**Simulating phosphorus loss to subsurface tile drainage
flow: a review**

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ABSTRACT

Agricultural land is a major source of phosphorus loss, and artificial drainage is one of the pathways for phosphorus transport. In this paper, we reviewed the methods and equations related to phosphorus loss through subsurface tile drain in water quality models. This review is presented through three topics: subsurface hydrology, fate and transport of phosphorus in soil, and phosphorus transport into tile drains. Major simulating methods and some recent updates are reviewed, and calculations in specific models are presented. Eight existing water quality models (ADAPT, ANIMO, APEX, HYDRUS, ICECREAM, MACRO, PLEASE, SWAP) can be used to simulate P transport to tile drainage, where three of them (HYDRUS, MACRO, SWAP) do not have a specific phosphorus module but P can be simulated using a general chemical module. Models which are not suitable for simulating fate and transport of P to tile drains under their current status, for example, AnnAGNPS, DRAINMOD, GLEAMS, RZWQM2, SurPhos, SWAT, are also reviewed due to their strength in one of the aspects: subsurface drainage or P dynamics. Based on the methods used in those models, ICECREAM could be the most current comprehensive model for P loss through tile drains from agricultural fields.

Key Words: computer models; subsurface tile flow; phosphorus; simulation methods

1. Introduction

Eutrophication is resulted from an overload of nutrients, in particular phosphorus (P), in water bodies. The number of lakes polluted by cyanobacterial blooms has been reported to increase dramatically, with 156 in 2007 in Quebec, Canada (Ministère de la santé et des services sociaux 2007). Agricultural land is the major source of the P pollution. In the Missisquoi Bay of the Champlain Lake, it was reported that 80% of the P pollution originated from agricultural lands (Hegman et al. 1999). About 220 Mt phosphate rock were supplied globally for agricultural

fertilizer use in 2015 (Heffer 2015), but only 1/5 of the P reaches the food and is consumed by humans (Cordell et al. 2009). Application of manure and fertilizer to croplands is primarily based on nitrogen requirement, while with higher P: N ratios in animal waste relative to crop needs, P can be over-applied and therefore, increase the risk of P loss to water bodies (DeLaune et al. 2004). Furthermore, 90% of P transported from manure-applied pastures may be in solute form (Edwards and Daniel 1993), which can contribute more to eutrophication, as “soluble P is directly available to algae and macrophytes, whereas particulate P is bioavailable only after being released from a sediment-bound form” (Sonzogni et al. 1982).

Surface runoff has long been known as an important pathway to transport phosphorus from agricultural fields into water bodies, while there is a common misconception that “P does not move via subsurface processes” (Radcliffe et al. 2015). Water drained from agricultural fields is an important component of water resource in both humid and dry regions in the world (Ayars and Evans 2015). While subsurface drainage occurs naturally in soil, it is greatly enhanced when tile drains are present (Hebraud 2006). In fields installed with tile drains, surface runoff was observed only during very wet conditions, when precipitation exceeded drainage capacity or soil infiltration capacity (Skaggs et al. 1994, Robinson and Rycroft 1999; Dolezal et al. 2001; Macrae et al. 2007). Fifty-one per cent of annual stream flow in agricultural lands was estimated to originate from tile drainage in Ohio, USA (King et al. 2014), and 42% in Ontario, Canada (Macrae et al. 2007). Tile drain installment can improve crop yield and reduce soil erosion, but it can also contribute to nutrient loss from agricultural fields (Skaggs and Schilfgaarde 1999). In a study by Ruark et al. (2012) in Wisconsin, U.S.A., it was found that tile drainage water flow contributed 17% to 41% of cumulative total phosphorus, and supplied 16% to 58% of dissolved phosphorus loads. Tan and Zhang (2011) reported that 95%-97% of P was leached to subsurface

drains at a site in southern Ontario, Canada. Overall, total P varies among different studies due to varying scales of space and time (0.01 to 8.0 mg/L), but generally exceeds the critical levels for eutrophication (0.02-0.03mg/L) (King et al. 2015).

Vadas et al. (2013) reported that models can assess and simulate agricultural management and interactions which cannot be measured physically. They can be used to predict the transport of P pollution where measured data are absent (Radcliffe et al. 2009). Given the constraints of time and resources, models can allow for wider order-of-magnitude investigations than field studies. Additionally, modeling research “forces scientists to formalize and test their understanding of P processes and thus identify knowledge and data gaps” (Vadas et al. 2013). There are many agricultural water quality models, including ADAPT, AGNPS, ANIMO, APLE, APEX/EPIC, CHEMFLO, DRAINMOD, FHANTM, GAMES, GLEAMS, HYDRUS-1D/2D/3D, ICECREAM, LEACHM, MACRO, PLEASE, RZWQM2, SurPhos, and SWAT. This paper aims to review the methods and calculations used in water quality models focusing on the specific problem of P transport through tile drainage from agricultural lands.

2. Overview of Tile Drainage Water Quality Models

Eight models (ADAPT, ANIMO, APEX, EPIC, HYDRUS, MACRO, ICECREAM, PLEASE, SWAP) could simulate phosphorus loss to tile drainage. Models like ANSWERS, APLE (Vadas et al. 2012), BASINS/HSPF, CENTURY, CHEMFLO, DAYCENT, GLEAMS, SPARROW and SurPhos possess phosphorus modules but lack tile drainage components. Models including DRAINMOD, DAISY, RZWQM2, and SOIL are equipped with tile drainage components, but do not simulate the fate and transport of phosphorus. AnnAGNPS and SWAT do not simulate P loss to subsurface tile flow, although there are tile drain and phosphorus components in these two models (Que et al. 2015; Radcliffe et al. 2015). We found that the

following eight models could be used to simulate P loss to tile drains by reviewing their methods and calculations.

ADAPT (Agricultural Drainage and Pesticide Transport) is a model derived from GLEAMS and DRAINMOD. Enhancements based on GLEAMS were mainly in adding tile drainage, snowmelt, macropore flow and Dorenbos-Pruitt PET method. Dalzell et al. (2004) tested management strategies influences on sediment and phosphorus loss under Minnesota conditions. To date, we are not aware of a study of P loss to tile drains using ADAPT.

ANIMO is a model developed in the Netherlands. The water balance calculation is adapted from WATBAL (Berghuijs-van Dijk 1985; Vinten 1999), while ANIMO requires an associated model (e.g. SIMGRO, SOIL, SWAP, etc.) to simulate the hydrologic process. McGechan and Hooda (2010) applied ANIMO to simulate P transport to tile drain in a field in Scotland, which showed that the simulated data fit the observed data well. Details of ANIMO can be found in Lewis and McGechan (2002).

APEX and EPIC are widely used models for agricultural management and water quality simulation, where APEX is the extension of EPIC. The P modules in most other models originated from the P subroutine of EPIC. There were many studies on simulating P loss through surface runoff, e.g. Pierson et al. (2001), but we are not aware of any study which simulated P loss into tile drainage.

HYDRUS is a model for simulating the movement of water, heat, and multiple solutes in variably-saturated media. It simulates water quality based on its solute transport module, which is a general simulation and lacks detailed phosphorus dynamics. Nahra (2006) coupled HYDRUS-1D with an aqueous chemical model NICA (Non-Ideal Competitive Adsorption) (Koopal et al. 1994) and developed HYDRUS-NICA in order to improve the predictions of P

transport in soil and water. Qiao (2013) simulated phosphorus fate using HYDRUS-2D/3D in the tile-drained clay loam soil of southern Ontario. Results showed that the model simulated well on a weekly scale, while poorly on a daily scale. The discrepancy between simulated and observed data mainly occurred during the winter period.

MACRO is a dual-permeability model which can be used to simulate solute transport and saturated water flow (Jarvis and Larsbo 2012). It does not comprise phosphorus dynamics simulations, but McGechan et al. (2002) applied it to simulate soluble and particulate inorganic phosphorus loss from slurry in a tile drain field in Scotland. The study found that colloiddally transported P through macropore flows to field drains was an important component of water pollution.

ICECREAM (Rekolainen and Posch 1993; Tattari et al. 2001; Liu et al. 2012) was developed based on the CREAMS model (Knisel, 1980) to adapt for Nordic conditions (cold weather including freezing/thawing, snow accumulation and snowmelt) and did not contain a water table based tile drainage component. A module was added into the model to simulate macropore and soil matrix flow and PP (particulate phosphorus) transport (Larsson et al. 2007; Jaakkola et al. 2012). Tile drainage was computed as the sum of water flux from the macropore and soil matrix. Results showed that the modified ICECREAM performed reasonably in simulating P loss to subsurface tile drains in Sweden and Finland, while the reliability of the model needed to be further tested under different soil and climate conditions (Larsson et al. 2007; Jaakkola et al. 2012).

PLEASE (Phosphorus LEAching from Soils to the Environment, Schoumans et al. 2013) is a new model which was developed based on the STONE model (Wolf et al. 2005). PLEASE is a field-scale model which can simulate P losses in tile drains. It was applied to 17 lowland sites

in Denmark and 14 lowland sites in the Netherlands, and performed well in simulating water quantity and quality in pipe drains, suction cups, and groundwater; however, poor performance was observed under heavy clay soil conditions, which is probably due to an absence of a macropore component in PLEASe (van der Salm et al. 2011).

SWAP (Soil-Water-Atmosphere-Plant) simulates the transport of solute, water and heat in the vadose zone, as well as the growth of vegetation (Kroes et al. 2008). Unlike HYDRUS and MACRO, three crop growth routines are considered in the model. To the best of our knowledge, there has been no past research on P loss in tile drainage using SWAP.

3. Modelling Methods and Simulation Approaches

To simulate phosphorus loss through tile drainage from agricultural land, the following three processes are usually involved. The first is the subsurface hydrology, which includes tile drainage and macropore (preferential) flow. The second one is soil P dynamics, such as P pools and P flow between pools (e.g. mineralization, and plant P uptake.). The third part is P transport to drainage water, which describes the total P losses to surface water bodies.

3.1. Subsurface Hydrology Simulation

3.1.1 Tile Drainage Simulation

Tile drain flow can be calculated by means of both steady-state and non-steady state methods. However, as non-steady state flow methods, e.g. Navier-Stokes equations (Van Schilfgaarde 1970), Glover equation, and Boussinesq equations are much more difficult “than time invariant problems” (Wu 1988), most agricultural water quality models use steady-state flow equations for subsurface drainage simulation. It was found that Hooghoudt, Tökösz-Kirkham, and Ernst equations are suitable for general steady state drainage simulation after

comparing 40 steady-state tile drain formulas based on 35 experimental fields (Wu and Chieng 1991). Most agricultural models are applying these three methods for tile drainage simulation.

Hooghoudt's Equation

Hooghoudt's equation (Hooghoudt 1940) is widely used and has a relatively simple structure (Smedema and Rycroft, 1983). The equation is derived based on the one-dimensional Boussinesq equations and Dupuit-Forchheimer (DF) assumptions to calculate water flow into two parallel drains. The steady-state Hooghoudt's equation is shown as follows (Bouwer and Schilfgaarde 1963; Simunek et al. 2013):

$$q = 4K_e m(2d + m)/L^2 \quad (1)$$

$$\text{or} \quad q = \frac{8K_b m d + 4K_a m^2}{L^2} + \frac{m}{\gamma_{entr}} \quad (2)$$

where q is the drainage rate [LT^{-1}]; K_e is the equivalent lateral hydraulic conductivity of the soil profile [LT^{-1}]; m is the water table height above the drain-level midpoint between two parallel drains [L]; d is the effective depth from the impermeable layer to the drains [L]; L is the drain spacing [L]; K_b and K_a are the saturated hydraulic conductivity below and above the drains, respectively [LT^{-1}]; γ_{entr} is the entrance resistance into the drains [T].

In Hooghoudt's equation, the depth from the impermeable layer to drain, D , was replaced with d , an imaginary depth smaller than D , to reduce the DF approximation error. Different methods have been developed to estimate the d value (Van Schilfgaarde 1963; van Beers 1965; Moody 1967; Sakkas and Antonopoulos 1981), and of note is that a new equivalent depth equation (Mishra and Singh, 2007) was derived using a combination of $2D/\pi$ and the area of groundwater flow above the drain in the radial zone to replace the original assumption of $D/\sqrt{2}$.

Kirkham Equation

The Kirkham equation (Kirkham 1958) is based on the two-dimensional steady-state Laplace equation, and can be written in the following form (Đurović and Stričević 2003):

$$m = \frac{qL}{K_b} F_k \quad (3)$$

where m is water table height of the midpoint between two parallel drains above drain level [L]; q is drainage coefficient/drain discharge rate [LT^{-1}]; L is drain spacing [L], and

$$F_k = \frac{1}{\pi} \left[\ln \frac{L}{\pi r_0} + \sum_{n=1}^{\infty} \frac{1}{n} \left(\cos \frac{2n\pi r_0}{L} - \cos n\pi \right) \left(\cosh \frac{2n\pi D}{L} - 1 \right) \right] \quad (4)$$

where r_0 is the drain radius [L]; D is the soil layer thickness below drains [L]. The Kirkham equation only accounts for water flow below drains and “ignored all flow above drain level” when it was developed (Shokri and Bardsley 2015), while in Kirkham’s later paper (Kirkham 1960) head loss due to vertical flow above the drains was also taken into account. And the equation was thus further developed as follows for drains installed in the interfaces of two soil layers:

$$m = \frac{qL}{K_b} \frac{1}{1 - \frac{q}{K_a}} F_k \quad (5)$$

When the water table is at or above the soil surface, the Kirkham equation becomes (Kirkham, 1957):

$$q = \frac{4\pi K_e(t+b-r_0)}{(G*L)} \quad (6)$$

where t is the depth of water on the soil surface [L]; b is the depth from the soil surface to drains [L]; G is a dimensionless factor determined by geometry.

Ernst Equation

The Ernst equation (Ernst 1956) is another method for the steady-state tile drainage simulation. It divides the total hydraulic head (h) into three components: vertical (h_v), horizontal (h_h) and radial (h_r). The relationship between water table and hydraulic head is:

$$m = h_v + h_h + h_r = q\gamma_v + qL\gamma_h + qL\gamma_r \quad (7)$$

where γ_v , γ_h , and γ_r are vertical, horizontal and radial drainage resistance, respectively [T]. After working out the resistance terms (Ernst 1962), the Ernst equation can be written in the following form (Wu and Chieng 1991):

$$m = q \frac{D_v}{K_v} + q \frac{L^2}{8KD} + q \frac{L}{\pi K_s} \ln \frac{aD_2}{u} \quad (8)$$

where D_v is the thickness of the layer where vertical flow happens [L] and in most cases this component is small, which could be ignored; K_v is the vertical hydraulic conductivity [LT^{-1}]; KD is the sum of the product of the permeability (K) and thickness (D) of the various layers for the horizontal flow component. a is the geometry factor for radial flow; u is the wetted section of the drain [L]; D and D_2 are the thickness of the respective layer [L].

Models with a Single Method

Many models use a single method to simulate tile drainage, including AnnAGNPS, RZWQM2, APEX/EPIC, ICECREAM, PLEASE and SWAT. Hooghoudt's Eq. (1) are adopted in AnnAGNPS and RZWQM2 to simulate subsurface flow to drains. In AnnAGNPS, d (equivalent depth) is computed differently for $0 < d/L \leq 0.3$ and $d/L > 0.3$ (Yuan et al. 2006). The one-dimensional Darcy's law was used for lateral subsurface flow simulation, and only saturated conditions are considered.

In other models including APEX/EPIC, ICECREAM, PLEASE and SWAT, the strategies to simulate tile drainage are different. Tile drainage simulation in APEX/ EPIC is regarded as a modification of natural lateral subsurface flow. Storage-routing theory and pipe flow simulation are used for subsurface flow. ICECREAM also adopts a storage-routing concept for soil water flow simulation, and the tile drainage is computed as the sum of the water flux from the macropore and micropore at the tile drain depth. In the PLEASE model, the annual horizontal

drainage flux is calculated based on water table depth, drainage resistance and depth of two drainage systems (Van Bakel, 1986; van der Salm et al. 2011):

$$q_{dr} = 10 \left[\frac{\max(0, z - h_{d,1})}{\gamma_1} + \frac{\max(0, z - h_{d,2})}{\gamma_2} \right] \quad (9)$$

where q_{dr} is the horizontal drainage flux [LT^{-1}]; z is the water table height [L]; $h_{d,1}$ and $h_{d,2}$ are the depth of deep and shallow drainage systems, respectively [L]; γ_1 and γ_2 are the drainage resistance of deep and shallow drainage systems, respectively [T].

It is assumed in the SWAT model that tile drainage occurs when the perched water table is above drain depth. Tile drainage in SWAT is calculated using (Neitsch et al. 2011):

$$tile_{wtr} = \frac{h_{wtbl} - h_{drain}}{h_{wtbl}} * (SW - FC) * (1 - \exp \frac{-24}{t_{drain}}), \text{ if } h_{wtbl} > h_{drain} \quad (10)$$

where $tile_{wtr}$ is the water removed from the layer by tile drain in a given day [L]; h_{wtbl} and h_{drain} are the depths of water table and the tile drain above the impervious zone, respectively [L]; SW and FC are the soil water content and field capacity of the soil profile, respectively [L]; t_{drain} is the time required to drain the soil to field capacity [T].

Models with Multiple Methods

Many models, including ADAPT, DRAINMOD, HYDRUS, MACRO and SWAP, adopt more than one method to simulate tile drainage under various situations. The tile drainage module in ADAPT was adopted from the method in DRAINMOD. In DRAINMOD, there are two algorithms for tile drainage simulation regarding different situations. Hooghoudt's Eq. (1) is used when the water table at the midpoint between drains is below the soil surface, while Kirkham's Eq. (6) is employed when the water table is above the soil surface (Singh et al. 2006). The HYDRUS model adopts analytical solutions to two equations, Hooghoudt's Eq. (2) and Ernst Eq. (8) to approximate tile drainage respectively. In MACRO, it is assumed that flow to drains occurs only when macropores are saturated. Two methods are used to simulate tile

drainage. Flow from saturated layers above drain depth is simulated using seepage potential theory (Youngs 1980), and flow from layers below drains is simulated using Hooghoudt's Eq. (1). While in SWAP, tile drainage is simulated under five different conditions based on soil properties (e.g. homogeneous and two layers) and the drain position. For a homogeneous soil profile, Hooghoudt's Eq. (1) is used where the drains are either on or above the impervious layer. For a two-layer profile, when the drains are located at the interface of the two layers, Hooghoudt's Eq. (2) is used; when the drains are either in the bottom layer or in the top layer, Ernst Eq. (8) is used (Kroes et al. 2008).

3.1.2 Preferential (macropore) Flow Simulation

Preferential flow, also known as "bypass flow" or "short-circuiting flow" (Hoogmoed and Bouma, 1980), is a significant factor affecting tile drainage flow. It was reported to account for 81% of the total peak flow in tile drainage (Stone and Wilson, 2006). Preferential flow was also reported to be a critical pathway for P loss to tile drainage in studies, either through cracks/fissures or biopores (Stamm et al. 1998; Simard et al. 2000).

Some models include macropore flow components. For example, HYDRUS, MACRO, RZWQM2, SWAT employ the double-domain method, developed by Barenblatt et al. (1960), for macropore flow simulation. Methods in macropore flow simulation include dual-porosity, dual-permeability, multi-porosity, and multi-permeability models (Gerke and van Genuchten 1993; Gwo et al. 1995; Jarvis 1998; Šimůnek et al. 2003). ANIMO, APEX/EPIC, PLEASE do not include a macropore flow process.

Dual-Porosity Model

The dual-porosity model divides soil pores into macropores and the soil matrix. It assumes that the soil matrix only stores water and exchanges water with macropores, but does

not host water flow. There are two approaches to calculate water flow in macropores. The first method is based on the Richards equation:

$$\frac{\partial \theta_f}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right] - S_f - \Gamma_w \quad (11)$$

where θ_f is the volumetric water content of macro pores [$L^3 L^{-3}$]; t is time [T]; z is the vertical axis [L]; K is the hydraulic conductivity [$L T^{-1}$]; h is the water pressure head [L]; S_f is the sink term for the macro pore region [T^{-1}]; Γ_w is the mass exchange rate (water transfer rate) between the matrix and macropores regions [T^{-1}].

The other method for macropore flow simulation is the kinematic wave equation which describes gravitational flow in macropores (Germann 1985; Germann and Beven 1985):

$$\frac{\partial q}{\partial t} + C \frac{\partial q}{\partial z} - C * s = 0 \quad (12)$$

where q is the macropore volumetric flux density [LT^{-1}]; C is the kinematic wave velocity [LT^{-1}]; s is the rate of water loss from the macropores to the soil matrix [T^{-1}]. For q and C :

$$q = b \theta_f^a \quad (13)$$

$$C = \frac{\partial q}{\partial \theta_f} \quad (14)$$

where b is the macropore conductance [$L T^{-1}$]; a is the kinematic exponent, which is dimensionless [-].

For soil matrix water, a mass balance equation is used to simulate the moisture dynamics in a dual-porosity model:

$$\frac{\partial \theta_m}{\partial t} = -S_m + \Gamma_w \quad (15)$$

where θ_m is the volumetric water content in the soil matrix [$L^3 L^{-3}$]; S_m is the sink term for the soil matrix region [T^{-1}].

Dual-Permeability Model

The dual-permeability model also divides soil pores into macropore and soil matrix regions, while assuming that water flows in the soil matrix region. Gerke and van Genuchten (1993; 1996) developed formulas based on the Richards equations for macropores and matrix flow, respectively:

$$\frac{\partial \theta_f}{\partial t} = \frac{\partial}{\partial z} \left(K_f \frac{\partial h_f}{\partial z} + K_f \right) - S_f - \frac{\Gamma_w}{w} \quad (16)$$

and

$$\frac{\partial \theta_m}{\partial t} = \frac{\partial}{\partial z} \left(K_m \frac{\partial h_m}{\partial z} + K_m \right) - S_m - \frac{\Gamma_w}{1-w} \quad (17)$$

where K_f and K_m are the hydraulic conductivity of macropore and matrix regions, respectively [LT^{-1}]; h_f and h_m are the pressure head of the macropore and matrix water, respectively [L]; w is the ratio of the macropore volume and the total pore volume in the soil [$L^{-3} L^{-3}$].

Another method mentioned by Larsbo and Jarvis (2003) used the Richards equation to calculate the flow in the matrix, while using the same expression of q (volumetric flux density) in Eq. (12) for macropore simulation:

$$q = b \left(\frac{\theta_f}{\theta_{sf}} \right)^a \quad (18)$$

where θ_{sf} stands for macroporosity, or the volumetric water content in macropores when saturated [$L^{-3} L^{-3}$].

A third method is to use the Green-Ampt and Richards equations to compute water infiltration and redistribution in the soil matrix, while assuming gravitational flow in macropores and using Poiseuille's law (Sutera and Skalak 1993) to calculate water infiltration into macropores. The formula for calculating gravitational flow in macropores is:

$$q = \frac{N_p \rho g \pi r_p^4}{8v} \quad (19)$$

where q is the macropore volumetric flux density [$L\ T^{-1}$]; N_p is the number of pores per unit area; ρ is the density of water [$M\ L^{-3}$]; r_p is the radius of macropores [L]; v is the viscosity of water [$L^2\ T^{-1}$].

Multi-porosity and multi-permeability models are generally based on the same theories as dual-porosity and dual-permeability models, except that they introduce overlapping regions in addition to the two regions. Examples of models that simulate water flow in more than two regions are MURF (Gwo et al. 1996) which divides soil pores into three categories (macropores, mesopores, and micropores), and TRANSMIT (Hutson and Wagenet 1995) which can simulate water flow in several overlapping regions.

ADAPT

Macropores were simplified and represented by soil cracks in ADAPT (Chung et al. 1992; Gowda et al. 2012), and water infiltration is a function of soil clay content, number of continuous dry days and daily evaporation demand (Pathak et al. 1989):

$$S_r = \alpha \sum_1^n E \quad (20)$$

where S_r is runoff adjustment volume [L]; α is a coefficient based on soil clay content [-]; n is the number of consecutive dry days [-]; E is daily evaporation demand [L]. It is assumed that S_r is the amount of water subtracted from runoff and moved directly to the water table.

HYDRUS

Both dual-porosity and dual-permeability models are provided as options to simulate non equilibrium water flow in HYDRUS. The Richards equation (Eq. (11)) is used for macropore flow simulation and mass balance equation (Eq. (15)) is used for the soil matrix flow simulation in dual-porosity model of HYDRUS. While both macropore and soil matrix flows are simulated

with Richards equations in dual-permeability model of HYDRUS, Eq. (16) and Eq. (17) respectively.

ICECREAM

Larsson et al. (2007) adopted the two domain (macropores and soil matrix) concept and developed equations based on a simpler storage-routing theory. A groundwater reservoir concept is introduced for simulating subsurface soil water. Water flows into macropores only if the water content of the two upper layers exceeds “the fraction of field capacity,” and whenever the infiltration capacity of micropores is exceeded. Downward flow in the micropore region occurs only if water storage exceeds the difference between field capacity and the wilting point of the soil layer. Macropore and micropore water flow are simulated, respectively, using:

$$q_{ma} = R_f(I_n - I_{mi}) \quad (21)$$

$$q_{mi} = \frac{\theta - (\theta_f - \theta_w)z}{\frac{\theta_s z}{\alpha} + 0.5} \quad (22)$$

where q_{ma} and q_{mi} are the flow rate in macropores and micropores, respectively [$L T^{-1}$]; R_f is the fraction of excess rainfall coming into macropores [-]; I_n is the infiltrating rate of total water [$L T^{-1}$]; I_{mi} is the infiltration capacity of micropores [$L T^{-1}$]; θ , θ_f , θ_w , and θ_s are current water storage, field capacity, wilting point and saturated water content of the layer, respectively [%]; z is the depth of the layer [L]; α is an empirical conductivity parameter [$L T^{-1}$]. This method was deemed to be less accurate than more physically-based soil water content simulation using the Richards equation (Larsson et al. 2007).

MACRO

MACRO employs a dual-permeability model using the Richards equation for water flow in soil matrix (Eq. (17)), and the kinematic wave approach for macropore flow (Eq. (18)). The

kinematic wave method reduces the required parameters, but a limitation would be that it only describes vertical gravity flow and ignores capillary flow (Šimůnek et al. 2003).

RZWQM2

The dual-permeability model is adopted, with macropore flow using Poiseuille's law approach (Eq. (19)), and water flow from macropore to matrix flow is computed by the Green-Ampt equation (Ma et al. 2012). It assumes the macropores are cylindrical (also used for planar fractures reported by DeCoursey et al. (1992)), and considers only gravitational flow in macropores (Šimůnek et al. 2003).

SWAP

The SWAP model includes detailed geometry of pore distribution and pore structure as proposed by Hendriks et al. (1999). Three geometric properties of macropores, continuity, persistence and horizontal distribution, are incorporated in the SWAP model. Several water flux processes, for instance, lateral infiltration into saturated/ unsaturated soil matrix, flow in and out of macropore, rapid drainage, are simulated. The Richards equation is used for simulating matrix water flow, and the theory of shrinkage cracks dynamics coupled with the first-order transfer calculation is applied to simulate macropore flow (Köhne et al. 2009).

3.2 Soil Phosphorus Simulation

The P subroutine in most current models (e.g. ADAPT, AGNPS, ANSWERS, APEX, APLE, CREAMS, GLEAMS, ICECREAM, SWAT) originates from the P model proposed by Jones et al. (1984) for EPIC. Although not capable of predicting P loss to tile drainage due to lack of a drainage component, SurPhos is brought to our attention because it is the most recently developed model to simulate the fate and transport of P in agricultural systems.

3.2.1 EPIC

The phosphorus dynamics in EPIC are shown in Fig. 1. Five soil P pools are used: labile, active, and stable inorganic (or mineral) P, and fresh and stable organic P. Grain, stover and root assimilates P from P_{lab} , while grain and stover P is added into P_{fresh} after growth termination. In addition, inorganic P fertilizer is added into P_{lab} , while for organic fertilizer, organic fractions and manure are placed into P_{fresh} , and the inorganic fraction is added into P_{lab} .

Figure 1. Phosphorus routine in the EPIC model (adapted from Jones et al., 1984). MN, mineralization (or decomposition); IM, immobilization; UP, uptake.

Organic P and Immobilization-Mineralization

When organic P fertilizer is applied to soil, the organic fraction is added into the soil P_{fresh} pool. Soil organic P pools are divided based on the C:N:P ratio. The P_{fresh} pool usually has a C:N:P ratio of 1: 12-25: ≥ 200 , while the $P_{stable(O)}$ pool has a C:N:P ratio of 1: 12: 125-200 (Lewis and McGechan 2002). Mineralized P in the P_{fresh} pool flows into two pools of P_{lab} and $P_{stable(O)}$, respectively. Mineralization (or decomposition) is the biochemical transformation of organic P. The opposite process is defined as immobilization. Further mineralized P in $P_{stable(O)}$ is added to the P_{lab} pool.

Simulation in P mineralization is adapted from the N mineralization module in the PAPRAN (Seligman and Keulen 1981) model. Mineralization in P_{fresh} and $P_{\text{stable(O)}}$ are calculated using Eq. (23) and Eq. (24), respectively:

$$R_{\text{mine(fresh)}} = K_{\text{decay}} * P_{\text{fresh}} \quad (23)$$

$$R_{\text{mine(stable)}} = \frac{K_{\text{mine(stable)}} * N_{\text{active(o)}} * P_{\text{stable(o)}} * (F_{\text{ot}} * F_{\text{om}}^*) * BD^2}{N_{\text{org}} * BD_{\text{til}}^2} \quad (24)$$

Where $R_{\text{mine(fresh)}}$ and $R_{\text{mine(stable)}}$ are the mineralization rates in P_{fresh} and $P_{\text{stable(O)}}$, respectively $[M(L^2T)^{-1}]$; K_{decay} is the decay rate constant for mineralization from the P_{fresh} pool $[T^{-1}]$; P_{fresh} and $P_{\text{stable(O)}}$, are the amount of fresh organic P and stable organic P, respectively $[M(L^2)^{-1}]$; $K_{\text{mine(stable)}}$ is the humus mineralization rate constant $[T^{-1}]$, which is set to 0.0003 d^{-1} ; $N_{\text{active(o)}}$ is the amount of “readily mineralizable” (Sharpley and Williams 1990) organic N in humus $[M(L^2)^{-1}]$; F_{ot} is the soil temperature factor [-]; F_{om}^* is the soil moisture factor for stable organic mineralization [-]; BD is the settled bulk density $[ML^{-3}]$; N_{org} is the amount of total organic N in humus $[M(L^2)^{-1}]$; BD_{til} is the bulk density affected by tillage $[ML^{-3}]$. K_{decay} is calculated by:

$$K_{\text{decay}} = \min(F_{\text{cn}}, F_{\text{cp}}, 1) * RC * (F_{\text{ot}} * F_{\text{om}})^{\frac{1}{2}} \quad (25)$$

$$F_{\text{cn}} = \exp\{-0.693 \left[\frac{0.58C_{\text{res}}}{N_{\text{res}} + N_i} - 25 \right] / 25\} \quad (26)$$

$$F_{\text{cp}} = \exp\{-0.693 \left[\frac{0.58C_{\text{res}}}{P_{\text{fresh}} + P_{\text{lab}}} - 200 \right] / 200\} \quad (27)$$

$$RC = \begin{cases} 0.8, & \text{when } \frac{O_{\text{res}}}{O_{\text{resi}}} > 0.8 \\ 0.05, & \text{when } 0.1 < \frac{O_{\text{res}}}{O_{\text{resi}}} < 0.8 \\ 0.0095, & \text{when } \frac{O_{\text{res}}}{O_{\text{resi}}} < 0.1 \end{cases} \quad (28)$$

$$F_{\text{ot}} = \begin{cases} \frac{T}{[T + \exp(9.93 - 0.312T)]}, & T > 0 \\ 0, & T \leq 0 \end{cases} \quad (29)$$

$$F_{\text{om}} = W / W_{\text{fc}} \quad (30)$$

$$F_{om}^* = W/\theta \quad (31)$$

where F_{cn} and F_{cp} are the C:N ratio and C:P ratio, respectively [-]; RC is the residue composition factor [-]; C_{res} is the amount of carbon in crop residue [$M(L^2)^{-1}$]; N_{res} , N_i and P_{lab} are the amount of N in residue and inorganic N (NO_3+NH_4), and amount of labile inorganic P, respectively [$M(L^2)^{-1}$]; O_{res} and O_{resi} are the residue and initial residue, respectively [$M(L^2)^{-1}$]; T is soil temperature[θ]; F_{om}^* is the soil moisture factor for stable organic mineralization [-]; W, W_{fc} , and θ are the measured volumetric soil water content, field capacity and soil porosity, respectively [$L^3 L^{-3}$].

For mineralization from P_{fresh} , it is assumed that 80% flows to the P_{lab} pool and 20% flows to the $P_{stable(o)}$ pool.

Immobilization from P_{lab} to P_{fresh} (Fig. 1) is calculated using:

$$R_{immo} = K_{decay}^* \cdot O_{res} \cdot (0.16C_{P_{micro}} - C_{P_{fresh}}) \quad (32)$$

$$C_{P_{micro}} = \begin{cases} 0.01 + 0.001C_{P_{lab}}, & C_{P_{lab}} \leq 10 \\ 0.02, & C_{P_{lab}} > 10 \end{cases} \quad (33)$$

$$K_{decay}^* = \frac{0.95N_{NO_3}}{O_{res}(0.016 - C_{N_{fresh}})} \quad (34)$$

or:

$$K_{decay}^* = \frac{0.95P_{lab}}{O_{res}(0.016 - C_{P_{fresh}})}$$

where R_{immo} is the immobilization rate [$M(L^2)^{-1}$]; K_{decay}^* is the adjusted decay rate constant for immobilization [T^{-1}]; $C_{P_{micro}}$, $C_{P_{fresh}}$ and $C_{P_{lab}}$ are the microbial P concentration, the fresh organic P concentration, and labile inorganic phosphorus concentration, respectively [MM^{-1}]; N_{NO_3} is the amount of NO_3 in the layer [$M(L^2)^{-1}$]; $C_{N_{fresh}}$ is the N concentration in crop residue [MM^{-1}]. Those two equations in Eq. (34) are used when N and P availability are limiting for immobilization, respectively.

420 **Inorganic/Mineral P**

When inorganic P (e.g. fertilizer) or the inorganic fraction in organic fertilizer is applied to the soil, sorption occurs instantaneously after P solution contact with solids (Belmont et al. 2009), which is followed by a slow adsorption that could possibly last for years (Barrow and Carter 1978; Torrent et al. 1990). The parameter representing the “fraction of fertilizer P remaining in the labile pool after the initial rapid phase of P sorption is complete” (Williams et al. 2008) is called the P sorption coefficient (or P availability index):

$$PSP = (P_{labf} - P_{labi})/P_{fer} \quad (35)$$

where PSP represents the P adsorption coefficient; P_{labi} [$M(L^2)^{-1}$] and P_{labf} [$M(L^2)^{-1}$] are labile P prior to and after fertilization and incubation; P_{fer} is the amount of fertilizer P [$M(L^2)^{-1}$].

The PSP value is determined by physical and chemical soil properties, but it is limited between 0.05 and 0.75:

For calcareous soils:

$$PSP = 0.58 - 0.0061 * C_{CaCO_3} \quad (36)$$

For noncalcareous and slightly weathered soils:

$$PSP = 0.02 + 0.0104P_{lab} \quad (37)$$

For noncalcareous and moderately weathered soils:

$$PSP = 0.0054BSA + 0.116pH - 0.73 \quad (38)$$

For noncalcareous and highly weathered soils:

$$PSP = 0.46 - 0.0916 \ln(C_{cl}) \quad (39)$$

where C_{CaCO_3} is the concentration of $CaCO_3$ in the soil [MM^{-1}]; P_{lab} is the amount of labile phosphorus [$M(L^2)^{-1}$]; BSA is the base saturation using the NH_4OAc method [%]; pH is the pH of the soil [-]; C_{cl} is the clay content of soil [%].

For flow from the P_{lab} to the P_{act} pool, it is assumed that the P flow will not stop until $P_{act} = P_{lab} * \frac{1-PSP}{PSP}$. Thus, based on soil temperature and soil moisture factors, this flow is calculated as:

$$R_{lab \rightarrow act} = K_{lab \rightarrow act} \exp(0.115T - 2.88) F_{om} \left(P_{lab} - P_{act} * \frac{PSP}{1-PSP} \right) \quad (40)$$

where $R_{lab \rightarrow act}$ is the flow rate from labile to active P [$M(L^2)^{-1}$]; $K_{lab \rightarrow act}$ is the constant rate factor or flow coefficient [T^{-1}], and is assumed to be $0.1d^{-1}$. For the reverse flow from the P_{act} to the P_{lab} pool, since the process was observed to be much slower, it is calculated by multiplying Eq. (40) by a rate factor 0.1 ($RF_{act \rightarrow lab}$).

For flow from the P_{act} to the P_{st} pool, it is assumed that the P flow will not stop until stable P is 4 times that of active P in soil (Russell 1977; Cox et al. 1981; Yost et al. 1981):

$$R_{act \rightarrow st} = K_{act \rightarrow st} (4P_{act} - P_{st}) \quad (41)$$

$$K_{act \rightarrow st} = \begin{cases} \exp(-1.77PSP - 7.05), & \text{noncalcareous soil} \\ 0.0076, & \text{calcareous soil} \end{cases} \quad (42)$$

For the reverse flow from the P_{st} to the P_{act} pool, since the process was observed to be much slower, it is calculated by multiplying Eq. (41) by a rate factor 0.1 ($RF_{st \rightarrow act}$).

Plant P Uptake

The plant P uptake is estimated based on the supply and demand approach. Potential plant P uptake is calculated by (Williams et al. 2008):

$$R_{upp} = 1.5 * R_{dm} * F_{lab} * M_{r0}/M_t \quad (43)$$

$$F_{lab} = 0.1 + \frac{0.9C_{P_{lab}}}{C_{P_{lab}} + 117 \exp(-0.283 * C_{P_{lab}})} \quad (44)$$

$$R_{dm} = bp_1 + bp_2 * \exp(-bp_3 * HUI) \quad (45)$$

where R_{upp} is the potential P uptake rate [$M(L^2)^{-1}$]; R_{dm} is the plant P demand for the day [$M(L^2)^{-1}$]; F_{lab} is the labile P concentration factor [-]; M_{r0} and M_r are the root weight in the layer

465 and total root weight respectively $[M(L^2)^{-1}]$; $C_{P_{lab}}$ is the concentration of labile P in the soil
 466 $[MM^{-1}]$; bp_1 , bp_2 and bp_3 are crop parameters expressing optimal P concentration as a function
 467 of crop development [-]; HUI is heat unit index [-].

468 If P demand is less than P supply, then:

$$469 \quad R_{up} = R_{upp} \quad (46)$$

470 If P demand is more than P supply, then P uptake is calculated as:

$$471 \quad R_{up} = R_{upp} + R_{dm} - R_{su} \quad (47)$$

472 where in Eqs. (46) and (47), R_{up} is the actual amount of P uptake per day $[M(L^2)^{-1}]$; R_{su} is the
 473 amount of P supplied by the soil profile for the day $[M(L^2)^{-1}]$.

474 **3.2.2 SurPhos**

475 SurPhos is “designed to be integrated into” other models to enhance their simulating
 476 ability focusing on surface applied manure and dissolved phosphorus loss in surface runoff
 477 (Vadas et al. 2007; Vadas et al. 2011). SurPhos does not simulate crop growth, P uptake, soil
 478 erosion, runoff generation or PP (particulate phosphorus) loss in runoff. Although this model
 479 does not simulate P loss in tile drainage, we reviewed its P simulations here as it is most recently
 480 developed. SurPhos P routines contain four manure P pools and three soil P pools. Water
 481 extractable pools are the fraction of P which can be leached by rain, while stable forms
 482 (accounting for 50%-70% of total manure P) cannot. Only inorganic P pools are simulated
 483 (organic P pools are not) in the soil pool, as shown in Fig. 2.

Figure 2. Phosphorus routines in SurPhos model (adapted from Vadas et al., 2007). WEP, water-extractable phosphorus.

Manure P pools

When manure is applied to the soil surface, manure dry matter starts to decompose. Manure dry matter decomposition is calculated by:

$$DM_{dec} = DM * AWDCR \quad (48)$$

$$AWDCR = 0.003TFA^{1/2} \quad (49)$$

$$TFA = \frac{2 \cdot 32^2 \cdot T^2 - T^4}{32^4} \quad (50)$$

where DM_{dec} and DM are the mass of daily decomposition and the mass of current amount of dry matter, respectively [M]; $AWDCR$ is the manure dry matter decomposition rate [-]; TFA is the temperature factor [-], which is between 0.0 and 1.0; T is the average daily air temperature [°].

Meanwhile, different forms of P in manure dry matter are partitioned into four pools (Fig. 2). Mineralization occurs in Non- WEP_O (stable organic P), Non- WEP_I (stable inorganic P) and WEP_O (water-extractable organic P) pools. Mineralization in Non- WEP_O is calculated by:

$$DMS_{mine} = DMS * DCOM \quad (51)$$

$$DCOM = 0.01 * \min(TFA, MOIST) \quad (52)$$

$$MOIST = \begin{cases} MOIST_0, & \text{if } 1mm < PREP \leq 4mm \\ MOIST_0 + (0.27 - 0.3 * MOIST_0), & \text{if } PREP > 4mm \\ MOIST_0 - \left(0.075 - 0.05 * \frac{M_{man}}{M_{mani}}\right), & \text{if } PREP < 1mm \end{cases} \quad (53)$$

where DMS_{mine} and DMS are the daily mineralization amount and the current amount of stable forms of manure dry matter, respectively [M]; $DCOM$ is the mineralization rate of the stable forms of dry matter [-]; $MOIST$ and $MOIST_0$ are the current manure moisture content and the manure water content of the previous day respectively [-]; $PREP$ is the precipitation of the day [L]; M_{man} and M_{mani} are the current mass and the applied mass of manure [M]. Mineralization from Non- WEP_I and WEP_O also computed using Eqs. (51) to (53) by replacing the parameter “0.01” in Eq. (50) with 0.0025 and 0.1, respectively.

Manure P assimilation by soil is calculated as the “product of dry-matter assimilation and manure P concentrations” (Vadas et al. 2011):

$$PASIM = MANASIM * C_{P_{man}} \quad (54)$$

$$MANASIM = 30.0 * \exp(2.5 * MOIST) * TFA * MANCOV$$

(55)

where $PASIM$ and $MANASIM$ are the amount of manure P assimilation and amount of manure assimilation by soil, respectively [M]; $MANCOV$ is the manure cover area [L^2].

Soil P pools

Soil P pools are based on the EPIC inorganic P routines. P transfer between labile inorganic and active inorganic pools is based on Eq. (40), while $K_{lab \rightarrow act}$ is replaced with a dynamic $K_{lab \rightarrow act}$ from the method reported by Vadas et al. (2006), and temperature and moisture factors are neglected. P transfer between active inorganic and stable inorganic pools is based on Eq. (41), while $K_{act \rightarrow st}$ is neglected.

3.2.3 Other Models

ADAPT, GLEAMS, ICECREAM

The P component in ADAPT and ICECREAM (Tattari et al. 2001) is adapted from GLEAMS. P dynamics in GLEAMS are adapted from EPIC with some modifications. P pools are similar to those shown in Fig. 1, while organic P fertilizer (animal waste) is assumed to flow into $P_{stable(o)}$ and P_{lab} pools, instead of P_{fresh} and P_{lab} pools in EPIC. It is assumed that 75% of mineralized P flows to $P_{stable(o)}$ and 25% flows to the P_{lab} pool. The processes calculated in GLEAMS are based on Eqs. (23) to (47), while the parameters are modified. For instance, for the PSP calculation, three equations (Eqs. (36), (38) and (39)) instead of four are used. Details in phosphorus simulations in GLEAMS (and ANIMO, DAYCENT) are presented in Lewis and McGechan (2002).

AnnAGNPS and SWAT

The P component in AnnAGNPS is adapted directly from EPIC. The P component in SWAT is adapted from EPIC as well. Modifications are made in the pools by adding one active organic soil P pool. Organic fertilizer P is assumed to flow into this pool only.

HYDRUS

Three options, including Freundlich, Langmuir and linear adsorption isotherms, are available for simulating chemical adsorption in HYDRUS. Two first-order reaction equations are

used for the simulation in degradation. One is the modified first-order decay reactions with modification of the Arrhenius equation (Šimůnek and Suarez 1993); the other reaction is independent of other solutes. For plant chemical uptake, passive root uptake is based on the Feddes equation and P in soil solution, and active root uptake is based on the Michaelis-Menten equation.

MACRO

A two-site model is used for simulating chemical adsorption in MACRO. The Freundlich isotherm with an empirical parameter is applied for computing chemical adsorption. Degradation is calculated using a first-order kinetic equation, with soil moisture and temperature factors modified using the Arrhenius equation (Boesten and Van der Linden, 1991). Plant chemical uptake is regarded as a source or sink term in the solute transport equation.

SWAP

The Freundlich equation is used for computing chemical adsorption, and the degradation is computed using the first-order decomposition rate. Plant chemical uptake is also treated as a sink term in the solute transport equation.

3.2.4 Recent Update in Soil P Simulation

As reported by Vadas et al. (2013), the EPIC phosphorus routines used in most models have not been updated in over 25 years and “now lag behind the demand for reliable predictions.” Vadas et al. (2006) updated the adsorption factor constant $K_{lab \rightarrow act}$ ($0.1 d^{-1}$) in Eq. (40) and the rate factor (0.1) in reverse flow using dynamic rate factors to cope with the underestimation of desorption flow:

$$K_{lab \rightarrow act} = 0.918 \exp(-4.603PSP) * DAY^{\{-0.238 \ln[0.918 \exp(-4.603PSP)] - 1.126\}} \quad (56)$$

$$RF_{act \rightarrow lab} = (-1.08PSP + 0.79)DAY^{-0.29} \quad (57)$$

where *DAY* is the “cumulative number of days since the labile P pool increased and created an imbalance with the active P pool” (Vadas et al. 2006).

Vadas and White (2010) reported that significantly underestimated total P in soil by SWAT was attributed to three possible reasons related to dissolved P and *PSP*. Therefore, *PSP* calculation has been modified based on the equation reported by Sharpley et al. (1984). The new *PSP* calculation is for highly weathered soils:

$$PSP = -0.053 \ln C_{cl} + 0.001C_{P_{lab}} - 0.029C_{C_{org}} + 0.42 \quad (58)$$

where $C_{C_{org}}$ is organic carbon content [%].

Nelson and Parsons (2006) applied the Langmuir equation to predict P adsorption of the GLEAMS model. This modification improved the prediction in P percolation (leaching) greatly, while failed to predict the P concentration variation for less than one year. This modification might also improve the simulation in P loss through tile drainage, where more future research should be conducted. Research on simulating the fate and transport of P in manure and animal waste pools was also conducted. Specifically, SurPhos, which is described above, was compared to SWAT in predicting manure phosphorus loss by Sen et al. (2012) who suggested that the “SWAT P model should be replaced by the SurPhos model”.

3.3 Phosphorus Transport to Tile Drains Simulation

Models such as SWAT and AnnAGNPS (Gollamudi et al., 2007; Que et al., 2015) are equipped with both tile drainage and P routines and cannot necessarily simulate phosphorus loss to tile drains. In this section, we review how P is simulated in tile drainage for these models.

The partitioning approach, in which total phosphorus (TP) was divided into particulate P (PP) and dissolved P (DP), is used in simulating P transport. Initially developed for pesticide transport (Knisel 1980), it was adapted to simulate P (Lung et al. 1976; Broberg and Persson

1988; Heckrath et al. 1995; Grant et al. 1996; Stamm et al. 1998; Simard et al. 2000; Uusitalo et al. 2001; Delgado et al. 2006; Vadas et al. 2008).

ADAPT

P loss in tile drains in ADAPT is calculated by:

$$drnmass_p = clpw(j) * accum_{drn} / 10.0 \quad (59)$$

$$clpw(j) = \frac{plab(j) * 10.0}{cpkd(j) * bd(j) * dlay(j) + osw(j)} \quad (60)$$

where $drnmass_p$ is the mass of P in drain water [M]; $clpw(j)$ is the concentration of labile P in water in layer j [ML^{-3}]; $accum_{drn}$ is the cumulative drain water [L^3]; $plab(j)$ is the amount of labile P in soil layer j [ML^{-2}]; $cpkd(j)$ is the partitioning coefficient of soil layer j [L^3M^{-1}]; $bd(j)$ is the bulk density of soil layer j [ML^{-3}]; $dlay(j)$ is the depth of soil layer j [L]; $osw(j)$ is the amount of soil water in layer j [L]. PP transport to tile drains is not calculated in ADAPT.

ANIMO

Linearized solute transport equations (under the conservation and transport law) are used to simulate DP loss to drainage. PP loss to drainage is not simulated in ANIMO. It only simulates the process of static P absorbing onto soil particles, without representing P absorbed by colloids, which is reported as an important pathway for P loss through preferential flow (McGechan and Hooda 2010).

APEX

The dissolved P in tile drainage is a linear function of labile P in top soil, tile drain flow volume, and a linear adsorption isotherm (Gassman et al. 2010):

$$P_{tile} = 0.01 * P_{lab} * \frac{Q_{tile}}{KD} \quad (61)$$

where P_{tile} is the P loss in tile drainage flow [ML^{-2}]; P_{lab} is the concentration of labile P in soil layer 1 [MM^{-1}]; Q_{tile} is the tile drain water flow volume [L]; KD is the partition coefficient,

which equals P concentration in sediment divided by P concentration in soil water [L^3M^{-1}]. In APEX, KD value is set to 100 (Williams et al. 2008). The PP loss to tile drainage is not simulated (Francesconi et al. 2013).

HYDRUS

DP and PP transport can be simulated using solute and virus/ colloid/ bacteria transport equations in HYDRUS. Solute loss could be calculated using the advection-dispersion solute transport equations. General forms of nonlinear non-equilibrium reactions between solid and liquid phases (equilibrium between liquid and gaseous phases) are used for simulating P transport. Virus, colloid, and bacteria facilitated transport of chemicals in subsurface flow could be simulated using the attachment-detachment model (two kinetic sites model). Calculations are based on the virus, colloid and bacteria transport (modified from the advection-dispersion equation) and solute sorption to the solids. Filtration theory is adopted from Logan et al. (1995).

ICECREAM

Although there were no tile drainage components based on water table in ICECREAM, tile drainage is simulated using water drained from the macropore and soil matrix (Larsson et al. 2007). Macropores are regarded as the dominant path for dissolved reactive P (DRP) loss in tile drains “due to the large adsorption in soil matrix” (Larsson et al. 2007). DRP loss to macropores is simulated using:

$$C_{DRP_{ma}} = \frac{P_{L_d}}{R + (x_d(\theta_1 + \gamma_1 k_{dw}))} \quad (62)$$

where $C_{DRP_{ma}}$ is the concentration of dissolved reactive phosphorus in macropores [ML^{-3}]; P_{L_d} is the amount of labile P at shallow surface depth x_d [ML^{-2}]; R is the daily net precipitation [L]; x_d is the depth of shallow surface soil [L], which is set to 1 mm; θ_1 is the water content of the topsoil layer [%]; γ_1 is the dry bulk density of topsoil [ML^{-3}]; k_{dw} is the sorption distribution

coefficient [LM^{-1}]. The DRP transport in the soil matrix is calculated by the convective mass transfer.

For PP loss in tile drains, macropore is regarded as the only pathway. The transport of soil suspended particles (SP) to tile drains is calculated as the product of SP concentration and the water flow to tile drains. However, SP entering macropores is reduced by the filter process in the pathway of entering tile drains, so the SP reaching tile drains can be calculated as follows:

$$M_d = q_{ma} * C_{SP_{ma}} * e^{(-fz_d)} \quad (63)$$

$$C_{SP_{ma}} = \frac{D}{R + x_d \theta_1} \quad (64)$$

where M_d is the flux of SP entering the depth of tile drains [$ML^{-2}T^{-1}$]; q_{ma} is the water flow in macropores [LT^{-1}], as calculated in Eq. (21); $C_{SP_{ma}}$ is the concentration of SP entering macropores [ML^{-3}]; f is the filter coefficient [L^{-1}]; z_d is the depth to the tile drains [L]; D is the amount of detachment of particles [$ML^{-2}T^{-1}$].

The Universal Soil Loss Equation (USLE) was used for predicting surface soil erosion in ICECREAM. However, particle generation and detachment for particulate P loss to tile drains are computed using the method introduced by Jarvis et al. (1999) rather than USLE :

$$D = k_d * EI * M_s * CROP \quad (65)$$

where k_d is the soil detachability coefficient [$[M(ML^2T^{-2})^{-1}L^{-1}]$; EI is the erosivity factor [$(ML^2T^{-2})LL^{-2}T^{-1}$], which was adapted for the Finnish climate (Posch and Rekolainen, 1993); M_s is the readily dispersible particles amount [MM^{-1}]; $CROP$ is the empirical crop management factor (Laflen et al. 1985).

The PP transport in tile drain water flow is calculated as a product of all P pools and a fraction factor (Knisel et al. 1993):

$$M_{PP} = \frac{M_d}{\gamma_1 x_d} (P_{lab} + P_{act} + P_{st} + P_{fresh} + P_{stable(o)} + P_{man}) \quad (66)$$

where M_{PP} is the PP loss to tile drainage [$ML^{-2}T^{-1}$] and P_{lab} , P_{act} , P_{st} , P_{fresh} , $P_{stable(o)}$ and P_{man} are the amount of phosphorus in labile inorganic, active inorganic, stable inorganic, fresh organic, stable organic and manure pools, respectively [ML^{-2}].

MACRO

Simulations in DP and PP transport are represented by solute and colloid transport equations, respectively, in MACRO. The advection-dispersion equation with source and sink terms (for mass transfer between two domains) is used for solute transport in subsurface water flow. The MACRO model includes a component for simulating colloid-facilitated transport of chemicals. Filtration theory is adapted based on Jarvis et al. (1999).

PLEASE

DP and TP losses to tile drainage are calculated in PLEASE. P losses from a field at depth z is described as (Schoumans et al. 2013):

$$P_{loss} = \psi \int_0^z C(z) * J(z) dz \quad (67)$$

where P_{loss} is the annual loss of total P [$ML^{-2}T^{-1}$]; ψ is a conversion factor for unit [-]; z is water table depth from soil surface [L]; C is the TP concentration [ML^{-3}]; J is the annual lateral water outflow [LT^{-1}].

The DP concentration at depth z is calculated based on the Langmuir coefficient and the adsorbed P concentration in soil (Van der Zee, 1988), as shown in Eq. (68), and TP is calculated based on an empirical exponential equation as shown in Eq. (69):

$$C_{MRP}(z) = \frac{Q(z)}{K(Q_m - Q(z))} \quad (68)$$

$$C_{TP}(z) = 1.1C_{MRP}(z) + 0.1 \exp[-C_{MRP}(z)] \quad (69)$$

where C_{MRP} and $C_{TP}(z)$ are the DP and TP concentrations in water, respectively [ML^{-3}]; Q and Q_m are the absorbed P and the maximum capacity of soil to absorb P, respectively [NM^{-1}]; K is the Langmuir adsorption constant [M^3N^{-1}].

Depth of annual lateral water outflow ($J(z)$) is calculated based on the lateral water flow flux and the water table depth z :

$$J(z) = \int_{z_L}^z \left(\frac{q_{dr}(z)}{z_L - z} \right) * D(z) dz \tag{70}$$

where z_L is the lower boundary depth below the soil profile surface [L]; q_{dr} is the horizontal flux [LT^{-1}], which is calculated in Eq. (9); D is the duration of water table staying at depth z per year [TT^{-1}]. Eq. (67) is used jointly with Eqs. (68) and (70) for simulating DP loss to tile drains, while Eq. (67) is coupled with Eqs. (69) and (70) for simulating TP loss to tile drains.

SWAP

The SWAP model uses convection-diffusion and advection-dispersion equations to compute solute transport in soil. This general solute transport equation can be used to simulate DP transport, while the transport of PP cannot be simulated in this model.

4. Comparison of methods and models

Hooghoudt's equation is commonly used in USDA models (Ronald and Theurer, 2005). It should be noted that these methods have their limitations. Hooghoudt equation is restricted for its availability to homogeneous soils (Eq. (1)), or two-layered soils with drains at the interface (Eq. (2)) (Wu and Chieng, 1991). Furthermore, it is reported to be not applicable under the situation where the hydraulic conductivity of the soil above the drains is much larger, or when there is more than one soil layer below the drains (van Beers, 1976). Under these situations, the Ernst equation is recommended (Wu, 1988). However, the Ernst equation is applicable for layered soils, but could underestimate the drain spacing or water table height if the hydraulic

conductivity of the soil above the drains is much higher than that below the drains. Meanwhile, the Kirkham equation (Eq. (3) to (5)) are complicated in form and difficult for practical use (Wu and Chieng, 1991), while Eq. (6) is usually used to simulate the situation when the water table is at or above the soil surface in models like DRAINMOD. Therefore, comparing the comprehensiveness in tile drainage simulations, models like DRAINMOD and SWAP which adopted multiple methods and considers a greater number of possible situations, could provide more accurate results.

According to Simunek et al. (2003), the Richard equation based macropore flow simulation considers both gravitational flow and capillary-driven flow. The kinematic wave equation of the dual-porosity model (used in HYDRUS) in simulating macropore flow reduces the required parameters such as water retention properties, but it only describes vertical gravity flow and ignored capillary flow. A similar limitation exists in the kinematic wave equation of the dual-permeability model (used in MACRO). Because macropores are assumed to be cylindrical, the Poiseuille's law (used in RZWQM2) would be less accurate in simulating macropore flow when the natural situation (shape, form and continuity of macropores) is different from the assumption (Simunek et al. 2003).

Used in most agricultural models (such as EPIC, ADAPT, GLEAMS, ICECREAM, SWAT), the EPIC P module generally functions well under the situation where manure is well mixed with the soil, while it performs unsatisfactorily where manures were surface broadcast and unincorporated (Vadas et al. 2007). The SurPhos model takes this problem into account, but does not simulate soil organic P pools and P transfer processes. To date, no research has been undertaken to incorporate those two aspects into one model. In addition, the method of using adsorption, decomposition and plant-uptake of general chemicals to represent soil P dynamics

(used in HYDRUS, MACRO and SWAP) result in less accurate prediction results compared with models adopted with complicated soil P dynamics. The same limitations will occur when simulating P transport with water flow using general solute and colloid module, rather than DRP and PP transport modules. Comparison of those models which are capable of simulating P losses through subsurface tile drainage is shown in Table 1. In models with P module, a few of them could simulate P transport in subsurface water flow (ADAPT, ANIMO, APEX and ICECREAM), and only two of them (ANIMO, ICECREAM) could simulate both DP and PP transport through subsurface flow.

Table 1 Comparison of models modules in addressing P loss through subsurface tile drainage.

Models	Subsurface hydrology		Soil P dynamics	P transport	
	Tile drainage	Macropore flow		DP transport	PP transport
ADAPT	√	√	√	√	×
ANIMO	×	×	√	√	√
APEX/EPIC	√	×	√	√	×
HYDRUS	√	√	×	×	×
MACRO	√	√	×	×	×
ICECREAM	√	√	√	√	√
PLEASE	√	×	×	√	×
SWAP	√	√	×	×	×

“√” means the model comprises the part of simulation, while “×” means the model cannot simulate the process.

5. Conclusions

Hooghoudt’s equation, the Kirkham equation and the Ernst equation are generally used for simulating steady state tile drain hydrology, but the capacity and accuracy of a model could be enhanced when adopting more than one equation as this could account for a variety of different situations. Dual-porosity and dual-permeability models are two fundamental methods for simulating macropore and soil matrix flow, and the Richard equation could be more accurate in simulating soil water flux than other methods such as storage-routing concept. For soil

phosphorus dynamics, the model developed by Jones et al. (1984) in EPIC is currently the most popular method for agricultural water quality models. Simulations in P sorption simulation and rate factors of P flow between inorganic pools have been recently updated, while surface-applied and unincorporated manure was not adequately handled by this method. SurPhos is a new model which employs new methods to simulate manure P pools. To predict P transport to tile drainage, DP (dissolved phosphorus) and PP (particulate phosphorus) are separated. Models including ADAPT, ANIMO, APEX, ICECREAM and PLEASE use the product of P concentration in tile flow water multiplied by mass of tile drainage water to calculate the total mass of P transport to tile drains, while models including HYDRUS, MACRO and SWAP adopt convection-diffusion and advection-dispersion equations for solute transport, combined with colloid for simulating P transport in tile drainage.

There is no known study that simulates P loss to tile drainage using ADAPT and APEX. For predicting P loss to subsurface tile flow, APEX lacks components for PP transport in subsurface drainage, and water flow and P transport in macropore flow (see table 1). ADAPT lacks PP transport in subsurface water flow simulation, and ANIMO needs to be linked to another separate model for hydrologic simulation. HYDRUS, MACRO and SWAP do not have a subroutine in soil P dynamics. PLEASE does not include a macropore flow routine and Soil P dynamics. Although tile drainage was computed using drained macropore and soil matrix flows rather than water table depth, in ICECREAM, macropore flow, soil phosphorus dynamics, as well as the transport of both DP and PP are simulated. Therefore, currently ICECREAM seems the most comprehensive model in predicting phosphorus loss to subsurface tile flow among all the models that are currently available.

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