27 Oct
1979	Spring wheat	12 Apr	120	0	0	12 Apr	4.4	18 Sep	20 Sep
1980	Barley	15 Apr	91+50	0	0	15 Apr, 23 Sep	4.8	14 Aug	16 Aug
1981	Winter rape	28 Aug	84+105	0	0	1 Apr, 27 Apr	2.0	4 Aug	9 Aug
1982	Winter wheat	18 Sep	45+77	45[b]	144[b]	31 Mar, 26 Apr	8.1	24 Aug	25 Aug
1983	Sugarbeets	20 May	112	0	0	16 May	33.6	Oct	Oct
1984	Spring wheat[c]	20 Mar[d]	92+15	0	0	20 Mar, 21 Jun	7.3	16 Sep	-
1985	Grass for seed	-	45+47	32[e]	59[e]	15 Apr, 7 May	0.9	28 Aug	29 Aug

[a] First day of harvest. [b] Applied on the 1 Oct. [c] Spring wheat and re-seed. [d] The sowing of the re-seed started on the 25 Apr. [e] Applied on the 3 Oct.

applied twice during ley production. Harvest of grain crops always took place after mid September. The ploughing of leys took place in late October 1978 but fairly early, on July 19 in 1985 and the conditions afterwards can therefore be regarded as a "semi fallow".

At Flinkesta, leys and mixed crops were also grown for cattle feeding in milk production but winter wheat and spring rape also occurred. Sowing of spring crops was done in the April-May period and sowing of winter wheat always in September. Split application of N-fertilizer was always used in ley production and once for winter wheat. Only solid manure was used and both autumn and spring applications were performed; when applied in the autumn the manure was always ploughed in. Harvest time of grain crops was no earlier than August 12 and no later than September 16.

In 1980 the ploughing of ley took place on November 18, thus being done fairly late.

Helleberg had no cattle and grass was therefore grown for seed purposes. Among the grain species oats and winter wheat were the most frequent with three years of each. For grass split application and for winter rape autumn applications of N-fertilizer were made. No manure was used. Harvesting grain crops was not earlier than August 14 and not later than September 23. The ploughing of grass in 1983 took place as early as on July 27 to ensure the establishment of the winter rape, which was sown on August 9.

Initially, Näsbygård had a regular crop rotation with spring wheat, barley and sugar beets, after eight years this was interrupted by winter rape sown in August 1981 followed by winter wheat and sugar beets. In 1984, spring wheat with re-seed was sown to establish grass for seed which then was ploughed on August 29 in 1985.

Sowing of grain crops (barley) was done as early as on March 9 one year and sugar beets were not sown later than May 20 in any of the years.

Split application of N-fertilizers occurred on five occasions. The winter rape was N-fertilized in the autumn about one month after sowing.

Harvest of and ploughing after grain crops took place in the August-September period and in October for sugar beets.

RESULTS AND DISCUSSION

Seasonal variation

The mean value for each month during all years was calculated in order to describe the typical seasonal variation pattern for precipitation, drainage discharge, concentrations and losses of nitrate (Figure 2).

The early arrival of cold winter decreased the precipitation figures at Vagle already in October but not until February at Näsbygård, where the climate was milder. The extension of the period of lowered precipitation during winter was about seven months at Vagle and about four months at Näsbygård. At Flinkesta and Helleberg the conditions were somewhere in between. The yearly mean precipitation was, as expected, larger at Näsbygård than at the other sites.

The drainage discharge rates were also influenced by the different

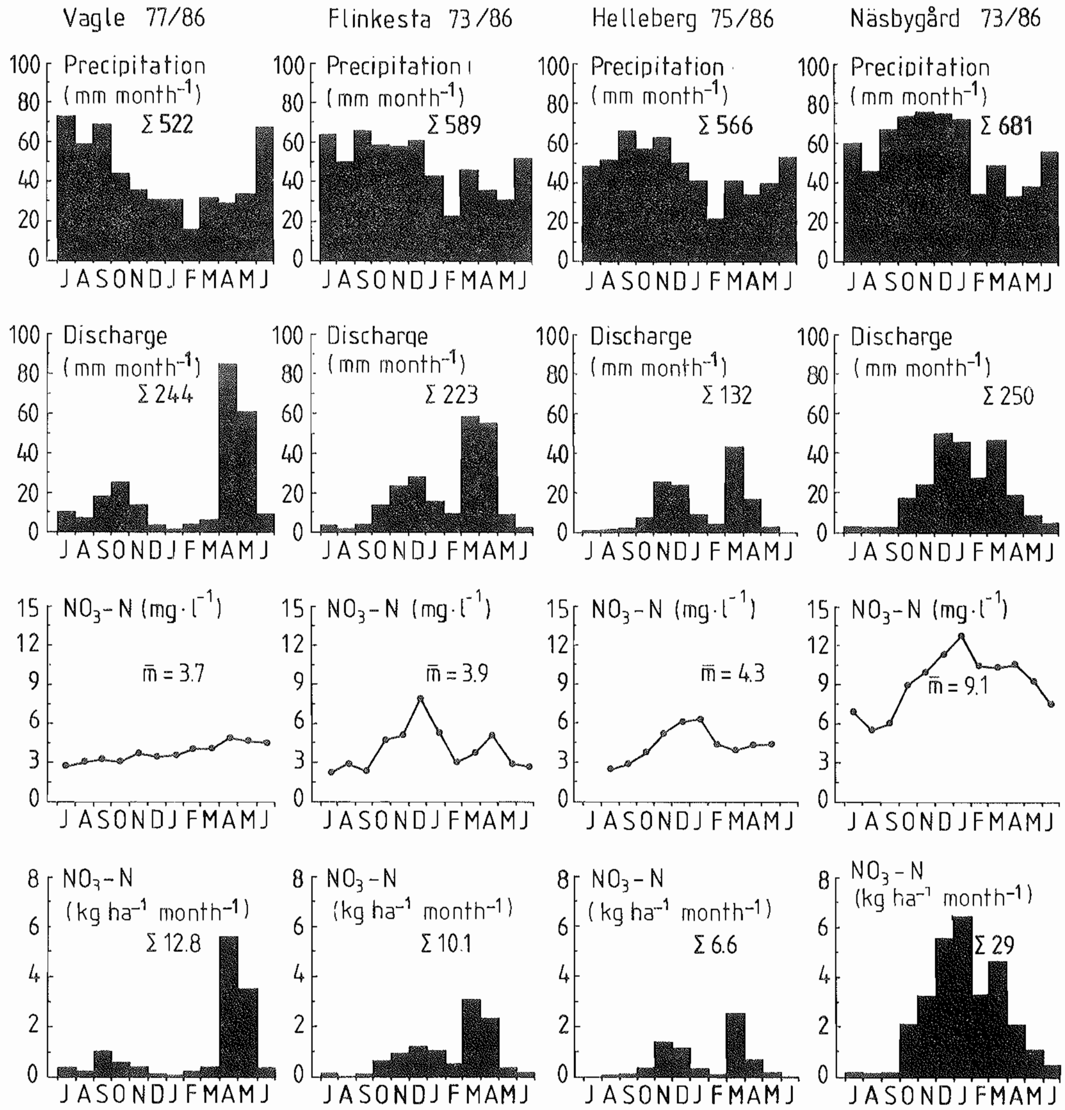

Figure 2. Monthly mean values of precipitation, discharge, nitrate concentration and loss at all sites.

winter conditions. Vagle had a very pronounced spring flow peak in April-May during snowmelt. At Flinkesta and Helleberg the spring flow peaks arrived in May-April and were less pronounced than at Vagle. The autumn flow peaks were smaller in intensity but of larger time extension at all three sites.

At Näsbygård the autumn and spring flow peaks followed closely upon each other and were only separated by lower discharge rates in February. The explanation is that both rain and snowmelt occurred frequently during the winter at this site.

The concentrations increased during the autumn period at all sites and reached maximum levels in December or January, except at Vagle where the maximum was reached in April. The concentrations decreased during the spring flood when tile drainage water was mixed and diluted by surface runoff from snowmelt water poor in nitrate and then recovered to some extent when the tile drainage water dominated again.

The different nature of surface- and drainage water as far as nitrate concentrations are concerned has been studied thoroughly by Gustafson & Torstensson (1983), reporting mean concentrations of 0.9 N mg l^{-1} and 3.0 N mg l^{-1} in surface- and drainage water respectively. Thus, dilution of drainage water with surface water should frequently be expected. The situation at Vagle was an exception as the tile drainage water and the snowmelt water had about the same nitrate content.

The lowest concentrations were recorded during the growing season since the high nitrate demand by the crop lowered the nitrate concentration in the soil solution.

The annual mean concentration at Näsbygård was exceptionally higher compared to the other sites. The mild climate, leading to large mineralization of crop residues even during late autumn and winter,plays an important role in this context (Gustafson, 1987).

Due to larger mean discharge rates and higher mean concentrations the losses at Näsbygård were 2-3 times larger than at the other sites.

Annual variation

Vagle. The discharge varied more than could be expected from the variation in precipitation (Figure 3), which may partly be explained by the fact that about one-third of the field lies in a discharge area for groundwater and more or less groundwater contributed to the discharge rate depending on the actual groundwater pressure (Gustafson & Torstensson, 1984). Moreover, the evapotranspiration rates may differ widely from year to year depending both on weather conditions and on crop type (Gustafson, 1987). Both maximum and minimum discharge rates occurred during ley production but during the first two years of ley in particular, the discharge rates happened to be small.

The mean concentrations of nitrate were lower during the three years of ley in 1982/85 than during other years but rose to maximum in 1985/86 as a consequence of the early ploughing of the ley in 1985 followed by repeated cultivations. The late ploughing of the ley in 1978 did not cause the mean concentration to increase, which emphasizes the importance of late ploughing to avoid mineralization of crop residues taking place during a period providing favourable conditions for mineralization.

The low discharge rates in combination with moderate mean concentrations in 1977/79 and the low mean concentrations in 1982/85 caused very small losses during the ley years, mean value 4.1 NO_3-N kg $ha^{-1}yr^{-1}$. A relatively large discharge rate and the high mean concentration in 1985/86 caused the loss to rise to a remarkable level, 50.0 NO_3-N kg $ha^{-1}yr^{-1}$. In a lysimeter study Bergström (1987) found an even larger loss, 67 NO_3-N kg $ha^{-1}yr^{-1}$, following early (August 10) ploughing of a grass ley.

The mean losses after cereals were 3.6 times larger than under the ley, which illustrates the importance of a crop cover to reduce the nitrate concentrations in the soil solution to keep the losses on a low level.

The relatively large loss in 1981/82 despite the re-seed covering of the ground was partly an effect of high discharge rate but probably also an effect of the frequent use of manure during the years with cereal production (Gustafson & Torstensson, 1984).

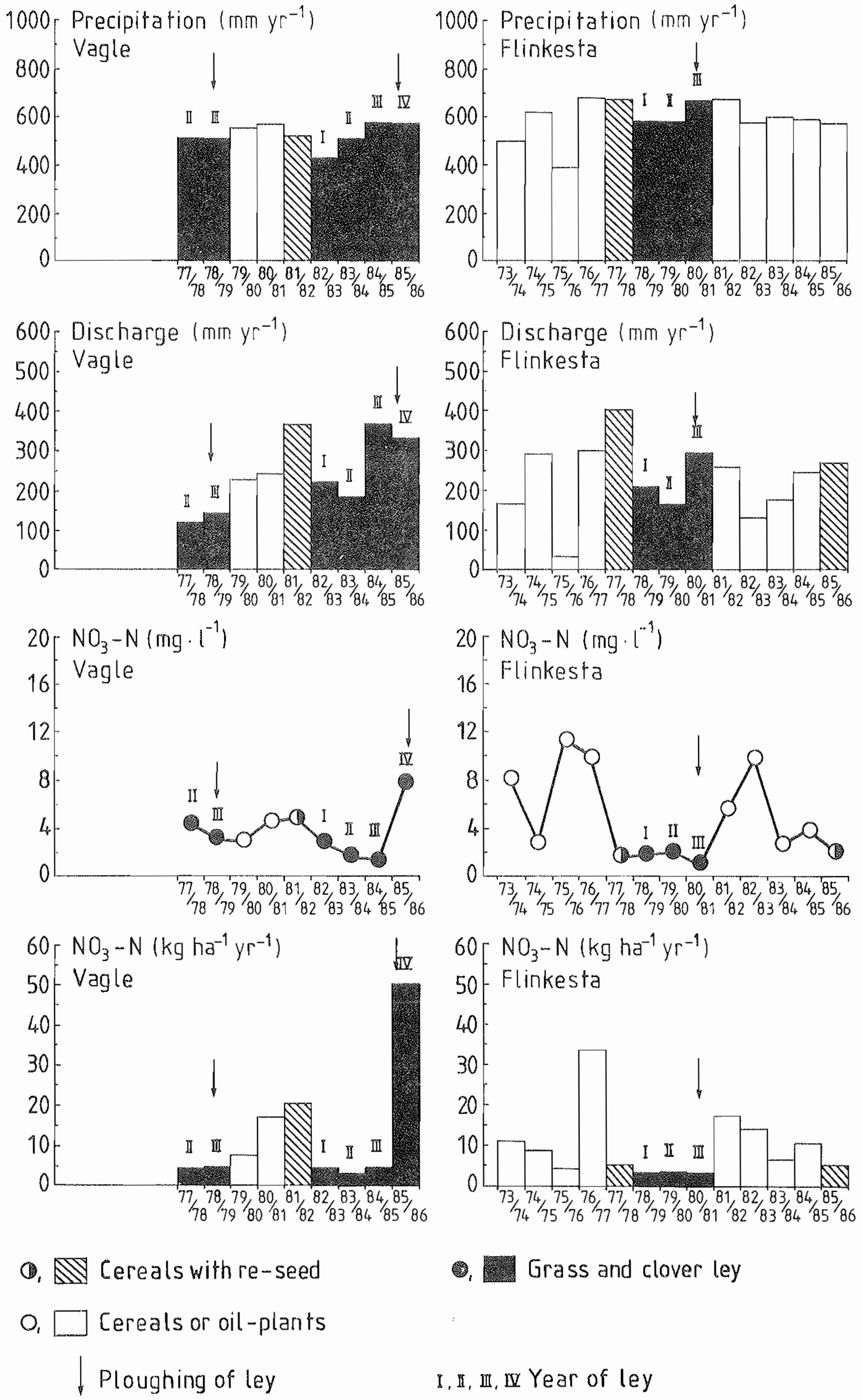

Figure 3. Yearly precipitation and discharge rate, mean concentration and loss of nitrate at Vagle and Flinkesta.

Flinkesta. The precipitation rates showed no drastic variation from year to year apart from the low rate in the dry year of 1975/76 which caused a substantial drop in discharge rate (Figure 3). As also at Vagle, the discharge rates were influenced by the groundwater pressure (Gustafson et al., 1984) leading to a more complex variation than could be explained only by the variation in precipitation rates.

The largest discharge rate occurred during the first year with the re-seed. During the ley period the discharge rates were quite "normal" with a variation comparable to the conditions during cereal years excluding the dry year.

The mean concentrations were generally lower and with smaller variations during years with re-seed and established ley compared to years when cereals were grown. Due to late ploughing of the ley in 1980 the mean concentration did not increase in 1980/81. In fact the lowest mean concentration was recorded this year. The highest mean concentration occurred during the dry year and can probably be explained by the small amounts of water available for dilution of soil water.

The increased mean concentrations in 1973/74 and 1976/77 can be explained by residual effects from the foregoing year, leaving unusually large amounts of nitrate in the soil profile. In the first case, this was caused by manured fallow and in the second case by the dry conditions leading to lowered nitrogen losses.

The most reasonable explanation of the increased mean concentration in 1982/83 seems to be the dry autumn, causing accumulation of nitrate in the soil profile, which led to high mean concentrations in drainage water during December and January when the discharge had started again (Ulén, 1984).

The combination of high mean concentration and larger discharge than normal caused the largest loss to occur in 1976/77. Owing to the re-seed keeping the soil nitrate mean concentration at a low level in 1977/78 the loss became small despite the highest discharge rate occurring in this year. Even during the second year with re-seed the loss remained low, which suggests the possibility of using the re-seed as a regular catch crop during cereal production to reduce nitrate losses. The losses during the two years with re-seed averaged 5.4 NO_3-N kg ha^{-1} yr^{-1} compared to 3.6 and 13.6 NO_3-N kg ha^{-1} yr^{-1} after ley and cereals, respectively.

Helleberg. The variation of discharge rates showed a closer relationship to the variation in precipitation rates than at Vagle and Flinkesta, indicating negligible contribution from deeper groundwater (of more or less distant origin) to the discharge rate. During the dry year of 1975/76 the discharge did not occur at all but varied between 53 and 212 mm yr^{-1} during the other years (Figure 4).

The highest mean concentration followed the dry year, similar to the situation at Flinkesta. After the early (July 27) ploughing of the ley in 1983/84, the mean concentration also rose but not as much as could be expected from results of, e.g., the early ploughing of ley at Vagle. The winter rape, which had developed well, seems to have consumed a lot of the nitrogen released by mineralization of the crop residues as well as nitrogen from the N-dressing. Under favourable conditions well-developed winter rape is capable of consuming large amounts of nitrogen in the autumn (up to 100 kg ha^{-1} has been recorded by Lindén, 1981) but also much lower consumption has been recorded during unfavourable development of rape (Gustafson, 1987; Gustafson & Torstensson, 1987). The risk for increased nitrate concentrations after early ploughing of a ley, even if a winter rape is sown, should therefore not be neglected.

During the year with re-seed the mean concentration was lowered and during the first year of the ley the lowest mean concentration was recorded.

The combination of highest mean concentration and largest discharge rate resulted in the largest loss occurring in 1976/77. Low losses in combination with "normal" discharge rates occurred during the year with re-seed and the first year of the ley. A relatively low discharge rate during the year the ley was ploughed caused a low loss despite the increased mean concentration.

Näsbygård. As also at Helleberg, the variation in discharge rates was related more to the variation in precipitation rates than at Vagle and

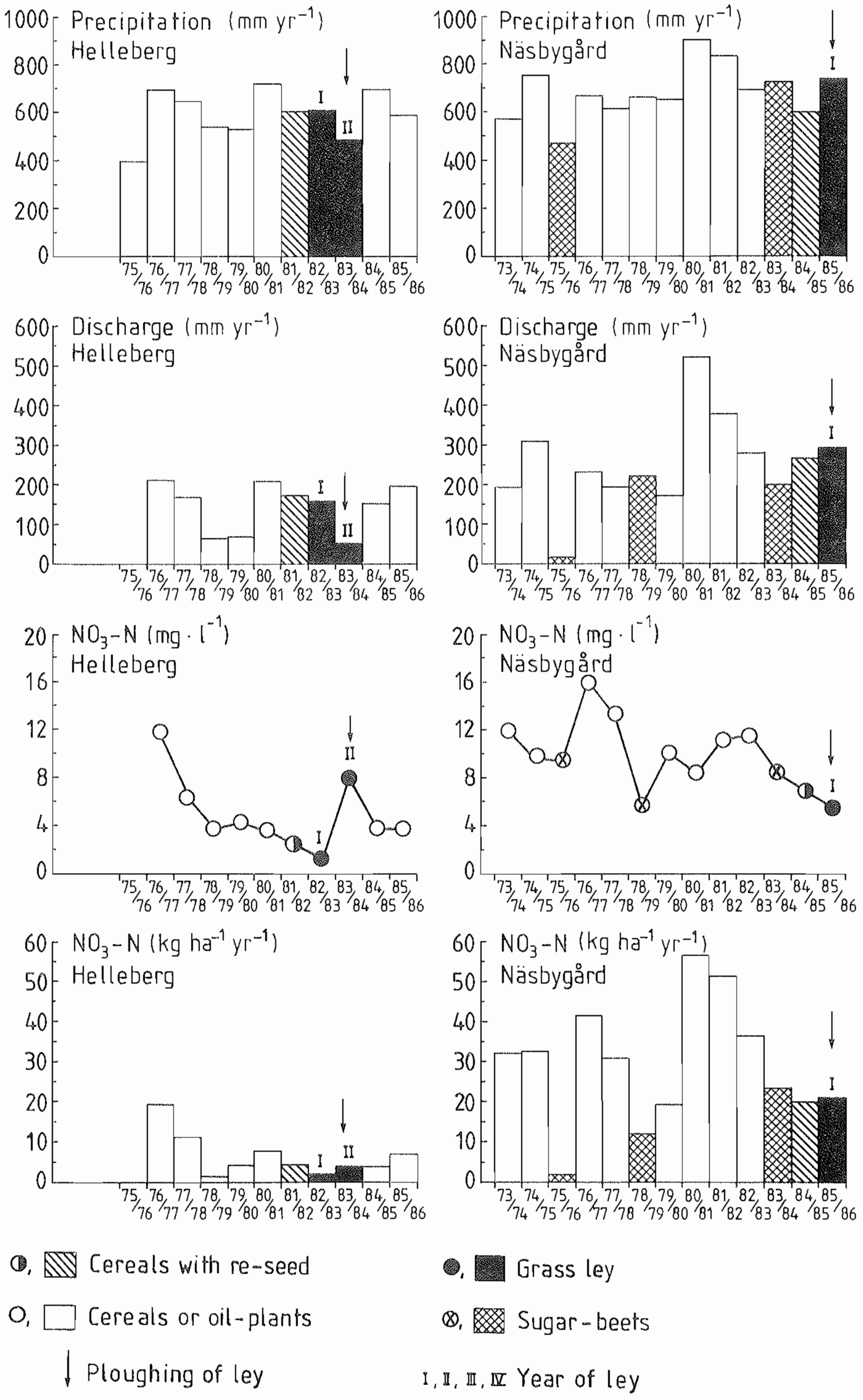

Figure 4. Yearly precipitation and discharge rate, mean concentration and loss of nitrate at Helleberg and Näsbygård.

Flinkesta. The groundwater conditions played an important role here since the field lies in a recharge area for groundwater, thereby excluding the contribution of deeper groundwater to the discharge rates (Gustafson, 1987). The largest and lowest precipitation and discharge rates were recorded in 1980/81 and 1975/76, which both can be regarded as extremes in the long term (Gustafson, 1986).

As at Flinkesta, the highest mean concentration followed the dry year of 1975/76. The lowest mean concentration was found after the ley followed by the sugar beets in 1978/79 and the re-seed. During the other two years with sugar beets the mean concentrations were in the low range of what is commonly found in connection with growing of cereals and oil plants.

The large discharge rate in 1980/81, together with relatively high mean concentration, caused the loss to rise to a remarkably high level, which was nearly repeated in the following year, 56.7 and 51.3 NO_3-N kg $ha^{-1} yr^{-1}$ respectively. The increased amount of nitrate available for leaching during these years could largely be explained by the excessively high fertilization rate to the oil plants in relation to their yield. During the remaining years with cereals the losses averaged 32.1 NO_3-N kg $ha^{-1} yr^{-1}$. During the years with re-seed and ley the losses were even smaller, as well as during the last two years with sugar beets, all in connection with normal discharge rates. The lowest losses occurred during the dry year.

CONCLUSIONS

Results from this study show that the crop type is of the utmost importance for the leaching magnitude of nitrate but also that climatic conditions and discharge rate are important. Similar results have been reported from other Nordic countries (Jaakkola, 1984; Kjellerup & Kofoed, 1983; Uhlen, 1978a; 1978b).

Grass and clover leys of several years standing and a grass ley of two years standing reduced the mean losses up to four and six times respectively compared to the mean losses after cereals under comparable discharge conditions. Also during years with re-seed, the losses were reduced by almost the same rate, which suggests the possibility of using re-seed as an effective catch crop to reduce losses when growing crops such as spring cereals.

When leys are ploughed late in the autumn (Oct.-Dec.) the losses were still on the same low level as during standing ley conditions. Early ploughing (July) followed by repeated cultivations increased the losses by at least three-fold in comparison with the situation after cereals. If early ploughing (Aug.) was combined with sowing of a winter crop then the leaching level was less than after cereals.

The losses after sugar beets were also lower than after cereals and close to the loss after a grass ley of one year´s standing.

The largest mean loss following cereals was recorded in the southernmost site. The milder winter climate, with a more intensive and longer time for mineralization of crop residues and higher fertilization levels compared to the other sites, are all important factors in this context.

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Leaching of Nitrate from Arable Land into Groundwater in Sweden[1]

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ABSTRACT / The agricultural influence on the quality of the groundwater in Sweden is mostly associated with infiltration areas. The local conditions here determine the extent of the nitrate leakage. It is evident that certain combinations of factors in normal cropping can give unduly high nitrate concentrations in the groundwater.

Introduction

During the last decade the impact of agriculture on groundwater has been discussed. Most of the interest has been focused on nitrate. At the Swedish University of Agricultural Sciences, investigations are in progress to determine the extent of and reasons for the leaching of nitrate. This represents a difficult problem because of the geohydrological complexity of the landscape. Nevertheless, it is possible to make a simple geohydrological model of a landscape to show where agricultural impact is and is not possible. From the standpoint of a specific geohydrological situation many factors, both inside and outside the agricultural area, will affect the extent of the nitrate leakage. The following factors will be discussed in this paper: climate, hydrodynamic pressure, type of soil, intensity of nitrogen dressing, type of crop, and chemical reduction of nitrate.

The results presented here are based on material from a network of experimental fields covering the whole country. The Division of Water Management is in charge of the investigations.

Geohydrological Conditions Preceding Agricultural Impact on Groundwater

Sweden has been glaciated. The country is therefore covered with Quaternary stratifications. A high proportion of the groundwater consumed thus derives from these stratifications which are thereby of great importance for the quantity of water available for consumption, for its age, and for its quality. A simple geohydrological model of a landscape in central Sweden can serve as a basis for estimates of where the risk of agricultural impact is great and where it is absent or small (Fig. 1). At bottom is the bedrock, followed by loose stratifications of permeable material such as moraine, gravel, and sand, and at the top in valleys and on plains an almost impervious layer of varying clay content.

This topography and succession of layers gives rise to specific geohydrological properties. Naturally only the groundwater in the permeable layers is of interest in terms of the water supply, since these can transmit enough water within a reasonable time. The head of the water pressure, which reflects the actual pressure at the depth of observation, will be established after drilling piezometric tubes down into the Quaternary layers. The observed groundwater pressures connected to one line show the pressure surface built up in the landscape at any given time.

Where the water is moving downward there is a decrease in the head with depth, and where it is ascending there is a corresponding increase. Thus, the head at some depth is likely to be lower than the water table in an intake area and higher in a discharge area. In consequences there is in a discharge area no possibility of agriculture affecting the deeper groundwater quality; this can only occur in intake areas. The magnitude of this impact on the groundwater quality is dependent on local conditions such as climate, type of soil, type of agricultural activities, and chemical conditions.

Climate Influence

Comparison

The great length of the country causes a considerable climate difference between northern and southern Sweden. For this reason the country was divided into three main regions, the northern, the central, and the southern, in order to differentiate and cover the most typical climatic zones. The bulk and distribution of the precipitation and runoff over the year, as well as the quality of the drainage water are included in this comparison. The experimental fields compared have soil types ranging from fine sand to clay.

Precipitation and Runoff

The bulk of the precipitation was lowest in the north and highest in the south. The months January, February, April, and May had, on average, lower precipitation than the remainder (Fig. 2). The total runoff averaged 192 mm, being heavier from the fields in the south compared with the other two

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[1] Presented at the International Symposium, International Association of Hydrogeologists, "Impact of Agricultural Activities on Ground Water Quality and Quantity," Prague, Czechoslovakia, September, 1982

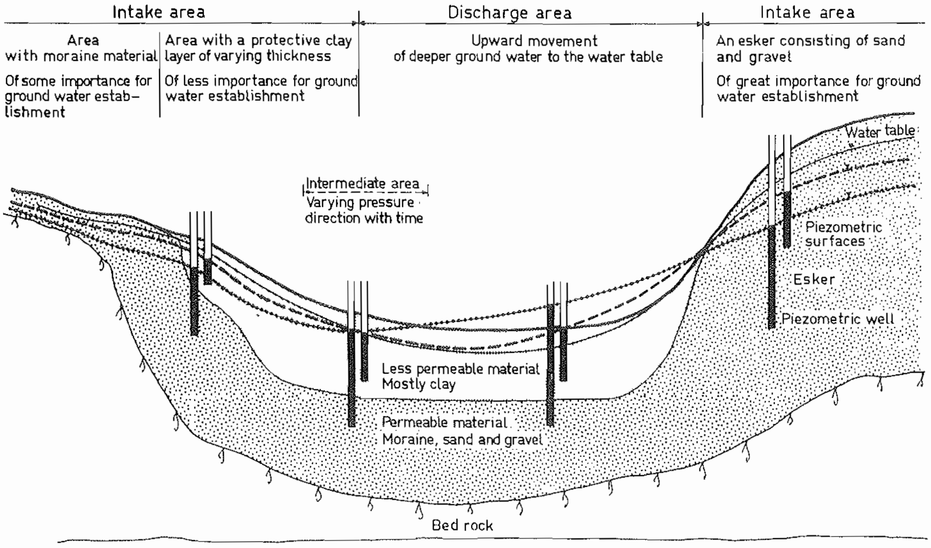

Figure 1. A geohydrological model of a landscape in central Sweden.

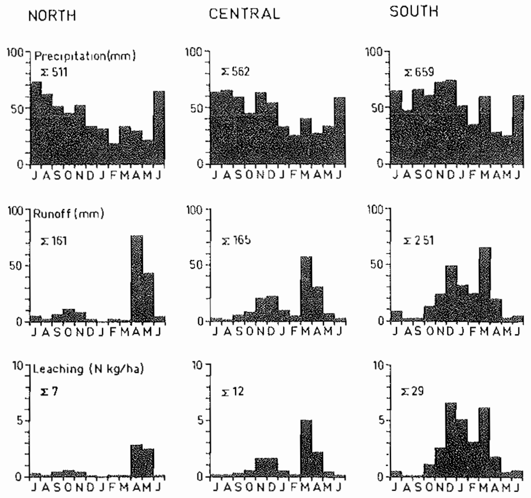

Figure 2. Precipitation, runoff, and leaching of nitrogen from experimental fields in three regions.

regions. The explanation primarily consists in the differing precipitation figures. The runoff during the summer months was normally low.

The winter runoff showed a clear climatic variation. In the northern area two very pronounced peaks were distinguished, in autumn and spring with, on average, a four-month period of frozen conditions in between (Dec.–Mar.). In the southern area, where the winter temperatures are normally higher, the runoff was considerable even during the winter. The runoff situation in the central area fell somewhere between those of the two other areas, as would be expected.

Table 1. Crop distribution (%) and nitrogen dressing with commercial fertilizers (N kg/ha per year) in three regions for counties and experimental fields represented

Area	Ley	Cereal crops	Rem. crops	Nitrogen dressing
North				
Counties	55	35	10	34
Experimental fields	50	40	10	56
Central				
Counties	23	64	13	85
Experimental fields	12	76	12	109
South				
Counties	21	55	24	113
Experimental fields	12	69	19	107

Nitrogen

The nitrogen transport was strictly correlated to the runoff. The difference in the total transport of nitrogen between the three regions was greater than the difference in runoff. This could be explained by consideration of how and when the runoff takes place. In the northern area most of the runoff occurs during the spring (80%), primarily as surface runoff, which decreases leaching of available nitrate in the soil profile. The apparent nitrogen transport during the spring was chiefly

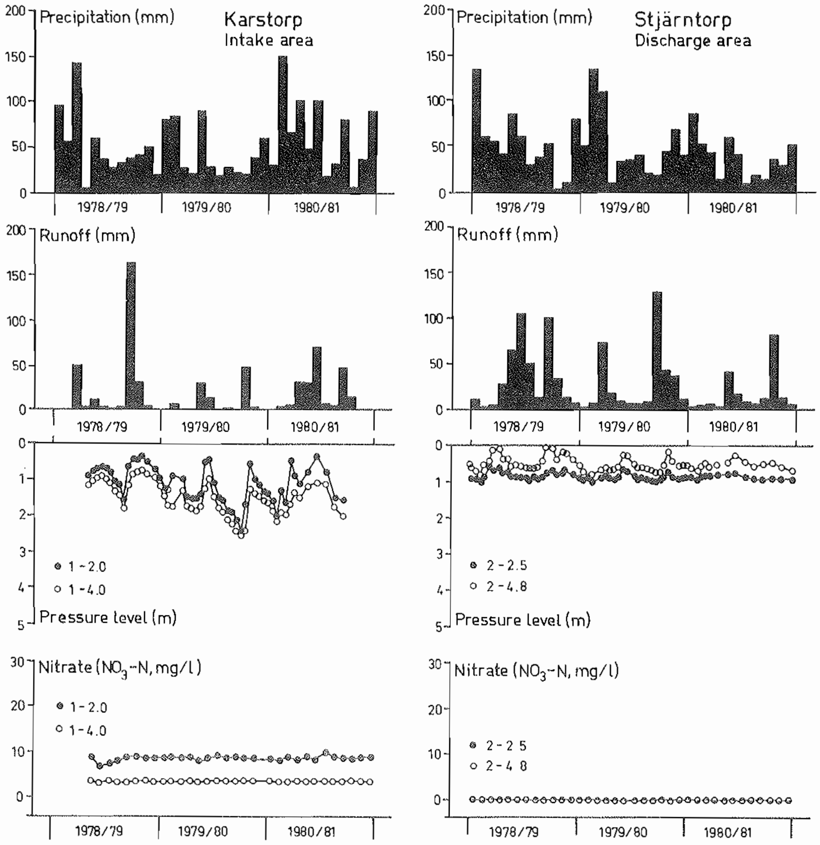

Figure 3. Precipitation, runoff, groundwater pressure, and content of nitrate in an intake area and a discharge area.

caused by spreading of manure on frozen ground. The manure disappeared with the surface runoff.

In the southern area the considerable winter runoff in combination with the limited time that the soil is frozen provokes heavy leaching of the soil profile. The mineralization of nitrogen during the autumn is also favored by the milder climate.

As a result of the climate, the proportion of the land used for cereal crops is increasing, from north to south, which means more crop residues available for mineralization. The amount of nitrogen dressing is also increasing (Table 1). All these facts combined explain why the leaching of nitrogen is much higher in the south than the north.

Hydrodynamic Pressure

The water from soils in intake areas originates in precipitation which infiltrates the field. In consequence the nitrate derives mainly from the surface. Many years may pass before the nitrate reaches deeper layers of the soil profile. The variation of the groundwater pressure is obvious during the year (Fig. 3).

The situation is different with soils in discharge areas. The water is usually of far distant origin. The conditions of the investigated field have no influence on the water quality at a depth somewhat deeper than the water table. The variation of the groundwater pressure is small (Fig. 3), and the nitrate content normally low. It has been established through tritium analysis that the groundwater from some fields, at a depth of 4 m, could be more than 30 years old.

If the groundwater reservoir is subjected to an excessive discharge of consumption water, the water emanating from the intake area is too slow in refilling the reservoir. The upward movement of deeper groundwater disappears and limited intake areas around the water wells are created. Strictly local pollution could influence the groundwater, and thereby cause a

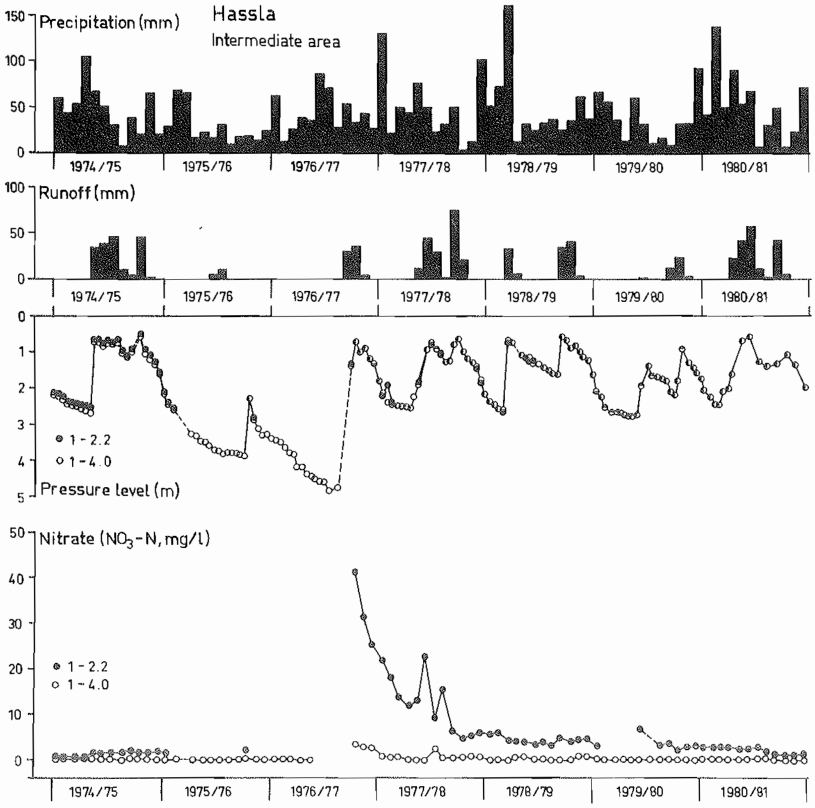

Figure 4. Precipitation, runoff, ground-water pressure, and content of nitrate in an intermediate area.

deterioration of the water quality. In intermediate areas the groundwater pressure shows considerable variation during the year. A substantial lowering of the groundwater table is common for years with low precipitation, as happened during the agrihydrological years 1975-76 and 1976-77 (Fig. 4). When the groundwater reservoirs were filled up again, after the precipitation reverted to normal, the water percolating the soil profile had a very high nitrate content. This was presumably an effect of a nitrate accumulation during the preceding dry period. The nitrate content of the shallow groundwater increased considerably. When normal conditions were established, the nitrate contents decreased and after four years the content was restored to the same level as before the groundwater depression.

Type of Soil

A factor of great importance for the nitrogen balance in the ground is the type of soil. The possibility of substantial differences as regards the nitrogen losses through leaching is illustrated in Figure 5. Mean values from fields with three different types of soil in the southern area are compared.

The sandy soils lost more than twice as much nitrogen compared with the clay soil. The root depth in the sandy soil rarely exceeds 40-60 cm, which is one explanation why the losses are so great. Nitrogen below this level is naturally not available for the crop and is exposed to leaching. For a clay soil with good structure, the situation is different. The root penetration can easily reach one meter and more, which results in more stable uptake of nitrogen by the crop.

Some of the nitrogen in a well-aggregated clay soil, i.e. the nitrogen found inside aggregates and micropores, is effectively protected against leaching. Most of the percolating water occurs in root canals and macropores. This physical state does not exist in a sandy soil, in which the water percolates all pores.

An interesting finding is that the runoff from the Skottorp field did not cause a higher leakage of nitrogen than at

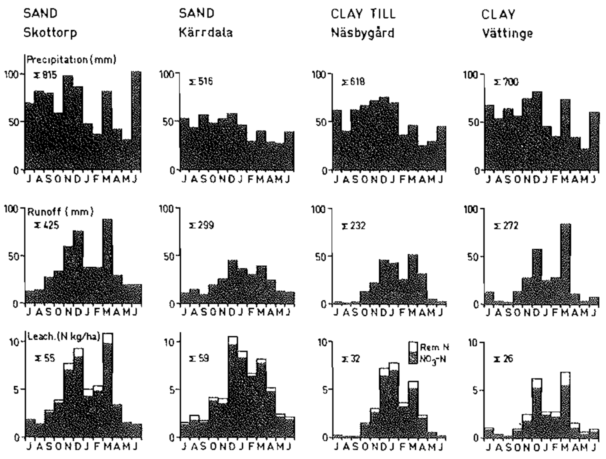

Figure 5. Precipitation, runoff, and leaching of nitrogen from four experimental fields in the southern area.

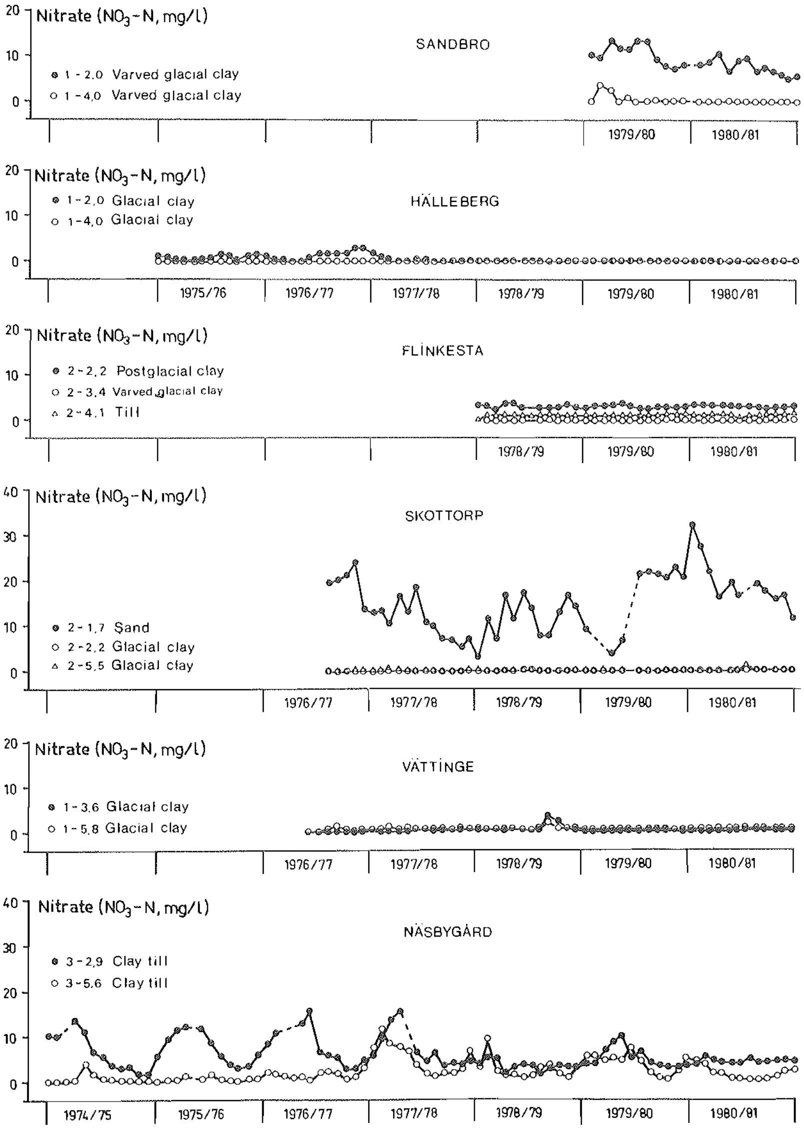

Figure 6. Nitrate in groundwater at some of the experimental fields.

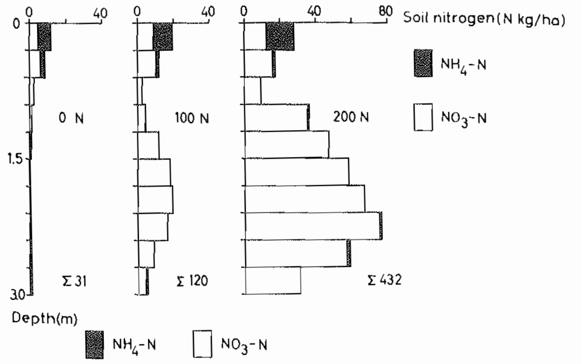

Figure 7. Nitrogen in the soil to a depth of 3 *m* in a cropping system with three different fertilization levels.

Table 2. Mean contents of nitrate found at 1.7 m in relation to crops sown

Crop	Potatoes	Grass ley	Ploughing up and oats
Nitrate (N mg/l)	24	11	20
Time of observation (months)	5	28	19

Kärrdala. The leaching of a sandy soil is apparently very effective, even when the runoff is moderate. In the event of a high runoff the supply of easily mobilized nitrate determines the leaching magnitude. At Kärrdala large amounts of nitrate were released through mineralization, primarily because of frequent use of manure. This is the main explanation why the leaching was highest from this field.

This indicates that raised nitrate contents in groundwater are to be expected for sandy and silty soils situated in intake areas. The results from the Skottorp experimental field seem to confirm this theory (Fig. 6). More unexpected are the raised nitrate contents in the deep groundwater (4–6 m) at Karstorp and Näsbygård with clay as dominant soil type (Figs. 3 and 6). One explanation would seem to be the occurrence of vertical deep crack planes, as observed at Näsbygård. These cracks can be either open or filled with a fine sand. The fertilizing intensity and cropping methods, which are discussed below, are naturally of great importance. In most cases the contents were fairly low in the deep groundwater. It must be remembered that there is no deep groundwater in a sandy soil represented in the material.

Fertilizing Intensity

The fertilizing intensity is obviously of great significance for the magnitude of nitrogen leakage. An intensive fertilizer dressing results in high amounts of crop residues, which are

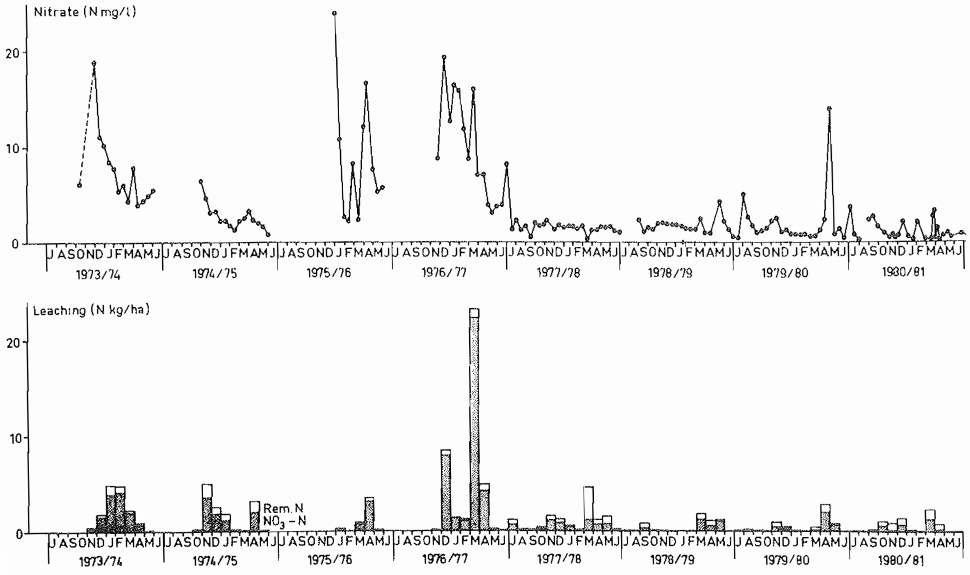

Figure 8. Nitrate in drainage water at Flinkesta.

exposed to mineralization after harvest. There is a clear risk of overdoses of nitrogen since the presence of other factors determining the yield is usually restricted. In other words the crop cannot make full use of applied fertilizer. This is very well documented in experiments using increasing amounts of nitrogen. A field experiment in progress since 1974 on a Swedish clay soil shows that repeated, excessive use of nitrogen fertilizer causes a considerable leakage within a few years (Brink and Lindén 1980).

Nitrogen profiles down to a depth of 3.0 m from three of the treatments included in this experiment (0, 100, and 200 *N* kg/ha per year) are discussed below. The soil samples were collected during December 1981. The highest amount of nitrogen used causes a substantial accumulation of nitrate in the soil profile. This accumulation is obvious throughout the profile (Fig. 7). There is a difference of 89 *N* kg/ha between the 100-N treatment and the treatment with no nitrogen at all. It is evident that crop production at normal fertilization level also causes a minor accumulation of nitrate in the soil profile.

Type of Crop

The crop has a considerable influence on the leakage, which lends significance to crop rotation. Crops harvested late cause less mineralization of crop residues, since the temperature normally drops steeply as winter approaches. Winter wheat and other crops sown during the autumn can absorb nitrogen late in the season. A grass ley of several years' standing would provide optimum conditions. Such a subdued nitrogen leakage caused by a ley is illustreated by a series of measurements from Flinkesta (Fig. 8). The following crop succession was started in 1973: winter wheat, spring rape, winter wheat, barley, oats with re-seed and finally three years of ley. The ley was ploughed in November 1980 with no effects on the nitrogen losses the following winter, presumably by reason of the late date of this ploughing. The influence of grass ley on the groundwater quality was also apparent on a sandy soil. Table 2 indicates the mean contents of nitrate found at a depth of 1.7 m. (see page 70).

A possible method of preventing losses of mineralized and unused nitrogen, accumulated after harvest, is to sow a "second crop" in connection with the harvest of the "main crop." This "second crop" stores the nitrogen in organic compounds. Late in the autumn or during the spring it is ploughed up. The organic matter will mineralize and be available for the next crop instead of being leached out.

Chemical Reduction of Nitrate

Danish investigations point to the ability of the soil to reduce nitrate (Lind and Pedersen 1980). This ability relates primarily to the purely chemical reactions, especially the ferrous iron-nitrate redox system. This process mainly occurs in clay soils due to slow water movements and anaerobic conditions. The results show that the contents of nitrate usually decrease with the depth of sampling, which indicates that the process is effective (Figs. 3, 4, and 6).

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SIMULATION OF WATER DISCHARGE RATES FROM A CLAY TILL SOIL OVER A TEN YEAR PERIOD

Arne Gustafson*

Abstract. A physical-based numerical model was used to predict daily rates of water discharge through tile drains, groundwater table and groundwater discharge rates over a ten year period. The model, which was run on standard meteorological data as input, was adapted for use on a field of arable land in the very south of Sweden. The output was compared with data from continous discharge measurements and piezometer readings made at two weeks intervals.

Parameters related to soil properties were partially based on a previous investigation at a nearby field with similar soil.

The agreements between simulations and measurements were fairly good when account was taken of the specific crop used and its seasonal course.

The most successful simulations were achieved under flood conditions in unfrozen ground. Repeated freezing and thawing led to pronounced discrepancies between simulations and actual observations.

The role of groundwater discharge below the drainpipes was demonstrated and the simulated groundwater discharge averaged 18 per cent of the total discharge.

Despite some shortcomings concerning winter conditions the model is a useful tool for predicting water movements in arable soils.

INTRODUCTION

A thorough knowledge of water discharge rates is of vital importance when constructing subsurface drainage systems and when calculating mass transport from arable land to surface waters and groundwaters. Longterm field measurements are generally the most traditional way to obtain such information. Unfortunately, due to the time consuming and expensive nature of such studies and because of experimental limitations, field data are not always sufficient comprehensive. The use of a simulation model, however, should decrease the time, energy, and costs necessary for estimating water discharge rates while also increasing our understanding of factors influencing discharge dynamics.

A large number of models tailored agricultural conditions have been developed during recent years. The models are often quite different depending on the purpose for which they were constructed. Two internationally renowned models, DRAINMOD (Skaggs, 1975) and CREAMS (Knisel, 1980), exemplify conceptual models primarily developed for practical use. The CREAM's model has been applied to several Scandinavian catchments (Kauppi, 1982; de Maré, 1982; Seip, 1984).

Another two models, WATCROS (Aslyng & Hansen, 1982) and Suså (Refsgaard & Hansen, 1982), are well established in Denmark. The former is based on simplifying concepts whereas the latter is largely based on established physical equations.

Various types of models have also been constructed in Sweden. The HBV model (Bergström, 1976) was initially developed primarily for practical hydrological purposes, whereas the SOIL model (Jansson & Halldin, 1979) was developed mainly as a tool to increase the understanding of physi-

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cal processes occurring in the soil. Both of these models have been applied to areas of a variety of size subject to various types of land use and temporal scale (Bergström & Sandberg, 1983; Bergström et al., 1984; Jansson & Thoms-Hjärpe, 1986; Lundin, 1984).

The present paper presents an adaption of the SOIL-model for use on a field site in southern Sweden that has been subject to long- term discharge measurements. The measurements were started in July 1973 (Brink et al., 1978).

MATERIALS AND METHODS

The field site

A network of representative experimental fields was established by the Division of Water Management at the Swedish University of Agricultural Sciences to gather information on long-term trends in discharge and mass transport of nutrients from arable land in Sweden. One field (Näsbygård) in the very south of Sweden was chosen for this investigation. The field site was drained by a tile drainage system and provided with wells for collecting the overland flow (Fig. 1). The field drains were placed at a depth of 1 m. On certain sites some of the main drains were installed at a depth of 3.5 m, thereby making it possible to drain smaller depressions in the hilly field. Drainage dis-

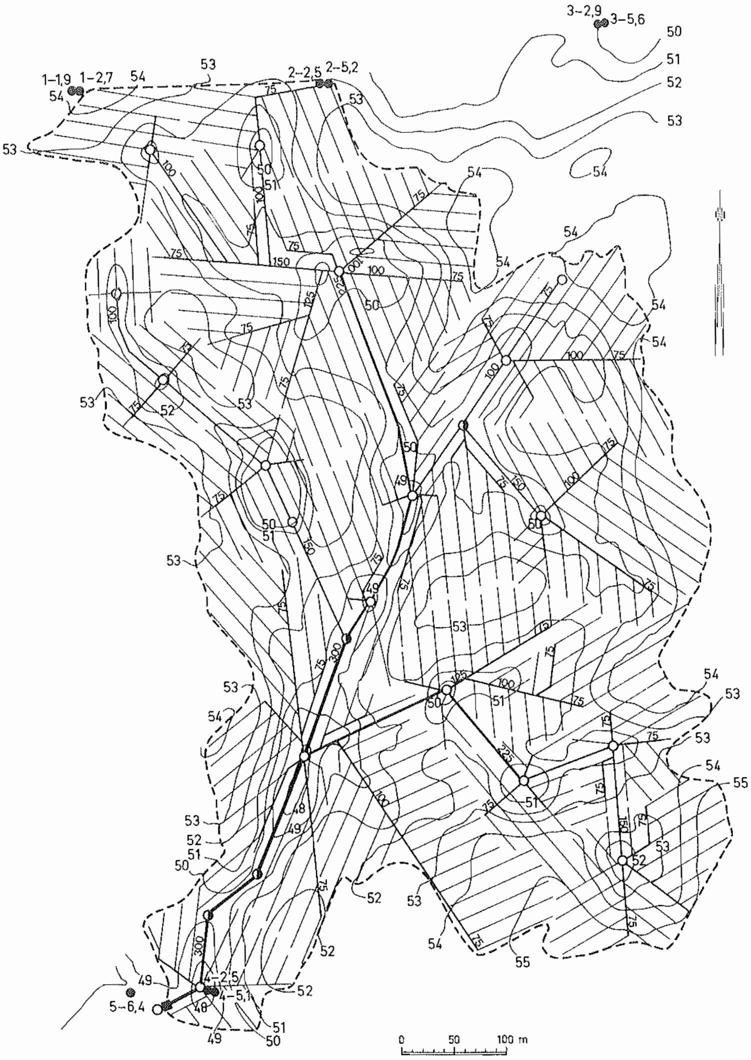

Figure 1. The pipe drainage system of the experimental field.

charge rates were quantified at a measuring station using a Thomson weir. Flow was registered continuously by a water-stage recorder.

Piezometers were installed at four subsites with intakes at two levels at each site. Pressure readings were taken every second week.

General description of the model

A detailed technical description of the model was given earlier (Jansson & Halldin, 1980), and modifications valid for arable land have also been presented (Jansson & Thoms-Hjärpe, 1986). Only the basic model assumptions are given below.

The model is based on one-dimensional numerical solutions of the partial differential equations for water and heat. The equation for water flow is:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial}{\partial z}\left(K_w\left(\frac{\partial\psi}{\partial z} + 1\right)\right) - S$$

where θ is the volumetric water content, ψ is the water tension, K_w is the unsaturated conductivity, S is the sink term or source term, t is the time and z is the depth. The same type of equation is valid for heat flow, including freezing-melting and convective effects of liquid flow:

$$\frac{\partial(C \cdot T)}{\partial t} - L\frac{\partial\theta_i}{\partial t} = \frac{\partial}{\partial z}\left(-K_h\frac{\partial T}{\partial z}\right) - C_w\frac{\partial(q_w \cdot T)}{\partial z}$$

where C is the volumetric heat capacity of soil, T is temperature, L is latent heat of freezing, θ_i is the ice content, K_h is the thermal conductivity, C_w is the volumetric heat capacity of water, and q_w is the vertical flow of water.

Boundary conditions for these equations are calculated with subroutines for interception, snow cover, drainage, groundwater, and evapotranspiration.

Standard meteorological data as daily means of precipitation, air temperature, wind speed, relative humidity, and global radiation are sufficient as driving variables.

Adaptation of soil characteristics to the site

Only a few soil texture analyses were available from the field site together with a survey map of the soil types showing that clay till was the dominant soil type (Brink et al., 1978). Consequently soil properties had to be taken from a nearby investigated site at Svenstorp representing the same soil type (Wiklert et al., 1983).

The water characteristic curve and the unsaturated conductivity function in the model have been adapted to modified expressions of Brooks & Corey (1964) and Mualem (1976), respectively. The water characteristics for three layers are presented in Figure 2.

Adaptation of the model to the site

Most attention was paid to parameters regulating the evapotranspiration rate. The aerodynamic resistance to evaporation was calculated from a logarithmic wind profile with the assumption that the roughness length increased from 1 to 7 cm as the crop height increased. The surface resistance, including both the soil surface and the sum of all stomata, was assumed to decrease with the increase in biomass. The minimal surface resistance was set at one of several values depending on crop type, while the maximal value was kept constant (s m^{-1}):

Crop	Min	Max
Spring wheat, barley	50	120
Sugar beets, winter rape and winter wheat	30	120

Since there was no information available on root distribution for any of the crop types at the site, this relative distribution was considered independently of crop type:

Layer (cm)	0-10	10-25	25-45	45-70	70-100
Relative value	0.40	0.30	0.15	0.10	0.05

The number of days needed for the roots to penetrate down to the different layers was set in accordance with observations on the crop development.

Another unknown value was the critical water tension in the soil below which a reduction of transpiration occurs. A number of widely different values have been suggested in the litterature (Feddes et al., 1974; Item, 1981). The value was varied widely in some of the earlier simulations but later it was kept constant (1600 cm water).

Parameters regulating the winter conditions were set in accordance with experiences gained when simulating surface runoff and drainage discharge in northern Sweden with the same model (Gustafson, 1986).

The initial values of the simulated period, starting on April 1 1973, were assumed to correspond to a mean groundwater depth of 1.0 m and to tensions at equilibrium with the ground water above.

The maximum rate for groundwater discharge was set at 0.6 mm day^{-1}.

Driving variables

Climatic data, consisting of daily mean values of air temperature, humidity, and daily sums of precipitation, were taken from a nearby meteorological station, at Skurup, 4 km NE of the field. Wind speed and global radiation were measured at Lund, 34 km NW of the field.

Measured precipitation is somewhat less than the true value, primari-

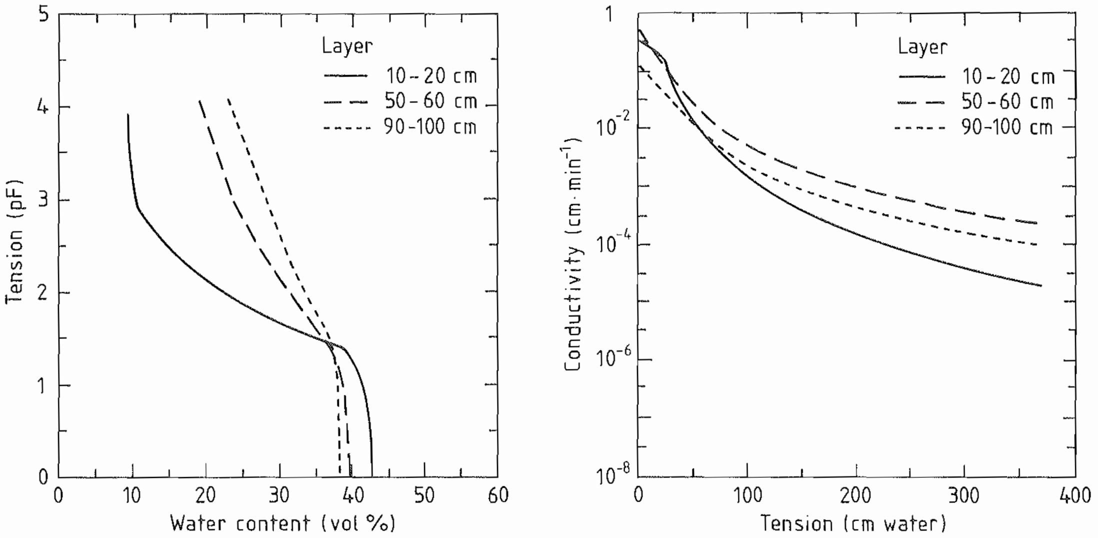

Figure 2. Curves describing soil water characteristics for the adapted soil profile.

ly due to wind losses, and must therefore be corrected. These losses are more pronounced for snow than for rain. Accordingly correction factors used for the simulations were set at 10 and 17 % respectively.

RESULTS AND DISCUSSION

Annual rates of drainage discharge

A wide range of humidity conditions occurred during the 10-year-long investigation period. The substantial between-year variation in annual precipitation (July 1 - June 30), caused strong fluctuations in the annual discharge, which varied from 16 to 520 mm y^{-1} (Fig. 3).

To achieve a high degree of correspondence between simulated and measured discharge rates, the summer conditions played an important role. Due to the shortage of discharge during the growing season, it was not possible, directly, to determine how accurate the values for simulated water uptake were. Nevertheless, the simulated discharge was highly sensitive to prevailing evapotranspiration rates, making it possible, indirectly, to test the simulations against measured discharge.

Potential rates of water uptake were very high during the first year, mainly due to high values for windspeed and global radiation during this period. Fairly low rates of water uptake occurred during the last 4 years, with a minimum during 80/81, which also happened to be the most humid year (Fig. 4).

This pattern of variation got almost lost as far as actual waterup-take is concerned, when using a low value (200 cm water) as the critical tension for reduction of water uptake (Fig. 4). The simulations, however, brought forward the necessity of increasing the actual water uptake during drier years in relation to wetter ones to get a better fit. This was achieved by increasing the critical tension. The results of simulations based on three increased values 600, 800, and 1600 cm are presented in Figure 4. Comparison of simulated and measured rates of discharge now indicated that 1600, was the best of the three values to use. This comparatively high tension was also in accordance with experiences from another simulation study involving a clay soil in the southern Sweden (Jansson et al., 1987).

By lengthening the estimated period of lowered surface resistance when growing wintercrops during the last two years, finally a good agreement between simulated and measured discharge rates for all years except the first was obtained (Fig. 5). A good agreement with the first year's data was only achieved when the actual water uptake was reduced

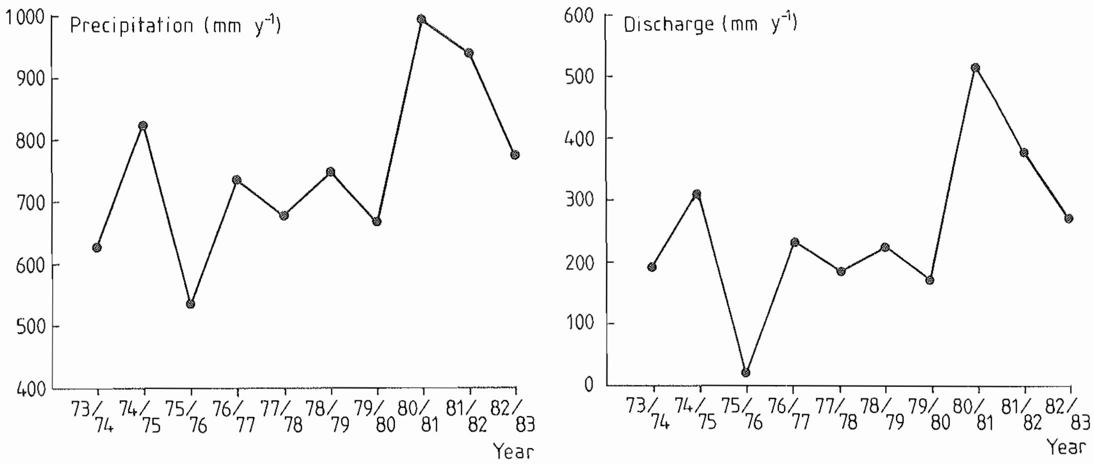

Figure 3. Annual rates of precipitation and discharge.

by using a critical tension of 200 cm water. However, this low value resulted in poor agreement with measurements from other years with similar crops and yields. Some hidden factor, not accounted for by the crop development parameters this year could have been involved, but it

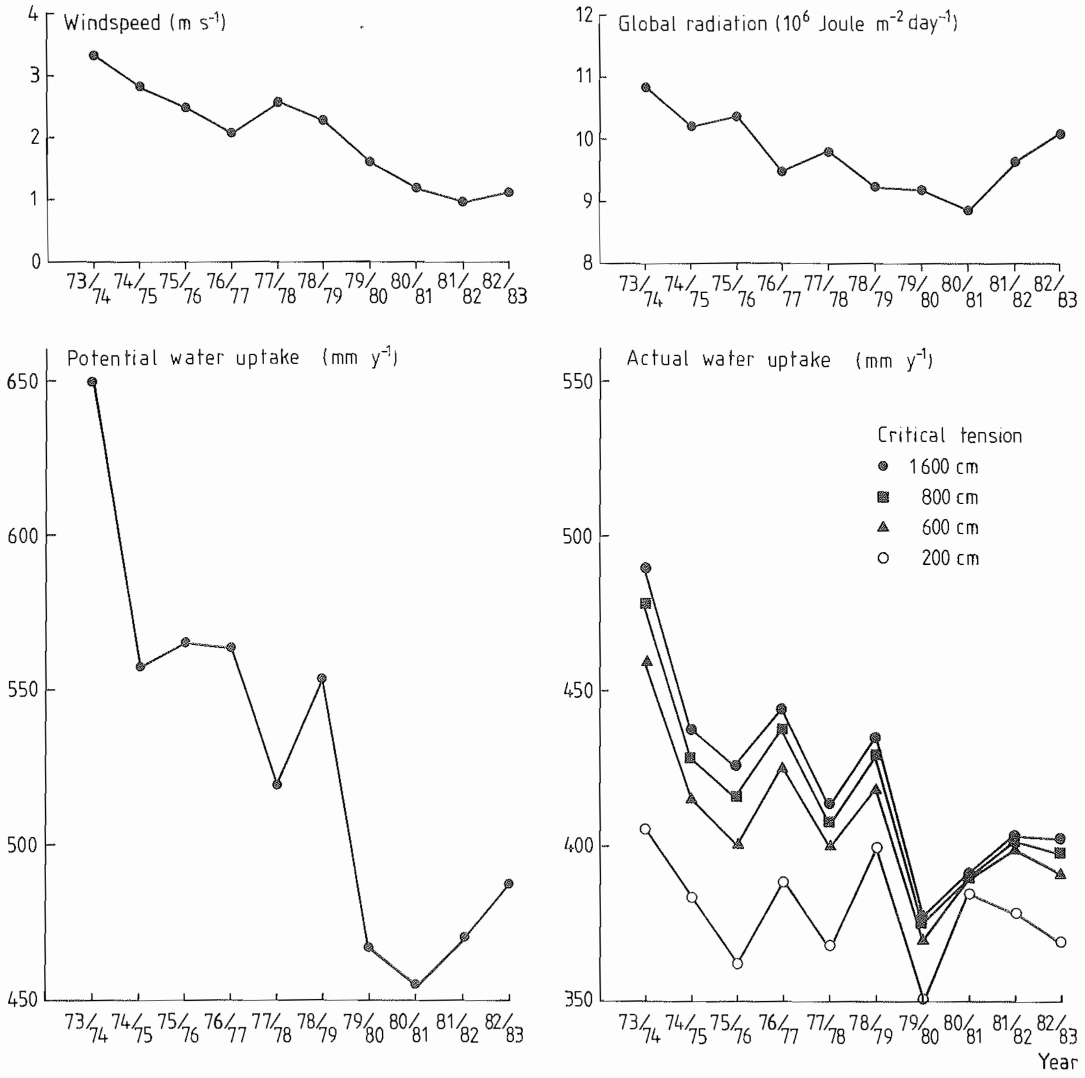

Figure 4. Annual means for wind speed and global radiation. Potential and actual rates of water uptake for different settings of the critical tension for reduction of water uptake.

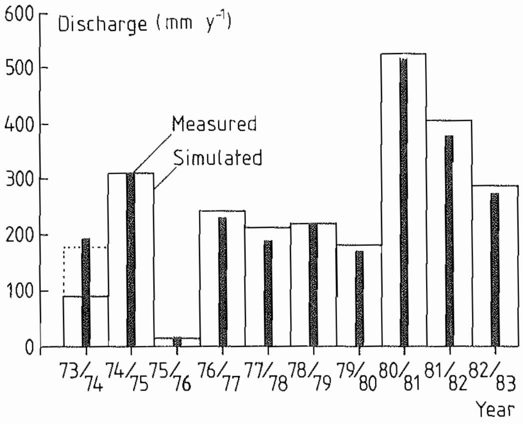

Figure 5. Simulated and measured annual rates of drainage discharge. The dotted line represents a simulation with a critical tension of 200 cm water during the first year. In all other simulations the value of 1600 cm was used.

is more likely that the potential water uptake had in some way, been overestimated.

Daily drainage discharge

When using daily mean values as driving variables, highly accurate values for simulated daily discharge cannot be expected. Nevertheless, the level of correspondence with the measured daily discharge was fairly good. The best fit was achieved during flood conditions, when the ground was not frozen. This is exemplified by the results from the mild and wet winter of 1974/75 (Fig. 6).

It was generally difficult to simulate the winter conditions. Some peaks never appeared while others occurred after some time-lag. In addition, the shape of the peaks was frequently distorted. For instance, there was often a rapid decrease in simulated discharge related to the freezing of the soil. This phenomenon not shown in the measurements, was probably the effect of exaggerated interactions between heat and water movements in the model.

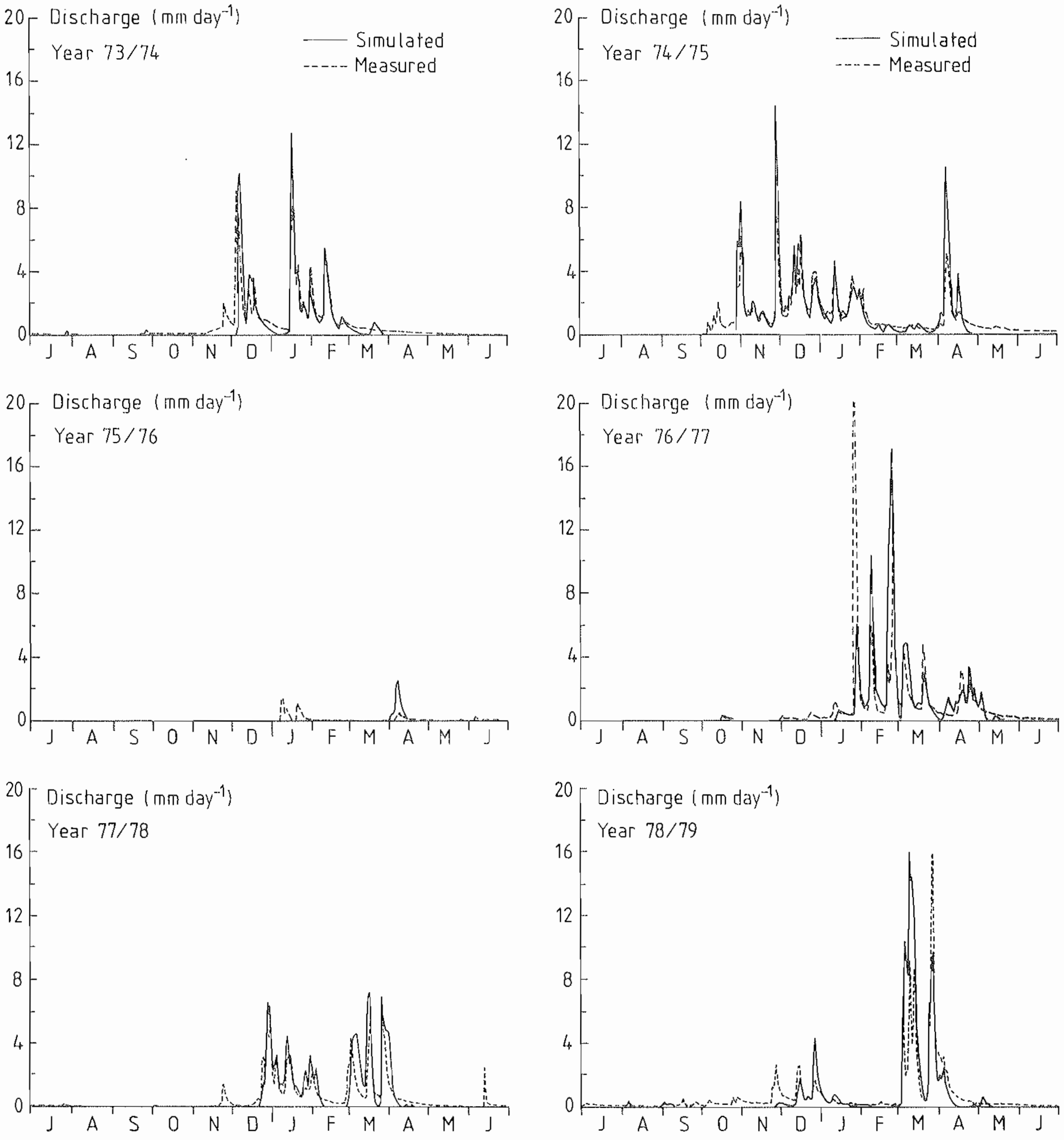

Figure 6. Simulated and measured rates of daily drainage discharge (cont.)

In spite of the dissimilarities between simulated and measured discharge rates, these results are encouraging since the simulation of partially frozen conditions is very difficult (Miller, 1980). This was a major obstacle, especially the repeated freezes and thaws that occurred during winter when temperatures fluctuated around the freezing point. Another difficulty encountered was that the simulated flow during base flow conditions had been underestimated. This probably occurred because the deepest main drains had been installed at a depth of 3.5 m; thus they could have contributed to the flow earlier during autumn and later in the spring, when the model only accounted for a drainage depth of 1 m.

One way to handle this problem could be the use of a submodel incorporating a drainage depth of 4 m over a smaller area and then mixing the two flows.

Groundwater level and discharge

The groundwater pipes installed at the field site were piezometers providing information on potential differences within the groundwater body. The piezometers are sensitive to the pressure in a water body at the point where its filter is placed and are not to be confound with watertable pipes measuring the groundwater table. Nevertheless, the piezometer pressure readings were used to validate the groundwater table fluctuations, generated by the model. This procedure should have been accurate since the depth of the piezometer observations was close to the depth interval of the groundwater table fluctuations.

There was a fairly good agreement between the simulated and measured variation dynamics even if there were differences regarding the pattern and the timing and level of maxima and minima (Fig. 7).

One interesting feature of the model was the ability to estimate rates of water percolation to the deeper groundwater body (groundwater discharge). The simulated percolation figures varied between 21 and 69

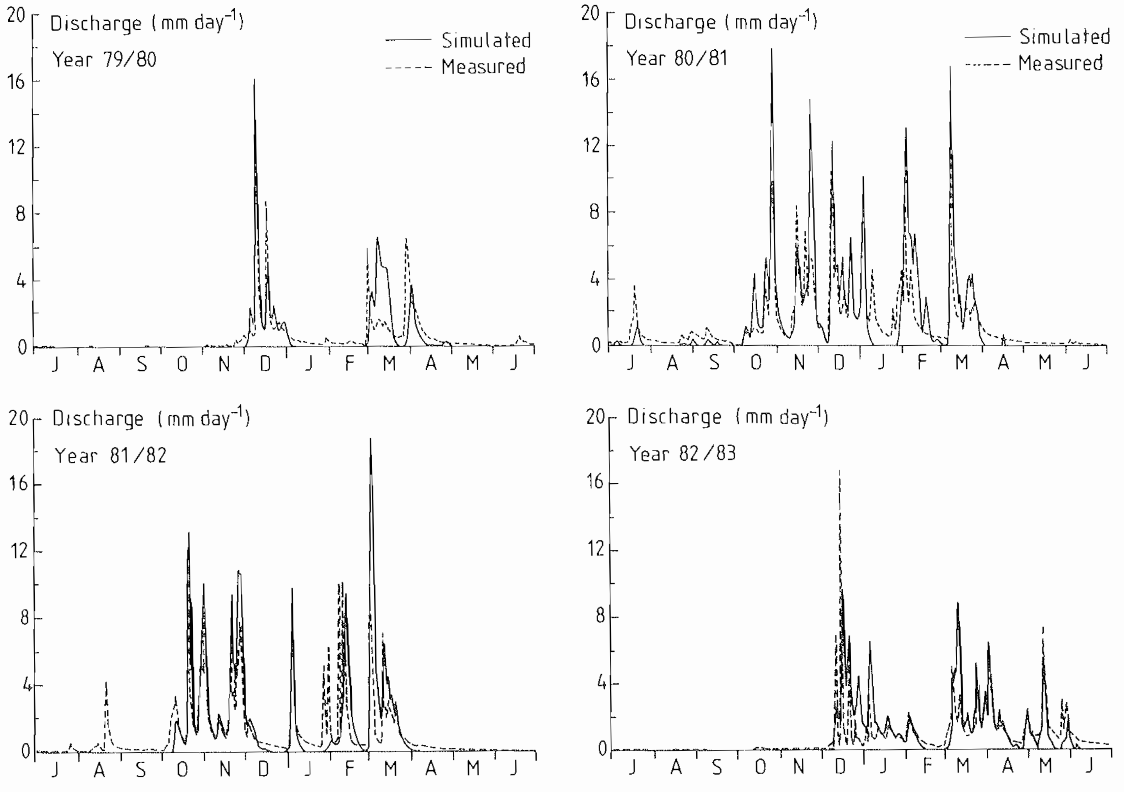

Figure 6. (cont.)

mm y^{-1} with a mean value of 46 mm y^{-1}; this was about 18 per cent of the drainage discharge. The percolation pattern was very closely associated with the water table fluctuations (Fig. 7). Although error in this estimate may have been substantial in the present example the important role of water flows between the drainpipes has been demonstrated. Further investigations on the physical properties of this subsoil should reduce the level of uncertainty in future simulations.

CONCLUSIONS

This study provides an example of how computer-simulated data can correspond well with observed discharge and piezometer measurements. A knowledge of plant and soil characteristics at the site would have improved both the accuracy and reliability of the results. Still it could be argued that as far as simulation of discharge and groundwater conditions are concerned, a shortage of such knowledge can be compensated by the use of adapted parameters if a longterm series of measurements are available.

Another method for improving the accuracy of the simulations would be to take the spatial variability of many parameters into account by making different runs with specific parameter settings; the results from all runs could then be integrated.

The parts of the model treating the winter conditions can still be improved, but this will undoubtedly be a difficult task. Despite its drawbacks, the present model is a very useful tool for predication water discharge rates from arable land.

ACKNOWLEDGEMENT

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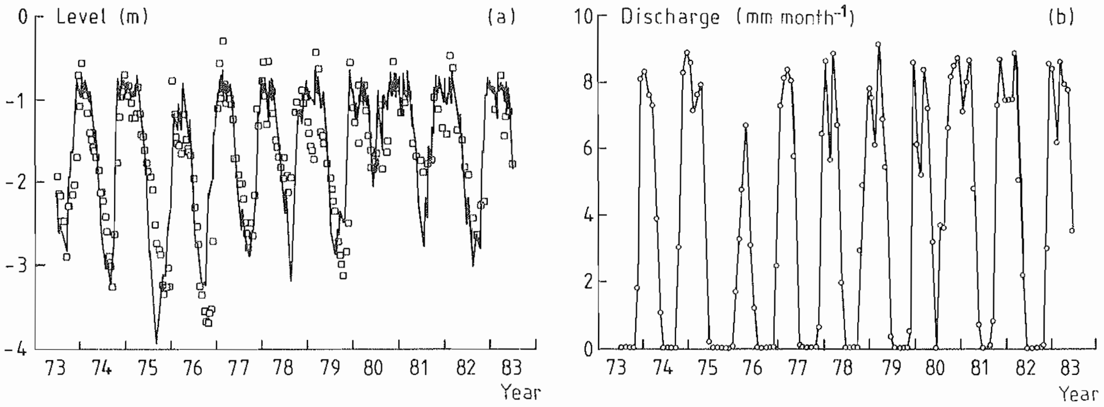

Figure 7. (a) Simulated groundwater table fluctuations and discrete piezometer readings; (b) monthly groundwater discharge.

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SIMULATION OF NITRATE LEACHING FROM ARABLE LAND IN SOUTHERN SWEDEN

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Abstract. Soil nitrate dynamics and nitrate leaching were simulated for a nine-year period. Hydrological time-series, previously simulated with a soil water and heat model were used as driving variables. Parameter values were derived from measurements and management practices or adapted from other comparable applications.

Model outputs were tested against measurements of leaching and nitrate content of the soil. Dominating crops were spring wheat, barley and sugar beets but also winter wheat and winter rape were grown.

Predictions of nitrate in the soil were good on six of eight occasions. Simulated yearly leaching was close to measured values in most years. The deviations could be explained by model failure in predicting surface runoff and uncertainties in the nitrogen harvest.

The between-year variation in the leaching magnitude during years with "normal" discharge rates could largly be explained by the amount of nitrate remaining in the soil profile in the beginning of September and the litter mineralization during the period September-March. Years with higher or lower discharge rates compared to "normal" resulted in increased or decreased nitrate leaching, respectively, compared to normal for the same amount of mineral nitrogen available for leaching.

INTRODUCTION

Long-term field measurements show that modern Swedish agriculture has widely contributed to enrichment of nitrate in both surface- and groundwater (Brink, 1982; Gustafson, 1983; Brink et al., 1986).

Thus, creation of accurate counter measures against nitrate pollution are of the outmost importance due to environmental and health hazards. This requires quantitative understanding of how different combinations of crop management, soils and climatic conditions influence the nitrogen balance.

The most traditional way of obtaining such understanding is long-term field measurements. In combination with field measurements a nitrogen model would be a useful tool when analysing the fate of nitrogen in the soil-crop system more thoroughly.

A number of nitrogen models have been developed (see reviews: Haith, 1982 ; Frissel & van Veen, 1981, 1982; Tanji, 1982). However, only a few have been thoroughly tested against field data. Most applications have been restricted to the site used in connection with the development of the model (Frissel et al., 1983). At the Swedish University of Agricultural Sciences an abiotic model describing water and heat processes was developed (Jansson & Halldin, 1979). To this abiotic model a nitrogen model was recently connected (Johnson et al., 1987) and applied to a three-year field experiment. The result indicated how both measurements of soil nitrogen and leaching can be used when testing the model.

Jansson et al. (1987) applied the model to four field sites three of which were situated in the south of Sweden. The model was used for cal-

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culation of nitrogen storage in the soil and leaching. Only data for validation of nitrogen storage was available in their application and good agreement between simulated and measured nitrogen storage was acchieved.

This paper presents an application of the nitrogen model to long-term leaching measurements at an experimental field, Näsbygård, in southern Sweden. The measurements were started in july 1973 and are still running (Brink et al., 1978; 1986). The first nine years of the experimental period were used for this model application. An application of the abiotic model to the same field site was performed in an earlier investigation (Gustafson, 1987) and all parts concerning the abiotic simulation are mentioned briefly in this paper.

MATERIAL AND METHODS

The field site

The dominating soil type of the field was clay till. The field was drained by a tile drainage system and provided with wells for collecting the surface runoff. The field drains were placed at a depth of 1 m. On certain sites some of the main drains were installed at a depth of 3.5 m, thereby making it possible to drain smaller depressions in the hilly field.

The pipe drainage and the surface runoff rates (drainage discharge) were quantified together at a measuring station using a triangular weir. Flow was registered continuously by a water-stage recorder.

Sampling and analyses

Drainage water for chemical analyses was collected every second week when discharge occurred but more frequently, during flood conditions. All samples were analysed for nitrate with the colorimetric Cd-reduction method (APHA, 1985). The analytical method was adjusted for an auto-analyser.

Tube drills were used for soil sampling. Sampling was performed only on eight occasions. The sampling methods are described in detail by Lindén (1981). The soil samples were deep-frozen in order to prevent N-conversion. For analysis, 120 g of the thawed and moist soil was weighed and extracted with 300 ml 2M KCl. Nitrate concentrations were determined in the extract using the same method as for the water samples. The moisture content of the soil samples was measured gravimetrically.

The water and heat model

The water and heat model is based on two coupled differential equations describing heat and water transport (derived from Fourier's and Darcy's laws respectively) in a one-dimensional soil profile. Precipitation, evapotranspiration, snow dynamics, frost, groundwater flow, water uptake by plants and drainage flow are included.

Most important requirements of model parameters concern soil and plant properties. Soil properties are defined by the water retention curve and the hydraulic conductivity as a function of water content or water tension. Plant properties are those controlling water uptake and transpiration.

The nitrogen model

The nitrogen model includes the major processes determining inputs, transformations and outputs of nitrogen in agricultural soils. The water and heat model provides driving variables for the model, i.e., surface runoff and infiltration, water flow between soil layers and flow to drainage tiles, soil water content and soil temperature.

Pools of inorganic and organic nitrogen are replicated for each soil layer. Organic N is classified as litter, manure-derived faeces and humus. The litter component contains undecomposed material (eg., crop residues, dead roots and microbial biomass) and readily decomposable secondary organic matter. The humus component represents stabilized, resistant material. Carbon pools for litter and faeces are included for controlling nitrogen mineralization and immobilization rates.

The plant is represented by a single state variable including the total N storage. The distribution of plant N, below and above ground, and C-N ratios for different fractions of the plant are model parameters specified by the user.

Inputs from manure, inorganic fertilizers and atmospheric deposition are made to the soil surface. Losses from denitrification and leaching nitrate in water flow to drainage tiles can occur from each soil layer. Nitrate in solution is transported between soil layers or to drainage tiles depending on the water flow.

Agricultural management practices and different crop characteristics can be used to estimate most model parameters controlling input and output of nitrogen. The most important information requirements for determining model parameters are those describing different nitrogen transformations in the soil. All nitrogen transformations are controlled by response functions which account for their dependence on water content and temperature. Some of these functions are well known from laboratory studies but are only qualitatively known and must be roughly estimated (see Johnsson et al., 1987).

Validation of the leaching output from the model

The simulation of nitrate leaching is dependent on both soil nitrate concentration and drainage water flow. For validation purposes a time series of leaching was calculated from measured nitrate concentrations and measured drainage discharge (hereafter referred to as measured leaching).

ADAPTATION OF THE NITROGEN MODEL AND PARAMETER DERIVATION

General

Many of the parameters, especially those concerning mineralization and immobilization, could be chosen identical or close to the values used by Jansson et al. (1987) due to their application of the model to a similar soil type and partly identical crops.

Driving variables

The driving variables for the nitrogen model were derived from the water and heat model, i. e., soil temperature, soil-water content and drainage discharge. Of these variables only the drainage discharge could be tested against field observations. The agreement between simulated and measured drainage discharge was good on a yearly base. Some missmatches occurred on a daily basis especially during periods with

Table 1. Crop, fertilization and management.

Year	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Crop	Spring wheat	Barley	Sugar beet	Spring wheat	Barley	Sugar beet	Spring wheat	Barley	Winter rape	Winter wheat
Fertilization (N kg ha^{-1})	112	79	135	112	78	140	120	91	50[a]+189	122
Fertilization date	26 Mar	14 Mar	21 Apr	20 Apr	23 May	11 Apr	12 Apr	15 Apr[b]	1 Apr[c]	31 Mar
Starting of plant uptake	26 Apr	10 May	10 May	4 May	30 May	10 May	14 May	8 May	1 Apr	10 Apr
Harvest date	29 Aug	15 Aug	15 Oct	26 Aug	18 Aug	15 Oct	18 Sep	14 Aug	4 Aug	24 Aug
Yield (t ha^{-1})	4.08	5.11	38.5	4.17	4.20	45.8	4.42	4.80	2.00	8.06
Ploughing date	8 Oct	20 Aug	27 Oct	7 Sep	20 Aug	27 Oct	20 Sep	16 Aug	9 Aug	25 Aug

[a] Applied 23 Sep. 1980. [b] First date of split application. Second date 27 Apr. [c] First date of split application. Second date 26 Apr.

repeated freezing and thawing (Gustafson, 1987).

Crop, fertilization and management

Type of crop rates and timing of nitrogen fertilization are presented in Table 1.

The first date of plant uptake was set to the day when seedlings emerged through the soil surface.

The yield was measured by the farmer using normal methods. These did not include analyses for determining the nitrogen harvest which, therefore, had to be estimated.

The field was usually cultivated twice after harvest. In the model, above-ground crop residues were mixed with the topsoil on the first occasion. The second occasion was only supposed to favour the conditions for mineralization.

Nitrogen deposition

The deposition of nitrogen was given values according to Monitor(1984). Dry deposition of mineral nitrogen was set to 3.65 N kg ha^{-1} yr^{-1} and concentration of nitrogen in wet deposition was given the value 0.80 N mg l^{-1}.

Root development

Timing of root developement was related to observations of phenological stages of the crops. The relative root distribution was based on general knowledge and was therefore not site specific, 70 percent of the roots occurred in the plow layer (0-25 cm) in all crops.

Potential plant uptake

The value of potential nitrogen uptake in the model is considered as an absolute value for each crop and the actual uptake of nitrogen is only limited by the potential nitrogen uptake and the availability of nitrogen in the soil. Other production factors, such as soil humidity, tem-

Table 2. Crop related parameters.

Year Crop	1973 Spring wheat	1974 Barley	1975 Sugar beet	1976 Spring wheat	1977 Barley	1978 Sugar beet	1979 Spring wheat	1980 Barley	1981 Winter rape	1982 Winter wheat
Potential nitrogen uptake (N kg ha^{-1})	170	160	270	180	140	280	200	160	50[a]+200	30[b]+240
Harvested fraction of plant N	0.50	0.40	0.30	0.50	0.35	0.35	0.55	0.50	0.50	0.50
Above-ground residue fraction of plant N	0.20	0.15	0.40	0.20	0.15	0.40	0.20	0.15	0.20	0.20
C-N ratio of above-ground residue fraction	50	50	25	50	50	25	50	50	50	50

[a] In the autumn 1980. [b] In the autumn 1981.

perature and meteorological elements are not considered. The yield reflects, to some extent an integrated result of all production factors. To make the actual nitrogen uptake more dependent on these factors the potential nitrogen uptake was given different values not only dependent on crop type but also related to the actual yield for each crop (Table 2).

Harvested fraction of plant N

The harvested fraction was supposed to be crop specific but also dependent on yield and nitrogen fertilization level (Table 2). Higher nitrogen fertilization levels often lead to higher protein content in the grain and thus increased nitrogen harvest.

The higher values of the harvested fraction for sugar beets in 1978, spring wheat in 1979 and barley in 1980 were due to higher yields in combination with higher fertilization levels. The lower value for barley in 1977 was due to poor harvest after bad growing conditions during that year.

Crop residues

The above-ground residue fraction of total plant-N was set different to each crop (Table 2). The high value (0.40) for sugar beets was due to the normally high level of above-ground crop residues.

The C-N ratio of the above-ground residue fraction of the individual crops was set to 50 for all crops except sugar beets, for which 25 was used (Table 2). The C-N ratio of roots was set to 25 for all crops.

Litter turnover

The litter specific decomposition rate was set to 0.035 of total mass per day.

The efficiency of microorganism synthesis was set to 0.50, i.e., 50 % of the carbon was retained in the soil, and 50% was respired to the atmosphere.

The litter carbon humification fraction was set to 0.12. This value is slightly lower than those used in other applications, e.g. Jansson et al. (1987) used 0.15. A lowered value causes a lowered humification rate.

Table 3. Simulated yearly nitrogen deposition and mineralization (N kg ha^{-1} yr^{-1}).

Year	73/74	74/75	75/76	76/77	77/78	78/79	79/80	80/81	81/82
Deposition	8.6	10.2	7.8	9.5	8.9	9.5	8.9	11.3	11.0
Humus mineralization	13.3	13.0	13.1	13.1	12.8	13.2	13.1	13.6	13.1
Litter mineralization	63.4	61.9	82.7	77.0	62.7	78.1	65.2	57.0	56.5

Humus mineralization

The initial amount of humus-N in the uppermost 100 cm of the soil profile was given the value of 8200 N kg ha^{-1} with the major part in the topsoil, 0-25 cm depth. Mineralization of humus is calculated as a first-order reaction. The rate coefficient for the humus specific mineralization rate, which represents optimal moisture and temperature conditions, was set to a value of 1.0 10^{-5} of total mass per day.

Nitrification

The rate coefficient for the specific nitrification was estimated to 0.20 day^{-1}. The nitrate/ammonium equilibrium ratio was set to 6 which was based on measured averages for a clay till soil (Jansson et al., 1987).

Soil moisture response-mineralization

The minimum water content for mineralization was adjusted until a reasonable mineralization rate was achieved during summers. The activity increased linearly to a maximum threshold level during the increase of water content by 8 volumetric per cent. A linear decrease, from the maximum to the minimum activity at saturated conditions, was also assumed to occur over an interval of 8 volumetric per cent. The saturation activity was put to zero.

Soil temperature response

The temperature response to a 10 °C change was given a value of 2, i.e. the rates of decomposition, mineralization and nitrification were doubled when the temperature increased by 10 °C. Data from Lindén & Nouno (1983) give a value around 2.1 in experiments.

Denitrification

The potential rate of denitrification was assumed to be low (0.10 N kg ha^{-1} day^{-1}). No denitrification was supposed to occur when the air porosity exceeded 10 volumetric per cent.

RESULTS AND DISCUSSION

General

The most difficult thing during the simulations was to get reasonable nitrogen uptake by the crops. This was of vital importance for the final result since nitrogen uptake is a major sink term. The fact that nitrogen availability is the only limiting factor for uptake and that no consideration is paid to other time varying factors, included such as drought stress or meteorological elements, made it difficult to get an accurate uptake without changing the potential uptake for different crops and years. The most practicable approach was to relate potential uptake to yield. In this context the lack of information concerning the nitrogen harvest was also troublesome.

Deposition, mineralization and crop uptake

The simulated yearly deposition was the smallest nitrogen source and varied between 7.8 and 11.3 N kg ha^{-1} yr^{-1} (Table 3).

The dominating mineralization took place in the litter pool, and as a mean for the investigated period was five times larger than the humus mineralization rate. The between-year variation in litter mineralization rate was also larger than in the humus mineralization rate (Table 3). However, compared to the yearly variation in fertilizer application rates, the variation in litter mineralization rates must be regarded as small (Tables 1, 3).

The yearly sum of deposition and net mineralization and yearly fertilization averaged 89 and 123 N kg ha^{-1} yr^{-1}, respectively. Thus the most important N-source was fertilization.

The litter mineralization showed a typical variation pattern with a net immobilization phase after ploughing in most years (Fig. 1). A substantial net mobilization (average; 16.6 N kg ha^{-1} yr^{-1}) took place during the winter months (January-March) each year. There was an increased mineralization during years following sugar beets (1976 and 1979), especially in the May-July periods.

The simulated crop uptake for different crops and years showed a large variation (values in N kg ha^{-1} yr^{-1});

Year	1973	1974	1975	1976	1977	1978	1979	1980	1981
Crop	Spring wheat	Barley	Sugar beet	Spring wheat	Barley	Sugar beet	Spring wheat	Barley	Winter rape
Uptake	159	139	212	161	127	213	176	184	154

The uptake by barley in 1980 also includes uptake by the winter rape during the autumn of that year.

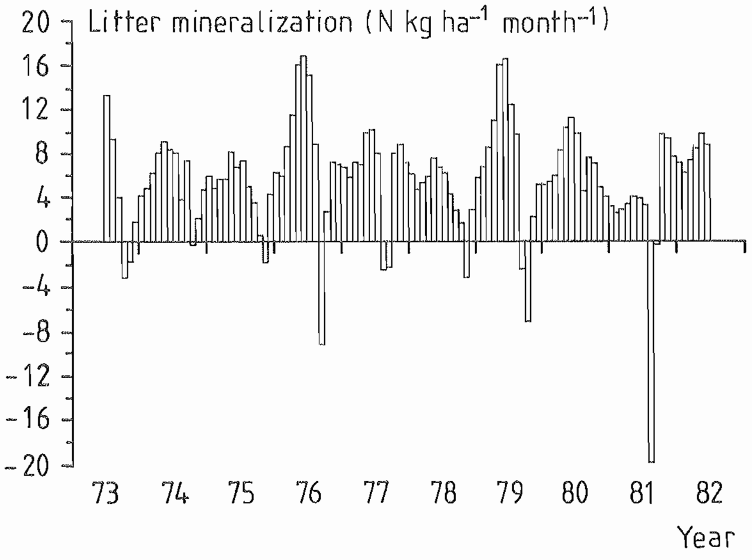

Figure 1. Simulated monthly mineralization from the litter pool.

Soil nitrate

The overall seasonal dynamics of simulated nitrate contents of the soil agreed well with other findings (e. g. Johnsson et al., 1987; Bergström, 1986). The simulated contents agreed well with measurements in six of eight occasions which must be considered as confirming that the simulation gave the correct result (Fig. 2).

The highest nitrate contents followed fertilization, after which the content decreased due to crop uptake until the time of harvest. Very low nitrate contents appeared after sugar beets in 1975 and 1978 due to their large nitrogen uptake. A very high value after harvest of winter rape in 1981 could be explained by the fertilization rate being to high in relation to yield.

There was mostly an increase in nitrate content from harvest to sowing in the following year (seven of nine occasions), implying that the increase of nitrate through mainly mineralization exceeded the losses through mainly leaching. This increase was especially pronounced during the winter of 1975/76 due to a low discharge rate that winter. It was also a memory effect of this increase in that the soil nitrate content after harvest in 1976 was also fairly large.

Leaching losses

The discharge rate and the amount of nitrate in the soil profile are two of the main controlling factors for the leaching magnitude. Since both were well described by the simulations, the simulated leaching also could be expected to be good.

The simulated yearly losses of nitrate agreed well with measured losses in most of the years. For the last year the agreement was bad (Fig. 3).

The low soil nitrate content after sugar beets in 1978 led to lowered leaching during 1978/79 than could be expected from the discharge rate.

Very high discharge rates and fairly large amounts of soil nitrate caused increased leaching during the last two years.

The big deviation from measured leaching in the final year can, to some extent, have been caused by the fact that a fairly large portion of the surface runoff took place during the spring flood that year while the water and heat model accounted for drainage discharge only. Nitrate concentrations are normally lower in surface runoff compared to drainage discharge (Gustafson & Torstensson, 1983). Thus, simulated leaching was apparently overestimated.

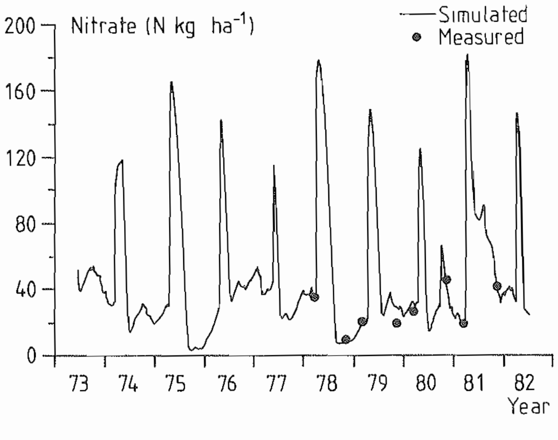

Figure 2. Simulated and measured nitrate in the soil.

Table 4. Simulated values of different factors affecting the leaching variation (totals from September-March in N kg ha^{-1}).

Year	73/74	74/75	75/76	76/77	77/78	78/79	79/80	80/81	81/82
Soil nitrate (1 Sep.)	47.3	24.9	9.1	42.6	20.6	7.4	28.2	27.1	69.5
Litter mineralization	16.1	30.1	27.0	27.0	37.3	24.9	14.3	31.7	46.5
Humus mineralization	6.2	6.6	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Deposition	5.8	6.8	4.8	6.1	5.9	6.1	5.3	7.2	6.7
Autumn fertilization	0	0	0	0	0	0	0	50	0
Crop uptake	0	0	13.6	0	0	5.2	0	45.7	18.5
Leaching of nitrate	32.9	26.8	0.1	35.6	27.4	12.4	18.8	57.9	67.8
Discharge (mm)	175	263	9	195	198	201	161	524	406

The relatively small deviations during the other years could probably have been lowered if better knowledge of harvested nitrogen had been available. The reason is that this sink term is of vital importance for the amount of nitrogen that can enter the litter pool and thus also for the amount of nitrate available for leaching after mineralization and nitrification.

Relative importance of different factors affecting the leaching variation

Many authors have tried to make correlations between the amount of nitrate in the soil profile at the end of the growing season and the amount of nitrate leached during the winter period. Bergström & Brink (1986), for example got a significant correlation (with $p < 0.001$) between the amount of min-N remaining after harvest and nitrate leached during the following winter period. Besides the soil min-N after harvest, other factors as mineralization and deposition during the winter should be taken into account. The simulated result can be used for looking more thoroughly into this.

By choosing September 1 as the end of the growing season and letting the winter period extend from September to March, the factors taken into consideration can be derived from the simulation (Table 4).

By looking into the discharge rates it can be concluded that the material can be divided into three groups: one for years with low discharge (1975), one for years with high discharge (1980 and 1981) and

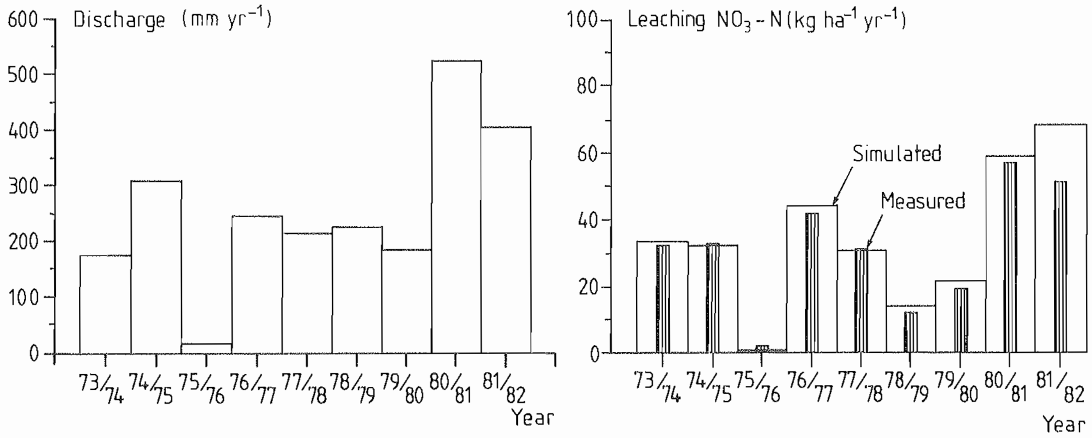

Figure 3. Simulated yearly drainage discharge rates. Simulated and measured yearly losses of nitrate.

one group with "normal" discharge in the other years.

For the group with normal discharge rates the correlation between different factors or combinations of factors, can be used to conclude which factors apart from the discharge are of vital importance in explaining the between-year variation of the leaching magnitude.

Since the soil nitrate (1 Sep.) and the litter mineralization have the most pronounced between-year variation among the actual factors they must also be most responsible for the between-year variation in the leaching. This can also be concluded from the following correlations where different factors have been gradually added to the soil nitrate value;

Dependent	Independent	r^2	p
Leaching	Soil nitrate (1 Sep.)	0.719	< 0.05
Leaching	Soil nitrate (1 Sep.) and litter mineralization	0.985	< 0.001
Leaching	Soil nitrate (1 Sep.), litter and humus mineralization and deposition (total mineral nitrogen available)	0.985	< 0.001

Thus, to get an fairly acceptable correlation and level of significance at least the soil nitrate and litter mineralization should be included. Using the total available nitrogen did not improve the correlation.

The two years with much higher and the one year with a much lower discharge rate compared to "normal", resulted in increased and decreased nitrate leaching, respectively, compared to the normal situation for the same amount of total mineral nitrogen available for leaching (Fig. 4). Adjustments have been made for fertilization and crop uptake.

CONCLUSIONS

The application of the nitrogen model to Näsbygård experimental field showed generally good agreement between simulations and measurements. Most parameters could easily be derived from measurements or adapted from other comparable applications.

In this study, more accurate information about the nitrogen harvest

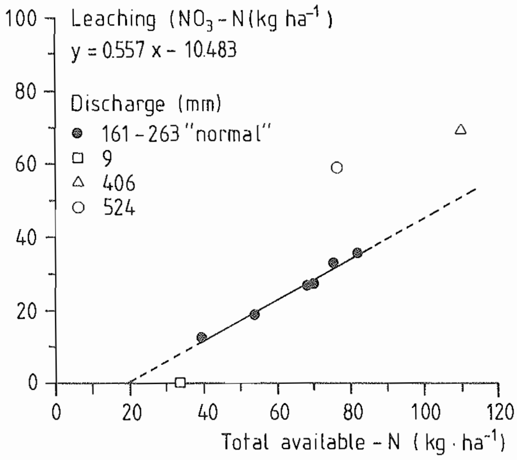

Figure 4. Correlation between total mineral nitrogen available and leaching during the September-March period for years with "normal" discharge rates (161-263 mm). Three years with pronounced diverging discharge rates, not included in the correlation, are also shown in the diagram.

would have improved the final result. But in spite of this, the result indicates that the model can be a useful tool for the estimation of nitrogen storage in the soil and leaching losses. One necessary condition is, of cause, that the water and heat simulation which provides the nitrogen model with driving variables must be successful.

To use the model for predicting future leaching losses would require an improvement of the part of the model handling the nitrogen uptake. The use of a fixed potential uptake curve with nitrogen availability as the only limiting factor for uptake is a very simple approach. Other time varying factors as drought stress and meteorological elements have to be included simply to make the model more production-orientated.

The between-year variation in the leaching magnitude could largely be explained by the amount of nitrate remaining in the soil profile in early September and the litter mineralization during the period September-March. Years with higher or lower discharge rates compared to "normal", resulted in increased or decreased nitrate leaching, respectively, compared to the normal situation for the same amount of mineral nitrogen available for leaching.

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ESTIMATION OF GROUNDWATER RECHARGE AND RELATED LOSSES OF NITRATE IN A TILE DRAINED CLAY TILL

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Abstract. Groundwater recharge in a tile drained clay till was previously estimated by use of a simulation model. The reliability of simulated recharge was analysed by comparison with the differences between stream runoff from a nearby flowing stream and tile drainage discharge. The area covered by the stream basin was such that the stream runoff could be considered to include also groundwater discharge. The comparison showed that the simulated recharge was of the same order of magnitude as the difference between stream runoff and tile drainage discharge.

The simulated groundwater recharge was dependent on the actual annual humidity conditions while the contribution to stream runoff from groundwater, due to the large regional groundwater aquifer involved, showed nearly no dependence on the annual humidity conditions.

Nitrate content in groundwater decreased with depth of observation. Estimated losses of nitrate passing the 2.9 m and 5.6 m horizons in the ground did not exceed 3.5 and 1.9 NO_3-N kg ha^{-1} yr^{-1} respectively.

INTRODUCTION

The importance of water flow passing tile drains for groundwater contamination by nitrate in recharge areas under Swedish conditions has been described earlier (Gustafson 1983, Bergström and Brink 1986). In this context it would be interesting to estimate the amount of nitrate lost by this groundwater recharge flow into deeper horizons in the ground and not only to describe variations in the nitrate content of the groundwater.

To quantify the recharge without using expensive and sophisticated methods is, however, a difficult task. An easier and more practical method is to use a simulation model to get at least a good estimate of the recharge. This was done in a previous investigation (Gustafson, 1987). The error in simulated recharge might, however, be substantial due to insufficient information on the subsoil.

One way of considering the reliability of the simulated recharge would be to compare it with the difference between stream runoff from a nearby flowing stream and tile drainage discharge. However, the area of the stream basin must be of such an extent that the stream runoff can be considered to include also groundwater discharge.

Both an analysis of the reliability of simulated groundwater recharge by comparison and an estimate of the nitrate lost by deeper percolating groundwater are made in this paper.

MATERIAL AND METHODS

The experimental field site

A network of representative experimental fields was established by the

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Division of Water Management at the Swedish University of Agricultural Sciences to gather information on long-term trends in discharge and mass transport of nutrients from arable land in Sweden (Brink and others 1979). One field (Näsbygård) in the very south of Sweden was chosen for this investigation.

The experimental field was drained by a tile drainage system and provided with wells for collecting the surface runoff. The field drains were placed at a depth of 1 m. Tile drainage discharge (including surface runoff) was quantified in a measuring station using a triangular weir. Flow was registered continuously by a waterstage recorder.

The quaternary stratifications in the area have a depth extension of about 100 m and the uppermost 50 m consists mainly of clay till (Holst 1911, Nilsson 1973).

Piezometers were installed at four sites with intakes at two levels at each site. Three of these sites, representing clay till (the dominating soil type in the field) were included in this investigation. Pressure readings were taken every second week.

The most elevated point of the experimental field is 54 m and the lowest 47.5 m above the sea level. The elevation and depths of piezometer observations are:

Site number	2		3		4	
Elevation above the sea level (m)	52.0	52.0	50.0	50.0	47.5	47.5
Depth under the soil surface (m)	2.5	5.2	2.9	5.6	2.5	5.1

Thus, piezometer site number 4 is located at the lowest point in the field. The observations at site 4 were started later than at the other sites.

For validation purposes during the simulations the results from site 3 were used to describe a mean situation.

The crop rotation included barley, sugar beets, spring wheat, winter wheat and winter rape, and can be considered representative for normal cropping practices in the area.

The stream basin

The nearest stream basin, Dybäcksån, within which the experimental field lies on the western water divide, could not be used owing to the impact of water regulations on stream runoff rates there. Another nearby stream basin, Skivarpsån, was therefore selected for the comparison between the stream runoff and the tile drainage discharge (Fig. 1).

The Skivarpsån basin has an area covering 12,400 ha. Dominating soil type is clay till. The land use percentages are distributed into; arable land 89, meadow 3, forest 4 and other land 4 (including water). Thus, arable land is entirely dominating which is also a necessary condition for making flow comparisons with the experimental field since most of the land then is tile drained and the evapotranspiration can be regarded as being similar.

Stream runoff was recorded by the Swedish Meteorological and Hydrological Institute (SMHI) using traditional techniques with a water stage recording station.

The precipitation was also recorded by SMHI at Skurup, in the centre of the investigation area, close to the western water divide of the stream basin and 4 km NE of the experimental field. These precipitation records were also used in the simulations. Since the topography of the area was quite similar throughout the whole stream basin the precipitation records can be regarded as having good representativity for the whole basin.

Sampling, analyses and calculations

Water samples for chemical analyses of groundwater were taken once a month but more frequently for drainage water. The samples were analyzed for nitrate using the colorimetric Cd-reduction method (APHA, 1985). The analytical method was adjusted for an auto-analyser.

Simulated groundwater recharge was taken from Gustafson (1987).

The yearly means of nitrate concentrations presented are arithmetic means. Yearly nitrate losses by groundwater recharge were calculated through multiplication by simulated yearly recharge and yearly mean concentrations.

Losses by drainage water were taken from an earlier publication (Brink and others 1986).

RESULTS AND DISCUSSION

General

To make the interpretation of the results easier, the use of a simplified groundwater model may be of great help. This approach was used by Gustafsson (1970) by assuming the presence of an idealized aquifer with an homogeneous composition of equal hydraulic conductivity. The hilly and inclined landscape causes the creation of a fairly complex stream-

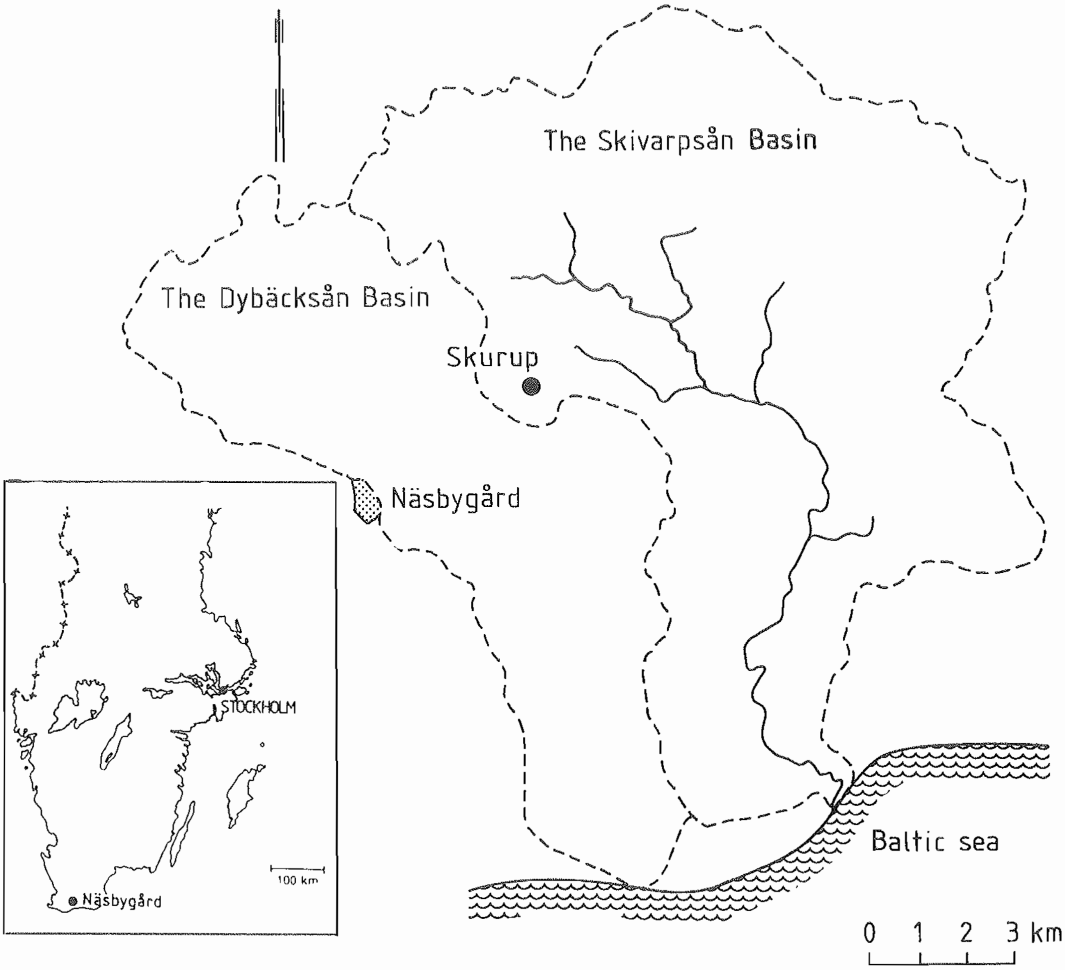

Figure 1. Map showing location of experimental field, stream basin and stream main drainage pattern.

line pattern depending on the actual momentary potential conditions. The landscape can be divided into recharge and discharge areas depending on the actual direction of the vertical flow component (Fig. 2). Most of the groundwater established in a hilly landscape will be discharged in local discharge areas but some will be discharged at greater distances away.

Grip and Rodhe (1985) suggest that most of the groundwater flow takes place near the soil surface due to decreasing hydraulic conductivity with depth. This ought to apply also to the thick clay till layer in the experimental field. The consequences of this are that waterflows following the short streamlines along the hill slopes closer to the soil surface are more intensive and have shorter transit times than the waterflows following deeper streamlines.

If the experimental field and its piezometer sites are placed into the hypothetical landscape presented in Figure 2, it must be positioned close to the uppermost water divide (dotted line). Consequently, if the theoretical approach is correct, the pressure gradient observed by the piezometers should decrease from the water divide and downhill. Most of the field is placed on a recharge area and only the lowest part around piezometer site 4 is close to a local discharge area.

Further, it can be concluded that groundwater originating from the experimental field will contribute both to the discharge for drainage systems of fields lying downhill as well as directly to the main stream in the valley bottom. As regards the latter, a considerable period must elapse first.

The possibility of drawing conclusions about the reliability of simulated groundwater recharge passing by the tiles by means of comparing the differences between the stream runoff and the tile drainage discharge is obvious. Of course, it is necessary to bear in mind the different transit times due to different pathways of the groundwater flow but provided that the time of observation is fairly long, the comparison method offers a practicable approach to a difficult task.

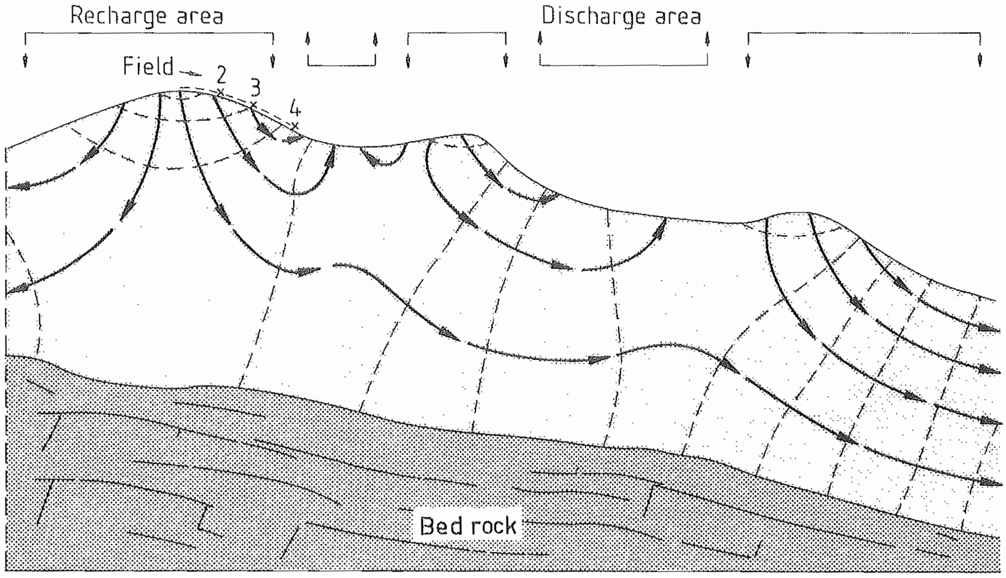

Figure 2. Total potential (dotted lines) and streamlines for groundwater in an idealized aquifer with an homogeneous composition of equal hydraulic conductivity in a hilly and inclined landscape. The experimental field and its piezometer sites (2, 3 and 4 can be given a probable position close to the upper water divide.

Pressure gradient

The piezometer readings at sites 2 and 3 always showed decreasing pressure levels with depth indicating downward movement of water. Both the pressure gradient and the pressure level amplitude were more pronounced at site 2, closer to the water divide (Fig. 3).

At site 4 there was nearly no vertical gradient at all, leading to a dominating horizontal flow component. The level amplitude was also very small, compared to the other sites, which is typical of a discharge area (Gustafson 1983). In fact, there were also occasions with upward movement of water at this site. However, the amount of water moving upwards must have been almost negligible.

Consequently, at all sites the observations were in good accordance with what could be expected from the model presented in Figure 2.

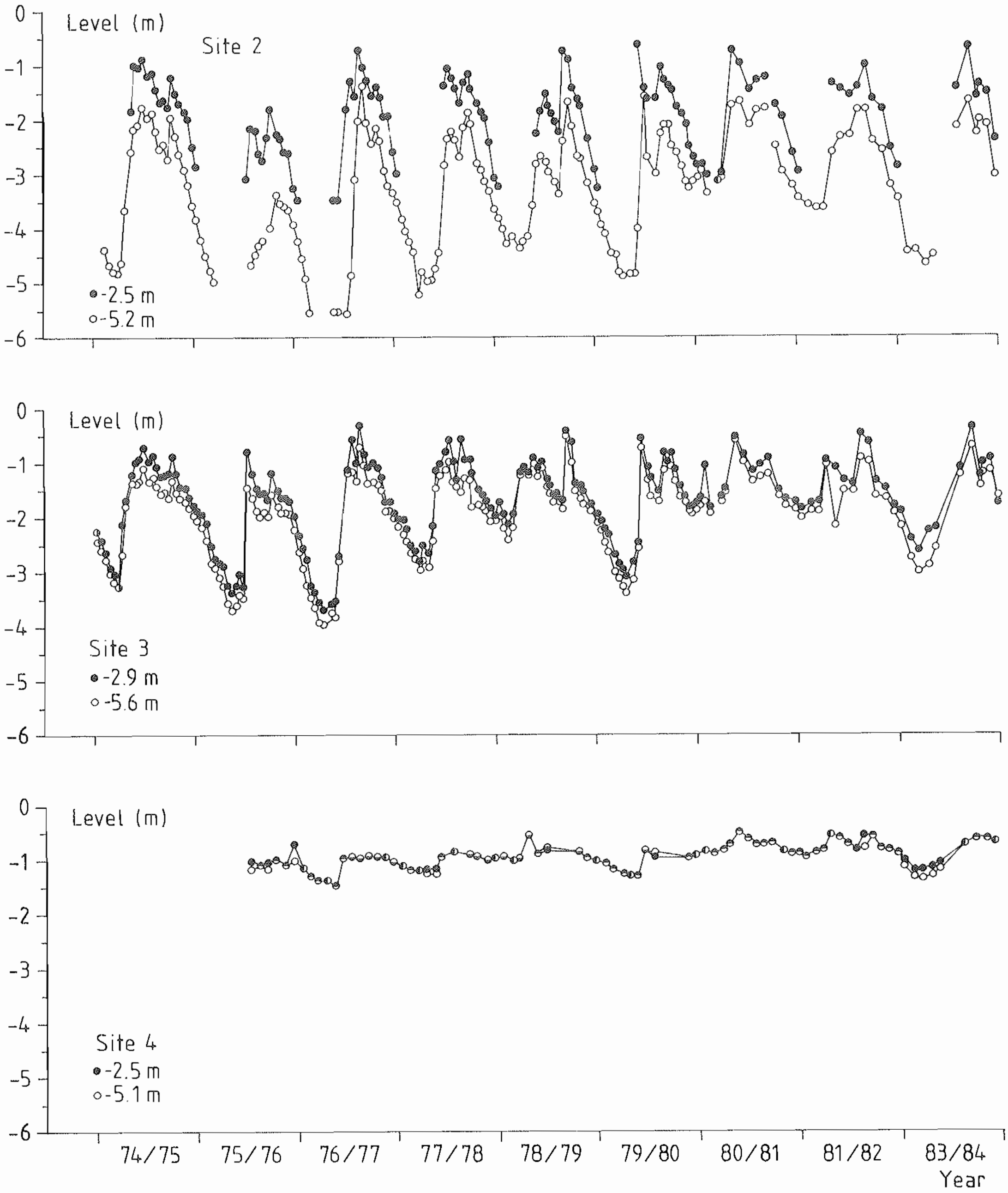

Figure 3. Measured pressure levels in the investigated piezometers.

Table 1. Annual precipitation and flows. (All values in mm yr^{-1}.)

Year	74/75	75/76	76/77	77/78	78/79	79/80	80/81	81/82	82/83
Precipitation[a]	825	535	735	680	745	665	990	935	770
Tile drainage discharge	305	16	235	189	219	171	520	377	276
Stream runoff	330	113	272	265	282	249	597	450	335
Differences between stream runoff and tile drainage discharge	25	97	37	76	63	78	77	73	59
Simulated groundwater recharge	56	21	40	39	51	39	69	55	54

[a] Corrected due to wind losses. Correction factors for rain and snow are 10 and 17 percent respectively.

Comparison between tile drainage discharge and stream runoff

The investigated period presented large between-year variations in precipitation, tile drainage discharge and stream runoff. Both low and high values during 1975/76 and 1980/81, respectively, were exceptional during the last 50 years (Gustafson 1986). The differences were as large as hundreds of mm of water (Table 1).

The differences between tile drainage discharge and stream runoff on a yearly base varied between 25 and 97 mm of water. The maximum disparity occurred during the dry year of 1975/76, the explanation being that the large regional groundwater aquifer effecting the stream runoff was only slightly influenced by the drier weather this year and therefore contributed about the same amount of water as during the other years.

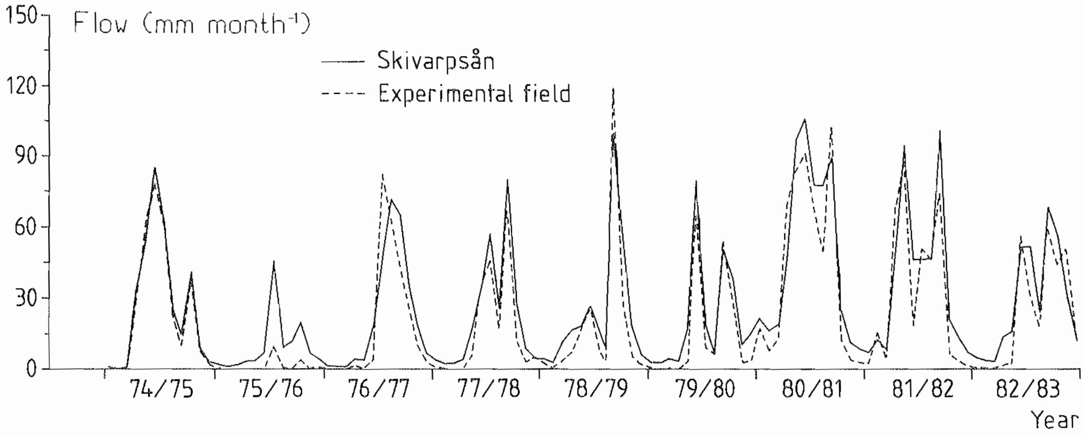

Figure 4. Monthly stream runoff and tile drainage discharge.

Table 2. Yearly mean concentrations and losses of nitrate.

Year	74/75	75/76	76/77	77/78	78/79	79/80	80/81	81/82	82/83
Concentration NO_3-N (mg l^{-1})									
Tile drainage water	9.7	9.9	16.4	14.3	5.8	10.0	9.0	11.5	11.5
Groundwater (2.9 m)	6.4	7.6	7.7	7.0	3.3	5.1	4.3	3.0	2.2
Groundwater (5.6 m)	0.6	0.5	1.4	5.0	2.4	3.8	1.5	1.1	0.7
Losses NO_3-N (kg ha^{-1} yr^{-1})									
Tile drainage water	32.5	1.9	41.6	30.9	11.9	19.4	56.7	51.3	36.4
Groundwater (2.9 m)	3.5	1.6	3.1	2.7	1.7	2.0	3.0	1.7	1.2
Groundwater (5.6 m)	0.3	0.1	0.6	1.9	1.2	1.5	1.0	0.6	0.4

The monthly variation patterns of the tile drainage discharge and stream runoff were fairly similar (Fig. 4). With few exceptions the tile drainage discharge was generally slightly lower than the stream runoff. During drier years the tile drainage flow ceased during the summer months, which was not the case with the stream flow. The importance of groundwater contribution to the stream flow was evident.

The simulated yearly groundwater recharge in the experimental field was largely related to actual humidity conditions with a minimum value during the dry year of 1975/76 and a maximum during the wet year of 1980/81 (Table 1).

Compared to the measured annual difference between stream runoff and tile drainage discharge it can be concluded that the simulated annual groundwater recharge was of the same order of magnitude and can therefore be regarded as a reliable estimate of groundwater flow into deeper horizons of the experimental field.

Nitrate in water

The yearly means of nitrate concentrations varied widely both in tile drainage water and groundwater and the nitrate content decreased with depth of observation (Table 2). This decrease might be caused by chemical reduction of nitrate (Lind and Pedersen 1976). Under all circumstances dilution can be excluded due to the flow pattern at the experimental field (Fig. 2).

The calculated mass transport of nitrate passing the 2.9 m and 5.6 m horizons was fairly small compared to losses by tile drainage water (Table 2).

Conclusion

The result indicates that comparison between stream runoff and tile drainage discharge offers a possibility to check the reliability of simulated groundwater recharge.

The estimated amount of nitrate lost by this bypass flow is of minor importance compared to the measured losses through tile drainage in the clay till investigated.

ACKNOWLEDGEMENT

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SIMULATION OF SURFACE RUNOFF AND PIPE DISCHARGE FROM AN AGRICULTURAL SOIL IN NORTHERN SWEDEN

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ABSTRACT

In order to test the ability of a physically based water and heat model to predict surface runoff and pipe discharge, adaptations were made to an agricultural field in the north of Sweden. A five-year period was selected, including observations of meteorological data, frost in the soil and discharge. Basic model requirements on soil properties, i.e., the water retention curve and the saturated hydraulic conductivity, were available from a previous investigation. Unsaturated conductivity was estimated from the water retention curve and by assuming a substantial influence of macro pores in the subsoil. Snow properties and thermal soil properties were adjusted to obtain a reasonable agreement with observed frost depths for areas with barley and with grass leys. Surface runoff was the dominating part of the total runoff, especially during conditions of frozen soil. The simulated discharge agreed well with the general partitioning between surface runoff and pipe discharge but discrepancies occurred in their temporal patterns. A probable explanation of these discrepancies was that the model did not account for the enhanced spatial heterogeneity in water flow through snow and in partially frozen soil.

INTRODUCTION

The importance of surface runoff as a source for the formation of stream runoff has long been an area of conflicting opinions among hydrologists. Recent studies in Sweden by Rodhe (1984 and 1985) have clearly demonstrated the importance of ground water flow in forested catchments during the snow melt period. The major portion of the snow melt was infiltrated into the soil profile and only a minor portion, in the saturated region close to the stream, formed surface runoff. In contrast, Gustafson et al. (1984) reported that 82 % of the spring flood was surface runoff from an agricultural field during a five-year period in the north of Sweden.

Occurrence of frost in the soils may be one of the key-factors behind the differences reported in the magnitude of surface runoff. The forested catchments investigated by Rodhe (1984 and 1985) were all heterogenous with respect to an organic soil cover which prevented the frost from penetrating deeply and homogeneously. In the agricultural soil investigated by Gustafson et al. (1984) the frost could penetrate deeper because the soil was bare after the end of the growing season and because of the lack of an organic soil layer.

Modelling of water movements in partially frozen soils was first presented by Harlan (1973) and was followed later by a number of similar studies, e.g., Jansson & Halldin (1979). Most of the models have been tested only for a limited data set, commonly covering a short time period. This restricted our hope to be able to accurately predict water movements in frozen field soils. In the study of Halldin et al. (1980) a considerable delay of the percolating water flow was found during a year with deep frost. During another year, with a shallow frost layer, the infiltrating water penetrated the frost without any delay. Unfortunately, these differences could not be quantitatively tested because of the lack of water flow measurements.

The purpose of this paper is to present our efforts to test the soil water and heat model (Jansson & Halldin, 1979) for the agricultural soil investigated by Gustafson et al. (1984). Emphasis was placed on the partitioning between surface runoff and drainage through pipes and the importance of a grass cover on the development of frost in the soil.

MATERIALS AND METHODS

Site description

The field is situated at Röbäcksdalen, immediately to the south of the town of Umeå in northern Sweden. The field was systematically tile-drained in 1952 (Hallgren and Rietz, 1963) and simultaneously a measuring station was constructed where the tile-drainage and the surface runoff could be measured separately in two triangular weirs. To make the collection of surface runoff possible the field was enclosed by a soil bank on three sides (Fig. 1) and at the lower short side of the field a small ditch was established from which the water was led to the measuring station through a surface water collector.

The soil immediately beneath the plough layer consists mainly of fine grained sediments dominated by the silt fraction. The contribution of silty clay and clay is considerable in some places. The sediments were deposited in the sea which covered the area around the field about a thousand years ago . The soil material originates partly from sludge which was transported by the river Umeälven and deposited in the sea at that time and partly from material which was surged out by wave actions on the more elevated terrain SW and SE of the field.

The soil below the plough layer is rich in vertical crack plains and has a stable and well-developed stucture with rust deposits formed on the outside of the aggregates. In the crack plains, and to some extent around the aggregates, the crops often establish a relatively dense root-carpet.

Perennial crops as grass ley and annnual crops as barley are cultivated at the field with different degrees of cover for each year. During the investigated period 1976 to 1980 annual crops, i.e., mainly barley occupied 58, 81, 81, 66 and 64 per cent of the total area.

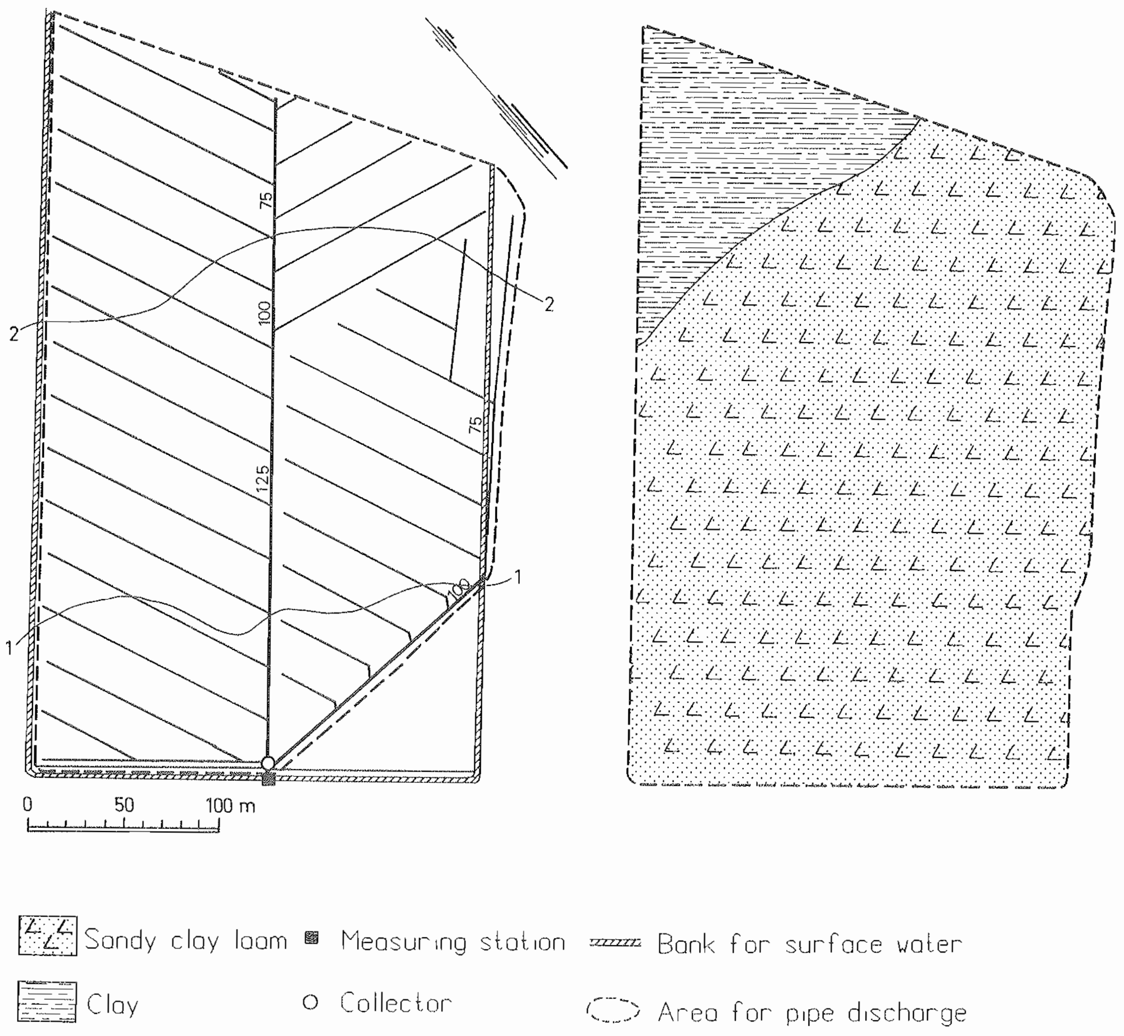

Figure 1. Map of the experimental field at Röbäcksdalen showing the drainage system and the geology of the area.

Model description

The model was described in detail by Jansson & Halldin (1980). A brief description of structure and the major assumptions is given below.

The water and heat model (Fig. 2) is based on two coupled differential equations describing heat and water transport (derived from Fourier's and Darcy's laws, respectively) in a one-dimensional soil profile (Jansson & Halldin, 1979). Snow dynamics, frost, evapotranspiration, precipitation, groundwater flow, plant water uptake and drainage flow are included. The model predicts soil climate variables (e.g. soil temperature, water content, etc.) with a daily resolution at any level in the soil profile.

The model, originally developed for a forest soil, has been modified and tested for agricultural soils (Jansson & Thoms-Hjärpe, 1986) and for application to agricultural watersheds (Lundin, 1984).

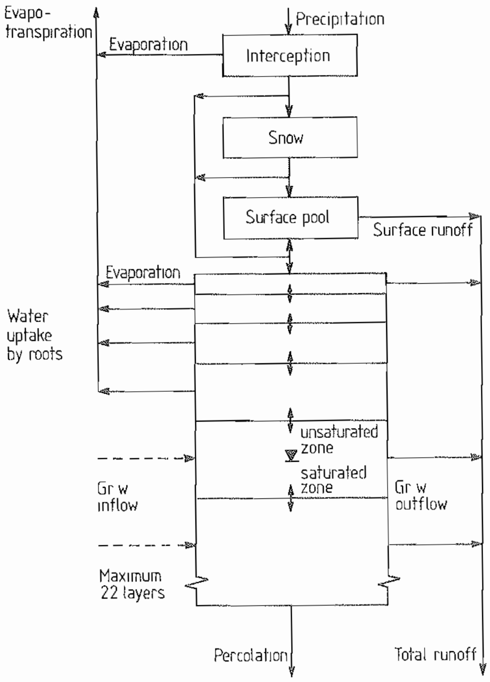

Figure 2. Model structure of the water and heat model. All flows in the soil profile except water uptake by roots represent both water and heat. (modified from Jansson & Halldin, 1979).

Water flow during partially frozen conditions is based on a similarity betweeen drying-wetting and freezing-thawing. The content of unfrozen water and the water tension is given as a function of the heat content of the soil (see Jansson & Halldin, 1980). The flow of water is calculated by Darcy's law in the same way as for unfrozen conditions. In order to minimize unrealistically high upward flow towards the frost boundary, a new procedure of calculating the interboundary conductivity between two adjacent layers was introduced. Instead of using a weighted mean value of two conductivities, the lowest conductivity of the two adjacent layers is used. By using this procedure, empirical consideration is paid both to the numerical error caused by the extremely steep tension gradient close to the frost boundary and to the resistance for water flow caused by the development of ice lenses. The new procedure, which is restricted to upward flows, has been tested by Lundin (1987).

Because of the one-dimensional vertical structure, lateral flow is not explicitly calculated. Water flow to drainage tiles occurs when the simulated groundwater is above the level of the tiles, i.e., flow occurs directly from a layer to drainage tiles when water content is at saturation. The flow rate is proportional to the hydraulic gradient (estimated from the depth of the groundwater table and the density of the drainage tiles), the thickness and the saturated hydraulic conductivity of each layer. Natural drainage may also be calculated, based on an empirical assumption accounting for a net horizontal groundwater flow.

Surface runoff can occur because of a limited infiltration capacity or a limited conductivity in the soil profile. When the infiltration rate exceeds the infiltration capacity a surface pool of water is formed on the soil surface. Drainage of the surface pool to the stream is simply calculated as a portion of the amount of water in the pool. If water infiltrates into the uppermost soil layer and the conductivity is too low in the subsoil, the excess of water (above the porosity of the soil) will be directed directly to the stream without any delay.

The water and heat model uses standard daily meteorological input data, i.e., air temperature, humidity, precipitation, global radiation (or duration of sunshine or cloudiness) and wind speed. If necessary, precipitation, air temperature and a simple estimate of potential evapotranspiration can suffice as input data. Parameter values for hydraulic and thermal soil properties can be estimated from standard soil physical characteristics, or independent measurements can be used.

Most important requirements of model parameters concern soil and plant properties. Soil properties are defined by the water retention curve and the hydraulic conductivity as a function of water content or water tension. Plant properties are those controlling water uptake and transpiration. Transpiration is calculated with a combination formula (Monteith, 1965), accounting for surface resistance. The reduction of water uptake because of limiting soil water availability is calculated from an empirical formula (Jansson & Halldin, 1979).

Adaptation of the soil water and heat model

The meteorological data required as driving variables to the model were selected from two meteorological stations located close to the investigated field. Daily mean values of air temperature, air humidity, wind speed and cloudiness were taken from the synoptic station at Umeå (within the network of the Swedish Meteorological and Hydrological Institute), 2 km from the field. Precipitation was measured at the field.

The precipitation was not corrected because of the aerodynamic error. Normally, snow precipitation is underestimated by measurements but the snow depth observations did not indicate this in the present case. One reason may be that snow drift occurred over the open field investigated. The daily mean air temperature was increased by 1^{o}C for three days in December 1979 in order to simulate a reasonable distribution between rain and snow. During these days a mass of warm air entered the region with considerable amounts of mixed rain and snow precipitation. The original daily mean temperature resulted in an overestimation of snow, because it represented also the colder periods prior to and after the period with the most intensive precipitation.

Laboratory analyses of texture, water retention and saturated conductivity were available from three different pits in the field (Andersson & Wiklert, 1977). Based on these data, functions for the water retention curve and for the unsaturated conductivity were estimated (Fig. 3). The major uncertainty concerned the unsaturated conductivity. In sandy soils we have previously used the equation by Mualem (1976) to estimate the unsaturated conductivity from the water retention curve only. A straightforward application of this procedure would have resulted in misleading

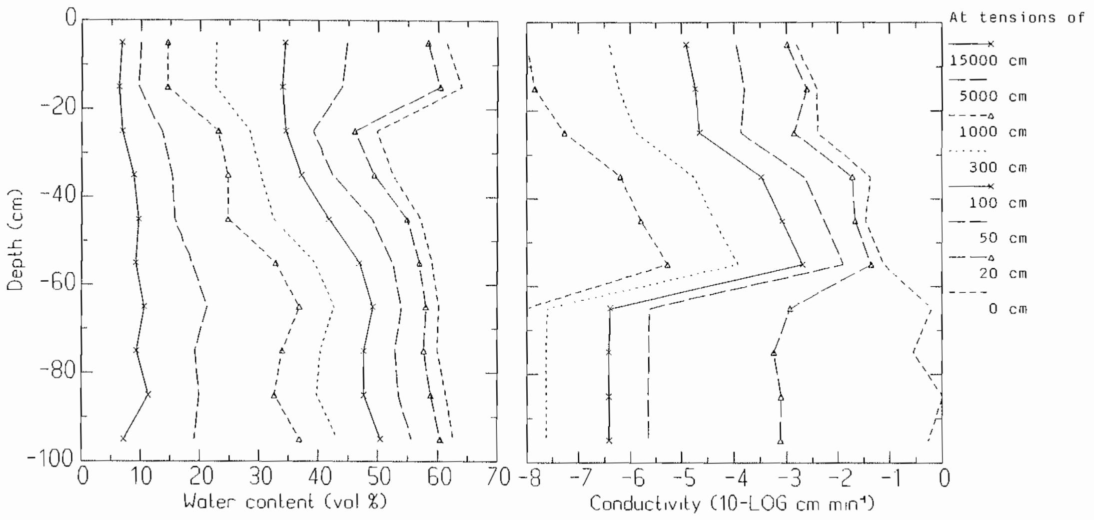

Figure 3. Soil moisture characteristics (left) and unsaturated conductivity (right) assumed in the simulation.

results because of the macropores in the present soil. The macropores are well developed and quite stable, especially in the deeper parts of the soil profile below 50 cm depth, giving very high saturated conductivities. In the same way as Jansson & Thoms-Hjärpe (1986), we now made a separate account for the macropores by assuming that smaller pores, representing tensions above 20 cm water, made a minor contribution to the measured saturated conductivity. The equation by Mualem was thereby restricted to the capillary pores.

Thermal soil properties were estimated from the dry bulk density as calculated from the porosity (Fig. 3) and a particle density of 2.65 g cm^{-3}. Thermal conductivity was estimated by using Kersten's equations (1949). Differences in soil surface boundary conditions between the ley and the barley were considered by reducing the thermal conductivity of the uppermost 10 cm of the grass-covered soil to a value that corresponds to humus. The humus thermal conductivity was chosen according to de Vries (1975). The heat capacity as well as the hydrological properties of the soil were kept unchanged. The soil surface temperature was assumed to be similar to the daily mean temperature except in situations with snow (see Jansson & Halldin, 1980).

The freezing point depression of the soil (Fig. 4) was based on the water retention curve by using the pore size distribution index in the expression by Brook & Corey (1964) and the water content at the wilting point. Since no independent measurements of the freezing point were available, the estimation of the freezing point was based on information from Beskow (1935) and by adjusting the freezing point to achieve an agreement between simulated and measured frost depths.

Snow melting coefficients accounting for the effects of air temperature and of global radiation were adjusted until reasonable agreement was achieved with snow depth observations. The temperature coefficient was put to 3 kg m^{-2}day^{-1} ^{o}C^{-1} and the global radiation influence was varied from 0.1 to 0.35 kg MJ^{-1} depending on snow age. No information on water equivalent in the snow was available which made the simulation of snow density and the corresponding thermal conductivity of snow uncertain. The density of new snow, free from rain, was put to 50 kg m^{-3}. Depend -

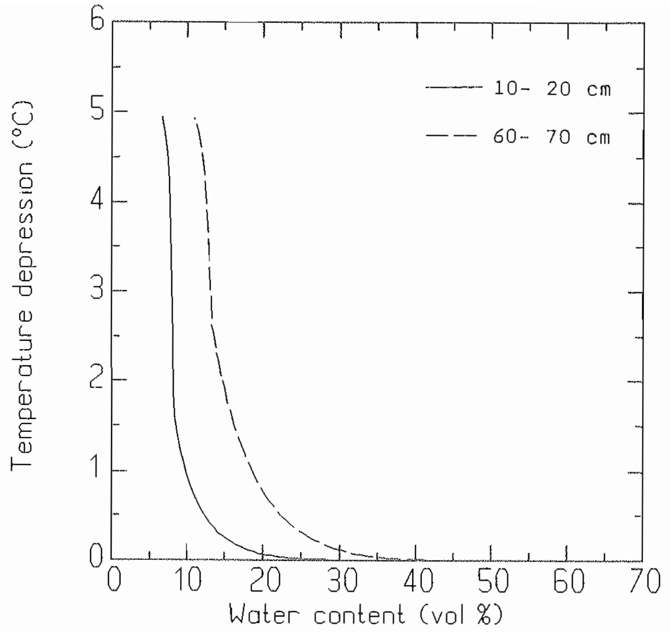

Figure 4. The assumed content of unfrozen water at temperatures below $0^{o}C$.

ing on wetness, the density of old snow increased by up to 100 kg m^{-3} and, depending on the total mass of snow, it was assumed that there was a further increase of 1.5 kg m^{-3} for each 1 kg m^{-2} increase in the total mass of snow. The thermal conductivity of snow was calculated using a function derived from Snow hydrology (1956).

No efforts were made to adjust the crop properties after comparison with the measurements of drainage and surface runoff from the field. The adaptation of the model was made different for the two dominating crops barley and grass ley. The annual course of their respective surface resistances and leaf area indexes were based on experiences gained when the model was adapted to similar crops at Kjettslinge in Central Sweden (Jansson & Thoms-Hjärpe, 1986; Jansson et al.,1987). Unfortunately, the higher transpiration and the higher interception losses simulated from the grass ley could not be tested since the drainage measured did not represent the treatments separately.

The depth distribution of roots and the maximal root depth (70 cm) was assumed to be similar for the two crops at the height of the summer, with 80 % of the water uptake demand in the 0-25 cm layer. The roots of the ley were only slightly varied during the year whereas the barley roots developed in the same way as assumed for the leaf area index above ground. The critical soil water tension, where the reduction of potential transpiration starts, was put to 400 cm water for both crops.

RESULTS AND DISCUSSION

The simulation period, covering five years from July 1st 1976 - June 30th 1981, represented a wide range of shifting temperature and moisture conditions (Fig. 5). A tendency for summers to be warmer from 1977 to 1980 occurred but no similar

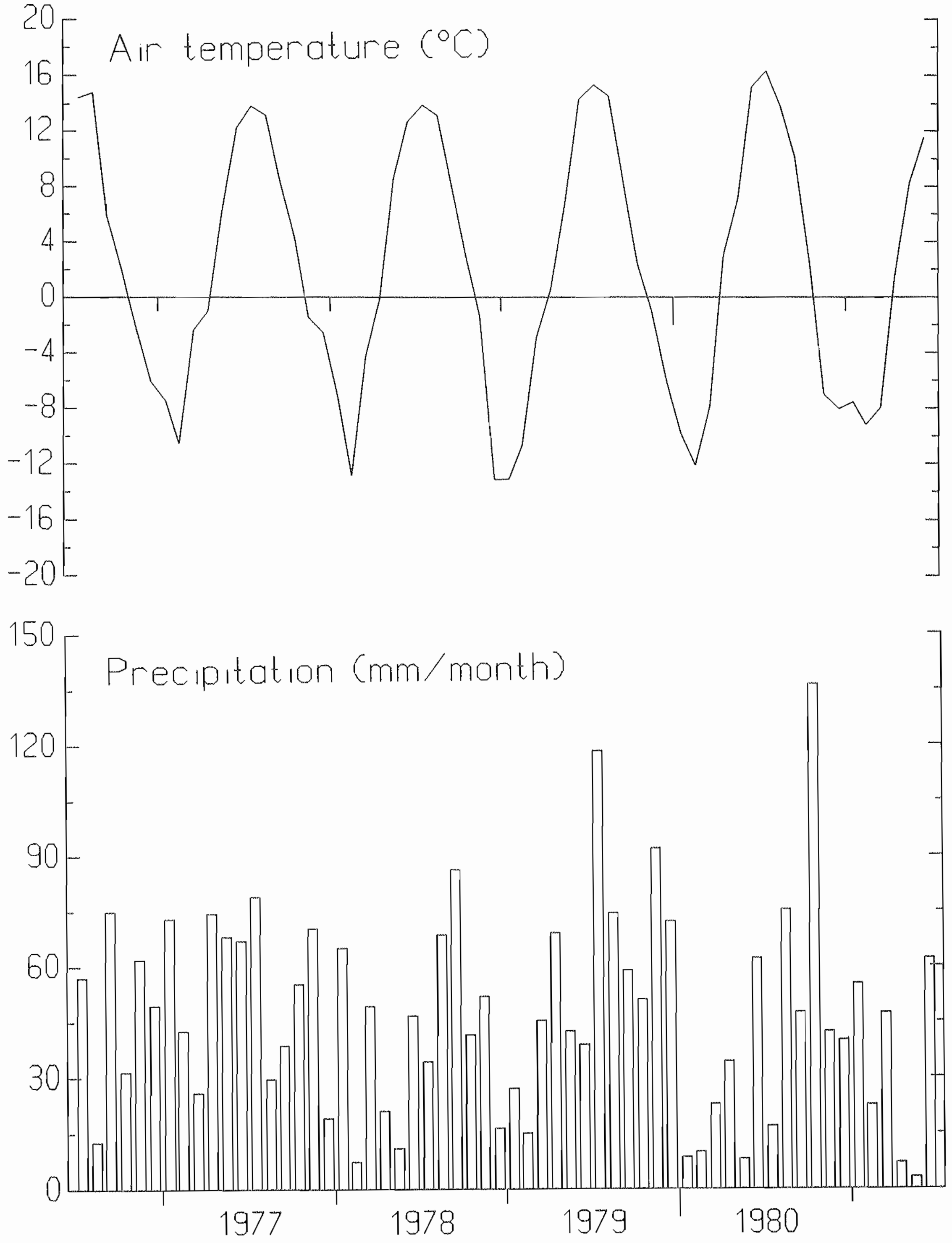

Figure 5. Monthly mean values of air temperature and monthly totals of precipitation.

tendency was seen for the winter temperatures. The coldest winter occurred in 1978/79 and the winter with the longest duration was 1980/81, the shortest being in 1977/78. The precipitation varied substantially from month to month which made it difficult to observe any particular pattern in the observations. However, the lowest monthly totals normally occurred during winters and the corresponding highest

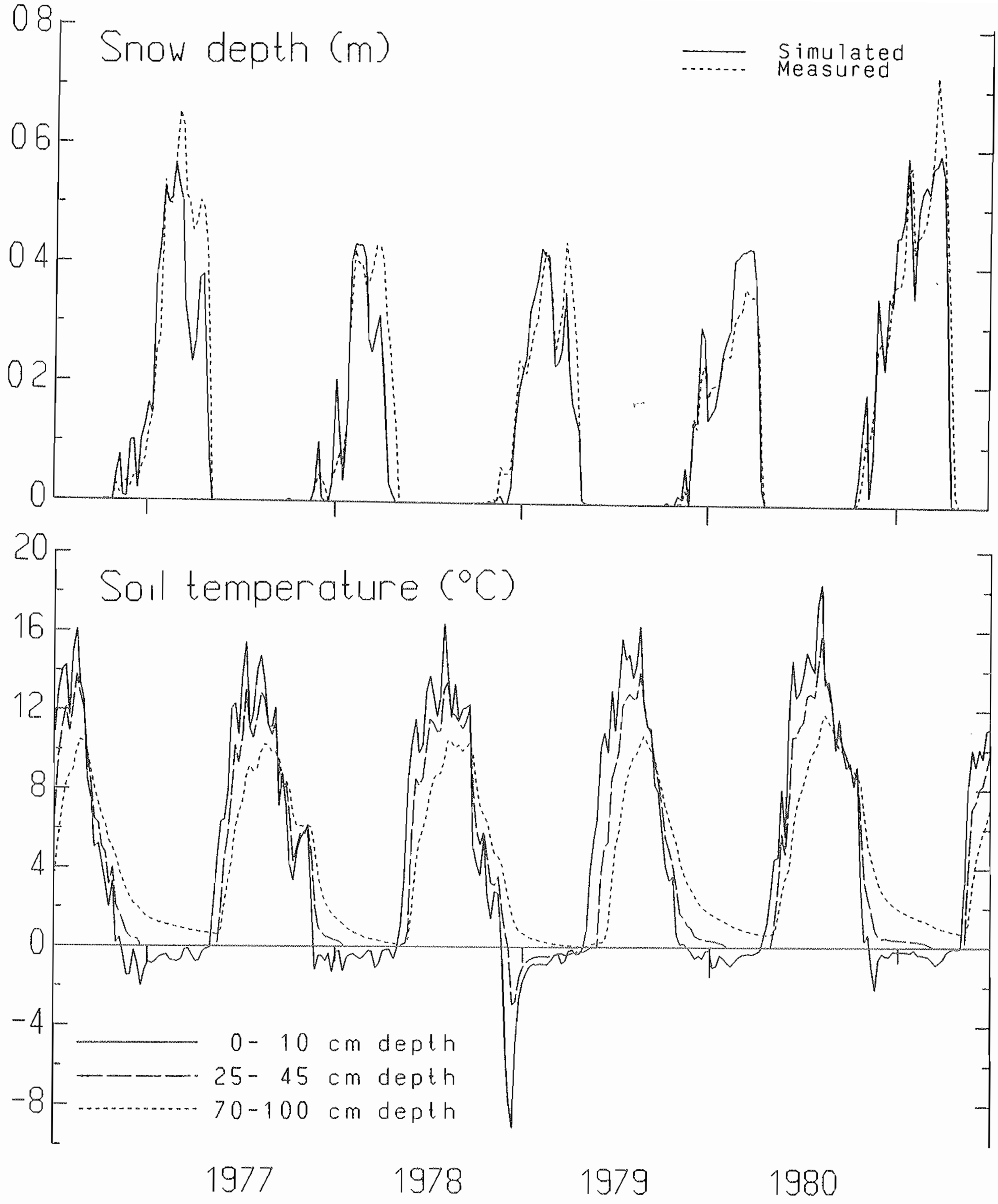

Figure 6. Simulated and measured snow depth and simulated soil temperatures.

totals occurred during summers and autumns. The summer of 1979 was the wettest and it was followed by an equally wet autumn which was followed in early 1980 by five months which together received less than 90 mm of precipitation.

The simulated snow depth agreed reasonably well with the observed depths after the adjustments of snow melt coefficients (Fig. 6). The exceptions, all orginating from individual meteorological events, were believed to be of minor importance for the simulation of frost so they were accepted. During both 1977 and 1978 the model exaggerated the compaction of the snow in connection with a melt period. In 1976/77 and 1980/81 the maximal snow depth was underestimated, in contrast to the overestimation during the winter of 1979/80. We believe that a further improvement

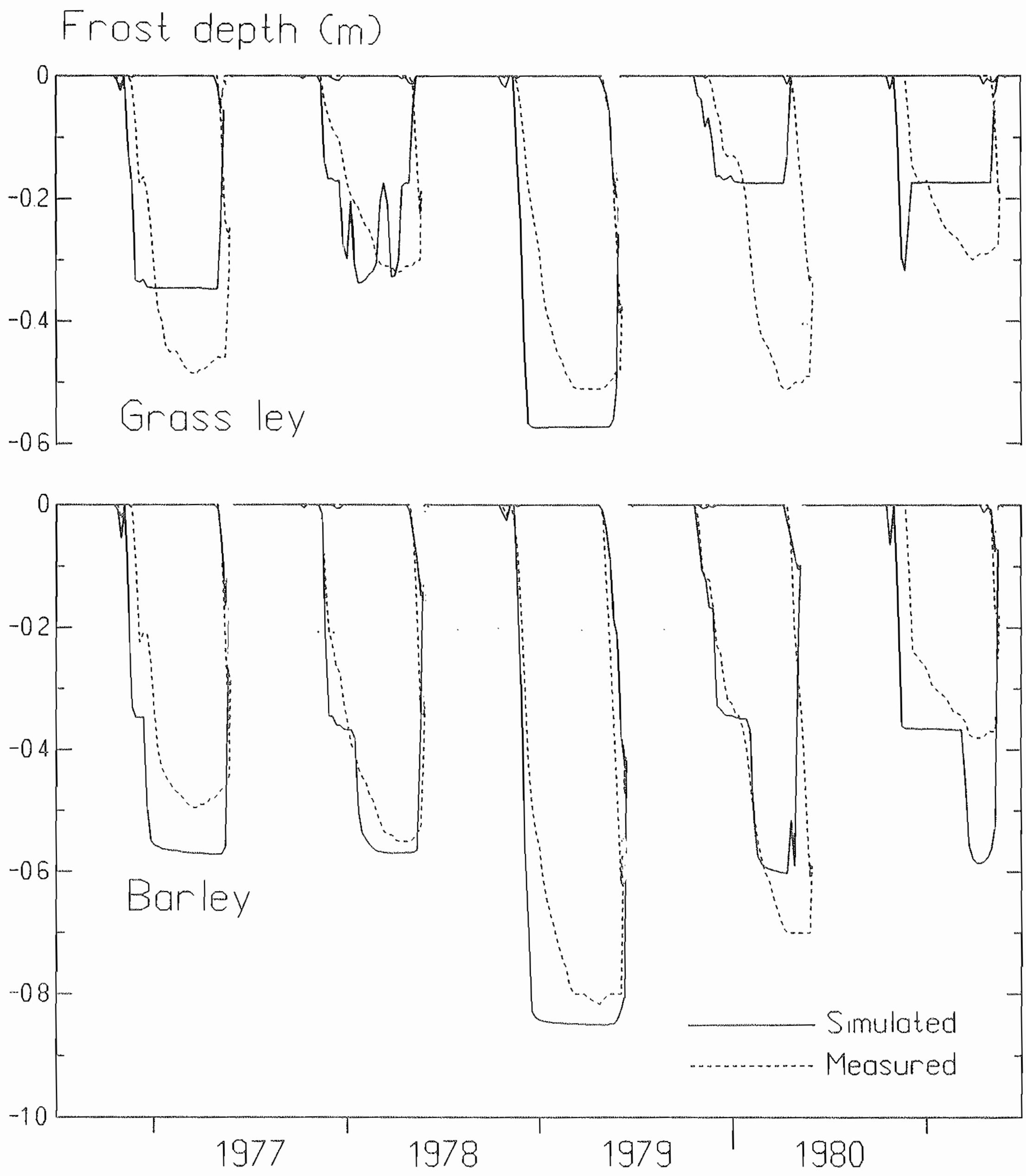

Figure 7. Simulated and measured frost depths.

of the simulated snow depth could be achieved only by increasing the precision in the meteorological input to the model. The use of daily mean temperatures for the partitioning between rain and snow may be questioned (see the section under Adaptation of the model).

When simulated and measured frost depths were compared (Fig. 7) the best agreement was obtained for barley, where the frost was deepest. The inclusion of a low thermal conductivity of the uppermost soil as a way of accounting for the grass cover in the ley was not successful in all years. Especially during the years 1979/80 and 1980/81, simulated frost depths were too shallow and with different temporal distributions compared with the measurements. To some extent the difference in patterns could be explained by the rough discretization of the soil profile in the model, as for 1977/78, but the differences for the ley were too large to be satis-

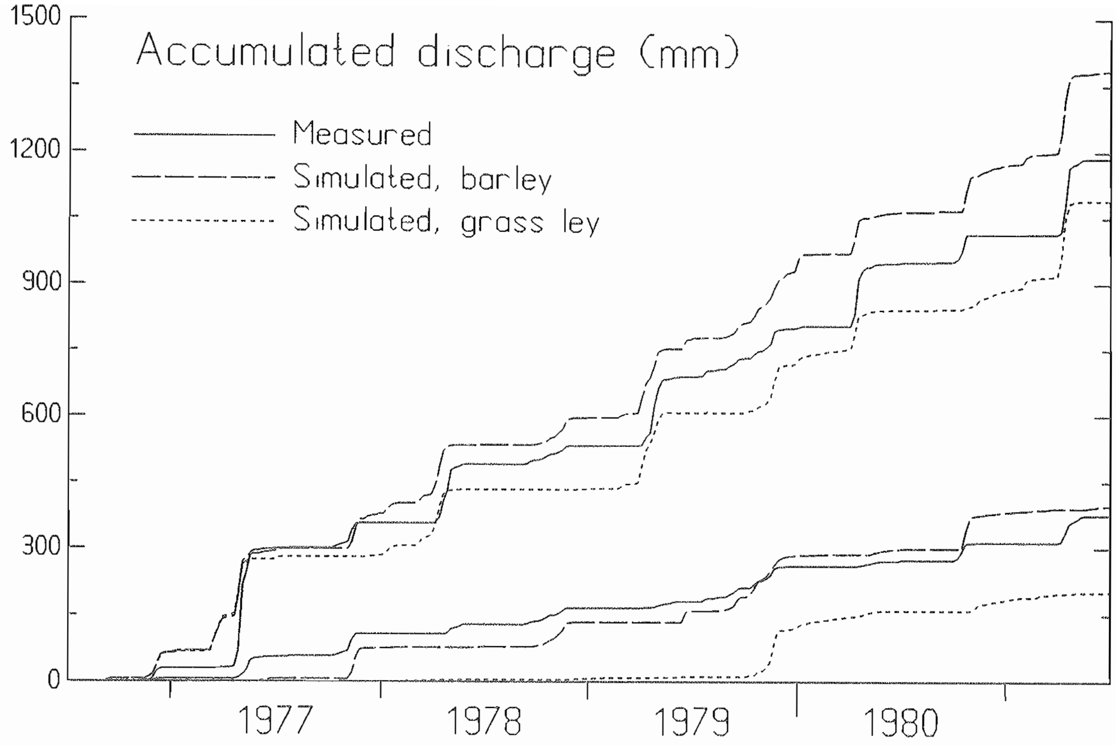

Figure 8. Simulated and measured accumulated water flows, pipe discharge (the lower curves) and total runoff (the upper curves).

factory. Further studies on frost penetration are therefore required to improve the consideration of the boundary between soil and snow or between soil and atmosphere in the model. A more detailed approach based on the energy balance at the soil surface has previously been used by Alvenäs et al. (1986) and Jansson et al. (1987) to explain differences in soil temperatures between barley and grass ley during summer. Such an approach may also be used during autumn and winter. However, it was not used in the present study since the soil temperature measurements needed for a careful test were not available.

Simulated soil temperatures (Fig. 6) illustrated the need for a better quantification of soil frost than the frost depth only. The lowest temperatures at 5 and 35 cm depth occurred in connection with the growth of the deep frost during 1978/79. But at the time for maximal frost depth the same soil levels were substanially warmer with temperatures only slightly below 0^{o}C. In the other winters the temperature at 35 cm depth never dropped below 0^{o}C, but the duration for the 0^{o}C temperature varied in the same way as the frost depth. The temperature rise during spring varied substantially from year to year, largely reflecting the prevailing frost. Normally, when the frost had been shallow, the temperature rise was only slightly delayed between the different soil depths, as in the spring of 1981. On the other hand, as in the spring of 1979 when the frost had been deep, a substantial delay occurred in temperature rise between the different soil depths.

An interesting phenomenon was the variation of simulated soil temperatures at 85 cm depth. The lowest temperature at that level commonly occurred in connection with the infiltration of melt water from snow. Especially during the spring of 1978 it was noticed that the temperature dropped to 0^{o}C at 85 cm depth simultanously as

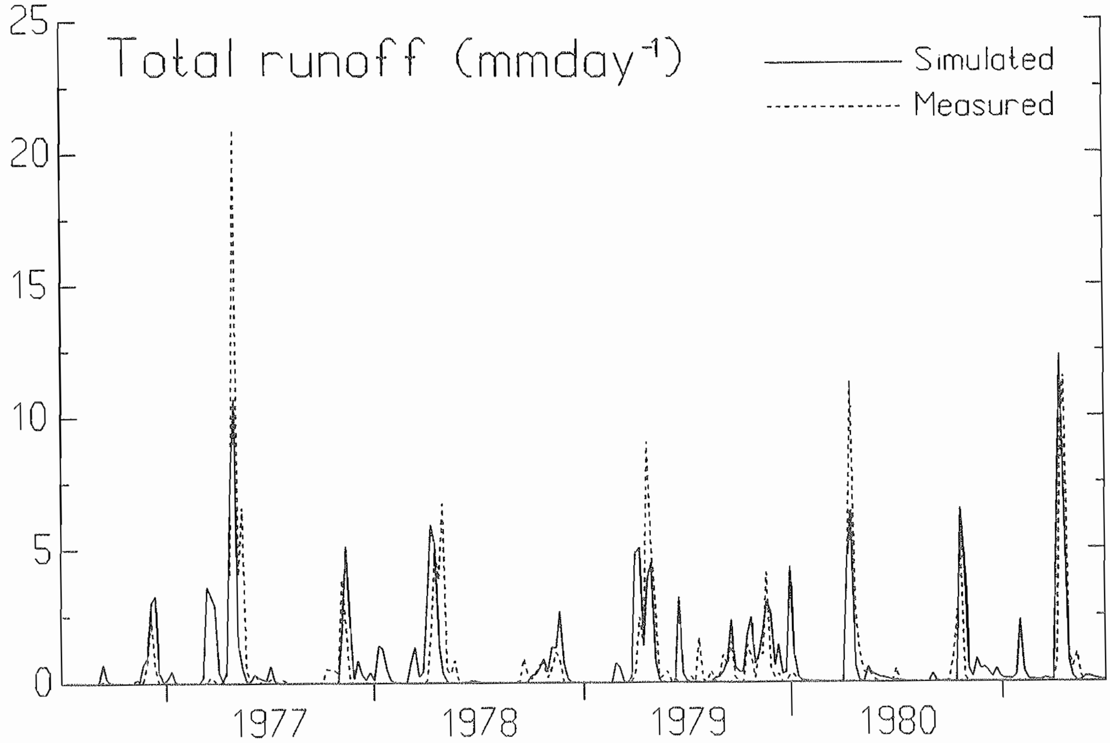

Figure 9. Simulated and measured weekly mean values of the total runoff. Simulated values represent barley.

a rapid temperature rise occurred at 5 cm depth. In this case, the temperature was a good tracer for the water flow, which will be discussed further below.

The measured runoff represented 70 % of annual crops and 30 % of grass ley for the whole five-year period. The total runoff simulated for barley was about 200 mm above the measured sum of 1180 mm and the corresponding simulated runoff for the ley was about 100 mm less than the observations (Fig. 8). A similar tendency was also observed for the simulated pipe discharge but in this case the barley simulation was just above the measured sum of 380 mm whereas the ley simulation was considerably below the measurements. The model overestimated the total surface runoff but, on the other hand, the best agreements with regard to the runoff patterns were obtained between the barley simulation and the measured runoff (Fig. 8). Thus, it was reasonable to believe that the evapotranspiration simulated from barley best represented the actual evapotranspiration from the whole field.

The barley simulation overestimated the total runoff during the winters of 1977/78 and 1979/80 (Fig. 9). The reason may be that the assumed water retention capacity of snow was too low (7 % of the total snow mass) or that input data on precipitation was erroneous. The simulated snow depth was reasonable when compared to observations but a tendency for a too sensitive compaction of the snow in connection with melt periods indicated an error in the assumed water movement in the snowpack. Experimental studies have demonstrated that water movement in snow takes place in a heterogenous structure (Wankiewicz, 1979) which makes it likely that assumptions of constant retention capacity for the whole snowpack may be unrealistic. The retention capacity may be considerably higher in an initial phase

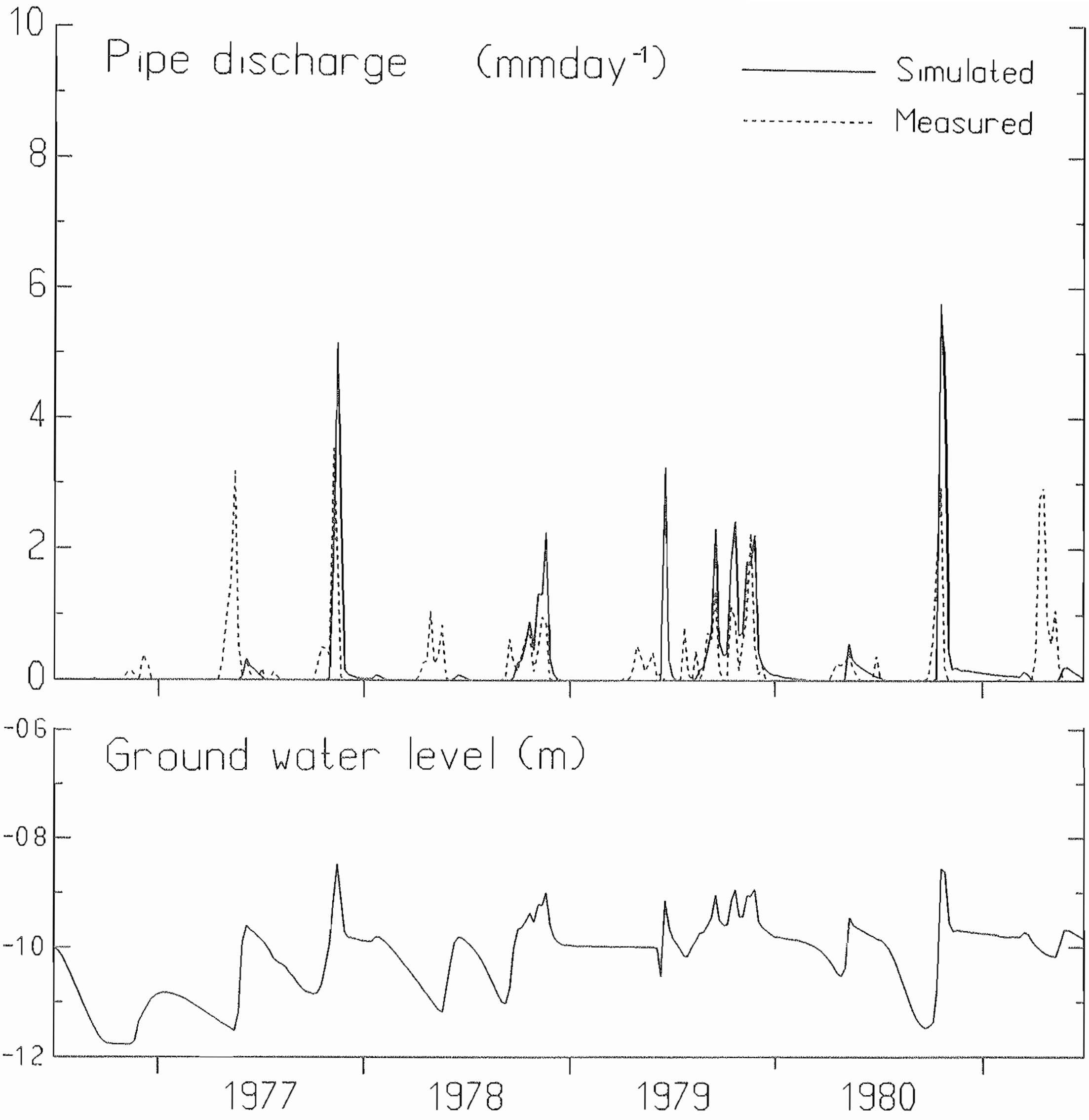

Figure 10. Simulated and measured weekly mean values of pipe discharge and simulated ground water levels. Simulated values represent barley.

before a stable flow pattern has been developed.

The overall partitioning between surface runoff and drainage through the pipes was very good in the simulations, especially for the barley simulation. Normally, the dominating drainage through the pipes was observed in the autumns, prior to development of frost in the soil. Smaller amounts were drained in connection with snow melt periods during spring. Generally, the simulation underestimated the pipe discharge in connection with snow melt and overestimated it during autumns (Fig. 10). However, small water flows were simulated through the frost layer which could be seen in the rise of the water table each spring (Fig. 10). The simulated pipe discharge was also delayed compared to the measurements, especially during spring but also in the autumns. The delay of the pipe discharge could either be an effect of the frost or an effect of an overestimation of the soil water deficit at the time when water infiltrates into the soil. These effects were influenced in opposite directions when the simulations were modified from grass ley to barley. The deeper

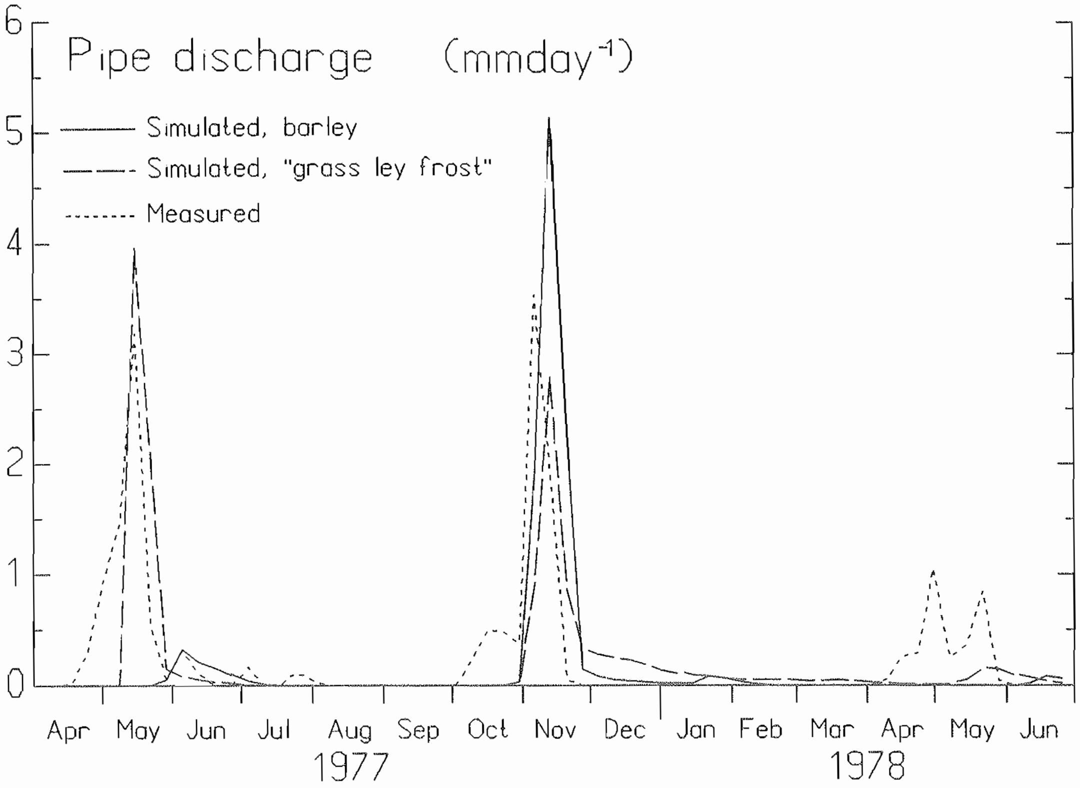

Figure 11. Simulated and measured weekly mean values of pipe discharge during a selected period. Simulated values represent barley (the same as in Fig. 10) and one additional simulation with frost depths according to grass ley but with hydrological properties according to barley.

frost delayed the response between infiltration and pipe discharge but the moister soil conditions resulted in a faster response. A simulation using hydrological properties according to barley but soil thermal properties according to grass ley, demonstrated the crucial role of these effects separately (Fig. 11). Especially during the snow melt period in 1977, the shallower frost resulted in a substantial change in simulated discharge, improving the agreement with the measured pipe discharge.

We believe that the main reason behind the inability of the model to correctly depict the pattern of the observed drainage flow was the spatial variability in the field. Important effects of spatial variability could occur both in a small and a large scale. In the small scale it may be reasonable that water flows may occur in macropores even if the soil is partially unsaturated, and in the large scale it is similarily reasonable to assume that lower wet areas will respond to changes in infiltration well before dry areas.

CONCLUDING REMARKS

The model application demonstrated the importance of correct quantification of soil frost if drainage from an agricultural soil is to be estimated. Frost penetration in the soil can be accurately simulated providing that detailed information on meteorological conditions are available.

The partitioning between surface runoff and pipe discharge was, on the whole. correctly simulated but discrepancies between simulation and measurements concerning the temporal distribution occurred. The main reason behind these discrepancies was believed to be the spatial structure of the field, not accounted for in the one-dimensional model. The spatial heterogeneity was probably enhanced by the occurrence of snow and frost, especially during melting periods.

Further research on small-scale plots, where detailed measurements could be made, is of vital importance to improve the understanding of frost phenomena and to improve the applicability of the model for winter conditions. If the requirements are restricted to seasonal estimates of the water balance components from agricultural fields, the present stage of knowledge seems satisfactory.

The present work could be considered as a first step towards modelling of nitrogen losses from soils strongly influenced by frost. However, a number of problems remain, e.g., on how the solute transport is influenced by freezing and by the substantial heterogeneity of water flow-paths.

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