Swedish University of Agricultural Sciences
Department of Soil and Environment

Simulations of Drainage and Phosphorus Leaching with the ICECREAM Model for 15 Years at Mellby Experimental Field

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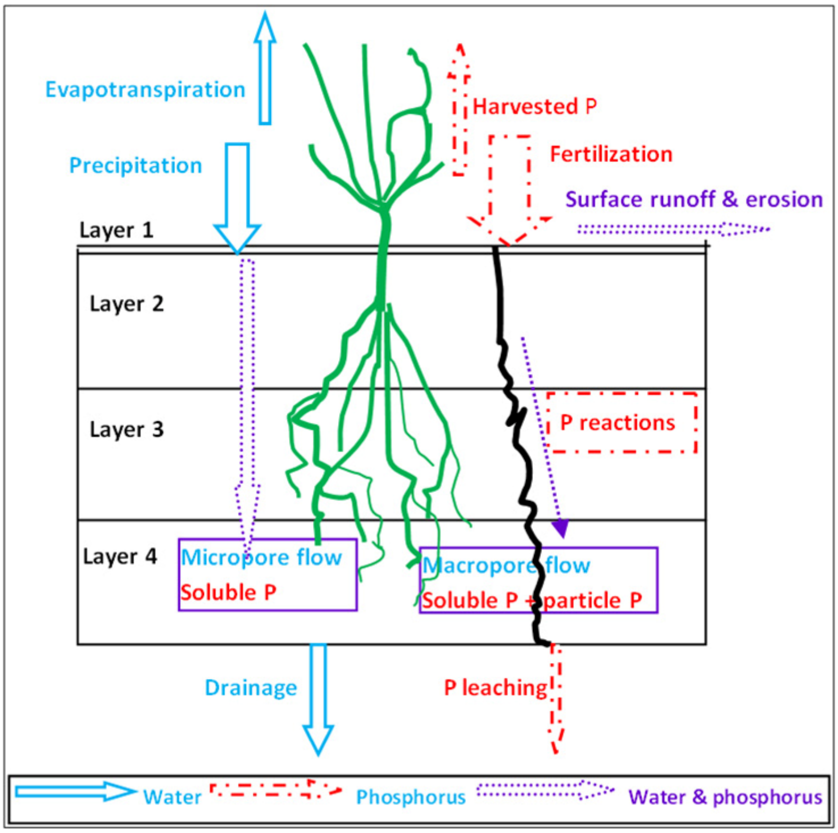

Master's Thesis in Soil Science
Environmental Pollution and Risk Assessment - Master's Programme

Institutionen för mark och miljö, SLU
Examensarbeten 2010:03

Uppsala 2010

SLU, Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
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EX0430, Independent project/degree project in Soil Science, 30 HEC, Master E
Environmental Pollution and Risk Assessment - Master's Programme

Institutionen för mark och miljö, SLU, Examensarbeten 2010:03
Uppsala 2010

Keywords: Drainage, phosphorus leaching, ICECREAM model, Mellby experimental field

Cover: Main processes of water and phosphorus transport in the ICECREAM model

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Abstract

Phosphorus (P) losses from agricultural fields have been recognised as one of the most important sources of P causing eutrophication in water bodies. Water transport in soil plays an important role in P leaching from drained fields. In this study, the ICECREAM model was employed to simulate 15-year drainage and P leaching from a sandy loam soil at the Mellby experimental site in south-western Sweden. The results were compared with measured data in order to test the applicability of the model at the Mellby site, identify important processes controlling drainage and P leaching at Mellby, and suggest potential future improvements to the model to better suit the Mellby soil.

Sensitivity analysis showed that parameters related to soil physical properties (soil texture, soil porosity, field capacity, wilting point and saturated conductivity), infiltration capacity (CN2) in connection with field management practices and macropore flow moderately or significantly affected the total amount of drainage. These parameters also indirectly affected P leaching, which was closely correlated to drainage. Soluble P leaching was also greatly sensitive to base saturation, while particle P leaching was greatly affected by parameters related to particle generation for macropore transport (detachability and particle extraction depth).

The model accurately simulated total drainage and drainage dynamics for the 15-year study period when the drainage partition coefficients for deep percolation (K1 and K2) and the parameters related to macropore flow (tresh_watin and frac) were calibrated. The simulation showed that considerable amounts of drainage water (17%) bypassed tile drains and that water was able to move very fast along preferential flow paths in this sandy soil.

The model accurately simulated the transport dynamics of soluble PO_4^{3-}-P and total P, but failed to simulate total amounts and concentrations. Leaching of both soluble P and total P was overestimated. One clear conclusion from this work was that new parameters are greatly needed in the model to better describe sorption-desorption processes for P to Fe-oxides or (and) Al-oxides in the soil. This would allow P leaching from a soil like this to be simulated with higher precision. It was also concluded that parameters related to particle generation need careful calibration in future simulations.

The simulations for the Mellby site showed that when the soil P pools were large, it was difficult to distinguish the effects of reduced P fertilisation on leaching. They also showed that management practices such as crop type, tillage practices, etc. can influence P losses. The model should be further tested on field data to determine the accuracy of such estimations.

Contents

Introduction

Since the general agreement reached in the 1970s that phosphorus (P) is limiting eutrophication by affecting phytoplankton growth in the majority of lakes (Schindler, 1977), it has been widely recognised that anthropogenic P inputs to aquatic ecosystems should be reduced to prevent further eutrophication and guarantee good drinking water supplies (Conley et al., 2009). The implementation of new and highly efficient technologies in production processes and industrial wastewater treatment have resulted in a massive reduction in point sources of P pollution, making the contribution of diffuse P losses from agricultural production even more important. For instance, in Sweden in 2006, 32% of the gross load of P to the Baltic Sea was from arable land (SNV, 2008a). Moreover, the highly intensive and specialised agricultural production since the 1950s has resulted in an increased potential for P losses to recipient water bodies (Bergström and Kirchmann, 2006), due to a long history of animal manure accumulation, excessive applications of fertiliser and, in some cases, use of animal feed additives such as urea phosphate. In Sweden, 50% of all agricultural soils have a high risk of P losses due to high or very high soil P content (Djodjic et al., 2004).

The P concentrations in the water percolating through soil and the P losses through subsurface drainage are generally small compared with the losses through surface runoff and soil erosion, due to P sorption by non-saturated subsoils containing iron and (or) aluminium oxides (Sharpley et al., 2001). However, drainage losses can be similar or even greater than those in surface runoff when the soil has a low sorption capacity (organic soils and sandy soils) or has been saturated with P (overfertilised), and when depth and hydrological conditions are suitable for leaching (Sims et al., 1998; Dils and Heathwaite, 1999). In addition, significant P losses through drainage can occur in unsaturated, structured soils because of preferential flow through macropores such as root and earthworm channels, fissures and interaggregate voids, especially when heavy rain occurs shortly after the application of animal manure or mineral fertilisers (Haygarth, 1997). For example, in a comparison of P leaching through a clay soil and a sandy soil, Djodjic et al. (1999) found that the average P leaching load in clay columns was 4.0 kg ha^{-1}, which was much higher than the mean 0.056 kg ha^{-1} found in sand columns. This was because the preferential flow in the well-structured clay soil greatly increased P leaching compared with the piston flow in the sandy soil. In Sweden, 1.2 million hectares of arable land are situated on permeable soils which need no artificial drainage, while 1.1 million hectares are artificially tile-drained. This collectively accounts for 85% of the total arable land area (Wesström, 2002). Good drainage conditions play an important role in removing excess soil water, eliminating waterlogging conditions and thus promoting crop production, but on the other hand they can greatly facilitate P losses by leaching through the soil profile. It has been estimated using the ICECREAM model (Bärlund and Tattari, 2001) that a mean rate of 0.52 kg P per hectare leached out (including both rootzone leaching and losses through surface runoff) from Swedish agricultural land in 2005 (SNV, 2008b). The simulated leaching showed great variation, ranging from 0.10 kg P per hectare in Öland and Gotland, which have low soil P content and small annual drainage amounts, to 1.31 kg P per hectare in western Sweden, where intensive crop and animal production is practised and where annual drainage amounts are large. The mean annual P concentration in drainage water is estimated to be 0.17 mg L^{-1}, with regional variations from 0.06 to 0.34 mg L^{-1} (SNV, 2008b), which can cause detrimental eutrophication of P-sensitive recipient waters.

There are many computer-based models for estimating nutrient loads from land to water in common use on a regional or national scale. In Sweden, the ICECREAM model has been used for calculations of P leaching losses from arable land at a regional and national scale. However, so far few model applications have been made at the field scale and information is lacking about model performance at this scale. In the present study, the ICECREAM model was used to simulate 15-year water drainage and P leaching from a sandy field at Mellby, south-west Sweden, and the simulated results were compared with field measurements. The objectives were: (1) to test the applicability of the ICECREAM model for simulating water drainage and P leaching at the Mellby site; (2) to identify the most important processes and soil characteristics for inclusion in order to simulate field conditions at the Mellby site successfully; and (3) to examine the limitations of the ICECREAM model for applications on the Mellby soil and to suggest potential improvements to the model.

Materials and methods

1. Site description

The Mellby experimental site (56°29′N, 13°00′E) is located 25 km south of Halmstad on the south-west coast of Sweden. It has mild and wet autumns and winters. The mean annual temperature is 7.2 °C and the mean annual precipitation is 803 mm. The field site was established in 1982 on a sandy soil. The soil profile is a Fluventic Haplumbrept (USDA), with 90-130 cm thick sandy deposits overlying a glacifluvial clay. Ten plots (30 m x 30 m) were separately tile-drained at about 90 cm depth and measurements of drainage from each plot and water sampling started in 1983. Since the start of the experiment, the site has been used to study the long-term effects of application of pig slurry and the use of catch crops on nutrient leaching. The field had a long history of manure application even before the leaching experiment started (Aronsson and Torstensson, 1998; Ulén et al., 2006).

Plot 9 was selected for the simulation work because the drainage dynamics and total amounts of drainage water were close to the average for the 10 plots at the field site. Plot 9 has received pig slurry in spring each year since 1983 at an average rate of 40 tonnes per hectare, which is equivalent to about 58 kg P per hectare and year. This is considered to be above the optimum level for the crops grown, which were mainly spring cereals and potatoes. No catch crops were used on this plot. After harvest in August-September, the soil was tilled by stubble cultivation followed by mouldboard ploughing to 30 cm depth. Thereafter the soil was left undisturbed until seedbed preparation in spring.

2. Water discharge and P leaching measurements

Water discharge from each plot at the site is measured using tipping-buckets connected to a datalogger which records daily values of drainage. Until 1998, water was sampled every one or two weeks (during high flow) by manual sampling at the outflow of each tile drain, illustrating the P concentration at that moment (Aronsson and Torstensson, 1998). In 1999, automatic flow-proportional water sampling was introduced. For each 0.2 mm of discharge, a sub-sample (10 mL) of water is taken using a peristaltic pump connected to the datalogger. These sub-samples are collected in a bottle which is emptied every two weeks, giving a composite water sample with the average P concentration for the preceding two weeks (Bergström et al., 2006). Phosphorus analyses differed during the experimental period used for the simulations. During the period 2001-2003, water was only analysed for total P, while during the period 1989-2000 it was analysed for total P and PO_4^{3-}-P. The difference between total P and PO_4^{3-}-P was defined as particulate P (or particle P).

Monthly values of measured and simulated P concentrations and the amounts of P leached were calculated and compared. Different methods were used in calculating measured monthly P transport due to differences in sampling methods. For the manual sampling period (1989-1998), daily P concentration was interpolated from the measurements and monthly transport was calculated as the sum of daily transport in each month:

Monthly P transport (kg ha^{-1}) = $\sum_{i=1}^{the\ last\ day\ of\ the\ month}$ *(Drainage$_i$ (mm) × P concentration$_i$ (mg L^{-1}) × 10^{-2}) (1);*

For the period with flow proportional sampling (1999-2003), monthly P transport was taken as the sum of transport in each sampling interval in the month, with total drainage for the interval calculated first and then multiplied by the concentration measured for that interval:

Monthly P transport (kg ha^{-1}) = $\sum_{i=1}^{the\ last\ interval\ of\ the\ month}$ *(Total drainage for the interval$_i$ (mm) × P concentration$_i$ (mg L^{-1}) × 10^{-2}) (2).*

Mean monthly P concentration for the whole period was obtained by dividing monthly P transport by total drainage in the month:

Monthly P mean concentration (mg L^{-1}) = Monthly P transport (kg ha^{-1}) / Monthly total drainage (mm) × 100 (3).

Equations (1) and (3) were used for calculating simulated monthly P transport and mean P concentration in drainage water.

3. Description of the ICECREAM model and input parameter and variable values

3.1 Model description

The ICECREAM model is a nutrient management model mainly used for simulating P losses through runoff and leaching from agricultural land. It is based on the models CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987; Knisel, 1993) and EPIC (Jones et al., 1984) and has been refined and adjusted for a cold, humid Nordic climate (Yli-Halla et al., 2005). Rekolainen and Posch (1993) describe the main adjustments compared with the CREAMS model, i.e. snow accumulation and snowmelt, soil frost, evapotranspiration, leaf area index and Universal Soil Loss Equation (USLE) parameters (Wischmeier and Smith, 1958).

In the model as it was applied here, the soil profile (0-100 cm depth) was divided into 4 layers (Fig. 1A) with a thickness of 1 cm, 29 cm, 35 cm and 35 cm, respectively. Layer 1 is most important for the occurrence of erosion and the detachment of soil particles, and together with layer 2 comprises the plough layer. Layers 3 and 4 are subsoil layers. Water and P are lost either to tile drains or to deep percolation from layer 4. The model consists of water and P balance systems with pools for water storage and different forms of organic and mineral P in each soil layer (Fig. 1B). The water balance components are precipitation as input, and evapotranspiration, surface runoff and percolation from the profile as outputs. Water percolates through micropore and macropore flow (Fig. 1A). The phosphorus balance components are fertilisation with inorganic and organic P as input, and P extracted from the soil with the harvested crop and soluble and particle-bound P losses in surface runoff and leaching as outputs (Fig. 1A). The P submodel consists of seven P pools (Fig. 1B); P in plants (P-PLANT), fresh organic P pool (P_{FO}), the slowly mineralisable organic humus pool (P_{SO}), the manure pool (P_{MAN}), mobile and thus plant-available P (P_L), the long-term stable mineral pool (P_S) and the active P pool (P_A) (Bärlund and Tattari, 2001; SNV, 2008b). Chemical processes such as sorption-desorption and biological processes such as mineralisation-immobilisation are involved in P flows between different pools (Bärlund and Tattari, 2001).

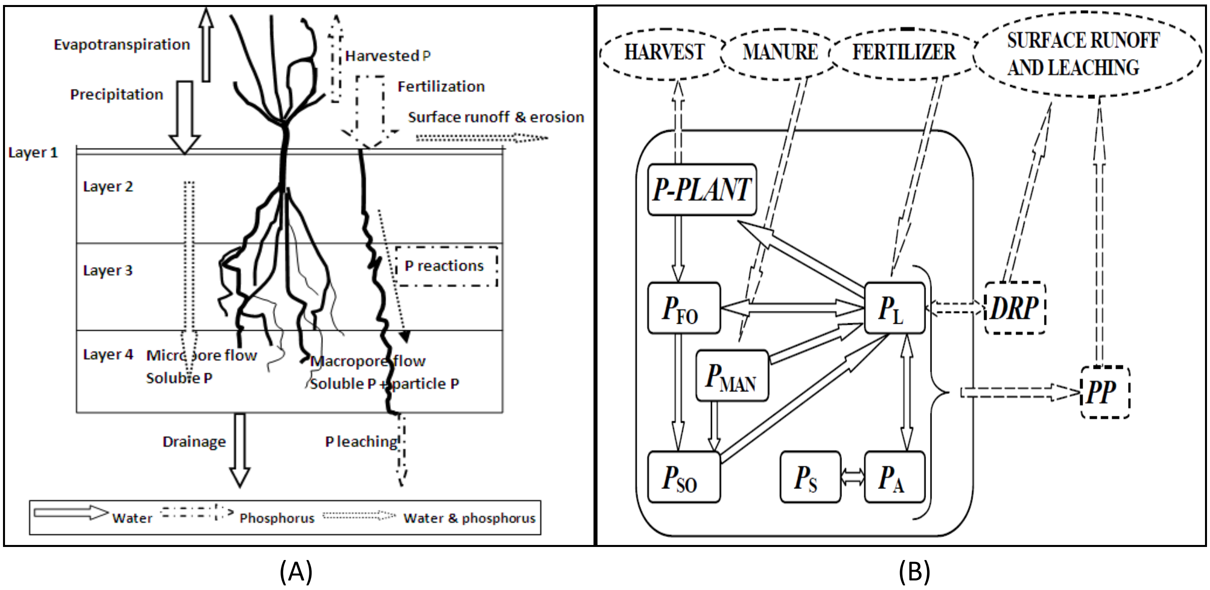


Figure 1. (A) Main water and P processes and (B) pools and flows of P (from SNV, 2008) in the ICECREAM model.

3.2 Description of important parameters

The partitioning of precipitation between surface runoff and infiltration into the soil is determined by the Soil Conservation Service (SCS) Curve Number model (USDA Soil Conservation Service, 1972). The parameter CN2 (SCS curve number in moisture condition 2) is central in the runoff calculations since together with the calculated soil moisture content, it determines the infiltration capacity of the soil. The CN2 parameter is set according to the soil properties governing the infiltration capacity of the soil, but it also changes with agricultural management practices such as sowing, harvesting and soil tillage, as well as with crop type.

The simulated erosion determines the losses of particulate P in runoff. The erosion is calculated by the Universal Soil Loss Equation (USLE) in the model. The parameter Manning´s Number (MN) determines the soil surface roughness and hence the sensitivity to erosion of the soil. The MN value is also set according to soil properties, as well as crop type, sowing, harvesting and soil tillage operations such as ploughing, harrowing and stubble cultivation.

The percolation of water through the soil is determined by the water storage capacity of the soil, i.e. the pore volume (m^3 m^{-3}) available for water storage. The maximum storage capacity at drainage equilibrium equals the field capacity minus the wilting point, and water percolates from one layer to the next when the water content exceeds the field capacity. The volumetric soil water content at 33 KPa matric potential is defined in the model as the field capacity and that at 1.5 MPa as the wilting point. The difference between field capacity and wilting point is also the volumetric plant-available water content. Soil porosity is the volumetric ratio of total pore space per unit volume of soil (m^3 m^{-3}). The water content of total soil porosity is used for calculation of the water retention value of the soil, which is used together with the CN2 parameter to calculate the surface runoff. The saturated hydraulic conductivity is given for the micropore region and determines the rate at which the percolating water moves between layers and out to tile drains. For macropores, water transport is assumed to be instantaneously and directly lost to tile drains.

Percolation water partitioning between tile drains and bypass drainage can be adjusted by changing the model parameters K1, K2, K3 and K4. Specifically, K1 is a coefficient for water flow from an imaginary groundwater pool existing at drain depth to tile drains in the micropore region, and K2 is a coefficient for water bypassing the drainage from the pool in the micropore region. K3 and K4 are for water partitioning in the macropore region, with water ending in drains and bypassing them, respectively. Furthermore, w_thresh_mic and w_thresh_mac are the threshold values for the occurrence of outflow from the groundwater pool in the micropore region and the macropore region, respectively.

Macropore flow (Larsson et al., 2007) is mainly simulated in the ICECREAM model by the parameters 'tresh_watin', 'frac', 'fcfrac', w_tresh_mac and K4. Tresh_watin is the precipitation threshold value, above which macropore flow is initiated; frac is the fraction of precipitation above the threshold, which is routed to the macropores; and fcfrac is the fraction of the field capacity in the uppermost soil layer that must be reached before macropore flow occurs.

The P submodel, involving different P flows and processes between the P pools and losses from the profile, demands a number of descriptive parameters. Base saturation, together with clay content and pH, determines the transformation of P between stable (P_S), active (P_A) and labile (P_L) pools by its use in calculating the P sorption distribution coefficient in sorption-desorption processes. Soluble P extraction depth describes the thickness of the soil layer from which soluble P going to macropores is extracted.

There are several important parameters related to soil particles in macropores and thus affecting particle P leaching, such as the replenishment coefficient governing generation of particles for macropore flow, the detachability coefficient governing detachment of available particles and particle extraction depth illustrating the thickness of the soil layer for the generation of particles. Moreover, together with drain depth (the depth of the drainage system in the soil profile), the filter coefficient is involved in calculating particle retention in the macropores.

3.3 Input values for databases

There are four databases in the model: climate, crop, variable and parameter. Climate data (temperature, precipitation, humidity, wind speed and cloudiness) for the whole simulation period (1989-2003) were collected from the local meteorological station at Mellby. Recorded field cropping data on crop types and yield, fertilisation, soil tillage dates and actions were used in the crop database. The variable database is for outputting various variables calculated by the model. The data in the parameter database were mainly based on the parameterisation for sandy loam soils used in the national calculations for PLC5 in Sweden (SNV, 2008b), here called standard parameterisation. Parameter values were also adjusted based on available field measurements and literature data to the greatest extent possible and some of them were estimated by calibration in the appropriate value ranges based on experiences at the Department of Soil & Environment. The adjusted values or value ranges for calibration of important model parameters for simulations of drainage and P losses are presented in Table 1.

Table 1. Adjusted parameter values differing from those used for the national calculations of PLC5 in Sweden (SNV, 2008b) and the appropriate parameter value ranges to be calibrated in

Parameter	Unit	Adjusted value or value ranges to be calibrated in	Source for change
Sspg (soil specific density)	$t\ m^{-3}$	2.51, 2.55, 2.65, 2.66*	Measurement
Clay	$m^3\ m^{-3}$	0.1, 0.1, 0.02, 0.01*	Measurement
Sand	$m^3\ m^{-3}$	0.77, 0.77, 0.91, 0.86*	Measurement
Organic matter	$m^3\ m^{-3}$	0.05, 0.05, 0.01, 0.005*	Measurement
Field capacity	$m^3\ m^{-3}$	0.258, 0.227, 0.056, 0.079*	Measurement
Soil porosity	$m^3\ m^{-3}$	0.418, 0.398, 0.324, 0.36*	Measurement
Wilting point	$m^3\ m^{-3}$	0.079, 0.078, 0.014, 0.015*	Measurement
Tresh_watin	m	0~0.05**	Experience
Frac	%	0~1**	Experience
Fcfrac	%	0.99-0.999**	Experience
Filter coefficient	m^{-1}	0~1**	Experience
K1	d^{-1}	0~1**	Experience
K2	d^{-1}	0~1**	Experience
Replenishment	$g \cdot m^{-2} \cdot h^{-1}$	0~1**	Experience
Detachability	$g \cdot J^{-1} \cdot mm^{-1}$	0~1**	Experience
Particle extraction depth	mm	0.1~1**	Experience
Base saturation	%	75~100**	Experience

*The four values are for layer 1 (0-1 cm), layer 2 (2-30 cm), layer 3 (31-65 cm) and layer 4 (66-100 cm), respectively. These specific values were used for all the simulations in this work, including sensitivity analysis.

**The ranges of values represent the values that can be selected in the range. They were used in the model calibration part of this work, where the most appropriate values in the ranges were selected and used in later simulations. They were not used in the sensitivity analysis part, where standard values for these parameters were used instead.

The soil type used in the simulations was mainly sandy loam based on texture analyses (Ulén et al., 2006). The preliminary simulations using standard parameterisation (SNV, 2008b) for sandy loam also generated better results in terms of matching field measurements than using loamy sand. The slope class of plot 9 was low (1.43%). The simulation period started with 1989, when the plot was drained and hydrologically isolated, and ended in 2003.

4. Sensitivity analysis

The method of changing a single parameter value was employed to perform an analysis on the sensitivity of the output variables (Appendix A1) drainage and P losses with respect to the changes in parameter values. Specifically, parameter values were individually changed by ±50% or ±20% within an allowable range, while keeping the others at their standard values or adjusted values (Table 1). The sensitivity to a parameter was then assessed as the relative change in the cumulative value of the output variable for the whole simulated time period. The sensitivity criteria for those output variables under 50% change in a parameter were: none =0, negligible <1%, slight 1-10%, moderate 10-50%, and significant >50%; while for those with 20% change in a parameter the criteria were: none =0; negligible <1%; slight 1-4%; moderate 4-20%; significant >20%.

5. Model calibration, simulations and comparison with measurements

The model setup and parameter calibration were carried out in two steps, with the aim to firstly get a good fit between simulated and measured drainage, and thereafter fit the measured P losses. The purpose was to determine appropriate values for decisive parameters and gain some information for future work. Since P leaching is mainly determined by water transport in the soil, the first priority was given to drainage. First of all, the values of the decisive parameters in relation to drainage were determined based on the principle that the simulated results had both good total and dynamic agreement with field measurements. The results were compared in terms of total amount and dynamics of water drainage and P leaching, respectively. At this step, standard parameter values (Table 1) related to P leaching were used. A balance analysis on simulated water and P was performed mainly based on the description of inputs and outputs in Section 3.1, with the exception that water percolation and thus P leaching partitioning between tile drains and bypass were included. The results were compared with measured data which had the same inputs of water and P as those in the model, but only total drainage and soluble and particulate P leaching available in the outputs. Attempts were then made to determine appropriate parameter values giving good agreement of P leaching between simulations and measurements.

Attempts were also made to determine a good combination of K1 and K2 values to estimate the deep percolation at the plot and to get good agreement of total simulated drainage for the whole period with total drainage measured in the field. K3 and K4 were not changed owing to the relatively small proportion of macropore flow (<10%), assumed to have an insignificant effect on drainage partitioning.

Although macropore flow accounts for less than 10% of total drainage in the simulations, its accounting in the model is very important for understanding drainage dynamics. Despite the soil at Mellby not having clear macropores as in e.g. clay soils, studies have shown that water percolating in this soil mainly follows preferential flow pathways such as root channels, hydrophilic zones, etc. (Larsson et al., 1999). It was therefore important to use parameters for macropore flow in order to simulate the measured drainage dynamics. Due to the insignificant effect of fcfrac within its value range (0.99-0.999) on simulation results, the simulations mainly focused on tresh_watin and frac.

In the P leaching part, the focus for calibration was on the parameters for P movement (base saturation, filter, replenishment, detachability, particle extraction depth) and the initial values for the P_S and P_A pools in soil (soil P class).

Results and discussion

1. Parameter sensitivity analysis

Table 2 summarises the important model parameters with moderate or significant effects on output variables for water drainage (drainage through micropores/macropores, and total drainage) and P leaching (soluble/particle P leaching through micropores/macropores, and total P leaching). More information about the sensitivity analysis can be found in Appendix A1.

Table 2. Important parameters (defined as those leading to moderate or significant sensitivity of output variables) for drainage and P leaching

Output variables	Significant	Moderate
Drainage through micropores	---	CN2 (implement)*, sand content, field capacity
Drainage through macropores	CN2 (implement)*, tresh_watin, frac, fcfrac, w_tresh_mac, k4, field capacity, wilting point	CN2 (action)**, clay, sand content, saturated conductivity, soil porosity
Total drainage	---	CN2 (implement)*, sand content, field capacity
P leaching through micropores	base saturation	CN2 (implement)*, sand content, field capacity
P leaching through macropores	CN2 (implement)*, tresh_watin, frac, fcfrac, w_tresh_mac, k4, field capacity, wilting point,	CN2 (action)**, soluble P extraction depth, sand content, saturated conductivity, base saturation
Soluble P leaching	base saturation	CN2 (implement)*, sand content, field capacity
Particulate P leaching	CN2 (implement)*, tresh_watin, frac, fcfrac, w_tresh_mac, K4, clay content, field capacity	detachability, particle extraction depth, sspg (soil specific density), sand content, saturated conductivity, , wilting point, P_{SO}
Total P leaching	---	CN2 (implement)*, tresh_watin, fcfrac, sand content, field capacity, base saturation

*CN2 in the 'Implement' table, implements such as plough, harrow and stubble cultivator for each crop.

**CN2 in the 'Action' table, practices such as planting, harvesting and straw removal for each crop.

The important parameters of moderate or significant sensitivity in the Mellby field can be divided into five groups: management practices (CN2), soil physical properties (sspg, sand content, clay content, soil porosity, field capacity, wilting point and saturated conductivity), macropore flow (tresh_watin, frac, fcfrac, w_tresh_mac and K4), P pools and flows (P_{SO}, soluble P extraction depth and base saturation), and particle extraction for macropore flow (detachability and particle extraction depth). The sensitivity analysis showed that careful consideration should be given to selecting values for these parameters.

CN2, especially in relation to the implements, had a great influence on total drainage and hence also on total P leaching, as well as leaching through micropores and macropores. This is because CN2 determines the runoff proportion of total water losses, and thus has an important effect directly on drainage and indirectly on P leaching.

Soil physical properties played a very important role in drainage. Sspg is used to calculate soil bulk density, which is involved in calculating the fraction of labile P leaching in the form of particulate P. The relative amounts of sand and clay, and the silt content calculated as the difference between these two fractions, determine the soil textural classification and are sensitive in predicting water flow through the soil. Soil porosity, field capacity and wilting point greatly affect water runoff, evapotranspiration and percolation. The moderate importance of saturated conductivity on macropore flow might be because low conductivity results in water accumulation in the soil profile exceeding the threshold for initiating macropore flow. The significant effect of sand, clay, soil porosity, field capacity, wilting point and saturated conductivity on P leaching probably results mainly from their influence on water transport. Clay is also important for P solubility.

All five parameters for macropore flow (tresh_watin, frac, fcfrac, w_tresh_mac and K4) were significantly sensitive for drainage and P losses through macropores. However, they generally had much less influence on total drainage and total P leaching due to the relatively small amount of drainage and P leaching through macropores compared with that through micropores.

Base saturation was significantly sensitive for P leaching through micropores and soluble P leaching, and moderately sensitive for total P leaching, due to its decisive role in soluble P desorption from stable P pools. Soluble P extraction depth affected soluble P leaching through macropores. As one of the sources of particulate P, stable organic P (P_{SO}) moderately contributed to particulate P leaching. Particle detachability and extraction depth also greatly influenced particulate P leaching, because these two parameters determine the production of soil particles and thus particulate P, which could potentially be leached through macropores.

The sensitivity analysis used to test the effects of a single parameter on water or P outputs was relatively simple and easy to perform. However, the results obtained are not quite certain, because the ICECREAM model is not linear between most of the parameters and output variables, and model output is often not solely influenced by one single input parameter (Bärlund and Tattari, 2001). In the simulations using ICECREAM, the interaction of K1, with a standard value of 1, and K2, with a standard value of 0, was very obvious. In this case, a change in either K1 or K2 did not influence total drainage, because they are confined by each other. However, great changes in total drainage can occur with an even slight simultaneous change in K1 and K2. In addition, the interaction between K1 and K2 was influenced by a third parameter, W_tresh_mic, which is a threshold for the outflow from the invented groundwater pool in the micropore region.

Interactions were also found between tresh_watin, frac and fcfrac for water flow through macropores, and between drain depth and filter coefficient. Therefore, the combined effect of two or more parameters should be considered based on model analysis, experience or literature. Fortunately, various sensitivity models such as UNCSAM (Janssen et al., 1992) have been specifically designed and can be used for this purpose (Bärlund and Tattari, 2001).

The parameter standard value used in simulations can also be decisive for the sensitivity of an output. For example, the filter coefficient with a standard value of 0.0001 was found to have no effect on any water or P output variable, but it did significantly influence particulate P leaching when its standard value became 1. Actually, the standard value of 0.0001 was too low to allow the filter coefficient to play any role in the particle filtration component. Consequently, it is very important to choose an appropriate standard value for an input parameter. However, it is not easy to determine this value due to the complexity of both the model and real field conditions.

It should be noted that sensitivity analysis is always site-specific, due to specific climate, soil, water, vegetation and management practices (Knisel, 1980). Bärlund and Tattari (2001) also reported that sensitivity results vary in the same study when soil type or crop type is changed. Consequently, the parameters sensitive for the Mellby field are not necessarily of the same importance for other fields.

2. Drainage parameterisation results

The model simulations without water bypassing tile drains showed that the 15-year total drainage (1989-2003) was generally around 20% higher than that measured in the field. This confirms earlier findings from this field that only about 80% of percolating water in the soil ends up in the tile drains (Torstensson & Aronsson, 2000). In order to get a good match of simulated total drainage with measured, a number of simulations with different K1 and K2 combinations were performed, but did not differ much in the cumulative drainage for each year (Fig. 2). The combination of K1 = 0.83 and K2 = 1 (Table 3) was selected for further simulations, on the assumptions that 83% of water went to tile drains and the rest bypassed the drainage system, and that the invented groundwater pool in the micropore region was emptied every day.

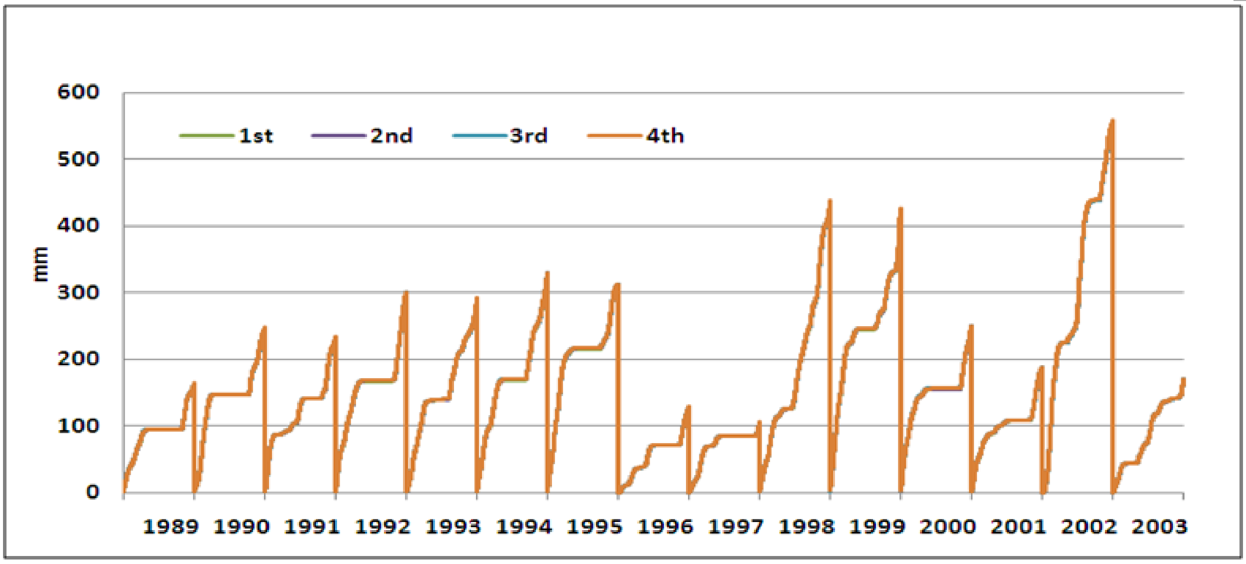


Figure 2. Annual cumulative water drainage (mm) from 1989 to 2003, simulated using different combinations of K1 and K2 values: 1st: K1=0.83, K2=1; 2nd: K1=0.71, K2=0.5; 3rd: K1=0.55, K2=0.25; 4th: K1=0.79, K2=0.75.

Table 3. Values of decisive parameters for drainage simulations

	Total drainage		Macropore flow		
	K1 (d^{-1})	K2 (d^{-1})	Tresh_watin (m)	Frac (%)	Fcfrac (%)
Standard values	1	0	0.0188	0.2	0.999
Selected values	0.83	1	0.0094	0.5	0.999

In general, macropore flow in a sandy loam soil such as the Mellby field is not expected to occur to any large extent, but the drainage dynamics at Mellby indicate that water can move very rapidly through the soil. The inclusion of gravel backfill when installing a drainage system in the soil is very likely to create a system of ‘artificial’ macropores, which may be one reason for this. Another reason could be that water moves through preferential flow pathways induced by water repellency in the topsoil (Larsson et al., 1999). The macropore parameters were quantified through calibration and based on the degree of dynamic agreement between simulations and field measurements. The parameter values that generated the best results for the Mellby soil were tresh_watin=0.0094, frac=0.5 and fcfrac=0.999 (Table 3). These values are close to those normally used for a loam soil (SNV, 2008b).

3. Water balance and drainage dynamics

3.1 Water balance

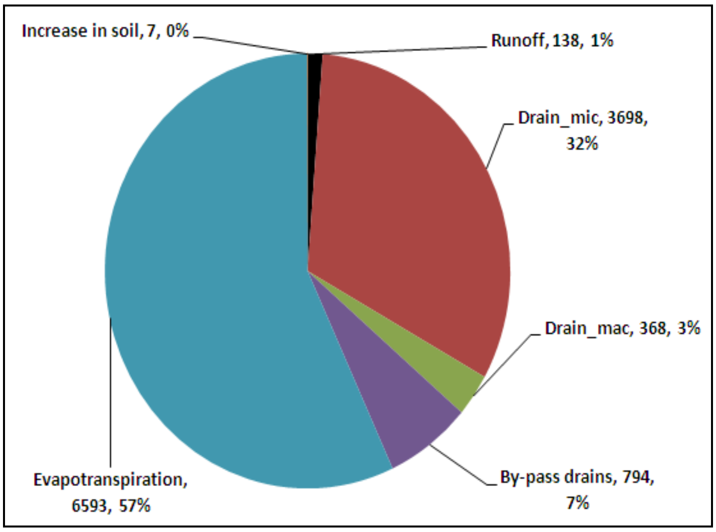


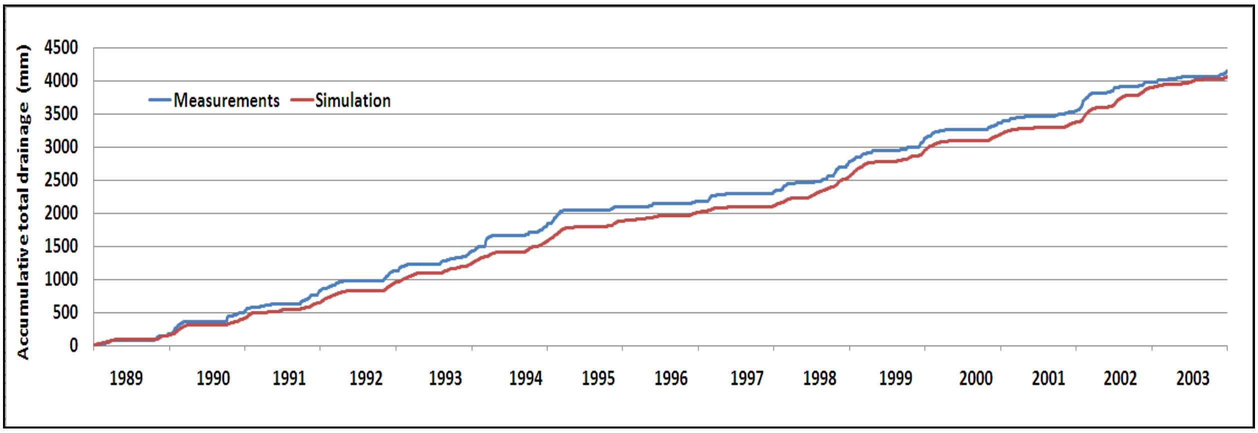
Figure 3. Simulated water balance (mm, %) for the whole period (1989-2003).

The water simulations from 1989 to 2003 had a very good balance between inflow and outflow, with a completely negligible change (7 mm) in soil water storage (Fig. 3). More than half of the precipitation (57%) was lost through soil and plant evapotranspiration. Because the studied field is quite flat, water runoff accounted for only 1% of the total water outflow. Around 42% of the precipitation percolated through the soil profile, of which 35% was lost through tile drains while 7% bypassed the drains. The simulated cumulative drainage of 4066 mm corresponded very well with the amount measured in the field (4144 mm). Most of the simulated percolation water (32%) was lost through micropore flow and only 3% through macropore flow.

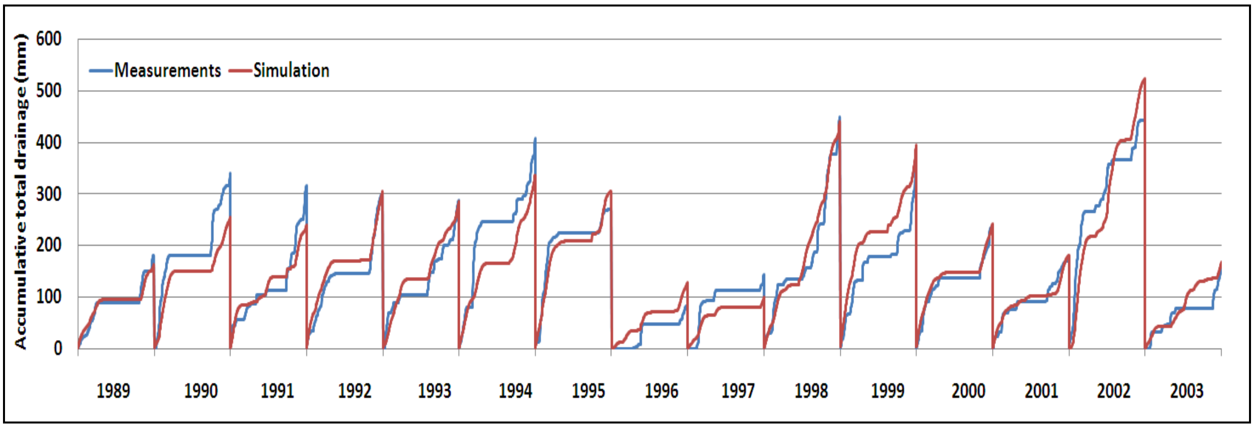
3.2 Total drainage and drainage dynamics

As mentioned in section 3.1, simulated cumulative total drainage for the whole 15-year period (1989-2003) agreed well with field measurements (1.9% lower than measured). There was generally satisfying dynamic agreement between simulations and measurements, with similar increasing or decreasing slope at the same time (Fig. 4).

As is apparent in Figure 4, different patterns arose in the annual cumulative curve. Specifically, the model simulated total drainage and dynamics that were closely similar to the measured values for 1989, 1995, 1998, 2000, and 2001. For 1992, 1993 and 2003, the model simulated total drainage quite well, but with a sudden increase in April, April and July, respectively. This abrupt increase in simulated drainage coincided with single short precipitation events. Drainage was either overestimated by the model or was not collected by the drains in the field. In contrast, the simulated drainage became abruptly smaller than the measured in February 1990 and March 1994, contributing significantly to the lower total drainage during these years. This was because the model failed to simulate some significant drainage events. In 1991, the model simulated higher drainage before October, but it simulated much less in the last three months of the year, which resulted in total drainage being about 80 mm lower than measured. The same pattern was found in 1997, with the turning point in February. In contrast, 2002 had the opposite pattern, simulating less drainage before August but more afterwards, leading to the simulated total drainage exceeding the measured by about 80 mm. The simulated drainage was generally higher than the amount measured over the year in 1996 and 1999.



(A)



(B)

Figure 4. (A) Total cumulative total drainage (mm) for the 15-year period and (B) annual cumulative total drainage (mm) for each year from 1989 to 2003 for the Mellby sandy loam soil.

The exact reasons for the difference between simulations and measurements can only be determined based on analysis of dynamic patterns, model input, model working mechanisms, and real field conditions. In particular, single intensive flow events are difficult to predict with the model, due to lack of exact coherence between model and reality.

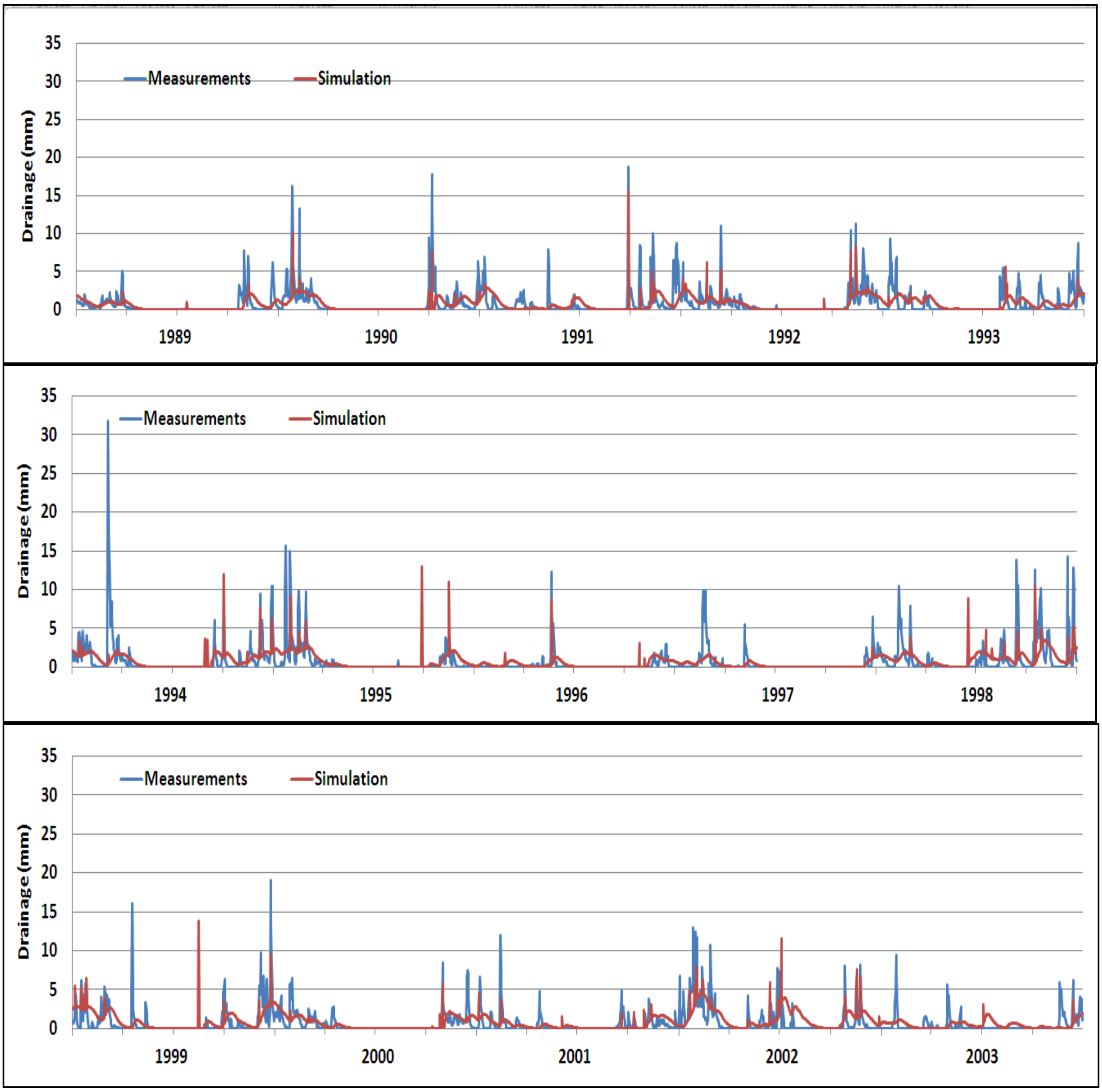


Figure 5. Daily drainage (mm) dynamics of the Mellby sandy loam soil from 1989 to 1993: 1989-1993 in the top graph, 1994-1998 in the middle and 1999-2003 below.

The model was generally able to simulate the daily dynamics of drainage from the Mellby field successfully for the whole period (Fig. 5). Although the simulated drain peaks were often lower than measured, the model managed to simulate most of them at the right time, for instance, in January and October 1990, from September 1991 to April 1992, from November 1992 to January 1994, from October 1994 to August 1995, from July 1998 to March 1999, from October 1999 to March 2002, and in October and November in 2002. This indicates reasonable parameterisation of the model, especially of the fast water movements in the soil represented by the macropore flow.

The reasons for the failure of the model to simulate some events could be uncertainty of input data, overestimation or underestimation of some processes such as snowmelt and evapotranspiration, or some field conditions or processes being excluded from the model.

Notably, some drainage events were simulated by the model where no water was captured by drains in the field, e.g. the drainage peaks on 19 July 1989, 16 September 1992, 29 September 1995, 18 June 1998 and 17 August 1999. A high total amount of precipitation of several tens of millimetres in a few days before the occurrence of drainage peaks was found to have been input for the model in all of these events, indicating that the model simulations were very reasonable and that the overestimation of the events was due to either incorrect input precipitation data or errors in the measurements.

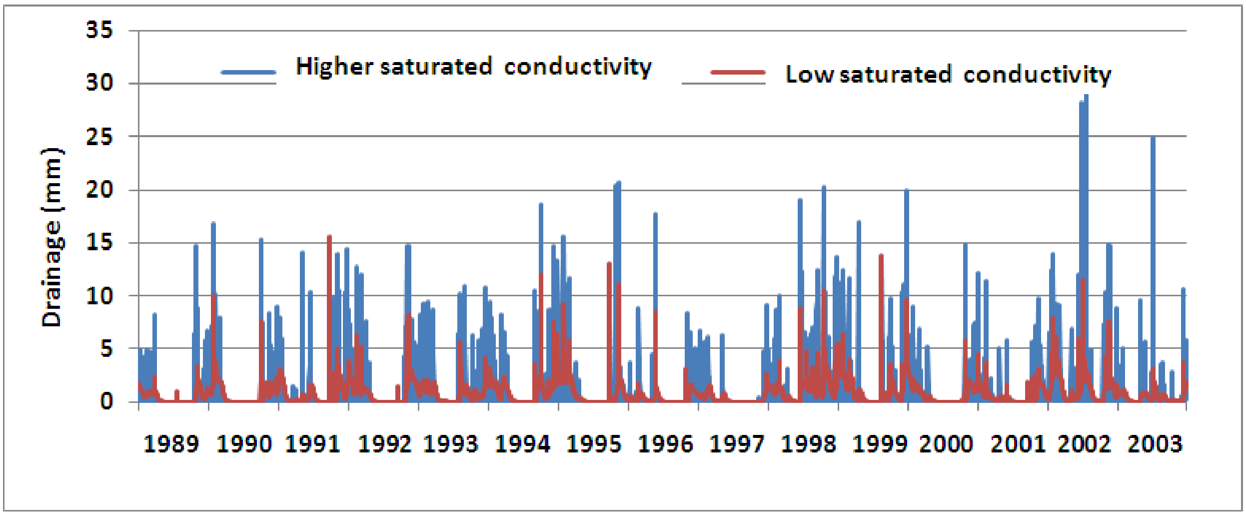
The model also failed to simulate some major drainage events such as the field drainage peaks in May 1991, March 1994, February 1997, April 1999 and April 2003, for different reasons. For example, the failure of simulation in May 1991 was because the model most likely overestimated soil evaporation and thus underestimated water percolation through the soil profile and drainage losses, whereas the failure in March 1994 was most likely due to incorrect precipitation input in the model. The measured drain peak (32 mm) for this event was higher than the total precipitation for the previous 30 days (30 mm).

It was more common for the model to simulate lower or higher drainage peaks compared with field measurements. For instance, the underprediction by the model in February 1990 that made the simulated annual cumulative amount of drainage suddenly become smaller than the measured amount might be due to insufficient accounting in the model for accumulated snow that melted and became drainage. The overpredicted drainage in June and July 2002 might be because part of the precipitation running off the field moved along channels formed on the soil surface by the ridges in a potato crop, which was not accounted for in the model.

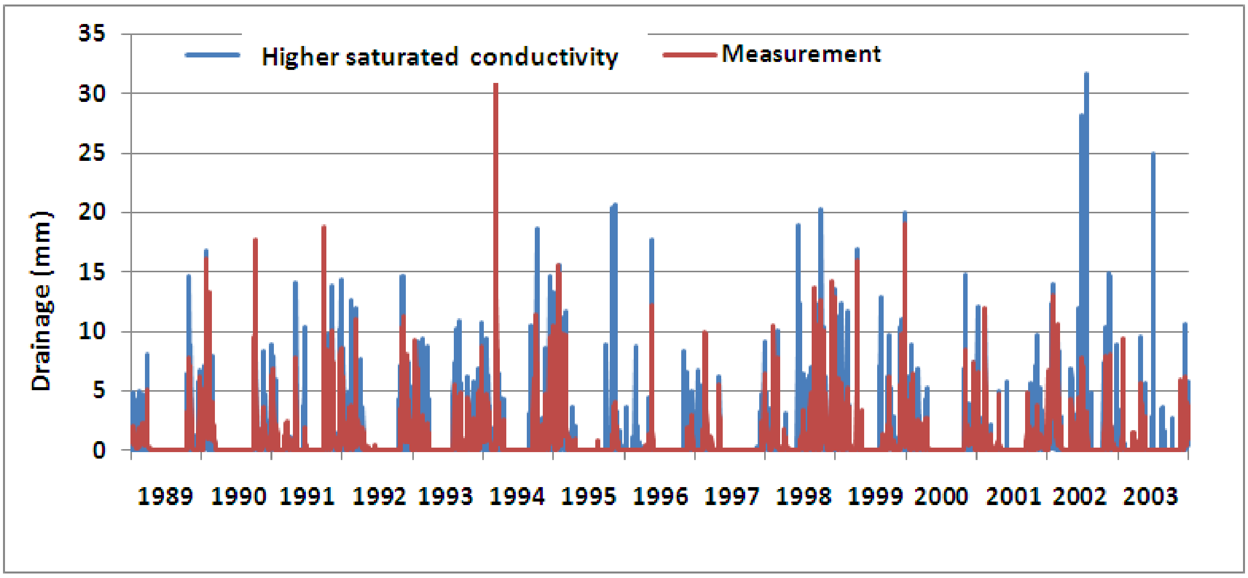
3.3 The influence of saturated conductivity

In accordance with earlier model applications (SNV, 2008b), the parameterisation of saturated conductivity was set low to only represent the micropore region. It was found that the values were too low for coarse soils such as this sandy loam and should have been approximately 10-fold higher. To check the influence of this mis-parameterisation, a higher saturated conductivity was used in a re-simulation.

The higher saturated conductivity and simulated macropore flow played the same role in simulating drainage peaks (Fig. 6). Compared with the former simulation with low macropore flow (Fig. 5), the simulation using higher saturated conductivity generally only simulated 10 mm higher drainage over the 15-year period, but generated more frequent peaks that were even higher than those measured. Through comparing both simulations with measurements, it was concluded that the simulation with the calibrated macropore flow fitted field measurements better.



(A)



(B)

Figure 6. Comparisons between (A) low and higher saturated conductivity from 1989 to 2003, and (B) higher saturated conductivity and measurements, illustrating its influence on drainage. In the simulation of higher saturated conductivity, the standard parameter values in relation to macropore flow were used: tresh_watin=0.0188, frac=0.2; while the simulation of higher saturated conductivity was the same as that in the former parts using tresh_watin=0.0094, frac=0.5.

4. P balance and P leaching dynamics

4.1 P balance

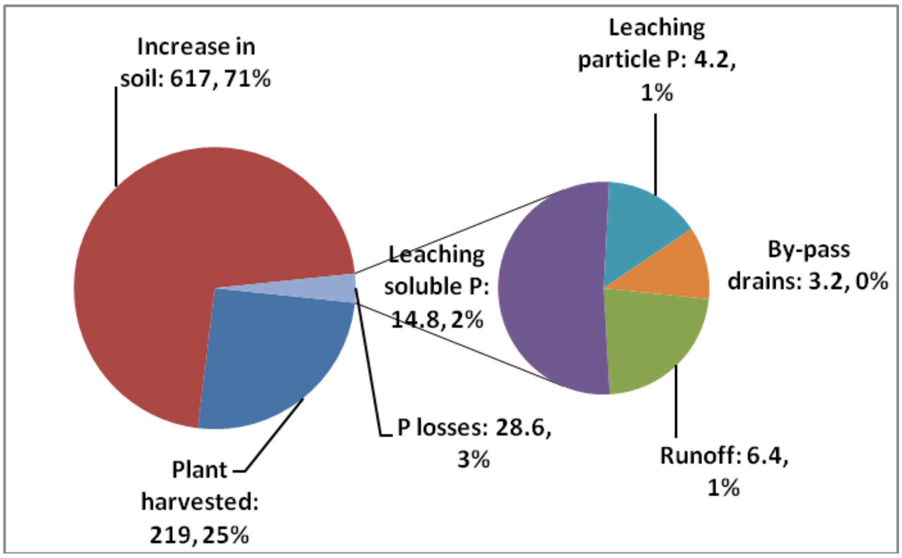


Figure 7. Simulated P (kg ha^{-1}, %) balance for the whole period (1989-2003).

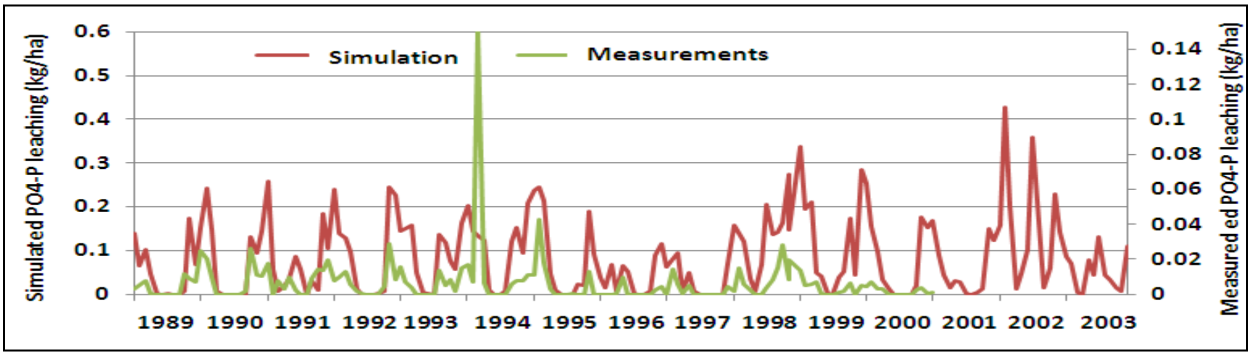
Phosphorus was applied to the plot at a level of 865 kg per hectare and year from 1989 to 2003. The majority (820 kg ha^{-1} yr^{-1}) was applied as pig slurry, and the remainder as mineral fertiliser. Of the total P applied, about 25% was removed from the soil with the harvested crop and, according to simulations, 3% was lost through drainage and runoff while 71% was retained in the soil (Fig. 7). Although P losses accounted for only 3% of the P applied in fertiliser, this is enough to result in eutrophication and threaten the ambient water environment. According to the model, leaching of soluble P through the drainage system was the most important route of P losses at Mellby, followed in decreasing order by runoff, leaching of particle P and P bypassing drains.

The retention and accumulation of P in the soil is likely to act as a potential source of P leaching in the future. However, the model was not sensitive enough to determine this fraction. When a simulation test was made with no P fertiliser applied, there was only a 2% change in total P leaching. Possible reasons were that most of the P input was added as manure, which has a lower transformation rate to labile P in the model compared with mineral fertiliser, and that when fertiliser was applied to the soil, P was greatly adsorbed in the topsoil, resulting in a low concentration in the subsoil and low leaching. Another reason could be that the value (0.85 g kg^{-1}) used in the model for the stable mineral P pool in layer 3 and layer 4 was much too high, and this pool controlled the source of labile P and active P for leaching. By comparison, P available for leaching due to fertilisation in the simulation period seemed to be very small. However, the measurements did not show any increase in P leaching over the 15-year-period as could have been expected due to the large doses of P applied. In other plots, only mineral P or manure P was applied, in amounts corresponding to about 50% of those in plot 9, but there were no clear differences in measured P leaching. Overall, the measurements showed that P leaching was low. There is a high amount of redcoloured iron oxides in the subsoil and precipitation of iron oxides creates problems in tile drains. This most likely contributes to high P sorption capacity for this soil.

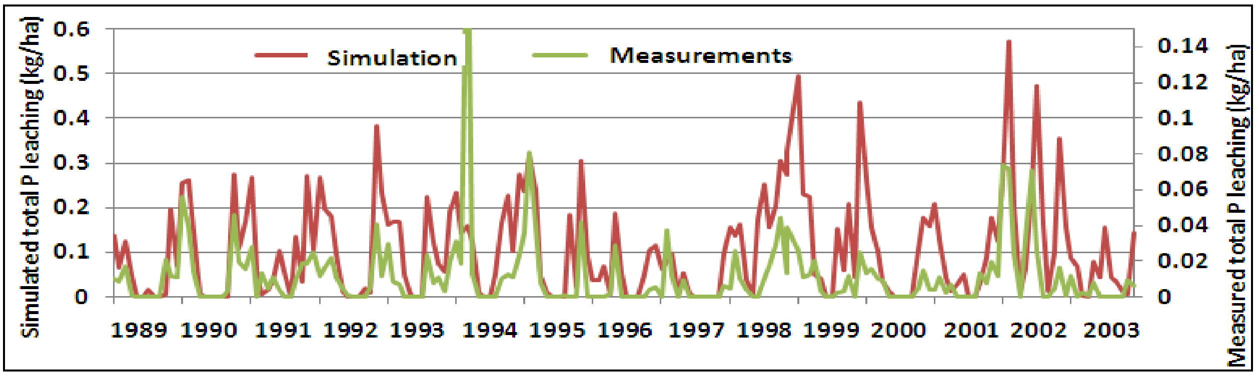
The simulated 15-year cumulative P leaching was much higher than that measured in the field. The simulated total P leaching consisting of soluble and particulate P and that of drain bypass was as high as 1.48 kg ha^{-1} yr^{-1}, which was 10-fold higher than that measured in the field (0.14 kg ha^{-1} yr^{-1}). The value is also almost three times the average P leaching (0.5 kg ha^{-1} yr^{-1}) estimated by ICECREAM simulations for a sandy loam soil in Sweden (SNV, 2008a). The simulated leaching of soluble and particulate P was about 18-fold and 4-fold higher than that measured in the field, respectively.

In the model simulations, 18% soluble P bypassed drains with drainage water, indicating that field measurements have probably underestimated soluble P leaching. Accounting for this eventual underestimation in measurements, the cumulative total P leaching for the 15 years would be around 2.3 kg ha^{-1}, with an average of 0.16 kg per hectare per year.

4.2 P losses and dynamics



(A)



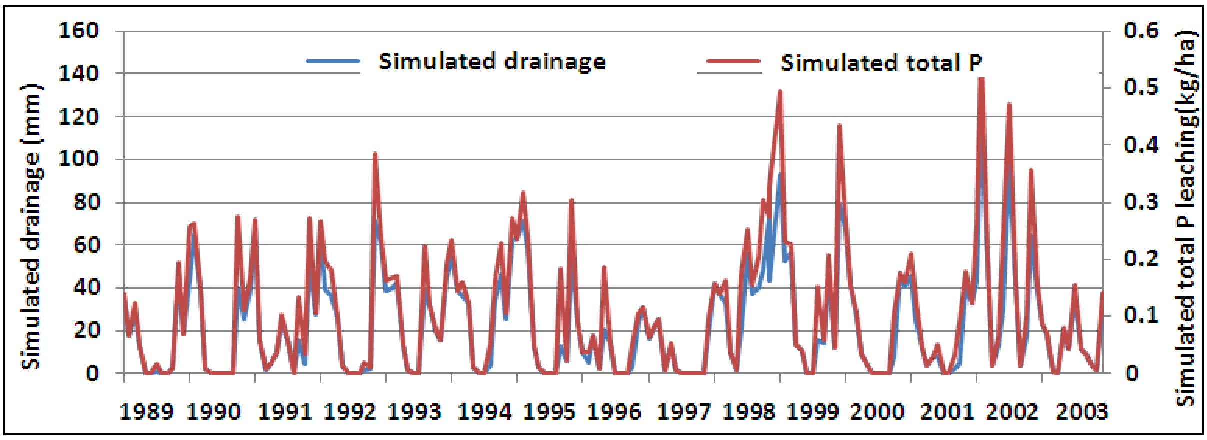
(B)

Figure 8. Comparison of 15-year P leaching between model simulation and field measurements for monthly transport (kg ha^{-1}) of (A) soluble P and (B) total P.

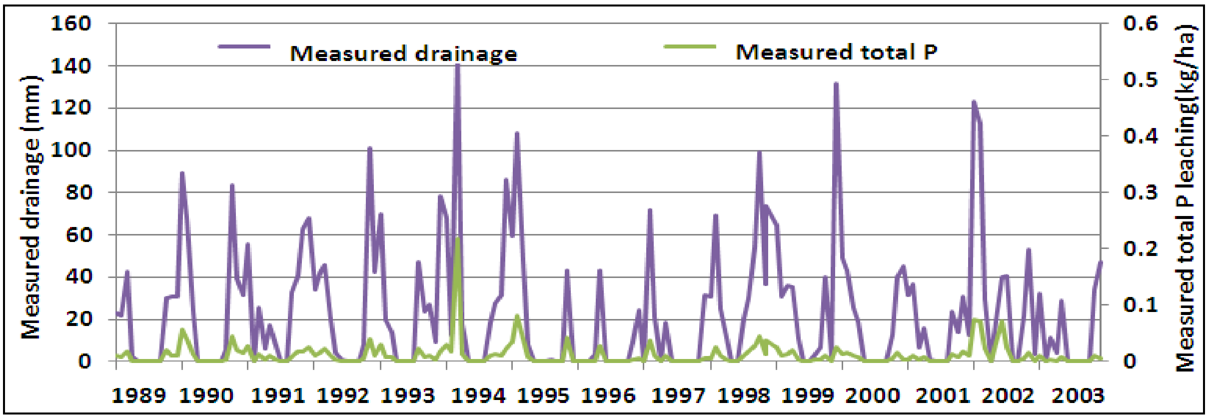
As shown in the P balance part, the model using standard P parameters greatly overestimated the 15-year total amount of P leaching, since measured leaching was much lower than simulated. Overestimation of P leaching occurred every month (Fig. 8). This was probably because a large amount of P was adsorbed by iron or aluminium oxides in the subsoil in the field, a process not included in the model.

There were no major differences in transport dynamics between soluble P (PO_4^{3-}-P) and total P (Fig. 8). The simulated monthly transport of both PO_4^{3-}-P and total P in general had a good dynamic agreement with the measured values, showing many transport peaks at the right time. The transport dynamics for the years 1989-1993, 1996-1997 and 2002 were very well predicted. The agreement of P was mainly attributed to a good match of simulated drainage (Fig. 9), which is one of the most important factors influencing P leaching, especially in the model. Real field conditions are much more complicated than the model, with more factors affecting P leaching, such as P sorption and adsorption processes on the surface of iron and aluminium oxides, and also the influence due to the change in redox potential.

However, for a similar drainage amount, the model simulated much higher total P transport than field measurements, which is most likely determined by the parameters related directly to P solubility and generation of soil particles. It also indicates the occurrence of P retention under field conditions. As some previous studies showed, the Mellby sandy soil has a high P sorption capacity but a relatively low degree of saturation, and therefore a considerable proportion of soluble P is probably retained due to iron and aluminium oxides in the subsoil.

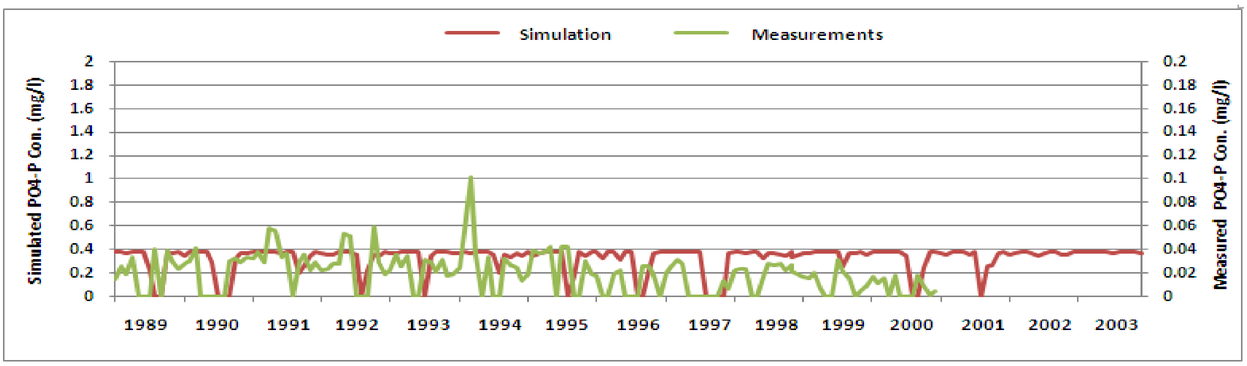


(A)

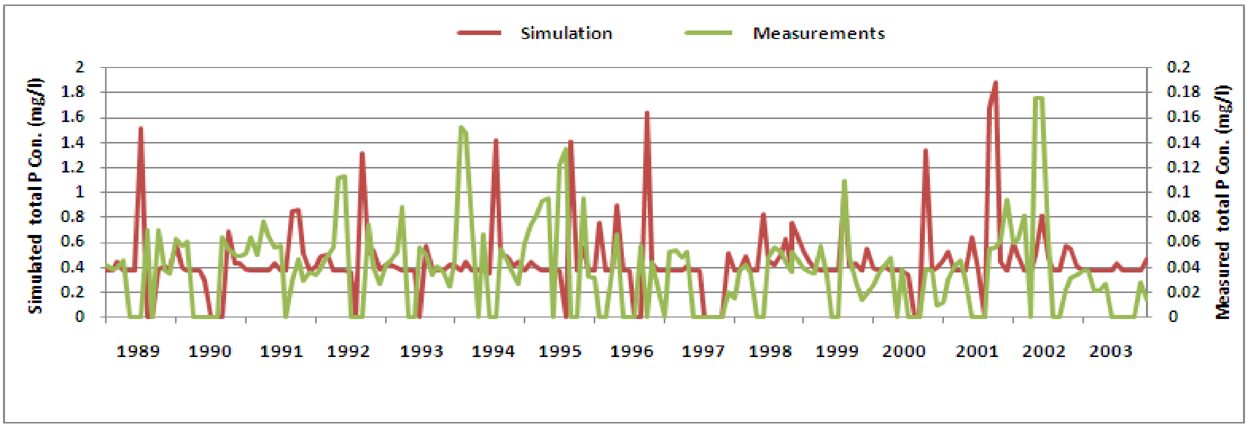


(B)

Figure 9. Correlation between drainage and total P leaching for (A) model simulations and (B) measurements. The y-axis on the left of each graph shows drainage (mm), while that on the right shows total P transport (kg ha^{-1}).



(A)



(B)

Figure 10. Comparison of 15-year P concentration in leachate between model simulation and field measurements for monthly mean concentration (mg l^{-1}) of (A) soluble P and (B) total P. The y-axis on the left of each graph shows the simulation results, that on the right the actual measurements.

Comparisons of measured and simulated monthly P concentrations did not show as good agreement as transport of P (Fig. 10). Measured concentration values were lower and had a different dynamic pattern than simulated values. Due to the high overestimation of P transport, the simulated P concentrations were also much overestimated.

4.3 Additional simulations

Considering the different extent of overprediction of soluble P (18-fold) and particulate P (4-fold) and the different mechanisms for their occurrence in the soil profile, the two categories of P leaching were simulated with the focus on different influential parameters. Based primarily on the results of the sensitivity analysis, attempts were made to determine appropriate values for base saturation affecting soluble P leaching in the sorption-desorption process and for parameters (replenishment, detachability, particle extraction depth, filter) related to macropore flow and particle detachment controlling particulate P leaching. Further simulations were performed on different soil P classes to test the effects on P leaching.

4.3.1 Soluble P leaching

Different values of base saturation were tested in order to simulate good agreement in soluble P leaching, and the best value was found to be 3. However, this is an unrealistically low value and is hence an indication that the model needs to be improved concerning P sorption-desorption. An improvement could be to include the chemistry component with iron and aluminium oxides illustrating P retention in the subsoil.

4.3.2 Particulate P leaching

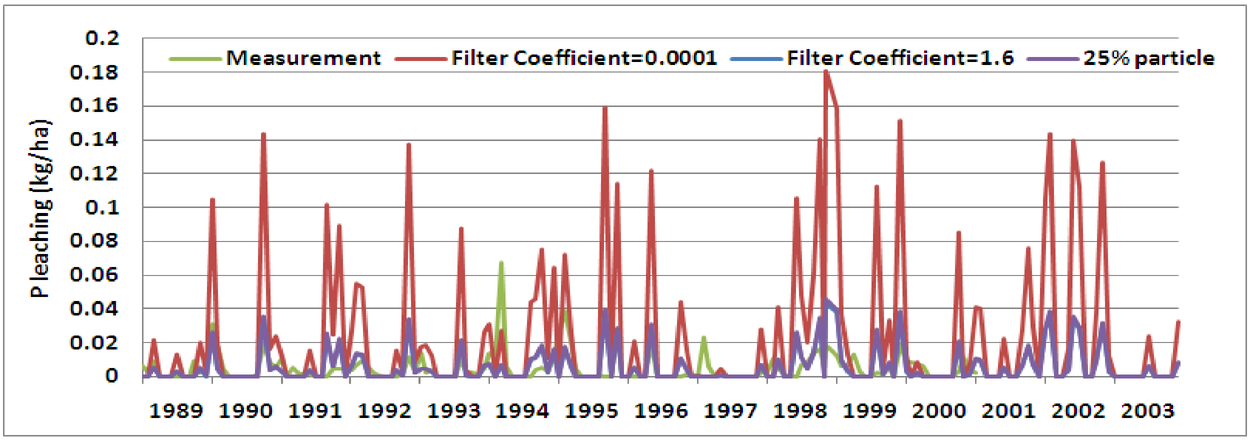


Figure 11. Monthly particulate P transport (kg ha^{-1}) in the field measurements and in the simulations using different parameter values: a filter coefficient of 0.0001 (standard) and 1.6 and 25% particle, respectively. '25% particle' means that compared with the standard values, the three particle-related parameters (replenishment, detachability and particle extraction depth) were reduced by 75% to 0.05, 0.06875 and 0.25, respectively.

A filter coefficient of 1.6 or a 75% decrease in the parameter values related to particle generation capacity gave almost the same 15-year cumulative and monthly dynamics of particle P transport as in the measurements (Fig. 11). The simulated and standard values both successfully simulated lower monthly transport of particle P with the same occurrence of transport peaks in time. They also gave good agreement with field measurements, in terms of cumulative particle P transport of approximately 1 kg per hectare over the 15 years. In addition, they accurately simulated monthly transport dynamics for the period 1989-1990, as well as some periods in other years. The dynamics of particle P leaching in the model were determined by the preferential flow at the Mellby field.

4.3.3 Importance of soil P classes

Total P of the soil is a very important input for simulating P leaching, since it determines the initial states of the P_S and P_A pools. Different values (Table 4) were used in the simulations to examine the effect of soil P class on P leaching.

Table 4. 15-year total soluble P (kg ha^{-1}), particulate P (kg ha^{-1}) and total P (kg ha^{-1}) leaching simulated using different P classes.

Soil P class (P_S)	0.68, 0.68, 0.85, 0.85[#*]	0.87, 0.87, 0.048, 0.048[##*]	1.05, 1.05, 0.22, 0.50[###*]
Soluble P	14.77	1.86	9.45
Particulate P	4.19	4.80	5.40
Total P	18.96	6.66	14.85

*The four values are for soil layers 1, 2, 3 and 4, respectively.

[#]Values used in this work for simulations in sensitivity analysis and comparison of drainage and P leaching.

[##]Values from simulations of some other Swedish fields.

[###]Values calculated from measured P content (HCl extraction method) by multiplying by a coefficient of 1.44 (SNV, 2008b).

Soil P class had a dramatic influence on soluble P leaching and thus total P leaching (Table 4). When soil classes used for earlier work and classes calculated from measured P-HCl were simulated, the soluble P was reduced significantly from 14.77 kg ha^{-1} to 1.86 and 9.45 kg ha^{-1}, respectively. By comparison, particulate P increased moderately to 4.80 and 5.40 kg ha^{-1}, respectively. The decrease in soluble P might be due to the lower P values used for layer 4, which mainly determined the drainage through micropore and soluble P leaching; while the increase in particulate P may mainly result from the increase in P values in layer 1, where soil particles are initiated and which is an important source of particulate P.

Conclusions

The ICECREAM model was able to simulate drainage during 15 years of a sandy loam soil at the Mellby site quite well. In general, good agreement was obtained with measured total drainage and daily drainage dynamics. The success was largely due to calibration of the parameters (K1 and K2) determining drainage water partitioning between tile drains and deep percolation and those (tresh_watin and frac) for simulating macropore flow. It was estimated that 17% of simulated drainage bypassed the drainage system, indicating that the field drains failed to collect all the drainage water. The simulations showed the importance of including macropore flow in the model and indicated that preferential flow is important for rapid water movements in the Mellby soil.

The model accurately simulated PO_4^{3-}-P and total P transport dynamics, because these were mainly determined by water movement in the soil profile. However, the simulated monthly amounts of transported P were much higher than the measured values and the model also failed to simulate the P concentration in leachate. One reason for the overprediction by the model was probably that soluble P was adsorbed to iron and aluminium oxides, which are visible in the Mellby subsoil. This sorption process was not included in the model and one of the main conclusions from this work was that this process must be included in order for the model to simulate P leaching from a soil of this type. Other possible reasons for the poor agreement are overestimation of particle generation capacity or underestimation of particle retention ability of the soil, or both. This resulted in overestimation of particle-bound P in drainage water. It was concluded that it is important to consider these parameters.

In the simulations, crop cover, tillage method and field management strategies had moderate to significant effects on drainage and P leaching through the determination of the CN2 parameter, and hence CN2 had an effect on partitioning of precipitation between surface runoff and percolation through the profile. This indicates a possibility to mitigate P leaching by improving cropping systems and soil management.

The soil P pools determined P leaching in this work, and in comparison to their large size, the amount of P added through fertilisation was small and made a very small contribution to overall P leaching.

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Appendix

A1: Sensitivity of water (mm) and P (kg ha^{-1}) output variables to related parameters (Explanations of abbreviations were given below the table.).

Parameters	R	Dmic	Dmac	D	RD	ET	RP	SeP	RSP	Pmic	Pmac	PL	PPL	TPL	SP	PP	TP
CN2&Mn table																	
CN2	M	Ne	Ne,M*	Ne	No	No	Sl,M	Sl,M	Sl,M	Ne	Sl,M	Ne	Ne,Sl	Ne	Ne	Sl	Ne
Mn	No	No	No	No	No	No	No	Ne	Ne	No	No	No	No	Ne	No	Ne	Ne
CN2&Mn implement table																	
CN2	Si	Sl,M	M,Si	Sl,M	Ne	Ne	Si	Si	Si	Sl,M	M,Si	Sl,M	Si	Sl,M	Ne,Sl	Si	M,Si
Mn	No	No	No	No	No	No	Ne	Si,M	Si,M	No	Ne	No	Ne	Ne	No	Si,M	M,Si
Crop																	
Residues:yield	Ne	Ne	No	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne,Sl	Ne	Ne	Ne,Sl	Ne
Canopy cover constant	No	No	No	No	No	No	No	Sl,Ne	Sl,Ne	No	No	No	No	Ne	No	Sl,Ne	Ne
Max LAI	Ne	Sl,Ne	Ne	Sl,Ne	Sl	Ne	Ne	Ne	Ne	Sl,Ne	Ne	Sl,Ne	Ne	Sl,Ne	Sl,Ne	Ne	Ne
Root:shoot ratio	No	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne
C:N yield	No	No	No	No	No	No	Sl	Sl	Sl	Ne	Sl	Ne	Sl,Ne	Ne	Ne	Sl	Ne
N:P yield	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
C:N Above ground biomass	No	No	No	No	No	No	Ne	Ne	Ne	No	Ne	No	Ne	Ne	No	Ne	Ne
N:P Above ground biomass	No	No	No	No	No	No	Ne	Ne	Ne	No	Ne	No	Ne	Ne	No	Ne	Ne
C:N Below ground biomass	No	No	No	No	No	No	Ne	Ne	Ne	No	Ne	No	Ne	Ne	Ne	Ne	Ne
N:P below ground biomass	No	No	No	No	No	No	Ne	Ne	Ne	No	Ne	No	Ne	Ne	Ne	Ne	Ne
MacroP																	
Tresh_watin	Ne	Sl,Ne	Si	Ne	Ne	Ne	Ne	Sl,Ne	Ne	Sl,Ne	Si	Ne	Si	M,Sl	Ne	Si,M	M,Sl
Frac	Ne	Ne	Si	Ne	Ne	No	Ne	Ne	Ne	Ne	Si	Ne	Si,M	Sl	Ne	M,Sl	Sl
Fcfrac	Ne	Ne	Si,M	Ne	Ne	No	Ne	Ne	Ne	Ne	Si,M	Ne	Si	M,Sl	Ne	Si,M	M,Sl
Filter	No	No	No	No	No	No	No	No	No	No	No	No	No	Ne	No	No	No
W_tresh_mac	No	No	Si	Ne	Ne	No	No	No	No	No	Si	Ne	Si	Sl	Ne	M	Sl
K1	No	Ne	No	Ne	Ne	No	No	No	No	Ne	No	Ne	No	Ne	Ne	No	No
K2	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
K3	No	No	No	No	No	No	No	No	No	No	No	No	No	Ne	No	No	No
K4	No	No	Si	Ne	Ne	No	No	No	No	No	Si	Ne	Si	Sl	Ne	M	Sl
Ini_mic_P	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Ini_mac_P	No	No	No	No	No	No	No	No	No	No	Sl	Ne	No	Ne	Ne	No	Ne
Replenishment	No	No	No	No	No	No	No	No	No	No	No	No	Sl	Ne	No	Sl	Ne
Detachability	No	No	No	No	No	No	Ne	Ne	Ne	No	No	No	M	Sl	No	Sl	Ne
Particle extraction depth	No	No	No	No	No	No	Ne	Ne	Ne	No	Ne	No	M	Sl	No	M,Sl	Sl
Soluble P extraction depth	No	No	No	No	No	No	No	No	No	No	M,Sl	Ne	No	Ne	Ne	No	Ne
Root depth																	
Maximum root depth	No	No	No	No	No	No	Sl	Sl	Sl	Ne	Sl	Ne	Sl	Ne	Ne	Sl	Ne
Soil																	
Ksoil	No	No	No	No	No	No	Sl	M	M	No	Ne	No	Ne	Ne	No	M	Sl
Max water input	Ne	Ne	No	Ne	No	No	Sl	Ne	Ne	Ne	No	Ne	No	Ne	No	Ne	No
Soil loss calibration parameter1	No	No	No	No	No	No	Sl	M	M	No	No	No	Ne	Ne	No	M	Sl
Soil loss calibration parameter2	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Soil loss	No	No	No	No	No	No	Ne	M,Si	M,Si	No	No	No	No	Ne	No	No	Sl

calibration parameter3																	
Soil loss calibration parameter4	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Soil loss calibration parameter5	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
									Soil_layer								
Sspg	Sl	Ne	No	Ne	No	No	M	M	M	Ne	Sl	Ne	M	Sl	Ne	Ne	Ne
Clay	Ne	Ne	Ne,M	Ne	Ne	Ne	Sl	Sl	Sl	Ne	Sl	Ne	Si	Sl	Ne	Ne	Sl
Sand	Sl	Sl,M	Ne,M	Sl,M	Sl,M	Sl,M	Sl	M,Si	M,Sl	Sl,M	Ne,M	Sl,M	Ne,M	Sl,M	Sl,M	Sl,M	Sl,M
Organic matter	No	No	No	No	No	No	Ne	Sl,Ne	Sl,Ne	No	Ne	No	No	Ne	No	No	Ne
Saturated conductivity	M	Sl,Ne	Sl,M	Sl	Ne	Ne	M,Sl	M	M	Sl,Ne	Sl,M	Sl,Ne	Sl,M	Sl,Ne	Sl,Ne	Sl,Ne	Sl
Filed capacity	Si	M	Si	M	M	Sl	M,Si	M,Si	M,Si	M	Si	M	Si	M	M	M	M,Sl
Soil porosity	M	Ne	M	Ne	Ne	Ne	M	M	M	Ne	Sl	Ne	Sl	Ne	Ne	Ne	Sl
Wilting point	M	Sl	Si,Sl	Sl	Sl	Sl	M	M	M	Sl	Si,Sl	Sl	M,Sl	Sl	Sl	Sl	Sl
pH	No	No	No	No	No	No	Sl	Ne	Ne	Sl	Sl	Sl	Ne	Sl	Sl	Sl	Sl
CaCO3	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Base saturation	No	No	No	No	No	No	Si	Sl	Sl	Si	M	Si	Sl	M	Si	Si	M
FOP	No	No	No	No	No	No	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne
Plab	No	No	No	No	No	No	Sl	Sl	Sl	Ne	Sl	Ne	Sl	Ne	Ne	Ne	Ne
SorgP	No	No	No	No	No	No	Sl	M	M	Ne	Sl	Ne	M	Sl	Ne	Ne	Sl

Abbreviations:

Output variables of water and P:

R: daily surface runoff

Dmic: water drainage through micropores

Dmac: water drainage through macropores

D: total drainage, the sum of water drainage through micropores and macropores

RD: the sum of daily runoff and drainage

ET: evapotranspiration

RP: soluble P in runoff

SeP: sediment P, particulate P in runoff caused by erosion and sedimentation process

RSP: the sum of soluble and particulate P in runoff

Pmic: P leaching through micropores including only soluble P

Pmac: P leaching through macropores including both soluble and particulate P

PL: soluble P of leaching

PPL: particular P of leaching

TPL: total P by leaching, the sum of PL and PPL

SP: total soluble P losses, including by both runoff and leaching

PP: total particulate P losses, including by both runoff and leaching

TP: total P losses, the sum of SP and PP

Sensitivity criteria:

No: none

Ne: negligible

Sl: slight

M: moderate

Si: significant

*Ne,M: negligible sensitivity when the value of the parameter decreases and moderate sensitivity when it increases. The other combinations of No, Ne, Sl, M and Si are similar.

Acknowledgements

I would like to express my most sincere gratitude to those who have contributed to this work or helped me in any way, especially:

My supervisors, Helena Aronsson and Karin Blombäck, who have supervised and helped me all through this work, from data collection to analysis, from model setup to simulations, from result explanation to discussion, and from thinking to writing… Each progress is full of their generous help, time and ideas. I could hardly have completed it without them.

My colleagues, Kristian Persson and Hanna Larsson. They also helped me a lot in this work. Whenever I had difficulties in understanding the model, they were always there and helped to solve the problems.

The opponent, Matthew Riddle, and the examiner, Lars Bergström. Thanks for their careful reading, commenting and valuable suggestions.

There are also many colleagues at the Department of Soil & Environment who provided kind and generous help, discussion, ideas, suggestions, etc.

Thank you very much!