Extended SWAT model for dissolved reactive phosphorus transport in tile-drained fields and catchments

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Abstract

We developed extensions (DrainP) for the Soil and Water Assessment Tool version 2012 (SWAT2012) to simulate leaching of dissolved reactive phosphorus (DRP) throughout soils with the Langmuir isotherm, and the subsequent transport from tile drains to streams. The DrainP module was evaluated for two small tile-drained fields and the River Odense catchment (486 km²) in Denmark. DrainP not only simulated well monthly DRP yields in the tile-drained fields but also improved the overall catchment DRP yields, and provided new insights into the source allocation of DRP at the catchment scale. The simulated soil total phosphorus (TP) accumulation in the tillage layer fell within the range of measurements.

Keywords:

Tile drain, DRP, soil TP accumulation, lowland, SWAT, leaching, Langmuir isotherm.

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1 Introduction

Phosphorus (P) is often an important factor for eutrophication and a key concern regarding the ecological status in freshwater systems (Sharpley et al., 1994; Carpenter et al., 1998). P input to aquatic systems consists of mixed soluble and particulate forms and turnover among different P pools is dynamic (Correll, 1998). Among all forms of P, dissolved reactive P (DRP) is readily utilised by bacteria, algae and plants (Correll, 1998). Moreover, DRP can be the dominant P form in watercourses within agricultural catchments and grasslands (Haygarth et al., 1998; Heathwaite and Dils, 2000; Kronvang et al., 2007). Therefore, it is important to understand and be able to quantify the transport and track the sources of DRP in those areas. In lowland agricultural catchments, tile drains have been widely installed to drain excessive water (Smedema et al., 2000; Blann et al., 2009). In some areas, tile drains have been estimated to contribute 30% to 60% of the stream flow (Xue et al., 1998; Kiesel et al., 2010; Koch et al., 2013). Moreover, intensive fertilization over decades can lead to accumulation of P in soils, which increases the risk of P leaching (Ekholm et al., 2005; Rubæk et al., 2013). As a result, tile drains rather than surface runoff can be a dominant source (>40%) for the DRP loads to surface waters in P accumulated areas (Schmalz et al., 2007; King et al., 2014a). Even though DRP concentrations during low tile drain flow are often less than those observed during surface runoff events (Haygarth et al., 1998; Simard et al., 2000), many studies have reported that DRP concentrations during high tile drain flow exceed limits for eutrophication (Dils and Heathwaite, 1999; Blann et al., 2009; King et al., 2014b). Besides DRP, tile drains also transport fine sediments and other forms of P to the receiving waters (Kronvang et al., 1997; Russel et al., 2001).

Modelling tools have been widely used to assess DRP losses from agricultural areas. Kleinman et al. (2015) and Radcliffe et al. (2015) reviewed modelling tools for P losses from tile-drained areas and concluded that models simulating P in tile drains, such as the Agricultural Policy/Extension eXtender (APEX) model (Steglich and Williams, 2013), HYDRUS (Šimůnek et al., 2008) and the Phosphorus LEAching from Soils to the Environment (PLEASE) model (Schoumans et al., 2013), are designed and therefore only suitable for the plot or field scale, whereas catchment models lack certain components to predict DRP losses from tile drains: The Hydrologic Simulation Program-Fortran (HSPF) model (Bicknell et al., 1997) does not simulate tile drain flow directly and the ICECREAMDB model (Larsson et al., 2007) tends to underestimate DRP in P-saturated soils (Radcliffe et al., 2015). The worldwide applied catchment model Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) does not calculate DRP loss from tile drains but contains the key processes: surface and subsurface hydrology, phosphorus cycling and agricultural practices. Moriasi et al. (2013) implemented a Hooghoudt-Kirkman equation for tile drain flow simulation and a new method for shallow water table calculation in the soil (Moriasi et al., 2011) in the SWAT model version 2012 (SWAT2012). The new equations simulated well monthly tile drain flow and nitrate transport in a monitored tile-drained field, though the Hooghoudt-Kirkman equation and tile drain nutrient transport have not been validated at the catchment scale. Previous studies have shown that the SWAT model underestimates the DRP loads in tile-drained lowland catchments, where DRP is the dominant form of P in surface waters (Lam et al., 2011; Lam et al., 2012). A SWAT model for the River Odense catchment in Denmark also underestimated DRP yields, probably due to the lack of DRP transport from tile drains, which contributed 30% of the stream flow (Lu et al., 2014). Therefore, the addition of DRP transport from tile drains in the SWAT model is necessary for simulation of P dynamics in lowland tile-drained catchments.

SWAT2012 simulates DRP loss in surface runoff and allows DRP percolation from the top 10 mm soil to the underlying soil layer. However, DRP leaching to the deeper soil layers and transport to tile drains and from there to surface waters is not included. The DRP concentration (mg l^{-1}) in the top 10 mm soil water in SWAT2012 is estimated from a linear sorption isotherm. Rossi et al. (2012) showed that the Langmuir isotherm simulates high DRP concentrations in surface runoff better than the linear isotherm in the SWAT model. Moreover, Nelson and Parsons (2006) found that the linear isotherm also underestimated P leaching in P-saturated soils, whereas the Langmuir isotherm improved the simulation of P percolation and P accumulation in the soil. Therefore, the Langmuir isotherm is more suitable for estimating DRP concentrations than the linear isotherm.

This study aims to achieve an extension of the SWAT model to enable simulations of DRP transport in tile-drained lowland catchments with more reliable source allocations. We developed an extension, named DrainP, to the SWAT2012 code (revision 637) to simulate DRP transport to tile drains and further to surface waters. DrainP calculates DRP concentrations and leaching through the soil profile with the Langmuir isotherm deduced by Nelson and Parsons (2006) and DRP transported with the tile drain flow to surface waters. Tile drain flow and DRP transport to tile drains were first evaluated at the field scale at two monitored tile-drained fields in a Danish lowland catchment. Subsequently, the impact of DrainP was evaluated at the catchment scale at the 428 km² River Odense catchment in Denmark.

2 Material and methods

2.1 SWAT extension module for DRP transport to tile drains (DrainP)

The SWAT model divides catchments into sub-basins according to a digital elevation model (DEM) and an optional user-input stream network. Then each sub-basin is further divided into hydrological response units (HRUs), which are unique combinations of land use, soil type and

topography (slope) and consist the smallest building blocks of the semi-distributed model. In each HRU, water balance, sediment erosion, crop growth, nutrient and pesticide movements are calculated and then summed at sub-basin level and routed through the streams (Neitsch et al., 2011). The DRP leaching module is active in all HRUs, whereas the amount of DRP transported from tile drains is active only in the tile-drained HRU, summed up at sub-basin level and then routed to the streams.

2.1.1 Leaching module

Van der Zee and Bolt (1991) describe the equilibrium between DRP concentrations in soil water (C) and inorganic P adsorbed to soil constituents (N) with the Langmuir isotherm as:

$$C = \frac{N}{k_L(N_{max}-N)} \quad (1)$$

where C is the DRP concentration in soil water (mg l^{-1}), N is inorganic P adsorbed to soil (mg kg^{-1}), k_L is the Langmuir adsorption constant (l mg^{-1}) and N_{max} is the adsorption maximum (mg kg^{-1}).

Vadas and White (2010) validated the soil P processes in the SWAT model and outlined that “solution P” in the SWAT model represents both the inorganic P in soil water and the P weakly adsorbed to the soil matrix. Therefore, “solution P” in the SWAT model will be referred to as labile P in this study, whereas dissolved inorganic P in soil water (which is part of the labile P) will be referred to as DRP. Nelson and Parsons (2006) calculated DRP concentration in each soil layer (C_{ly}) with labile P using the Langmuir isotherm and deducted equation (1) to:

$$C_{ly} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (2)$$

$$a = k_L \theta_{ly}$$

$$b = N_{max,ly} k_L \rho_{b,ly} + \theta_{ly} - \frac{P_{labile,ly} N_{max,ly}}{Z_{ly}}$$

$$c = -\frac{P_{labile,ly}}{Z_{ly}}$$

θ_{ly} is the relative soil moisture content of the soil layer (mm mm^{-1}), $\rho_{b,ly}$ is the bulk density of the soil layer (Mg m^{-3}), $P_{labile,ly}$ is the labile P in the soil layer (kg P ha^{-1}) and z_{ly} is the soil layer thickness (mm).

N_{max} in variable b Equation (2) can be estimated from the sum of oxalate extractable aluminium and iron concentrations (Van der Zee and Van Riemsdijk, 1988):

$$N_{max} = \beta_m (Al_{ox} + Fe_{ox}) \cdot 31 \quad (3)$$

where Al_{ox} and Fe_{ox} are oxalate extractable aluminium and iron concentrations in the soil (mmol kg^{-1}), β_m is the maximum adsorption fraction and 31 is the atomic weight of P. The amount of DRP leached to the next soil layer is calculated as the product of C_{ly} and the water percolated to the next soil layer, and the mass of labile P is updated for each soil layer.

Equation (2) was implemented into the SWAT model code to calculate DRP concentration for the soil layer (C_{ly}) with existing SWAT soil variables and phosphorus variable labile P, the new variable N_{max} and a calibration parameter k_L . The new variable N_{max} is calculated based on user input of Al_{ox} and Fe_{ox} and a calibration parameter β_m .

2.1.2 Transport to the tile drain module

Solutes transported with tile drain flow are often calculated with the solute concentration in each soil layer multiplied by the tile drain flow from each soil layer (Brevé et al., 1997; Larsson and Jarvis, 1999). However, tile drain flow is derived from the whole soil profile and not separately for each soil layer in the SWAT2012 model. Therefore, in the DrainP module, tile drain flow (Q_{tile}) is partitioned among the soil layers situated between the perched shallow water table (swt) from the impermeable layer and tile drain depth ($DDRAIN$) (Figure 1). The contribution of each soil layer ($fr_{tile,ly}$) to the tile drain flow is calculated from the layer thickness relative to the total height difference between swt and $DDRAIN$ ($Drain_{diff}$) (Figure 1).

The amount of DRP transported via tile drain flow to the tile drains (DRP_{drain}) is calculated as a sum of the tile drain flow in the SWAT model multiplied by the DRP concentration of each soil layer C_{ly} from Equation (2) between *swt* and *DDRAIN*:

$$DRP_{drain} = \sum_{ly=top}^{bottom} C_{ly} \cdot fr_{tile,ly} \cdot Q_{tile} \quad (4)$$

2.2 Study sites and monitoring

The model was first tested on two monitored tile-drained fields located on the island of Funen, Denmark (Figure 2a), then on the River Odense catchment upstream of the Kratholm station (Kratholm) also on Funen (Figure 2a). The monitored tile-drained fields, TileL1 (4.5 ha) and TileL2 (2.8 ha), are located within the Lillebæk catchment (4.28 km²) at the southeast coast of Funen, while Kratholm is situated around 40 km northwest of the Lillebæk catchment.

In the Lillebæk catchment, the soil texture is mainly sandy loam (DK5067 in Table 2) with low to moderate permeability and poorly drained (Pedersen et al., 2010). Tile drains have been installed in 22% of the agricultural fields (Figure 2d) at depths between 0.8 and 1.4 m with a spacing of around 20 m. Plastic tubes of 100 mm diameter were typically installed as drainage pipes in sandy loam soils. However, detailed information on tile drainage system was not available for the monitored tile-drained fields. Therefore drainage depth and spacing were subject to calibration (Table 3), whereas the effective radius of the drainage tubes (RE) was set to 50 mm. TileL1 and TileL2 are both intensively cultivated and mainly fertilized with solid animal manure and slurry (Table 1). Agricultural management data on sowing and harvesting dates, fertilizer application and tillage operations were collected from previous farmer survey by Pedersen et al. (2010) (Appendix).

Kratholm covers an area of 486 km², dominated by agriculture (71%) and sandy loam soils (DK5067 in Table 2). Tile drains are likely installed in around 40% of the catchment area according to a national tile drain probability map (Olesen, 2009). Average annual precipitation on Funen was

840 mm during the study period from 1998 to 2006. During this period, August was the warmest month, with an average daily temperature of 17°C, and January was the coldest month, with an average daily temperature of -1°C.

In TileL1 and TileL2, the water levels of the tile drain flow were measured continuously in a collecting well with a Thompson weir and a pressure sensor. Tile drain discharges were then calculated with the measured water levels and flow rating curves. Water for orthophosphate concentrations analysis was collected proportional to flow with automatic samplers in the collecting wells. Prior to analysis, water samples were pooled for discrete periods, typically for one week and ranging from one to nine days. The orthophosphate concentrations were measured with the Murphy and Riley (Murphy and Riley, 1962) method after filtering the composite water samples through 1.2 micrometre Whatman GF/C glass microfiber filters (Pedersen et al., 2010). Composite orthophosphate measurements in TileL1 and TileL2 were available from 1993, but the years 1995 to 1997 were very dry with very few measurements. Therefore, the study period chosen was 1998 onwards. The composite concentrations were linearly interpolated into daily concentrations to derive monthly DRP yields. At the Kratholm station, daily discharge and orthophosphate concentrations were available from 1998 onwards (Lu et al., 2014).

Soil P measurements were not available for the study sites; instead measurements of soil P were available on a 7 km grid covering Denmark with 337 grid points in agricultural and forest soils. Inventory data on total P (TP), oxalate extractable iron (Fe_{ox}) and aluminium (Al_{ox}) at 0-25cm, 25-50 cm, 50-75cm and 75-100 cm depth in agricultural areas and deciduous forests from the nationwide grid sampling programme are published by Rubæk et al. (2013). Total inorganic P (mineral P) was estimated from Bondorff P, in which P was extracted with 0.2 N H_2SO_4 . The Bondorff analysis extracts close to 100 percent of the total inorganic P in soils (Rubæk and Sibbesen, 2000). The soil samples were categorised into seven soil texture classes based on silt,

clay, fine sand and organic material content, which make up the Danish soil classification system, and measured values for soil P, Al_{ox} and Fe_{ox} were averaged for the soil texture classes. Soil analysis and detailed data are described by Rubæk et al. (2013).

2.3 SWAT model input and set up

The SWAT2012 model was set up for the Lillebæk and Kratholm. Topographic data used for catchment delineation were based on a 1.6 m LIDAR DEM resampled to a 16-m-grid DEM (GST, 2010) and a digital stream and tile drain network (Figure 2b). A land use map derived from aerial photos (Pedersen et al., 2010) (Figure 2c), a 250-m grid, three-layer soil map (Greve et al., 2007) (Figure 2d) and three slope classes derived from DEM were used for HRU definition. The TileL1 and TileL2 fields were specified as separate land use types in the Lillebæk catchment, so TileL1 and TileL2 could be represented by their own unique HRU in SWAT. The land use types representing TileL1 and TileL2 were exempted from thresholds of multiple HRU specification. After model delineation and HRU specification, the Lillebæk catchment covered 4.28 km², had one sub-basin and 3 HRUs, of which two represented TileL1 and TileL2. Catchment delineation and HRU definition at Kratholm was taken from a previous study by Lu et al. (2014) and the catchment covered 486 km² with 29 sub-basins and 429 HRUs.

Climate data consisted of 10 km-grid daily precipitation data corrected for rain gauge undercatch due to wind effects (Frich et al., 1997), 20 km-grid daily solar radiation and wind speed data (Scharling and Kern-Hansen, 2012), and station-based daily maximum and minimum temperature and relative humidity data (Vilic et al., 2013) from the Danish Meteorological Institute. The spacing of the rain gauges used for deriving the 10 km-grid data is uneven, one station is close to Lillebæk and nine stations are within Kratholm (Scharling and Kern-Hansen, 2012). For both Lillebæk and Kratholm, the new shallow water table method and the Hooghoudt-Kirkman method from Moisasi et al. (2013) were used for tile drain flow simulation. The SCS curve number method (ICN = 0)

(USDA–SCS, 1972) was used for surface runoff and the Penman–Monteith (Monteith, 1965) method was used for evapotranspiration. In-stream nutrient routing processes were inactivated to focus on the DRP transport at landscape.

The initial soil P content, Al_{ox} and Fe_{ox} were derived from the Danish nationwide soil P inventory. Each SWAT soil type was assigned to a soil texture classes (STCs) in the Danish soil classification system in order to derive initial conditions. The summed Al_{ox} and Fe_{ox} of each SWAT soil type was assigned to the mean value of the measurements for the STC. The SWAT model allows the user to initialise labile and organic P, while active inorganic and stable inorganic P are estimated from soil organic matter and clay content (White et al., 2010). Initial labile P value was derived by changing value from 0 to 20 mg kg⁻¹ with increments of 0.1 mg kg⁻¹, after which active P and stable P were calculated based on equations from the SWAT model. Next, the summed labile, active and stable P (SWAT soil mineral P) values for each SWAT soil type were compared with the measured soil mineral P of the STC. The value for labile P that gave the SWAT soil mineral P closest to the measured soil mineral P was used as the initial SWAT labile P content. The organic P content was calculated as the measured soil TP minus the SWAT soil mineral P. Input data for the soil P content and oxalate extractable minerals for each SWAT soil type are shown in Table 2.

2.4 Calibration and sensitivity and uncertainty analysis

A stepwise calibration of first flow and then DRP load was carried out with Nash-Sutcliffe Efficiency as the objective function. The SWAT2012 model was first calibrated for tile drain flow at TileL1 and TileL2 and stream discharge at Kratholm station. Then with the calibrated flow parameters fixed, the extended SWAT model with DrainP module (DrainP model) was calibrated for tile drain DRP yields at TileL1 and TileL2 and stream DRP yields at Kratholm. The SWAT2012 model was also calibrated for stream DRP yields at Kratholm and compared to the DrainP model.

The SWAT2012 and DrainP model shared identical streamflow and surface DRP transport parameters, there were but two parameters for DPR leaching in DrainP more than the SWAT2012 model. The SWAT2012 model does not simulate tile drain DRP load and therefore was not compared with the DrainP model at TileL1 or TileL2. To evaluate DrainP module on DRP dynamics, simulated composite DRP concentrations in tile-drained fields and at Kratholm were compared with measured composite orthophosphate concentrations. Simulated composite DRP concentrations were derived from the sum of the simulated DRP loads divided by the sum of the simulated tile drain flow during the sampling days.

Parameters and ranges for tile drain flow and stream discharge were selected and defined after manual calibration (Table 3). The parameter ranges were set so that the simulated annual water budgets were realistic, following guidance from Arnold et al. (2012). In TileL1 and TileL2, only tile drain flow was calibrated, therefore parameters not related to tile drain flow, like ALPHA_BF, GW_DELAY and RCHRG_DP etc., were not calibrated. For tile drain DRP and stream DRP loads, DrainP parameters ranges were defined from literature. Nelson and Parsons (2006) estimated k_L from measured reversibly adsorbed P and DRP concentrations in loamy soils receiving swine slurry and found that k_L ranged from 0.5 to 2.4 l mg⁻¹. Schoumans et al. (2013) conducted an uncertainty analysis of k_L and β_m for P leaching in Dutch sandy soils and found that β_m varied from 0.06 to 0.23.

The impact of the DrainP module on the SWAT model was evaluated by sensitivity and uncertainty analysis of the new parameters k_L and β_m on DRP transport in tile-drained fields and at Kratholm. Calibration, sensitivity and uncertainty analysis were carried out with the Sequential Uncertainty Fitting Algorithm (SUFI2) in SWAT Calibration and Uncertainty Procedures (SWAT-CUP) (Abbaspour et al., 2007). In SUFI2, the parameter sensitivity was measured with a t-test, where higher absolute t -Stat values indicated more sensitivity, and a P-value determining the significance of the sensitivity. Parameter uncertainties were given with a 95% prediction

uncertainty (95PPU) band around the best simulation. SUFI2 quantifies the 95PPU with two factors: the percentage of observations included in the 95PPU (P-factor) and the average thickness of the 95PPU band (R-factor). An ideal model would have a P-factor of 1 and an R-factor of 0. SUFI2 only accounts for prediction uncertainties from the calibration parameters. Other uncertainties from model structure, input data and measured observations etc. are not included. The models were run from 1989 to 1997 for warm up, from 1998 to 2002 for calibration and from 2003 to 2006 for validation. Calibrations of the tile drain flow and stream discharge parameters were run for 1000 iterations, whereas sensitivity, uncertainty analysis and calibration of tile drain and stream DRP load parameters in the DrainP module were run for 500 iterations.

3 Results

3.1 SWAT2012 for tile drain and stream flow

The SWAT2012 model simulated well the monthly tile drain flow yield in the monitored tile-drained fields TileL1 and TileL2 (Figure 3a and b) and stream discharge at the Kratholm station (Figure 3c). The SWAT model captured the seasonal variation of observed tile drain flow – active in winter and inactive in summer in both TileL1 and TileL2, though the simulated onset of tile drain flow occurred earlier than the observations in both 2000 and 2001 (Figure 3a and b). The Nash-Sutcliffe efficiency (NSE) and the percent bias (PBIAS) confirmed that the simulated tile drain flows are “very good” and “good” during calibration and remain “good” and increase to “very good” during validation relative to the criteria defined for stream flow by Moriasi et al. (2007).

3.2 DrainP for tile drain and catchment DRP yields and concentrations

The extended SWAT model with the DrainP module (DrainP model) simulated well the monthly DRP yields in TileL1 (Figure 4a) despite mismatches in 2000 and 2001 due to the early onset of the

simulated tile drain flow (Figure 3a). The NSE and PBIAS indicated that the simulated DRP yields in TileL1 were “satisfactory” during calibration and increased to “good” during validation. In TileL2, the DrainP model missed the peak in winter 2001 during calibration and two peaks in 2004 during validation (Figure 4b), when the field was turned into grassland without tillage (Appendix), and the simulated DRP yields did not match the observations as well as in TileL1.

The DrainP model simulated the monthly DRP transport much better than the SWAT2012 model at the Kratholm station (Figure 4c). The DrainP model captured the catchment DRP peaks very well during winter when tile drains were active, whereas the SWAT2012 model missed all the peaks. However, both the DrainP and the SWAT model underestimated the DRP transport during summer when the tile drains were inactive. Calibrated DRP yields were higher than the upper limit of 95PPU band, indicating high tile drain DRP yields to the streams. The 95PPU band of the simulated DRP yields at Kratholm did not cover the observations, indicates a systematic underestimation. The NSE and PBIAS confirmed that simulations by the DrainP model were better than those of the SWAT2012 model, even though they were still somewhat less than the observed DRP yields.

The composite DRP concentrations in the tile-drained fields simulated by the DrainP model matched well the observed ones (Figure 5a), even though observed DRP concentrations higher than 0.2 mg P l^{-1} were not captured by the DrainP model. On the other hand, at the Kratholm station, the simulated DRP concentrations from the DrainP model were higher and much less biased than those simulated by the SWAT2012 model (Figure 5b).

3.3 Impact of DrainP on the SWAT model

Except k_L in TileL1, both tile drain and stream DRP yields were sensitive to the DrainP parameters k_L and β_m with P-values less or close to 0.001, which indicate significant sensitivity. (Table 4). However, the absolute *t-Stat* value, which measures the level of sensitivity, at Kratholm was higher than in the tile-drained fields, indicating DrainP parameters are more sensitive to DRP

transport at the catchment scale than in tile-drained fields. *t-Stat* evaluates changes of the objective function with parameters, and DrainP improved the objective function NSE at Kratholm (0.8 in Figure 4c) more than at the tile-drained fields (<0.6), and therefore DrainP parameters were more sensitive for catchment DRP yields. On the other hand, the 95% prediction uncertainty (95PPU) band of DrainP at Kratholm (R-factor 0.35) was similar to the tile-drained fields (R-factor 0.31 and 0.12) (Figure 4). In other words, the overall DRP yield at the catchment scale was more sensitive to the DrainP module than the tile drain DRP yields in the tile-drained fields, while the uncertainties were similar.

The DrainP model changed the overall source allocation of the simulated DRP transport at the Kratholm station. In the SWAT2012 model, groundwater contributed 55% of the simulated DRP transport, though it contributed less than half to the stream flow, and the tile drains contributed 38% to the stream flow and did not contribute at all to the DRP transport (Table 5). After inclusion of the DrainP module, tile drains contributed the most to the simulated DRP transport at the Kratholm station, followed by groundwater. Point sources contributed the least to the simulated DRP transport in both the SWAT and DrainP module during the study period of 1998 to 2006.

3.4 Soil phosphorus accumulation and budget

The simulated soil total P (TP) in the top 30 cm soil layer increased in both the tile-drained fields (Figure 6a) and in the River Odense catchment (Figure 6b). However, the increases in the tile-drained fields (Figure 6a) compared to the initial TP content in 1989 were higher and more dynamic than in the River Odense catchment (Figure 6b). Moreover, the soil TP content in the tillage layer in TileL1 and TileL2 also varied and exhibited very different patterns (Figure 6a) despite identical initial conditions. The simulated TP increase at 0-30 cm depth from 1989 to 1998 in the study areas (first columns in Figure 6a and b) were close to the mean values of the measured soil TP increase

from 1986 to 1998 for the soil texture classes (STCs) assigned to the SWAT soil types at 0-25 cm depth (red dots in Figure 6a and b).

The simulated accumulation of TP in the soil profile was mainly due to the excess input of P fertilizers compared to the P yields (Figure 7). The average annual P inputs from 1998 to 2006, mainly as animal manure (Table 1), were much higher than the total P export from the fields in both the tile-drained fields and in Kratholm. The total P export is the sum of P export with harvested crops and a minor contribution from total P lost through surface runoff, tile drain flow and leaching out of the soil profile. The P fertilizer data at Kratholm (Figure 7c) were derived from 2005 general statistics and showed lower annual P fertilizer application than at the tile-drained fields (Figure 7a and 7b). Still the simulated soil TP in River Odense catchment increased at an annual rate of around 15 kg P ha⁻¹.

4 Discussion

4.1 Simulated flow and DRP at the field and catchment scale

The SWAT2012 model simulated very well the monthly tile drain discharge in the tile-drained fields TileL1 and TileL2, even though the two fields exhibit great temporal variability. Studies that simulate sub-daily or daily tile drain discharge typically require on-site sub-daily precipitation observations, location and spacing of tile drain pipes and a detailed description of soil properties (Arabi et al., 2006; Tiemeyer et al., 2007; Branger et al., 2009). Such detailed information were not available in this study: precipitation data were daily aggregated grid data, tile drain installation depths and spacing were calibrated and the soil data had a 250 m-resolution. With similar model input data, the simulated daily tile drain discharge in TileL1 and other tile-drained fields in the Lillebæk catchment from the fully distributed MIKE-SHE model coupled with the Daisy model were “unsatisfactory” (NSE < 0.2) (Hansen et al. 2012).

The DrainP module captured the seasonal dynamics of DRP yields in the tile-drained fields. In our study, the Nash-Sutcliffe Efficiencies of simulated tile drain DRP yields were close to the findings in a study simulating bi-weekly DRP transport using the CREAMS model (Larsson et al., 2007). On the other hand, DrainP missed the major peak events in both tile-drained fields and could not simulate the tile drain DRP concentrations higher than 0.2 mg P l^{-1} , probably due to a lack of a macropore flow component. The observed DRP yields peaked in TileL2 when it was turned into grassland for 2 to 3 years with no tillage (Table 1 and Appendix). Zhang et al. (2015) found that in continuous grassland without tillage, DRP concentrations in tile drains were higher than the ones with tillage, probably due to better macropore connectivity. Other studies have also found an increased transport of soluble tracer and pesticide out of the soil in no tillage fields compared to fields with tillage (Malone et al., 2014; Petersen et al., 2004). Therefore, there might be more preferential transport via macropores in TileL2 during the years without tillage. Many studies have shown that water and P concentrations may peak in tile drains during storm events via macropore transport (Iversen et al., 2011; Ball Coelho et al., 2012). However, the DrainP model lacks the macropore transport component and therefore could not generate the peak concentrations. As a result, the DrainP module might overestimate DRP concentrations in lower soil layers in order to compensate the lack of macropore transport. Moreover, studies have shown that both the soil P content in the root zone and the presence of shallow groundwater have a significant impact on the DRP concentrations in tile drains (Heckrath et al., 1995; Gachter et al., 1998; Vadas et al. 2007). Therefore, the lack of on-site soil P measurements and the lack of interaction with groundwater in DrainP may decrease the ability to simulate dynamic DRP concentrations.

The DrainP module enabled the SWAT model to simulate DRP transport from tile drains, and thereby generated higher DRP yields and improved the simulated DRP transport at the Kratholm station. Moreover, the DrainP module changed the source allocation of DRP transport at the

catchment scale. After including the DrainP module, tile drains contributed most (46%) of the simulated DRP yields at Kratholm and second most (38%) of the stream flow after groundwater. According to a review by King et al. (2014b), tile drain flow may contribute from 40% up to 80% of the stream flow, but typically only 16% to 58% of the DRP yields in tile-drained agricultural catchments. The simulated tile drain contribution to stream flow and DRP yields at Kratholm fell within this range. The relative importance of the tile drain contribution depends, however, on the magnitude of other sources, e.g. point sources. The P input from point sources in Denmark has been reduced by more than 80% since 1990 (Wiberg-Larsen et al., 2015), thus the relative importance of the tile drain component has increased over time.

The SWAT2012 model generally underestimated the DRP yields at Kratholm, though we found less underestimation when including the DrainP module. However, the DrainP model still systemically underestimated DRP yields, indicating that the model is missing processes that cannot be compensated for by calibration. The missing processes might include in-stream nutrient routing processes, that might be important for DRP yields (van der Perk et al., 2006), as the in-stream processes were inactivated to focus on the DRP transport at landscape. There is a risk that the differences between simulated and observed values were compensated for by the calibration of DRP yields from tile drains, which might not be realistic. Therefore, DRP leaching experiments should ideally be conducted to further validate DrainP parameters (k_L and β_m) from the Langmuir isotherm, in order to avoid overestimation of tile-drain DRP yields. This requires, though, extensive work at the catchment scale due to the great heterogeneity in soil properties.

4.2 Soil phosphorus accumulation

The simulated soil total phosphorus (TP) matched the observed general soil TP accumulation in Danish agricultural areas. Rubæk et al. (2013) reported that soil TP increased between 1986 and 1998 in lighter soil textures (STC 1-5), whereas soil TP in heavier soil textures (STC 6-7) remained

unchanged or decreased. They also reported that the increase of measured soil TP at 0-25 cm depth was positively correlated with the amount of applied animal manure. The simulated TP accumulation in the plough layer was also driven by animal manure input. The accumulated TP increase varied greatly between fields and among years in the tile-drained fields, where the management practices, including fertilizer type and application rates, were based on on-site interviews and varied from year to year (Table 1). In contrast, for the River Odense catchment, 5-year crop rotations were based on agricultural statistics for 2005 (Lu et al., 2014). Thus, the accumulated TP increases were more stable and exhibited a repeated pattern for every 5 years.

TP accumulation due to extensive animal manure input is common worldwide (McLaughlin et al., 2011; Jiang et al., 2013), which increases the risk of P leaching and may damage the ecosystems of the receiving waters (Bennett et al., 2001). In order to reduce the risk, nationwide nutrient loss regulations were initiated in the 1980s. The estimated P surplus in Denmark has declined from around 20 kg P ha⁻¹ y⁻¹ in late 1980 to around 4 kg P ha⁻¹ y⁻¹ in 2010 (Vinther and Olsen, 2011). However, the effect of rapidly declined P surplus on soil TP accumulation requires crop managements with declined fertilizer application rates over time. In our study, P fertilizer application at the tile-drained fields (Table 1) and Kratholm (constant) did not follow the decline trend during the study period.

5 Conclusion

The SWAT2012 model extension DrainP for dissolved reactive phosphorus (DRP) transport from tile drains simulated well the monthly DRP transport in the tile-drained fields and substantially improved the simulation of monthly DRP transport and changed the overall source allocation at the catchment scale. In order to avoid overestimation of tile-drain DRP yields, DrainP parameters in the Langmuir isotherm should ideally be validated with DRP leaching experiments.

The DrainP model lacks a macropore transport component and this could be partly responsible for the inability to reproduce peak DRP concentrations in tile drain flow. Macropores can transport fine sediment and particulate and other forms of phosphorus to the tile drains and further to the receiving waters. Therefore, future relevant work include analysis of the potentials for macropore and other forms of phosphorus transport from tile drains to surface waters.

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Appendix

Crop, date of agricultural activities and applied fertilizers equivalent to mineral nitrogen (N) and phosphorus (P) in the monitored tile-drained fields TileL1 and TileL2 in the Lillebæk catchment.

TileL1		Management date				Fertilizer amount							
Year	Crop	sow	harvest	plough	fertilizer	Mineral			Manure				
						N (kg ha ⁻¹)	N	P (kg ha ⁻¹)	P	N (kg ha ⁻¹)	N	P (kg ha ⁻¹)	P
1997/1998	Winter grass	8/16/1997	8/10/1998	8/15/1997	9/29/1997					182.3		58.4	
					3/24/1998	28							
					3/25/1998	84							
					4/26/1998	42							
1998/2000	Grass	8/11/1998	8/6/1999	8/11/1998	8/11/1998	35							
			10/20/1999		4/1/1999	70	13.1						
			8/9/2000		4/14/1999	7							
			3/30/2000					131.3	37.7				
2000/2001	Winter wheat	9/15/2000	8/19/2001	9/15/2000	4/7/2000	45							
					4/14/2001	83.9							
2001/2002	Winter wheat	9/29/2001	8/19/2002	9/29/2001	5/9/2001					125.2	35.5		
					4/11/2002	67							
2003	Spring barley	3/28/2003	8/20/2003	10/26/2002	5/9/2002					160.8	48.3		
					4/25/2003	87							
2003/2004	Grass	8/21/2003	5/1/2004	9/12/2004	3/28/2004	34							
					4/1/2004					127.9	34.5		
2004/2005	Winter wheat	9/12/2004	7/21/2005	8/9/2005	4/5/2005	43.19							
					4/20/2005					137.5	35.5		
2006	Spring barley	8/10/2005	7/27/2006	9/21/2006	4/12/2006	28.14							
					4/24/2006					185	46		
TileL2													
1998	Sugar beet	4/14/1998	9/30/1998	3/26/1998	3/25/1998					179		34	
					5/18/1998	27							
1999	Spring barley	4/11/1999	7/18/1999	3/29/1999	3/29/1999					76		12	
					5/27/1999	34							
1999/2001	Grass	7/18/1999	11/1/1999		7/20/1999	40							
			11/1/2000		8/10/1999	40							
			11/1/2001		9/1/1999					76	12		
			3/21/2000						297	46			
			4/11/2000		30								
			5/1/2000						43	7			
			5/1/2000		120								
			7/1/2000						43	7			
			7/1/2000		120								
			4/3/2001						102	15			
2002	Spring barley	4/1/2002	7/16/2002	3/29/2002	5/1/2001					102	15		
					5/1/2001	70							
					5/31/2001								
					7/1/2001					102	15		
					7/1/2001	70							
					3/29/2002					120	17		
					4/24/2002	34							

					7/25/2002			120	17
					9/1/2002			120	17
2003	Spring barley	3/30/2003	7/9/2003	3/26/2003	3/26/2003			74	13
					4/19/2003	27			
2003/2004	Grass	7/9/2003	11/1/2003		7/20/2003	40			
			11/1/2004		8/1/2003			74	13
					3/10/2004			132	24
					4/1/2004	31	5		
					5/24/2004	70			
					5/30/2004	21			
					6/24/2004	70			
2005	Grass	4/2/2005	11/1/2005	3/26/2005	3/8/2005			129	24
					5/14/2005	43			
					6/19/2005			129	24
					7/22/2005			129	24
2006	Corn	5/4/2006	10/16/2006	5/3/2006	5/2/2006			182	33

Table 1 Crop rotation and fertilizer application in the monitored tile-drained fields TileL1 and TileL2. The fertilizers have equivalent amounts of mineral nitrogen (N) and phosphorus (P).

Year	Crop	Mineral fertilizer		Manure	
		N (kg N ha ⁻¹)	P (kg P ha ⁻¹)	N (kg N ha ⁻¹)	P (kg P ha ⁻¹)
TileL1					
1997/1998	Winter grass	307.9	0	182.3	58.4
1998/2000	Grass	157	13.1	131.3	37.7
2000/2001	Winter wheat	83.9	0	125.2	35.5
2001/2002	Winter wheat	67	0	160.8	48.3
2003	Spring barley	87	0	0	0
2003/2004	Grass	34	0	127.9	34.5
2004/2005	Winter wheat	43.19	0	137.5	35.5
2006	Spring barley	28.14	0	185	46
TileL2					
1998	Sugar beet	27	0	179	34
1999	Spring barley	34	0	76	12
1999/2001	Grass	490	0	765	117
2002	Spring barley	34	0	360	51
2003	Spring barley	27	0	74	13
2003/2004	Grass	0	5	206	37
2005	Grass	43	0	387	72
2006	Corn	0	0	182	33

Table 2. Soil organic material (OM), texture, Danish soil texture class (STC), initial soil phosphorus (P) content and the sum of the oxalate extractable iron and aluminium (Fe_{ox} + Al_{ox}) in three layers for each soil type in the SWAT2012 model for the Lillebæk and River Odense catchment.

SWAT soil	Soil layers (mm)	OM (%)	Silt (%)	Clay (%)	STC	Labile P (mg kg ⁻¹)	Mineral P* (mg kg ⁻¹)	Total P (mg kg ⁻¹)	Fe _{ox} + Al _{ox} (mmol kg ⁻¹)
DK5037	0-300	1.45	15.51	7.99	3	9.6	246.5	496.8	98.5
	300-700	0.59	21.14	15.86	7	6.4	176	382.8	71.6
	700-1500	0.15	20.21	18.96	7	6.9	185	304.5	
DK5038	0-300	1.45	15.51	7.99	3	9.6	246.5	496.8	98.5
	300-700	0.57	16.16	7.98	4	4.9	121.2	280.5	73
	700-1000	0.16	13.37	8.22	4	3.6	86.7	154	
DK5047	0-300	1.4	20.06	8.71	4	10.5	262.2	573	81.3
	300-700	0.59	21.14	15.86	7	6.4	176	382.8	71.6
	700-1500	0.15	20.21	18.96	7	6.9	185	304.5	
DK5048	0-300	1.4	20.06	8.71	4	10.5	262.2	573	81.3
	300-700	0.57	16.16	7.98	4	4.9	121.2	280.5	73
	700-1000	0.16	13.37	8.22	4	3.6	86.7	154	
DK5067	0-300	1.42	22.63	12.5	6	10.4	272.5	573.9	75.2
	300-700	0.59	21.14	15.86	7	6.4	176	382.8	71.6
	700-1500	0.15	20.21	18.96	7	6.9	180	299.5	

* sum of labile P, active P and stable P in the SWAT model

Table 3 Parameter ranges and calibrated values for the SWAT2012 model for tile drain and stream flow and DrainP module for dissolved reactive phosphorus leaching (DRP) in TileL1 and TileL2 and Kratholm station on River Odense.

Parameters	Description	Range	TileL1	TileL2	Kratholm
SWAT2012 tile flow & stream flow parameters					
CN2	Curve number for moisture condition II	15-92	71	70	20-72*
ESCO	Soil evaporation compensation factor	0.2-0.7	0.25	0.23	0.64
SOL_AWC	Available water capacity	0.15-0.34	0.21-0.25*	0.20-0.24*	0.19-0.30*
DDRAIN	Depth of the tile drains (mm)	800-1200	992	958	1194
DEP_IMP	Depth to the impervious layer in the soil (mm)	1500-4000	3635	3726	2761
SDRAIN	Distance between two tile drain pipes (mm)	10000-15000	14286	10314	10247
DRAIN_CO	Drainage coefficient (mm day ⁻¹)	20-50	26	43	31
LATKSATF	Multiplication factor to determine lateral K _{sat} from SWAT K _{sat}	1-4	3.3	3.0	2.4
ALPHA_BF	Base flow factor	0.6-1			0.83
GW_DELAY	Groundwater delay time (day)	20-100			86
RCHRG_DP	Ratio of groundwater entering the deep aquifer	0.02-0.3			0.24
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/hr)	60-120			65.6
DrainP DRP leaching parameters					
k_L	Langmuir adsorption constant (l/mg) for 0-30cm soil	0.50-2.40	1.11	0.61	0.53
β_m	Maximum adsorption fraction for 0-30 cm soil	0.06-0.23	0.10	0.11	0.08

* Range of values for different soil types and soil layers

Table 4 Sensitivity analysis of the Langmuir adsorption constant (k_L) and maximum adsorption fraction (β_m) on dissolved reactive phosphorus (DRP) yields in tile-drained fields TileL1 and TileL2 and Kratholm station on River Odense. *t*-Stat is the result from a *t*-test, where larger absolute values indicate higher sensitivity. *P*-Value determines the significance of the sensitivity.

	k_L		β_m	
	<i>t</i> -Stat	<i>P</i> -Value	<i>t</i> -Stat	<i>P</i> -Value
TileL1	-1.8	0.07	3.6	0.0003
TileL2	-10.1	0	-38.6	0
Kratholm	-18.4	0	-52.8	0

Table 5 Contributions (%) of different sources to the average annual stream flow simulated by the SWAT2012 model and average annual dissolved reactive phosphorus (DRP) yields simulated by the extended SWAT2012 with DrainP module from 1998 to 2006 at Kratholm station on River Odense.

Sources	Stream flow	DRP transport	
	SWAT2012	SWAT2012	DrainP
Surface runoff	7	25	20
Groundwater	49	55	25
Tile drains	38	-	46
Lateral flow	4	-	-
Point source	2	20	9
Sum	100	100	100

Figure 1 Illustration of how soil layers between the shallow water table (swt) and the tile drain depth (DDRAIN) contribute to the tile drain flow ($f r_{tile,ly}$).

Figure 2 (a) Location of the Lillebæk and River Odense catchments in Denmark; (b) elevation map of the Lillebæk catchment; (c) land use of the Lillebæk catchment; (d) soil map of the Lillebæk catchment.

Figure 3 (a) and (b) Monthly tile drain flow yield observed in the tile-drained fields TileL1 and TileL2 in the Lillebæk catchment (Obs) and simulated by the SWAT model version 2012 (SWAT2012); (c) monthly stream discharge observed at the Kratholm station on River Odense (Kratholm) and simulated by the SWAT2012. NSE stands for Nash-Sutcliffe Efficiency and PBIAS for percent bias.

Figure 4 (a) and (b) Monthly dissolved reactive phosphorous (DRP) yields observed in the tile-drained fields TileL1 and TileL2 in the Lillebæk catchment (Obs), simulated by SWAT2012 with the DrainP module (DrainP), and the 95% prediction uncertainty band (95PPU) of DrainP; (c) monthly DRP yields observed in River Odense at the Kratholm station (Obs), the SWAT2012, DrainP and 95PPU of DrainP. NSE stands for Nash-Sutcliffe Efficiency and PBIAS for percent bias.

Figure 5 (a) Dissolved reactive phosphorous (DRP) concentrations observed in the tile-drained fields TileL1 and TileL2 in the Lillebæk catchment against simulated by SWAT2012 extended with the DrainP module (DrainP) during the study period; (b) DRP concentrations observed in River Odense at the Kratholm station against simulations from the DrainP model.

Figure 6 (a) Total phosphorus (TP) increase at 0-30 cm depth in the tile-drained fields TileL1 and TileL2 in the Lillebæk catchment. The TP increase is calculated as the annual mean soil TP content minus the initial soil TP in 1989; (b) average annual soil TP increase at 0-30 cm depth of all soil types in agricultural areas in the River Odense catchment upstream station Kratholm. Error bars indicate standard errors of the mean. Red dots in (a) and (b) indicate the means of the measured TP increase from 1986 to 1998 for the soil texture class (STC) at 0-25 cm depth from the nationwide grid sampling programme. Initial soil TP contents are given in Table 2.

Figure 7 Average annual phosphorus (P) budget from 1998 to 2006 in tile-drained fields TileL1 (a), TileL2 (b) and in the River Odense catchment upstream Kratholm station (c). P yield comprises harvest yield

includes P export with harvested crops and in addition a small hardly visible contribution of P lost through soluble and particulate P in surface runoff, tile drain flow, lateral flow and leaching out of the soil profile.