IDENTIFICATION OF HYDROLOGICAL FACTORS CONTROLLING PHOSPHORUS CONCENTRATION IN DRAINAGE WATER IN SANDY SOILS

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ABSTRACT

The relationship between total phosphorus (TP) and molybdate-reactive phosphorus (MRP) concentrations in subsurface drainage waters in the hydrological conditions prevailing during autumn and spring flow events was statistically analysed using multiple linear regression analysis. Data on hydrological conditions in three drainage experimental plots in a loamy sand in south-east Sweden complemented with DRAINMOD-predicted data were used as independent variables. Regression models explained at least 80% of the variation in TP and MRP concentrations in drain outflow, based on adjusted coefficient of determination (R^2_{adj}) calculations. DRAINMOD-predicted cumulative infiltration ($INFIL_{cum}$) was identified as the most important hydrological condition controlling TP and MRP concentrations in drain outflow in three autumn events and in two out of three spring events. This suggests that the first infiltrating water found more soluble P forms available for transport, after which TP and MRP concentration in drainage outflows gradually decreased during the flow events.

Keywords: Controlled drainage, DRAINMOD, Matrix flow, Preferential flow, Subsurface flow.

INTRODUCTION

In Sweden, environmental consequences of eutrophication by phosphorus (P) losses from non-point sources, such as agricultural areas, are now considered to be a major problem (Boesch *et al.*, 2005). Concerns about P losses in Sweden arose due to the serious condition of the closed and eutrophication-sensitive Baltic Sea, where, in some parts, P is considered to be the most limiting nutrient for Cyanophyceae bloom (Ulén *et al.*, 2007). Swedish authorities have proposed that by 2010 Swedish waterborne anthropogenic emissions of P compounds into lakes, streams and costal water will have decreased by at least 20% from the 1995 level (SJV, 2007).

The application of phosphorus (P) to agricultural land is essential for sustaining economical optimum crop yields in soils with low P availability. However, a continued use of P inputs, by fertilization or manure application, greater than crop needs produce a build-up of P in soil, which is a source potentially transportable (McDowell *et al.*, 2002). This excessive P enrichment in soils can increase the potential for losses of P to groundwater by leaching (Hooda *et al.*, 2000). Although the P concentration in water percolating through the soil profile by leaching is small, this dissolution process is frequently greater in sandy soils with low P sorption capacities and in soils which have become waterlogged (Sims *et al.*, 1998). In Sweden, leaching seems to be the most important P loss process in large areas (Bergström *et al.*, 2007).

Phosphorus enriched drainage water has been reported as an important nonpoint source pollution of water bodies (Sims *et al.*, 1998). When P leaches below the root zone, intensive subsurface drainage will increase potential for subsurface transport (Havlin, 2004). In addition, extensive research has correlated soil P concentration and dissolved P loss by subsurface drainage (Heckrath *et al.*, 1995; McDowell and Sharpley, 2001).

Phosphorus forms in water are conventionally determined on the basis of operational procedures, which include molybdate-reactive P (MRP) or reactive P, unreactive P (UP) and total P (TP) (i.e., reactive + unreactive) (Haygarth and Sharpley, 2000; Leinweber *et al.*, 2002). These forms of P have been related to transfer of P from soil to water under different soil types and land uses (Haygarth *et al.*, 1998). The risk of MRP and total P TP transport from land to groundwater is dependent on hydrological conditions controlling subsurface outflow (McDowell *et al.*, 2002). These processes are more complex than for overland flow, due to the variable paths (spatial variables) and time (temporal variables) of water flow through a soil with subsurface drainage (Haygarth *et al.*, 2000).

Spatial variables control the subsurface pathway and the form of P entering the drainage network (Haygarth *et al.*, 2000). The main pathways of P loss include matrix flow and preferential flow (Stamm *et al.*, 1998; Dils and Heathwaite, 1999). Matrix flow implies a uniform vertical movement downwards of soil water, common in very porous media (i.e. sandy soils), which only occurs after the soil pores have become saturated (Haygarth and Sharpley, 2000). Preferential flow is a rapid and direct transfer of water through a small portion of the whole soil volume, such as wormholes and fissures, often occurring in unsaturated conditions (Haygarth and Sharpley, 2000). It has been mainly associated to clay soils that are susceptible to shrinkage cracking, often after dry weather (Li and Ghodrati, 1997). However, preferential flow has been identified as an efficient mechanism of P transport into tile drains in coarse- and fine textured soils (Stamm *et al.*, 1998; Simard *et al.*, 2000). In addition, different preferential flows have been reported in sandy soils, such as short circuiting flow (Bouma, 1981), funnel flow (Kung, 1990) and fingering flow (Starr *et al.*, 1986; Glass *et al.*, 1989). Hendrickx and Flury (2001) noted that usually in soils a stable horizontal wetting front moves downwards without breaking into fingers, but it may break into fingering flow if is found for example a less permeable layer overlying a more permeable layer. At the textural interface between the fine and the coarse layer finger formation results from hysteresis in the water retention function, where once fingers are established, hysteresis causes fingers to recur along the same pathways during following rain events (Ritsema *et al.*, 1998). In fingering flow the solutes moves in these fingers induced by infiltration flow instability, where fingers facilitate recharge flow and transport of contaminant to groundwater (Glass *et al.*, 1989; Kung, 1990).

Haygarth *et al.* (2000) noted that the temporal variation in precipitation amount and intensity is clearly important in governing the magnitude of P transfer from agricultural soils to receiving water.

They suggested a temporal classification that includes two levels of hydrological activity: level 1 activity occurs during light precipitation for a high proportion of time; in contrast level 2 activities will be of low frequency but high intensity, with a high propensity for P transfer during a short period and resulting in storm flow.

Although it is impossible to measure all the spatial and temporal variables affecting P transfer, these can be estimated from well-validated hydrological models (Shoumans and Chardon, 2003). In situations with shallow groundwater levels, modelling approaches to simulate P leaching should consider that the vertical water fluxes in the unsaturated zone are governed by the groundwater level (Nelson and Parsons, 2007), as is done in the DRAINMOD model (Skaggs, 1978). For instance, Havlin (2004) proposed that DRAINMOD can be readily incorporated into practical P loss assessment tools.

The overall aim of this study was to identify hydrological conditions during autumn and spring flow events controlling TP and MRP concentrations in drain outflow using a stepwise multiple regression analysis. The multiple regression models used included as independent variables data on field-measured and DRAINMOD-predicted hydrological conditions from conventional and controlled drainage plots located in south-east Sweden.

MATERIALS AND METHODS

Site description, drainage design and crops

The experimental site is located at Gärds Köpinge, a costal area of Skania, in south-east Sweden (55°56´N, 14°10´E). The study was run during four periods between 2001 and 2004: July 2001-June 2002 (Period 1), July 2002-June 2003 (Period 2), July 2003-June 2004 (Period 3) and July 2004-December 2004 (Period 4), which correspond to four different hydrological years. A plot with conventional subsurface drainage (CD) and two plots with controlled drainage (CWT1 and CWT2) were used in this study (see Wesström (2006) and Salazar *et al.* (2008) for a detailed description of the site and methods).

The study area has a Marine West Coast climate (Cfb) according to the Köppen-Geiger system (Kottek *et al.*, 2006). The mean annual air temperature is 7.6 °C (using 1961−1990 data from a meteorological network station at Kristianstad) and two months (January and February) have a mean air temperature below zero degree (Alexandersson *et al.*, 1991). The period March-April is regarded as spring, May-August as summer, September-November as autumn and December-February as winter. The mean annual precipitation is 562 mm. Seasonally, summer (36%) and autumn (29%) receive the largest precipitation amounts, and the smallest precipitation amount occurs in spring (13%) and winter (22%).

The soil is an Aquic Hapludolls (Soil Survey Staff, 2003), characterised by distinct textural horizons: a loamy sand topsoil (0-40 cm), weakly structured with an organic matter content of 5%, overlies a sand layer (40-100 cm) with low organic matter content. Below 1 m depth there is a clay layer, which effectively restricts downward seepage. A summary of typical properties of the soil is presented in Table 1.

Air temperature and precipitation were measured hourly at the research site during Period 1 to 4, while the potential evapotranspiration (PET) was calculated

Table 1. Soil properties at the Gärds Köpinge experimental site in south-east Sweden.

Soil properties*	**Soil depth (cm)**		
	0-40	**40-100**	**100-130**
Clay (%)	9	2	56
Silt (%)	10	3	36
Sand (%)	81	95	8
ρb (Mg m^{-3})	1.3	1.6	1.5
Organic matter (%)	5.2	0.5	-
Soil pH	7.5	7.5	-
Soil water retention (cm^3 cm^{-3})			
θ_{33kPa}	0.22	0.10	0.44
$\theta_{1500kPa}$	0.09	0.02	0.31
K_s (cm h^{-1})	9.70	14.07	0.00

*ρb is the soil bulk density; Ks is the vertical saturated hydraulic conductivity.

using the FAO Penman-Monteith combination equation (Allen *et al.*, 1998) during the same periods. More than 32% of the total precipitation in these periods occurred during summer season. In Period 1 and Period 2, 30% to 40% of precipitation falling during storm events in autumn.

All plots were incorporated into an ordinary Swedish conventional farming system, which included winter wheat (*Triticum aestivum L.*), sugarbeet (*Beta vulgaris L.* ssp. *vulgaris*) and two years with spring barley (*Hordeum vulgare L.*) in the crop rotation. During the study period, crops were grown with conventional tillage, fertilizer and pest management practices typical of the region. Pig slurry, at a rate of 30 m^3 ha^{-1} (20 kg P ha^{-1}), was the main P input during the study period, which was applied on early April in Period 1. In late April in Period 1, 9 kg P ha^{-1} of fertilizer were applied to the plots. Finally, the plots received 7 kg P ha^{-1} on early April in Period 3.

Drainage measurements, sampling, and analysis

The drain outflow rate from each plot was measured continuously in a measuring well by means of tipping buckets wired to a multichannel data logger (CR10X, Campbell Scientific). Samples of drainage water were collected for analysis twice a month during flow events by a flow-controlled water sample device (6712 Portable samplers, ISCO). The water was analyzed for molybdate-reactive phosphorus (MRP) and total phosphorus (TP) according to Swedish standards. The concentrations of RP or molybdate-reactive P were determined with the colorimetric ascorbic acid reduction method, whereas concentrations of TP were determined in same way after oxidising P fractions with potassium persulfate. Daily values of MRP and TP concentrations in drain outflow were calculated by linear interpolation of the measured values according to Kronvang and Bruhn (1996).

In this study, six drainage flow events of more than one month duration that had at least two measurements of TP and MRP concentrations were selected. To analyse the effect of seasonal patterns in flow events, these were categorised in autumn or spring events (Table 2 and Figure 1).

DRAINMOD application

The field hydrology model DRAINMOD is a water balance model that uses functional algorithms to approximate the hydrological components of shallow groundwater soils. The main features of the DRAINMOD model have been described in detail by Skaggs (1978, 1999). It is a field-scale computer simulation model that characterises the response of the soil water regime to various combinations of surface and subsurface water management, such as surface drainage, subsurface drainage, controlled drainage and subirrigation. The model simulates the effects of water management on watertable depth by performing a one-dimensional water balance at the midpoint between adjacent drains, by means of the equation:

$$\partial Va = D + ET + DS - F \qquad (1)$$

where ∂Va is the drained volume (cm), D is the lateral drainage (cm) from the section, ET is evapotranspiration (cm), DS is the deep (vertical) seepage (cm), and F is infiltration (cm) entering the section in time increment ∂t. Subsurface runoff (D) is computed using the Hooghoudt steady state equation, as used by Bouwer and van Schilfgaarde (1963). This equation can be written as:

$$q = \frac{8K_e d_e m + 4K_e m^2}{L^2} \qquad (2)$$

where q is the flux (cm h^{-1}), d_e is the equivalent depth of the impermeable layer below the drain (cm), m is the midpoint watertable height above the drain (cm), K_e is the effective lateral hydraulic conductivity (cm h^{-1}), and L is the distance between drains (cm). This approach assumes an elliptical watertable shape and is based on the Dupuit-Forchheimer assumptions with corrections for convergence near the drain lines. The change in watertable depth is based on the assumption that the soil water profile above the watertable is drained to equilibrium with the watertable. The amount of drainage determines a new drained-to-equilibrium profile. The amount of drainage from lowering the watertable is determined as the difference in soil water between the new and the original drained-to-equilibrium profiles.

Rainfall is used to compute infiltration rate using an approximate equation of the type presented by Green and Amp (1911). This equation can be written as:

$$f = \frac{K_s MSav}{F} + K_s \qquad (3)$$

where f is the infiltration rate (cm h^{-1}), K_s is the vertical saturated hydraulic conductivity (cm h^{-1}), M is the initial soil water deficit (difference between final and initial volumetric water contents in cm^3 cm^{-3}), Sav is the suction at the wetting front (cm), and F is the cumulative infiltration (cm).

The amount of evapotranspiration (ET) is computed from potential evapotranspiration (PET) as limited by soil water availability. Actual ET is the amount that can be supplied from the watertable plus the amount available from

Table 2. Event drainage data and mean total phosphorus (TP) and mean molybdate-reactive phosphorus (MRP) concentrations in drainage water.

Event	Plot[a]	Period/ Season[b]	Days	Total Precipitation (mm)	Total drainage (mm)	Mean TP ($mg\ L^{-1}$)	Mean MRP ($mg\ L^{-1}$)
1	CD	1/A	4 Sept–8 Oct	239.9	72.4	0.056	0.035
2	CD	2/A	13 Oct–17 Nov	153.6	139.0	0.037	0.017
3	CD	2/S	2 Mar-13 Apr	18.0	78.5	0.024	0.019
4	CD	4/A	17 Oct–15 Nov	55.8	20.0	0.056	0.013
5	CWT1	1/S	27 Feb–31Mar	36.0	79.9	0.054	0.038
6	CWT2	1/S	24 Feb–19 Mar	45.0	73.4	0.045	0.030

[a]CD = conventional drainage plot; CWT1 and CWT2 = controlled drainage plots
[b]A = autumn; S = spring.

the unsaturated zone. *PET* represents the maximum amount of water that will leave the soil system by *ET* when there is a sufficient supply of soil water.

The model has been successfully calibrated and validated for the cold climate of southern Sweden (Wesström, 2002; Salazar *et al.*, 2008; Salazar *et al.*, 2010). The hydrological parameters selected for the present study were based on a previous DRAINMOD calibration for the Gärds Köpinge field drainage experiment (Salazar *et al.*, 2008). Hydrological outputs from the model include infiltration, evapotranspiration, depth to the groundwater from the soil surface, soil volumetric water content, depth of the dry zone, snow cover and average soil temperature. A maximum effective root depth of 45 cm was used according with visual observations on the field. Table 3 lists some selected DRAINMOD input data required from drainage system parameters, crop production and soil temperature.

Regression analyses

A stepwise multiple linear regression with backward selection procedure was used to investigate the relationships between TR and MRP concentrations in drain outflow (dependent variables, *y*) and hydrological conditions (independent variables, *x*) on a daily basis during flow events. A linear regression model was generated for each flow event. The Pearson's correlation coefficient (*r*) was used to determine the extent to which values of the two variables were proportional to each other. Statistical analyses were performed using Minitab software release 15.

A regression model was generated for each flow event. The backward selection procedure was performed by deleting predictors from the existing model based on the *F*-test. To test the hypothesis of linearity a pure error lack-of-fit test was calculated in each regression model. When the overall lack of fit was significant ($p < 0.05$), which suggest possible curvature in the independent variables, a polynomial model was approximated. The independent hydrological parameters chosen were those that had the potential to explain the variation in TP and MRP concentration in drain outflow (Table 4). Cumulative values for precipitation, potential evapotranspiration, infiltration and evapotranspiration were calculated for each flow event and were also included as independent parameters.

As a measure of the overall success of the regression analysis, the adjusted coefficient of determination (R^2_{adj}) was used, which is defined as:

$$R^2_{adj} = 1 - \left[1 - R^2\right]\left[\frac{n-1}{n-(1+p)}\right] \qquad (4)$$

where R^2 is the coefficient of determination, *n* is the number of observations and *p* is the number of *x*-variables. Regression analysis assumed that the residuals were normally distributed (normality), with a constant variance (homoscedasticity) and independent (independence). To check these assumptions residuals plots generated by Minitab program were analysed.

RESULTS AND DISCUSSION

Regression models

Table 5 shows the regression models generated through multiple regression analysis. These had only one explanatory variable that yielded an adjusted coefficient of determination (R^2_{adj}) higher than 0.80. The R^2_{adj} in these regressions

Table 3: DRAINMOD inputs parameters for plots conventional drainage (CD) and controlled drainage (CWT1 and CWT2).

Parameter	Value		
Drainage system design	CD	CWT1	CWT2
Drain spacing (m)	9.0	9.0	9.0
Drain depth (m)	0.99	0.83	0.96
Effective radius (mm)	3.5	3.5	3.5
Depth to restrictive layer (m)	1.0	1.3	1.4
Drainage coefficient (cm day^{-1})	1.0	1.0	1.0
Kirkham´s coefficient, *G*	3.1	11.4	11.2
Initial depth to groundwater (cm)	50	65	70
Weir setting (m)	1.0	0.5	0.5
Crop production			
Wheat			
Sowing date	April 17, 2001		
Number of days from sowing to harvest (day)	329		
Maximum effective root depth (cm)	45		
Sugar beet			
Sowing date	April 8, 2002		
Number of days from sowing to harvest (day)	185		
Maximum effective root depth (cm)	45		
Barley			
Sowing date	April 8, 2003		
Number of days from sowing to harvest (day)	129		
Maximum effective root depth (cm)	45		
Barley			
Sowing date	April 3, 2004		
Number of days from sowing to harvest (d)	132		
Maximum effective root depth (cm)	45		
Soil temperature			
Thermal conductivity function coefficients (W m^{-1} °C)	a= 0.552, b= 2.372		
Diurnal phase lag of air temperature (h)	8.0		
Base temperature as the lower boundary (ºC)	7.6		
Rain/snow dividing temperature (ºC)	0.0		
Snowmelt base temperature (ºC)	2.0		
Degree day coefficient (mm day^{-1})	4.0		
Critical ice content (cm^3 cm^{-3})	0.2		

was not appreciably increased by inclusion of other hydrological variables.

Figure 2 showed that a linear regression model was adequate for events 1, 4, 5 and 6, which was confirmed with the non significant pure error lack-of-fit test. However, in events 2 and 3, pure error lack-of-fit test were significant ($p < 0.05$) and these regression models were expanded to second and third-order models. In addition, residual plots showed that in all the models the assumptions of

Table 4. List of independent hydrological variables.

Variable	**Symbol**	**Units**
Drain outflow[a]	$DRAIN_{day}$	cm
Precipitation[a]	PP_{day}	cm
Cumulative precipitation[a]	PP_{cum}	cm
Maximum air temperature[a]	$T_{air\text{-}max}$	ºC
Minimum air temperature[a]	$T_{air\text{-}min}$	ºC
Potential evapotranspiration[a]	PET_{day}	cm
Cumulative potential evapotranspiration[a]	PET_{cum}	cm
Amount on rainfall which infiltrate[b]	$INFIL_{day}$	cm
Cumulative infiltration[b]	$INFIL_{cum}$	cm
Amount of evapotranspiration[b]	ET_{day}	cm
Cumulative amount of evapotranspiration[b]	ET_{cum}	cm
Total air volume in the soil[b]	*TVOL*	cm
Depth of the dry zone[b]	*DDZ*	cm
Depth to the groundwater from the soil surface[b]	*DTWT*	cm
Average soil temperature[b]	$T_{soil\text{-}avg}$	ºC
Depth of snow[b]	*SNOW*	cm

[a] Field-measured from the Gärds Köpinge experimental site
[b] DRAINMOD-predicted after Salazar *et al*. (2008)

Table 5. Multiple regression equations relating molybdate-reactive phosphorus (MRP) and total phosphorus (TP) concentrations in drainage water to hydrological conditions during outflow events.

Event	**Regression equation**[a]	R^2_{adj} [b]
1	$TP = 0.6480 - 0.000063INFIL_{cum}$	0.859
	$MRP = 0.0383 - 0.000021INFIL_{cum}$	0.810
2	$TP = 0.06355 - 0.00573INFIL_{cum} - 0.1460INFIL_{cum}^2 + 0.1224INFIL_{cum}^3$	0.948
	$MRP = 0.03337 - 0.00842INFIL_{cum} + 0.1223INFIL_{cum}^2 - 0.05561INFIL_{cum}^3$	0.795
3	$TP = -0.7699 + 0.03005DTWT - 0.000377DTWT^2 + 0.000002DTWT^3$	0.844
	$MRP = 0.9420 - 0.03774DTWT + 0.000509DTWT^2 - 0.000002DTWT^3$	0.925
4	$TP = 0.0207 - 0.003490INFIL_{cum}$	0.978
	$MRP = 0.0472 - 0.000802INFIL_{cum}$	0.976
5	$TP = 0.0832 - 0.001020INFIL_{cum}$	0.832
	$MRP = 0.0672 - 0.001020INFIL_{cum}$	0.832
6	$TP = 0.0462 - 0.000029INFIL_{cum}$	0.797
	$MRP = 0.0315 - 0.000060INFIL_{cum}$	0.817

[a]*DTWT* = DRAINMOD-predicted depth to the groundwater from the soil surface (cm) and *INFILcum* = DRAINMOD-predicted cumulative infiltration (cm). [b]*R2adj* is the adjusted coefficient of determination.

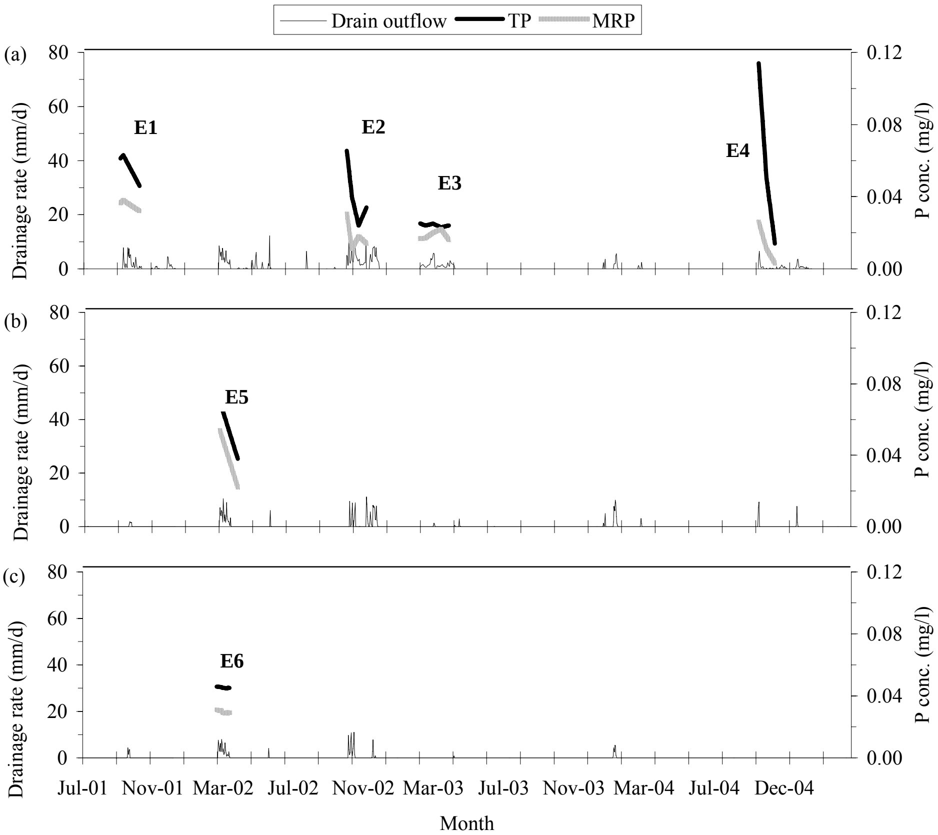

Figure 1. Daily subsurface drainage, measured TP and MRP concentrations during flow events (E) for: (a) CD, (b) CWT1 and (c) CWT2, from Period 1 to Period 4. See details for each event (E) in Table 2.

normality, heteroscedasticity and independence were correct.

Flow events and P concentrations

The daily drain flow pattern was very similar for the three plots during the study period (Figure 1). In the first two periods of measurement, there were two distinct phases of flow events from the drainage plots, autumn (i.e., event 1 and 2) and early spring (i.e., event 3, 5 and 6), with an intermediate phase soil frost in between. In Period 3, there was not outflow from the plots during the summer and autumn months, and most of the outflow was recorded in February. In Period 4, most of the outflow was recorded in autumn (i.e., event 4). Autumn flow events were recorded simultaneously with intensive precipitation, with flow peaks measured during storm events, which were classified as level 2 activities according to Haygarth *et al.* (2000). About 30-36% of the gross precipitation for event 1 and 4 was accounted for as drainage in the water balance, while event 2 had a

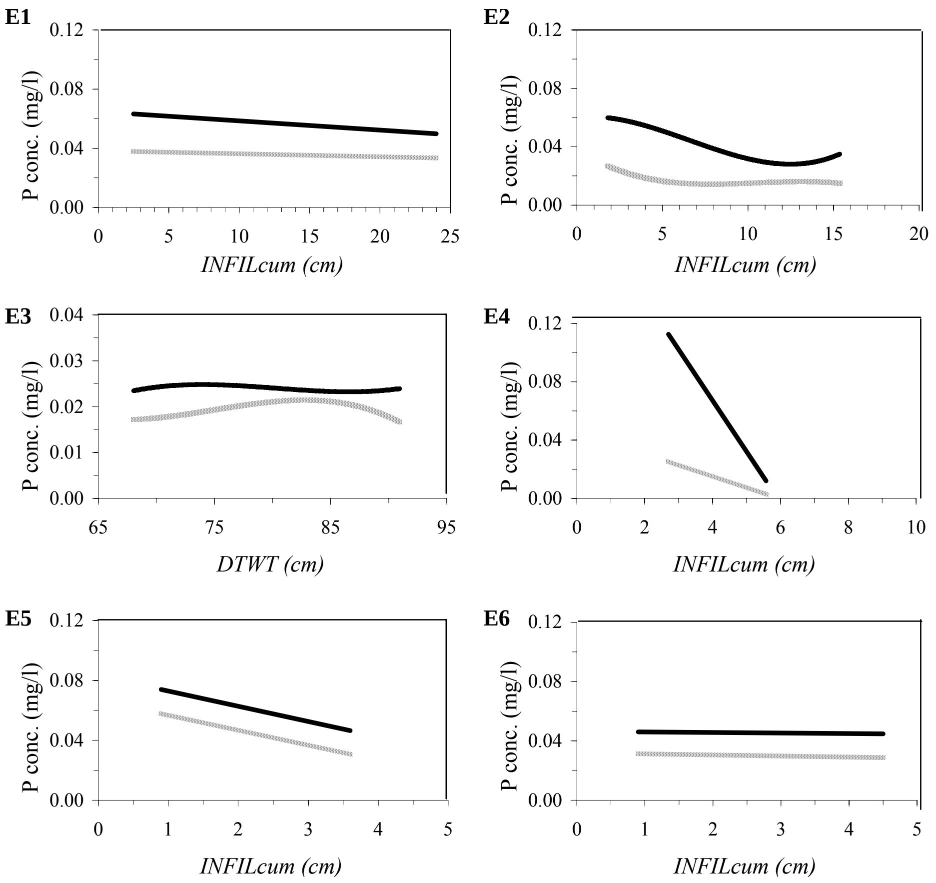

Figure 2. Regression models fitted to total phosphorus (solid line) and molybdate-reactive phosphorus (dashed line) (dependent variables) with DRAINMOD-predicted depth to the groundwater level from the soil surface (DTWT) and DRAINMOD-predicted cumulative infiltration (INFILcum) as independent variables for events (E) 1 to 6.

drainage of 91% of gross rainfall (Table 2). In spring the flow events were initiated after a rapid snowmelt process, with light precipitation recorded during this period, which were classified as level 1 activity (Haygarth *et al.*, 2000). There was not visual evidence of surface runoff events from snowmelt or rainfall during the study period.

Mean concentrations of TP and MRP in drainage outflow are given in Table 2. In autumn events (1, 2 and 4) mean TP concentrations ranged from 0.037 to 0.56 mg l^{-1}, while mean MRP concentration ranged from 0.013 to 0.035 mg l^{-1}. In spring events (3, 5 and 6) mean TP concentrations ranged from 0.024 to 0.054 mg l^{-1}, while mean MRP concentration ranged from 0.019 to 0.038 mg l^{-1}. Seasonally, TP and MRP tended to decline over autumn (Figure 1). In spring events, event 5 showed higher TP and

MRP concentrations at the beginning of the selected flow events than at the end. In event 3, TP and MRP concentrations increased prior peak to peak flow and then decreased. Event 6 showed no large variations in TR and MRP concentrations.

Hydrological conditions controlling dissolved P losses

Autumn events

In autumn events (1, 2 and 4), DRAINMOD-predicted cumulative infiltration ($INFIL_{cum}$) was negatively correlated to TP and MRP concentrations (r = -0.93 to -0.99), which is related with the fact that TP and MRP concentration peaks were recorded at the beginning of the flow events, when most of the rainfall was predicted to infiltrate due to the high hydraulic conductivity values in the coarse-textured soil profile (>80% sand). In addition, multiple regression showed that only $INFIL_{cum}$ explained 86–98% of the variation in TP and 80–98% of the variation in MRP. Therefore, the results suggested that the first infiltrating water found a higher amount of P forms available for transport, after which TP and MRP concentrations in drainage outflows gradually decreased during the flow event. This higher initial dissolved P concentration may indicate a dynamic pool of P in the soil that can be released to infiltrating water, bypassing subsoil material with a lower capacity to retain P (McDowell *et al.*, 2002), such as the subsurface sandy layer at the Gärds Köpinge field experiment.

On the other hand, DRAINMOD-predicted depth to the groundwater level from the soil surface (*DTWT*) (r = 0.49–0.69) and the DRAINMOD-predicted depth of the dry zone (*DDZ*) (r = 0.53–0.78) showed a positive correlation with TP and MRP concentrations, then most summer rainfall that did occur was stored in the dry soil and removed by evapotranspiration (*ET*). Thus much *ET* lowered groundwater level increasing the pore space available for infiltration of rainfall. In early autumn, the groundwater level (*DTWT*) between tile drains was initially closer to the impermeable layer and then gradually rose during autumn events, due to recharge to the groundwater from excess rainfall (r = -0.59 to -0.90). It indicated that during autumn events most water movement into the soil profile was initially under unsaturated conditions, which is confirmed with higher *DDZ* in the soil surface.

Spring events

In spring events 5 and 6, $INFIL_{cum}$ was strongly negatively correlated to TP and MRP concentrations (r = -0.90 to -0.92), while in event 3 there was a weak (r = -0.31 to -0.45) negative correlation. Similarly, in events 5 and 6, multiple regression showed that $INFIL_{cum}$ explained 80–83% of the variation in TP and 82–83% of the variation in MRP, while in event 3, multiple regression showed that *DTWT* explained 84% and 93% of the variation in TP and MRP, respectively. The important effect of the $INFIL_{cum}$ factor on TP and MRP concentrations as discussed for the autumn events was also apparent for the spring events, with TP and MRP concentration decreasing with increasing $INFIL_{cum}$ during flow events.

Other parameter such as DRAINMOD-predicted depth to groundwater from the soil surface (*DTWT*) was negatively correlated to TP and MRP concentrations (r = -0.64 to -0.85) in events 3 and 5, and showed a weak (r = -0.20) negative correlation in event 6. It is important to note that event 3 was recorded under conventional drainage, where *DTWT* initially rose to a maximum value of 70 cm and then gradually declined to 90 cm. In contrast, during events 5 and 6, which were under controlled drainage, *DTWT* approached the surface (30 cm) and then declined to 60 cm. In these events *DTWT* declined during spring due to a higher amount of evapotranspiration (r = 0.84 to 0.94). These results suggest that during spring events, initial shallow groundwater level caused that most water movement into the soil profile was under saturated conditions.

On the other hand, DRAINMOD-predicted depth of snow (*SNOW*) was positively correlated to TP and MRP concentrations (r = 0.66–0.88) in events 5 and 6, while in event 3 there was a weak (r = 0.27) positive correlation. A possible explanation is that in spring, the highest TP and MRP concentrations occurred at the beginning of flow events, when DRAINMOD predicted snow accumulation and rapid thawing. Similar trend have been reported in previous research on subsurface P leaching (Jensen, 2000). Snowmelt water can cause ponding on a partly frozen soil. Ponding enhances flow transport and may also extend the loading by prolonging the contact between stagnant water and the P source (Jensen, 2000).

Pathways of phosphorus transfer

Phosphorus concentration in drainage water decreased with $INFIL_{cum}$, but overall there was a weak correlation between drainage outflow and P concentration, which suggest the importance of preferential flow on P transport (Wesström and Messing, 2007). Several studies of P transport in tile drainage experiments and lysimeters highlights the role of preferential flow as an efficient hydrological pathway of P transport (Stamm *et al.*, 1998; Hooda *et al.*, 1999; Simard *et al.*, 2000; Turner and Haygarth, 2000). Results from our study showed that the soil was mostly dry at early autumn. It suggests that preferential flow may be occurred particularly during autumnal rewetting after intensive precipitation. Similarly, Simard *et al.* (2000) found that preferential flow was most important following storm events after a period of drought. In addition, Dils and Heathwaite (1999) noted that soil drying during summer months increases the likelihood of preferential flow particularly as the soil wets up in autumn.

The Gärds Köpinge site had a stratified soil that presented a top loamy sand layer (0–40 cm) much finer (81% sand) than the overlying sandy layer (40-100 cm) (95% sand). It is possible that the P forms may be moved in preferential flow influenced by wetting front instability when the water front reached the textural boundary between the loamy sand and the sandy layers. However, measurement of preferential flow of P characterized in quantitative terms by using tracers would be necessary to confirm this trend.

Matrix flow, which is the main pathway described in coarse soils, may be dominant during spring event due to saturated conditions after rapid snowmelt and thawing during the period late winter-early spring, where DRAINMOD predicted that most of the soil profile was saturated.

These results show the importance of antecedent soil moisture status in governing the pathway of subsurface movement of P forms through the soil and also suggest a possible annual cycle of P losses in sandy soils, such as proposed by Weaver *et al.* (1988).

CONCLUSIONS

In this study the $INFIL_{cum}$ was identified as the most important hydrological condition controlling TP and MRP concentrations in drain outflow in autumn and spring events. This suggests that the first infiltrating water found more soluble P forms available for transport, after which TP and MRP concentration in drainage outflows gradually decreased during the flow events. This higher initial dissolved P concentration may indicate a dynamic pool of P in the soil that can be released to infiltrating water, bypassing subsoil material with a lower capacity to retain P.

DRAINMOD model predicted that in autumn events most water movement into the soil profile was initially under unsaturated conditions, while in spring events saturated water flow was initially dominant within the soil. Therefore, results of our study suggest that layered coarse soils in southern Sweden may be prone to P transfer by preferential flow in autumn flow events, while matrix flow may dominate P transfer in spring flow events. These results show the importance of antecedent soil moisture status in governing the pathway of subsurface movement of P forms through the soil. To minimise the losses and maximise the effectiveness of P application to agricultural land, fertilisers and manure should not be applied during high-risk periods for P loss, such as early autumn and late winter-early spring.

ACKNOWLEDGEMENTS

The authors wish to thank the Swedish Farmers' Foundation for Agricultural Research and the Swedish Board of Agriculture for financial support of this project. We also wish to thank Dr. Mohamed A. Youssef and Dr. R. Wayne Skaggs for helping during DRAINMOD calibration.

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