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Development and evaluation of a phosphorus (P) module in RZWQM2 for phosphorus management in agricultural fields

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ABSTRACT

A few management tools can simultaneously describe dissolved and particulate P losses from agricultural fields. In this study a phosphorus (P) management tool was developed based on most recent scientific findings to meet this need, and it was subsequently incorporated into Root Zone Water Quality Model 2 (RZWQM2) to take advantage of its featured hydrologic and agricultural management subroutines. The RZWQM2-P model was evaluated against data collected in a tile-drained corn-soybean rotated field fertilized with inorganic P at South Woodslee, Ontario. The results indicate that overall the model satisfactorily simulated dissolved reactive P and particulate P losses through surface runoff and tile drainage with Nash-Sutcliffe model efficiency coefficient > 0.65, percent bias within 25% and index of agreement > 0.75. RZWQM2-P is a promising tool for P management, particularly for subsurface-drained fields. Further testing is needed to assess its performance under different fertilization (manure), soil, climate, and cropping conditions.

1. Introduction

Agriculture phosphorus (P) demand accounts for 80%–90% of global phosphorus consumption. The supply of P is heavily dependent on mined rock phosphate, a non-renewable resource becoming increasingly scarce and expensive day by day. In plants, phosphorus plays a role in cellular energy transfer, respiration, and photosynthesis; and is a structural component of the nucleic acids of genes and chromosomes, as well as many coenzymes, phosphoproteins and phospholipids (Grant et al., 2001). While proper crop growth and the maintenance of high yields are critical to agricultural production, crop P use efficiency in the year of application is rather low (15–30%; Syers et al., 2008). The build-up of legacy P in soils under long-term application has increasingly caused P losses from soil to surface waters. Such P losses from agricultural fields via water and sediment have become a serious environmental concern, degrading the quality of water in fresh water bodies (*e.g.*, lakes and rivers), as well as brackish sea waters (*e.g.* sea coast rivers outlets), by causing a rapid increase in algal populations leading to eutrophication (Guildford and Hecky, 2000). Such algae infested water is resulting in adverse ecological conditions for aquatic flora and fauna. It is now an established fact that excessive P loading of fresh water bodies and coastal sea areas can be confidently attributed to an over application of fertilizer in upstream agricultural fields. It is estimated that 80% of the P pollution reaching Lake Champlain's Missisquoi Bay originated in upstream agricultural lands (Hegman et al., 1999). In Quebec alone, some 156 lakes were already deemed polluted by P (MSSS, 2007).

As removal of excess P from water by chemical (Surampalli et al., 1995) or biological (Oehmen et al., 2007) means is complex, expensive and time consuming, remediation of eutrophication in rivers and lakes is difficult. One practical option to mitigate this problem is to arrest P loss right at the source by adopting proper agricultural management practices. To control P loss from an agricultural field one must understand the P dynamics of an agricultural field. Kleinman et al. (2015) indicated that computer modelling drawing on measured P data was a currently priority in achieving this goal. Of available agricultural P management models, ICECREAM (Tattari et al., 2001) seems to be the best at simulating P losses through tile drains (Radcliffe et al., 2015). However, in the absence of a water table-based tile drainage component, ICECREAM uses matrix and macropore flow flux at a certain soil depth to mimic tile drainage (Qi and Qi, 2016; Radcliffe et al., 2015). ICECREAM adopts simple storage routing concepts to simulate matrix

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Abbreviations List:

P	Phosphorus
P^{frsh}_{org}	Fresh organic P
P^{stbl}_{org}	Stable organic P
P^{stbl}_{inorg}	Stable inorganic P
P^{act}_{inorg}	Active inorganic P
P_{lab}	Labile P pool
$^{man}P^{H_2Oex}_{inorg}$	Manure water extractable inorganic P
$^{man}P^{H_2Oex}_{org}$	Manure water extractable organic P
$^{man}P^{stbl}_{inorg}$	Manure stable inorganic P
$^{man}P^{stbl}_{org}$	Manure stable organic P
$^{fert}P_{av}$	Available fertilizer P
$^{fert}P_{res}$	Residual fertilizer P
P_{dr}	Dissolved reactive P
P_{part}	Particulate P
P_{udr}	Dissolved unreactive P
^{fert}P	Fertilizer P
^{man}P	Manure P
P_{tot}	Soil total P
P_{sum}	Sum of P_{dr}, P_{part}
PBIAS	Percent bias
NSE	Nash-Sutcliffe model efficiency
IOA	Index of agreement
GH	Grain harvested
OB	Observed
SIM	Simulated
ET	Evapotranspiration
ΔS	Soil water change
RZWQM2	Root Zone Water Quality Model version 2
RZWQM2-P	Root Zone Water Quality Model version 2-Phosphorus
P_b	Air entry pressure
λ	Pore size index
k_{sat}	Saturated hydraulic conductivity
k_{lat}	Lateral hydraulic conductivity
ρ	Soil bulk density
OM	Soil organic matter content
θ_{fc}	Volumetric soil moisture content at field capacity
φ	Soil porosity
θ_{wp}	Volumetric soil moisture content at permanent wilting point
pH	Soil pH

flow within the soil profile. This can be improved by adopting the soil-matric-potential-based Richards equation (Richards, 1931) to simulate matrix flow and Hooghoudt's equation (Bouwer and Van Schilfgaarde, 1963) to simulate tile drainage. With no separate P pool to simulate manure and fertilizer P dynamics, ICECREAM assumes that manure or fertilizer P are mixed with the soil upon application.

Modelling P in an agricultural field involves modelling of hydrological processes on and below the ground surface and the effects of agricultural management practices. A P model needs to simulate both surface hydrological processes (*e.g.*, soil evaporation, plant transpiration, runoff, and soil erosion), and subsurface hydrological processes (*e.g.*, infiltration, matrix flow, preferential flow or macropore flow, flow to tile drainage, fluctuation of water tables, root water and nutrient uptake, and soil moisture redistribution). Agricultural management practices such as surface irrigation and sub-irrigation, drainage, fertilization, tillage and residue management, and crop rotation influence the fate and transport of P. The success of a P model greatly depends on how effectively and efficiently the model captures these hydrological processes and how these processes are parameterized within the model. RZWQM2 (Ahuja et al., 2000), a widely tested field-scale process-based model, is an ideal option as a base of a P model, because it is equipped with subroutines to simulate all the hydrological processes and agricultural management practices mentioned above. It has been extensively evaluated at locations across the United States (Fang et al., 2014; Gillette et al., 2018; Hanson et al., 1999; Ma et al., 2004, 2007a, 2007b; Malone et al., 2014; Qi et al., 2011, 2013; Thorp et al., 2008; Wang et al., 2015) and in Canada (Ahmed et al., 2007a, 2007b; Al-Abed et al., 1997; Madani et al., 2002; Jiang et al., 2018). Nonetheless, current P models lack the capacity to adequately simulate P losses, particularly those occurring through tile drainage (Radcliffe et al., 2015). In this study an attempt was made to develop a model based on most recent scientific finding regarding the fate and transport of P from an agricultural field available in the literature, and to test this new P management tool against measured hydrologic and P data in a tile-drained cropland.

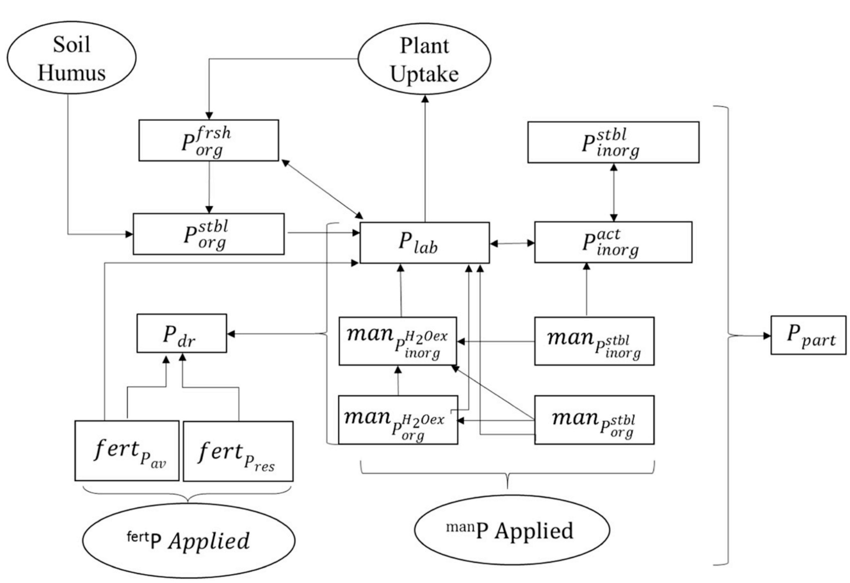

Fig. 1. RZWQM2-P Model's P pools.

2. Materials and methods

2.1. P model

The P model (Fig. 1) is designed with five different soil P pools: three inorganic, namely labile P (P_{lab}) active inorganic P (P^{act}_{inorg}) and stable inorganic P (P^{stbl}_{inorg}); and two organic pools namely fresh organic P pool (P^{frsh}_{org}) and stable organic P pool (P^{stbl}_{org}) respectively following the nomenclature of Jones et al. (1984). Besides these soil P pools, as an advanced feature the model also has four surface manure P pools and two surface fertilizer P pools to simulate P dynamics arising from the application of fertilizer and manure (Vadas, 2014). The manure P pools (${}^{man}P$) are inorganic water extractable P (${}^{man}P^{H_2Oex}_{inorg}$), inorganic stable P (${}^{man}P^{stbl}_{inorg}$), organic water extractable P (${}^{man}P^{H_2Oex}_{org}$), and organic stable P (${}^{man}P^{stbl}_{inorg}$). The fertilizer P pools (${}^{fert}P$) were available fertilizer P (${}^{fert}P_{av}$) and residual fertilizer P (${}^{fert}P_{res}$).

P^{frsh}_{org} , fresh organic P; P^{stbl}_{org}, stable organic P; P^{stbl}_{inorg}, stable inorganic P; P^{act}_{inorg}, active inorganic P; P_{lab}, labile P pool; ${}^{man}P^{H_2Oex}_{inorg}$, manure water extractable inorganic P; ${}^{man}P^{H_2Oex}_{inorg}$, manure water extractable organic P; ${}^{man}P^{stbl}_{inorg}$, manure stable inorganic P; ${}^{man}P^{stbl}_{org}$, manure stable organic P; ${}^{fert}P_{av}$, available fertilizer P; ${}^{fert}P_{res}$, residual fertilizer P; P_{dr},dissolved reactive P; P_{part}, particulate P; ${}^{fert}P$, fertilizer P; ${}^{man}P$, manure P.

Among these P pools, the P_{lab} pool is considered to be in dissolved form and the most dynamic P pool. In addition, it is the only P pool from which plants can uptake P. Plant root density is the highest near the soil surface so plant P uptake in the upper portion of the soil profile is more than that in deeper layers. This depth distribution of plant P uptake is controlled by plant P uptake distribution parameter. The governing equations of plant P uptake were adopted from Neitsch et al. (2011). There is constant absorption and desorption happens among these three inorganic P pools to maintain an equilibrium. The P_{lab} pool is in rapid equilibrium with the P^{act}_{inorg} pool, which is in slow equilibrium with the P^{stbl}_{inorg} pool. The rapid adsorption and desorption of inorganic P in the soil between P_{lab} and P^{act}_{inorg} is simulated based on Jones et al. (1984), with advanced dynamic absorption and desorption as prescribed by Vadas et al. (2006). This modification enables the model to simulate P movement among these pools by using a dynamically changing rate factor rather than a constant rate factor. The slow adsorption and desorption of inorganic P in the soil between P^{act}_{inorg} and P^{stbl}_{inorg} is simulated based on Jones et al. (1984). After decomposition, P from plant residues and soil humus are added to the P^{frsh}_{org} pool and the P^{stbl}_{org} pool, respectively. Mineralization happens from P^{frsh}_{org} pool and mineralized P is added to the P_{lab} and the P^{stbl}_{org} pools. A slow mineralization also follows in the P^{stbl}_{org} pool and mineralized P is added to the P_{lab} pool. Immobilization happens in the P_{lab} pool and immobilized P is added to the P^{frsh}_{org} pool. When fertilizer and/or manure is applied in the field the fertilizer and/or manure P is subsequently added to the ${}^{fert}P$ and ${}^{man}P$ pools based on application depth, type and properties of fertilizer and/or manure applied (Vadas, 2014). These independent ${}^{man}P$ and ${}^{fert}P$ pools enable the model to simulate more precisely the P dynamics arising from the application of fertilizer and manure in an agricultural field. Then the leaching and decomposition takes place from these pools. Decomposed and leached P are added to the soil P pools. The ability of the P model to simulate P_{dr} through tile flow is improved by adopting the recommendations of Francesconi et al. (2016) whereas the P_{part} loss through tile drainage is simulated by considering colloidal particle transport through macropore flow (Jarvis et al., 1999; Larsson et al., 2007). In the model, the first soil layer is set to a 0.01 m depth as the model assumes that particle bound P originates from the first 0.01 m depth of the soil profile. All the P pools contribute to P_{part} loss whereas the P_{lab} pool, ${}^{man}P^{H_2Oex}_{org}$ and ${}^{man}P^{H_2Oex}_{inorg}$ pools and all the ${}^{fert}P$ pools contribute to P_{dr} loss. To simulate P_{dr} and P_{part} loss through tile drainage the linear groundwater reservoir based approach, as suggested by Steenhuis et al. (1997), was used. In this approach P_{dr} is generated through matrix flow and macropore flow, while P_{part} is only

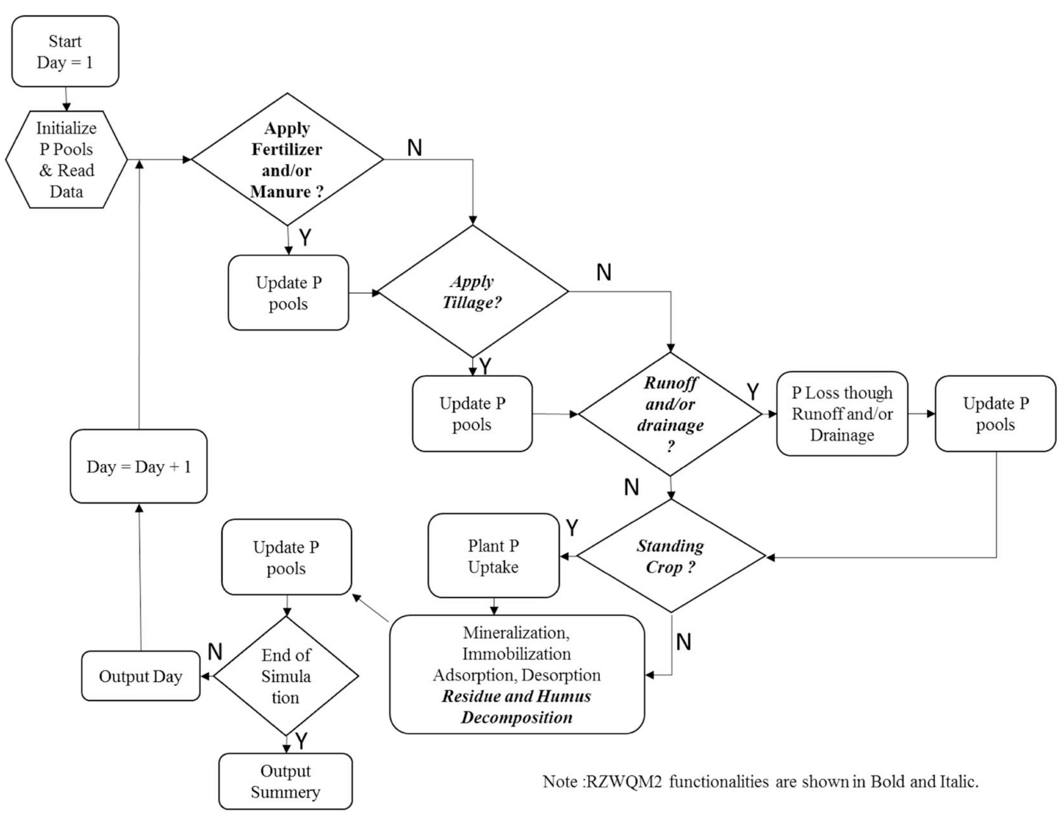

Fig. 2. RZWQM2-P model's working algorithms and its dependencies on RZWQM2.

Table 1
Crop and management practices at the Site.

Year	Date	Management practices
2008	08-Jun	Inorganic fertilizer
	18-Jun	Maize planting
	5-Nov	Maize harvest
2009	5-Mar	Chisel plow
	22-May	Soybean planting
	20-Oct	Soybean harvest
	1-Nov	Chisel plow
2010	17-Jun	Inorganic fertilizer
	26-Jun	Maize planting
	8-Nov	Maize harvest
	1-Dec	Chisel plow
2011	15-Jun	Soybean planting
	13-Dec	Soybean harvest
	20-Dec	Chisel plow
2012	20-May	Chisel plow
	22-May	Inorganic fertilizer
	25-May	Maize planting
	05-Nov	Maize harvest
	20-Nov	Chisel plow

generated through macropore flow and is first to contribute to a groundwater reservoir. Subsequently a daily mass balance is calculated, then P_{dr} and P_{part} is lost along with the tile drainage water from this groundwater reservoir. All the equations used in the model are provided in the attached supplementary documents.

2.2. RZWQM2 overview

Developed by the USDA-ARS, the RZWQM2 model (Ahuja et al., 2000) is a field scale, one-dimensional model which integrates physical, biological, chemical and hydrological processes and simulates crop growth, hydrologic cycle, fate and transport of nutrients and pesticides under different agronomic management practices and climate patterns. Within the RZWQM model soil water retention is described using the Brooks-Corey equation (Brooks and Corey, 1964). The Green-Ampt approach (Green and Ampt, 1911) is used to compute the infiltration. The model employs the Richards equation (Richards, 1931) to simulate soil water redistribution following infiltration in the soil profile. Tile drainage flow is calculated by Hooghoudt's steady state equation (Bouwer and Van Schilfgaarde, 1963) and the macropore flow is governed by the Poiseuille's law. The Simultaneous Heat and Water (SHAW) model (Flerchinger, 1987) is linked to RZWQM to simulate ice in soil, snow accumulation, snow melting, as well as soil freeze-thaw cycles. The crop growth can be simulated either by embedded DSSAT 4.0 crop models (Jones et al., 2003) or a generic crop production model (Hanson, 2000) whereas evapotranspiration is estimated using the double layer Shuttleworth-Wallace model (Shuttleworth and Wallace, 1985).

2.3. P model and RZWQM2 integration

The P model described above was first developed then incorporated into the RZWQM2 model. While the P model simulates P dynamics, the RZWQM2 governs the physical, biological, chemical and hydrological processes that influence the P simulation. The developed P model combined with RZWQM2 performs as a single tool, the P model being dependent on RZWQM2 for the simulation of crop growth, runoff, drainage, soil moisture and its flux, soil temperature, sediment yield, macropore flow, residue and soil humus decomposition and agriculture management practices. All these components are simulated by RZWQM2 within its original functionalities and then the P model uses model outputs to simulate P dynamics and P loss through surface runoff and tile drainage from an agricultural field. The P model's working algorithms along with its dependencies on RZWQM2 are presented in Fig. 2.

2.4. Field experiment

To evaluate the P model, observed runoff and drainage water flow, as well as P_{dr} and P_{part} mass in both runoff and tile drainage water were collected from an Agriculture Agri-Food Canada (AAFC) experimental site, the Hon. Eugene F. Whelan Research Farm, near South Woodslee, ON (42.21N, 82.74W) from June 2008 to December 2012. The site was comprised of 16 plots (67.1 m × 15.2 m) receiving different fertilizer types and drainage system treatments. Among these, plot numbers 5 and 9, selected for the present study, received inorganic NPK fertilizer applications and were subject to standard tile drainage (depth: 0.85 m, spacing: 3.8 m) (Zhang et al., 2013). The crop was rotated between maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] in alternating years. In 2008, 2010 and 2012 maize was planted at a density of 79,800 seeds ha^{-1}, while in 2009 and 2011 soybean was planted at a at a density of 486,700 seeds ha^{-1}. The inorganic fertilizers (114.5 kg P_2O_5 ha^{-1} (roughly 50 kg P ha^{-1}), 200 kg N ha^{-1} from NH_4NO_3, and 100 kg K ha^{-1} from KCl) were surface-applied before planting in the maize planting years. Chisel plow tillage was done each year after harvest or in the following year before planting. The dates of cropping and other crop management practices are presented in Table 1. The P content in corn and soybean grain were measured after harvest (between 20 October and 13 December) each year. Grain samples were dried at 55 °C, ground and passed through a 1-mm sieve and digested using a H_2SO_4-H_2O_2 procedure. Phosphorus concentrations in all of the filtrates and digests were determined using a QuikChem Flow Injection Auto-Analyzer (Lachat Instruments), employing the ammonium molybdate ascorbic acid reduction method (Murphy and Riley, 1962).

The soil type was clay loam and the measured soil properties for plots 5 & 9 were averaged (Table 2) and used as the soil input data for

Table 2
Model input data for soil physical and chemical properties, average of Plots 5 & 9.

Soil Layer depth (m)	ρ (Mg m^{-3})	Clay (%)	Sand (%)	OM (%)	θ_{fc} ($m^3 m^{-3}$)	Φ (m^3 m^{-3})	θ_{wp} (m^3 m^{-3})	pH	P_{lab} (g kg^{-1})	P_{org}^{frsh}(g kg^{-1})	P_{org}^{stbl} (g kg^{-1})	P_{tot}(g kg^{-1})
0.00–0.01	1.326	34.2	29.0	3.7	0.368	0.54	0.175	7.5	0.0230	0.100	0.2303	0.9045
0.01–0.10	1.326	34.2	29.0	3.7	0.368	0.54	0.175	7.5	0.0210	0.085	0.2174	0.9000
0.10–0.25	1.391	34.2	29.0	3.7	0.361	0.54	0.175	7.5	0.0210	0.085	0.2174	0.9000
0.25–0.45	1.391	40.7	25.7	2.0	0.351	0.50	0.175	7.5	0.0110	0.055	0.1148	0.6500
0.45–0.80	1.326	40.4	27.0	0.7	0.356	0.48	0.175	7.5	0.0055	0.028	0.0580	0.5000
0.80–1.20	1.326	39.3	24.6	0.5	0.356	0.48	0.174	7.5	0.0055	0.028	0.0580	0.4000

ρ, soil bulk density; Clay, soil clay content; Sand, Soil Sand Content; OM, Soil organic matter content; θ_{fc}, Volumetric soil moisture content at field capacity; φ, Soil Porosity; θ_{wp}, Volumetric soil moisture content at permanent wilting point; pH, soil pH; P_{lab}, Soil labile P, P_{org}^{frsh}, Soil fresh organic P, P_{org}^{stbl}, soil stable organic P; P_{tot}, Soil total P.

the model. The soil profile was delineated into six layers. The soil properties such as soil texture, field capacity (θ_{fc}), permanent wilting point (θ_{wp}), and saturated hydraulic conductivity (k_{sat}) were measured before the start of the experiment. Soil bulk density (ρ) and porosity (φ) were measured in 2010 where as k_{sat} was measured in the year 2008. Prior to the onset of the experiment in 2008, soil P was measured using the Olsen P method (Olsen et al., 1954). Volumetric soil moistures (θ) for the soil layer ranging in depth between 0 and 0.08 m were measured twice a week using a portable probe, while soil temperature (T_{soil}) at depth of 0.05 m was measured hourly from June to October for the years 2010, 2011, and 2012, using sensors. Hourly T_{soil} were averaged to obtain daily mean T_{soil}.

The required weather data (air temperature, precipitation, relative humidity, solar radiation and wind speed) to run the model were collected for the period of 1st Jan. 2008 to 31st Dec. 2012 from the automated meteorological weather station located at the Whelan farm, located less than 500 m from the experimental site. During the winter (1st Oct. – 30th April of 2009, 2010 and 2011), rain gauge inaccuracies for snowfall precipitation, led to data being obtained from Environment Canada's Harrow Weather Station (Station ID 6133362, 42.03^{0}N, 82.90 ^{0}W) located 16.6 km from the study field. In each experimental plot there was a catch basin similar to a sewage sink at their downstream end to collect the surface runoff. Surface runoff and tile drainage from the experimental plot were directed to a central instrumentation building via underground PVC pipes. In the instrumentation building, the flow rate was measured automatically using electronic flowmeters and recorded in a multi-channel data logger. Surface runoff and tile drainage water samples were collected automatically using auto-samplers (CALPSO, 2000S, Buhler Gmbh & Company). Surface and tile water samples were collected continuously (year-round), proportionally to flow volume, samples being taken for every 1000 L of flow during the growing season and for every 3000 L of flow during the non-growing seasons. After the collection the samples were analyzed in the laboratory for P_{dr} and total dissolved P (P_{td}) using an acidified ammonium persulfate [$(NH4)_2S_2O_2$] oxidation procedure (USEPA, 1983). Unfiltered water samples were analyzed for total P (P_{tot}) using the sulfuric acid-hydrogen peroxide digestion method (USEPA, 1983). The P_{part} was computed by the difference between P_{tot} and P_{td}.

2.5. Model calibration and validation

The RZWQM2 with this newly developed P model was run using the four and a half years (June 2008–Dec 2012) of data collected from the experimental site. There were some limitations on flow event separation during the flow data collection, so to ensure the precision of P loss estimation, the collected data was aggregated into 19 different periods (Table 3) and out of these the first twelve periods (01 June 2008 to 21 Dec 2010, two and half years) were used for calibrating the model, while the last seven periods (22 Dec 2010 to 09 Dec 2012, two years) were used for validating the model. During the calibration process, parameters related to soil moisture, soil temperature, surface runoff and tile drainage were initially calibrated, as these processes control the P loss from an agricultural field. Then the parameters related to P loss through surface runoff and tile drainage were calibrated. The calibration was undertaken manually while changing the calibration parameters within the range as obtained from prior studies and available literature, by a trial and error method following the protocol given by Ma et al. (2011) and iterated several times until a good match with the observed data was obtained. Three model evaluation statistics: Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and Index of agreement (IOA) (Moriasi et al., 2007, 2015) served to evaluate the performance of the model in simulating hydrology, soil moisture, soil temperature and P loss through surface runoff and tile drainage. Model performance was catergorised as very good, good, statisfactory and unsatifactory based on the criterion of those model evaluation statistics as recommended by Moriasi et al. (2007, 2015). The model is regarded to perform satisfactorily when NSE > 0.50 and good when NSE > 0.65. Model performance is deemed to be satisfactory when |PBIAS| is between 15% and 25% for water flow and is between 40% and 70% for P and it is deemed to be good when |PBIAS| is between 10% and 15% for water flow and is between 25% and 40% for P (Moriasi et al., 2007). Model performance is regarded as acceptable when IOA > 0.75 (Moriasi et al., 2015).

In RZWQM2 model soil moisture content is parametrized with air entry pressure (P_b) and pore size distribution index (λ). Initially the values P_b and λ were set to the default values of these parameters according to soil texture as given by Ma et al. (2011) then subsequently these values were adjusted to match the observed values. The value of λ was found to be more sensitive than that of P_b in soil water simulations: an increase in λ resulted in reduction in soil water content whereas an increase of P_b led to increase of soil water content. Once the soil moisture content was calibrated and a good fit with the observed value was found, then calibration of runoff and tile drainage followed. To calibrate runoff parameters such as saturated hydraulic conductivity (k_{sat}), surface crust hydraulic conductivity (k_{crust}) and albedo were adjusted. In RZWQM2 runoff is simulated when the rainfall rate exceeds the infiltration rate (Ma et al., 2012), so the top layer k_{sat} and k_{crust} values were adjusted to obtain a good fit with the observed runoff. Furthermore, the albedo was adjusted for simulation of evapotranspiration, which in turn affected surface runoff. For tile drainage calibration, k_{sat}, P_b and lateral hydraulic conductivity (k_{lat}) were adjusted. Increasing k_{sat} resulted in an increase in tile drainage, whereas increasing P_b resulted in decrease in tile drainage. Moreover, k_{lat} had very prominent influence in tile drainage simulation and it was adjusted to $2 \times k_{sat}$. In addition, P_b was slightly adjusted to better match tile drainage without hampering the previous calibration for soil moisture.

Table 3
Periods of water flow and P measurement data for calibration and validation.

Period no.	Period	Period no.	Period
	Calibration		Validation
1	1/Jun/2008–16/Jun/2008	13	22/Dec/2010–23/Mar/2011
2	17/Jun/2008–17/Jul/2008	14	24/Mar/2011–22/Jun/2011
3	18/Jul/2008–22/Oct/2008	15	23/Jun/2011–7/Sep/2011
4	23/Oct/2008–11Feb/2009	16	8/Sep/2011–7/Sep/2011
5	12/Feb/2009–27/Mar/2009	17	10/Nov/2011–22/Dec/2011
6	28/Mar/2009–26/May/2009	18	23/Dec/2011–12/May/2012
7	27/May/2009–16/Jul/2009	19	13/May/2012–09/Dec/2012
8	17/Jul/2009–23/Oct/2009		
9	24/Oct/2009–20/Apr/2010		
10	21/Apr/2010–11/Jun/2010		
11	12/Jun/2010–5/Aug/2010		
12	6/Aug/2010–21/Dec/2010		

The loss of P_{dr} through surface runoff was calibrated by adjusting the soil P extraction coefficient while calibration of P_{dr} loss through tile drainage depended on macroporosity, P_b and λ of the deeper soil layers. In the model, macropore flow is initiated when the top soil layer becomes saturated and P_{dr} carried away through macropore flow depends on the volume of macropore flow. Therefore, to control the P_{dr} loading to the groundwater reservoir the macroporosity value was adjusted. Finally, the P_b and λ of the deeper soil layers were slightly adjusted to control the P_{dr} loading to groundwater reservoir by matrix flow without altering the earlier results for tile drainage and soil moisture simulations. The P_{part} loss through surface runoff was calibrated by adjusting USLE soil loss coefficients (soil erodibility factor, cover and management factor, support practice factor) and Manning's N. These parameters control the sediment yield thereby controlling the P_{part} loss through surface runoff. Increasing soil erodibility increased the sediment yield, while increasing the Manning's N reduced it. Accordingly, to obtain a good match of P_{part} loss through surface runoff these two parameters were carefully adjusted along with the cover and management factor and support practice factor. The P_{part} loss through tile drainage is controlled by parameters like soil replenishment rate coefficient, soil detachability coefficient, and soil filtration coefficient. These parameters govern the colloidal particle loss to subsurface flow hence limit the P_{part} loss through tile drainage. The high soil filtration coefficient leads to less colloidal particle loss whereas the increase of soil detachability coefficient and soil replenishment rate coefficient leads to more colloidal particle loss. So, these parameters were carefully balanced over the calibration period to get a reasonable simulation with respect to P_{part} loss through tile drainage. Finally, to adjust the plant P uptake from the P_{lab} pool, the P uptake distribution parameter for each crop was adjusted. Calibrated soil hydraulic parameters and their values are presented in Table 4 and all other calibrated parameters are presented in Table 5.

3. Results

3.1. Soil moisture and soil temperature

The time series of simulated and observed soil temperature (T_{soil}) at 0.05 m depth and soil moisture (θ) between 0 and 0.08 m depths are presented in Fig. 3. The simulation statistics are summarized in Table 6. Model simulation of θ and T_{soil} ware satisfactory with NSE of 0.64, PBIAS of 0.30% and IOA of 0.89 and with NSE of 0.59, PBIAS of 13.08% and IOA of 0.89 respectively.

3.2. Hydrology

Simulated *vs.* observed surface runoff and tile drainage are depicted in Fig. 4a and b, respectively, and the accuracy statistics presented in Table 7. For the calibration period, simulation in surface runoff was very good and in tile flow was satisfactory based on the model evaluation criteria. During the calibration period, surface runoff was estimated with PBAIS of −12.47% and with NSE of 0.85 while drainage was estimated with PBAIS of 12.46% and the NSE of 0.60. The simulated average annual runoff and tile drainage were 129.57 mm and 375.43 mm (Table 8), respectively. These values were very close to the observed annual mean values. Overall, the model's performance was very good in simulating runoff (NSE > 0.75, PBIAS within ± 10% and IOA > 0.75) and good in simulating tile drainage (NSE > 0.65, PBIAS within ± 10% and IOA > 0.75). The simulated *vs.* observed water balance components are summarized in Table 8. During the four and a half years of simulation, simulated average annual ET (449.73 mm) was 47.45% of the observed annual precipitation (947.71 mm). This was similar to annual ET that was 45% of measured precipitation in the same region (Tan et al., 2002). Between the simulated average annual surface runoff and tile drainage, most (74.34%) of the water moved out of the field through the tile drainage system.

3.3. Dissolved Reactive Phosphorus (P_{dr}) loss

Simulated and observed P_{dr} loss through runoff and drainage for the calibration and validation periods are presented in Fig. 5aand b and the simulation statistics are summarized in Table 7. The simulation statistics show that the P model's simulation of P_{dr} loss through surface runoff during the calibration period was in very good agreement with the observed data (NSE > 0.75, PBIAS within ± 25% and IOA > 0.75) whereas for tile drainage it was good (NSE > 0.65, PBIAS within ± 25% and IOA > 0.75). During the validation period, simulated P_{dr} loss through runoff was satisfactory and simulated P_{dr} loss through tile drainage was good (Table 7). Overall the P model could simulate the P_{dr} loss through both surface runoff and tile drainage in very good agreement with the observed data (NSE > 0.75, PBIAS within ± 25% and IOA > 0.75) and it was found that most of the P_{dr} (75.74% of total simulated P_{dr} loss) was lost through the tile drainage system during the simulation period (Table 9).

3.4. Particulate Phosphorus (P_{part}) loss

Simulated P_{part} loss through runoff and tile drainage agreed well with the observed data. Simulation results and statistics are presented in Fig. 5cand d and Table 7, respectively. Analysis of observed data revealed that 68.07% of the net P loss (P_{dr} + P_{part}) was lost in the form of P_{part} and tile drainage contributed (63.47% of the total P_{part} loss) more P_{part} loss than the surface runoff (Table 9). The model captured this well and simulated 68.04% of the net P loss in the form of P_{part} and simulated tile drainage P_{part} loss was 63.36% of the total P_{part} loss. Overall, the model's ability in simulating P_{part} loss through surface runoff and subsurface drainage was very good and good respectively. (Fig. 5c and d and Table 7).

3.5. Sum of P_{dr} and P_{part} ($\mathbf{P_{sum}}$) loss

The simulation results of the sum of P_{dr} and P_{part} loss (P_{sum}) through surface runoff and tile drainage) and its statistics are presented in Fig. 5e, f & g and Table 7 respectively. Observed data revealed that tile drainage dominated the P_{sum} loss composing 67.04% of total annual P_{sum} loss while the simulated P_{sum} loss through tile drainage was 67.32% of the total annual P_{sum} loss. The simulation of P_{sum} loss through surface runoff was very good (NSE > 0.75, PBIAS within ± 25% and IOA > 0.75) while it was good during the validation period (NSE > 0.65, PBIAS within ± 25% and IOA > 0.75). The simulation of P_{sum} loss tile drainage during the calibration and validation period was good and very good respectively. Overall, the P_{sum} loss simulations through both surface runoff and tile drainage were very good (Table 7). The simulation of total P_{sum} loss from the field, such as sum of P_{dr} in both runoff and drainage and P_{part} in both runoff and drainage for the entire simulation period was also very good (Fig. 5g and Table 7).

Table 4
Calibrated soil hydraulic parameters.

Soil Layer depth (m)	Soil hydraulic parameters			
	P_b (mm)	λ	k_{sat}(mm d^{-1})	k_{lat}(mm d^{-1})
0.00–0.01	−200.60	0.16	0.60	1.20
0.01–0.10	−290.31	0.15	0.84	1.68
0.10–0.25	−146.45	0.20	1.32	2.64
0.25–0.45	−121.78	0.19	1.32	2.64
0.45–0.80	−251.15	0.15	0.41	0.84
0.80–1.20	−351.72	0.14	0.41	0.84

P_b, Air entry pressure; λ, Pore size index; k_{sat}, Saturated hydraulic conductivity; k_{lat}, Lateral Hydraulic Conductivity.

Table 5
Calibrated parameters and their values.

Parameters	Calibrated Values	Default (Range)
Surface k_{crust} (mm h^{-1})	0.50	0.01 (0.01–20)
Albedo		
Dry soil	0.50	0.20 (0.01–0.9)
Wet Soil	0.65	0.30 (0.02–0.9)
Crop at Maturity	0.55	0.70 (0.01–0.9)
Fresh Residue	0.85	0.22 (0.01–0.9)
Macroporosity (m^3 m^{-3})	0.03	–
P extraction coefficient (−)	0.35	1.00 (0.10–1.00)
USLE Coefficients		
Soil erodibility (ton ac^{-1})	0.25	0.02 (0.005–0.80)
Cover and management factor	0.85	0.50 (0.01–1.00)
Support practice factor	0.85	0.50 (0.01–1.00)
Manning's N	0.02	0.01 (0.01–0.40)
Soil filtration coefficient (m^{-1})	0.002	0.00 (0.00–1.00)
Soil detachability coefficient (gm J^{-1} mm^{-1})	0.90	0.40 (0.00–1.00)
Soil replenishment rate coefficient (gm m^{-2} day^{-1})	0.10	0.20 (0.00–1.00)
P uptake distribution parameter		
Corn	10.00	1.00–15.00
Soybean	10.00	1.00–15.00

4. Discussion

The field experiment showed that subsurface drainage was the major pathway of P loss from the field, comprising 67.04% of total annual average P_{sum} loss. The annual average P_{sum} loss through tile drainage was dominated by P_{part}, which accounted for 63.47% of total annual average P_{sum} loss through tile drainage (Table 9). In contrast, a study conducted by Qi et al. (2017) with the ICECREAM model at the same site reported that ICECREAM failed to simulate the P_{part} loss through tile drainage and that soil moisture content was also not simulated satisfactorily. They concluded that it could be improved by adopting the soil matric potential-based Richards equation to simulate soil matrix flow. Radcliffe et al. (2015) noted that, although ICECREAM was one of the best P simulation models available to date, it lacked macropore and tile drainage components. The newly developed P model combined with RZWQM2 addressed all the concerns that were previously highlighted. Qi et al. (2017) reported that ICECREAM simulated P_{dr} loss through tile drainage within 18% of observed values and with NSE of 0.66 while it failed to simulate P_{part} loss through tile drainage (NSE < 0.0 and PBIAS 44%). While comparing the simulation results of this study (Table 7) with those of Qi et al. (2017), we found that the P model's capability was particularly improved in its simulation of P loss through the tile drainage system. The model's simulation of P loss particularly through tile drainage system improved after the proper calibration of soil moisture. The adoption of Richards equation led to better soil moisture and soil matrix flux simulations (Table 6). This had a direct impact on P dynamics, as soil moisture governs the decomposition and mineralization rate and P flows among the various pools and soil matrix flux determines the amount of P loading to the tile drainage system. The use of Poiseuille's law resulted in better macropore flow simulations, which is one of the major pathways of P_{dr} and P_{part} loading to the tiles. Finally, the use of Hooghoudt's steady state equation further improved tile drainage simulations and P loss through tile drainage. Soil temperature also has an important role in simulation of P dynamics in agricultural fields. An acceptable soil temperature simulation (Table 6) led to good estimation of P flow rate among various P pools, decomposition and mineralization rates of residue and soil organic matter.

Analysis of the observed data for both growing seasons (periods 2–3, 7–8, 11–12, 15–17, 19) and non-growing seasons (periods 1, 4–6, 9–10, 13–14) revealed that 75.71% of total drainage volume and 60.14% of total runoff volume occurred in the non-growing seasons. Consequently, the P loss during non-growing seasons was dominant. During non-growing seasons, runoff carried away 56.24% of the total runoff bound P_{dr}, whereas 64.47% of total tile drainage-bound P_{dr} loss occurred during non-growing seasons. The same was observed for the P_{part} loss, with 64.97% of total runoff associated P_{part} and 74.34% of total drainage associated P_{part} being lost during the non-growing seasons. P_{sum} loss in the non-growing seasons during the whole simulation years comprised 68.19% of total P_{sum} loss through surface and subsurface water flow. The newly developed model satisfactorily simulated the fact that the major flow and P loss from the field occurred during non-growing seasons. For simulated discharge, 66.97% of total runoff and 67.91% of total drainage occurred in the non-growing seasons whereas simulated P_{sum} loss during non-growing seasons represented 65.76% of the total P_{sum} lost through surface and subsurface water flow. These simulated results also corresponded well to the observations of King et al. (2015), who found that the non-growing period "represents a significant proportion of annual discharge and P loss".

The developed RZWQM2-P model is easy to run with menu driven graphical user interface. Although the data required to run the model seems to be meticulous but it can be easily collected from many resources when in-situ measurement is not feasible. Weather data can be obtained from online resources for free or with nominal charges.

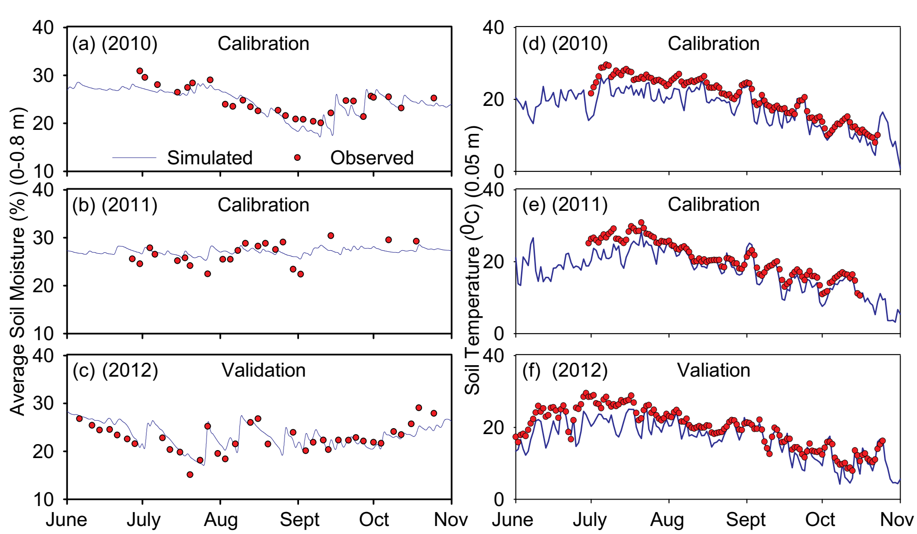

Fig. 3. Comparison between simulated and observed (a, b, c) soil moisture (%) (0–0.08 m), (d, e, f) soil temperature (^{0}C) (0.05 m).

Table 6
Statistics for model performance in Soil Moisture and Soil Temperature simulation.

Statistics	Soil Moisture			Soil Temperature		
	Calibration	Validation	All Period	Calibration	Validation	All Period
PBIAS	1.63%	−1.67%	0.30%	12.67%	13.72%	13.08%
NSE	0.57	0.56	0.64	0.63	0.52	0.59
IOA	0.88	0.86	0.89	0.91	0.88	0.89

PBIAS, Percent bias, NSE, Nash-Sutcliffe model efficiency; IOA, Index of agreement.

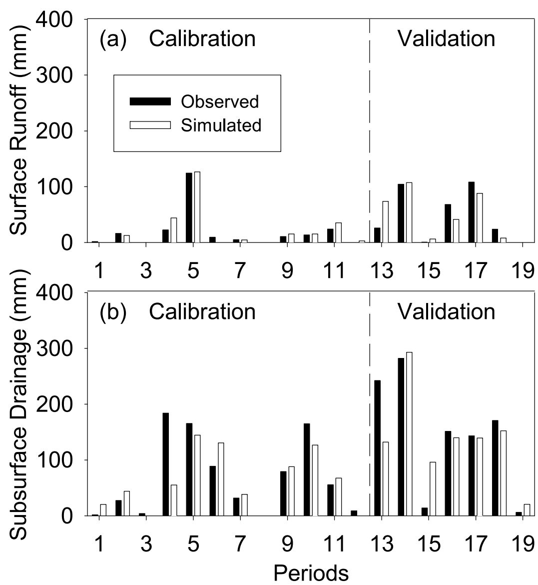

Fig. 4. Comparison between simulated and observed (a) surface runoff (b) subsurface drainage. Periods are the time periods as mentioned in Table 3.

Agricultural management data can be collected while interviewing the farmer or the farm manager of the site. It can also be made available from various factsheets as published time to time by various agricultural agencies. Soil data can be derived using basic county soil survey information along with pedotransfer functions (Schaap et al., 2001) or tables as provided by Ma et al. (2011) and Rawls et al. (1982). Initial soil P values can be estimated while running the model for certain amount of years prior to start of actual simulation year with typical agronomical management practices and cropping system of the site. RZWQM2-P has in built database of crop phenology parameters for most common crop cultivars. This database can be used to default the crop phenology parameters.

Computer simulation models inevitably have some limitations because they are built on assumptions and simplified version of the very complex real world phenomenon. In this context RZWQM2-P model is limited to one dimensional and assuming soil as a homogeneous medium. The model is not designed to simulate dissolved unreactive P (P_{udr}) loss. It also assumes that P_{part} originates from the first 0.01 m soil layer and only the macropore flow contribute to tile drainage bound P_{part} loss. Another shortcoming of RZWQM2-P is that it is a field scale model, which cannot be applied over large-scale watershed. Despite these limitations and assumptions, RZWQM2-P can be used in a wide range of scenarios to mitigate P pollution under various agricultural management practices along with different cropping systems that are commonly adopted in North America. Agricultural management practices include tile drainage, control drainage with or without sub-irrigation, various type of tillage application, surface, sub-surface and injected inorganic fertilizer/manure application. Manure type includes poultry, swine, beef cattle and dairy cattle under solid and liquid phases. RZWQM2-P can also be applied to identify the impact of winter manure application, which is a common practice in many areas of North America.

In this present study we presented the development of RZWQM2-P and its very first evaluation with a tile drained corn soybean rotated field under inorganic P fertilization over a period of four and half years. The evaluation resulted in satisfactory performance of the model over the both calibration and validation periods. Although RZWQM2-P seems to be a promising tool to manage agricultural P under the given management practices, to be certain about the efficacy of the model further tests are recommended at several other locations under different fertilization (i.e. manure), soil, climate, and crop conditions for a longer period with more observational data.

5. Conclusions

In this study, a model based P management tool was developed to simulate the fate and transport of P_{dr} and P_{part} from an agricultural field based on most recent scientific findings while overcoming the limitations of the ICECREAM model as highlighted by previous researchers (Qi et al., 2017; Radcliffe et al., 2015), and taking advantage of the process-based agro-hydrologic model RZWQM2. The new P model incorporated into RZWQM2 combined the proven strengths in simulating the impacts of agricultural management practices and hydrological processes in an agricultural field with the ability to simulate P dynamics. The P model was evaluated against four and a half years of data collected from a subsurface-drained corn-soybean rotated field with clay loam soil in southwestern Ontario, Canada. The simulation results showed that the newly developed model performed satisfactorily in simulating the P_{dr} and P_{part} losses through both surface runoff and subsurface drainage with all periods Nash-Sutcliffe model efficiency coefficient > 0.65, percent bias within 25% and index of agreement > 0.75. The P model's P loss simulating ability was improved particularly through tile drainage by adopting Richards equation for simulation of soil matrix flow, and Hooghoudt's equation for simulation of tile drainage flow. The use of Poiseuille's law may have resulted in better macropore flow simulations, which led to better simulations of P_{part} loading to the tile system. However, this needs further investigations. The simulation results were consistent with the observed trend that the non-growing season dominated the P loss over growing seasons, tile drainage contributed more towards these losses, and P_{part} was the major form of P loss. The newly developed P module integrated with RZWQM2 is a promising tool for P management, particularly for subsurface-drained fields. Further tests are needed to evaluate this model under different fertilization (manure), soil, climate, and crop conditions.

Software availability

1. **Name of the Software:** Root Zone Water Quality Model 2-Phosphorus (RZWQM2-P)
2. **Developer Details:** Debasis Sadhukhan and Zhiming Qi, Department of Bioresource Engineering, Macdonald Campus, McGill University, Sainte-Anne-de-Bellevue, QC, Canada, H9X 3V9. Email: debasis.sadhukhan@mail.mcgill.ca; zhiming.qi@mcgill.ca.
3. **Year First Available:** 2018

Table 7
Statistics for model performance in simulation of water, dissolved reactive phosphorus(P_{dr}), particulate phosphorus (P_{part}) and sum of P_{dr} & P_{part} (P_{sum}).

Water						
Statistics	Runoff			Drainage		
	Calibration	Validation	All periods	Calibration	Validation	All periods
PBIAS	−12.47%	1.71%	−4.08%	12.46%	2.95%	7.18%
NSE	0.85	0.71	0.81	0.60	0.72	0.73
IOA	0.96	0.92	0.95	0.86	0.91	0.92
Dissolved Reactive P (P_{dr})						
	P_{dr} in Runoff			P_{dr} in Drainage		
	Calibration	Validation	All periods	Calibration	Validation	All periods
PBIAS	10.63%	−2.80%	4.58%	−13.40%	6.17%	−1.19%
NSE	0.95	0.59	0.80	0.65	0.74	0.83
IOA	0.99	0.90	0.95	0.91	0.94	0.95
Particulate Phosphorus (P_{part})						
	P_{part} in Runoff			P_{part} in Drainage		
	Calibration	Validation	All periods	Calibration	Validation	All periods
PBIAS	13.79%	−10.24%	0.10%	−8.28%	5.55%	0.54%
NSE	0.76	0.72	0.76	0.58	0.69	0.73
IOA	0.93	0.91	0.93	0.86	0.86	0.90
Sum of P_{dr} and P_{part} (P_{sum})						
	P_{sum} in Runoff			P_{sum} in Drainage		
	Calibration	Validation	All periods	Calibration	Validation	All periods
PBIAS	12.87%	−8.34%	1.40%	−10.15%	5.76%	−0.07%
NSE	0.84	0.73	0.78	0.71	0.84	0.86
IOA	0.96	0.92	0.94	0.92	0.94	0.95
	P_{sum} in Runoff + Drainage					
	Calibration	Validation	All periods			
PBIAS	−1.38%	1.59%	0.41%			
NSE	0.86	0.82	0.86			
IOA	0.96	0.94	0.95			

PBIAS, Percent bias, NSE, Nash-Sutcliffe model efficiency; IOA, Index of agreement.

4. **Hardware and software required:** General PC with 4 GB RAM and 1 GB of free space. Winnows 7 or higher.
5. **Availability:** http://www.water-environment.lab.mcgill.ca/
6. **Cost:** Free
7. **Program Size:** 72.1 MB
8. **Program Language:** English

Acknowledgements

This research is sponsored by Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant (RGPIN 04784-14): Development of a model-based phosphorus management tool for manure applications in subsurface drained field. The authors also

Table 8
Water balance table for simulation period (mm).

Year	Rainfall	ET	Runoff		Drainage		ΔS	Lateral Flow	Deep Seepage
	OB		SIM	OB	SIM	OB			
06/01/08–05/26/09	1034.90	441.51	183.56	174.68	389.72	470.53	−4.56	0.00	8.69
05/26/09–06/11/10	721.20	417.68	35.56	29.72	251.64	275.73	−11.31	0.00	3.43
06/11/10–06/22/11	1171.50	422.96	219.26	154.82	499.38	588.51	−9.14	0.00	12.26
06/22/11–05/15/12	994.70	335.28	144.14	200.89	532.06	479.19	7.61	0.00	6.33
05/15/12-12/09/12	342.40	406.35	0.55	0.12	16.64	6.26	56.80	0.00	0.78
Total	4264.70	2023.80	583.07	560.23	1689.45	1820.22	39.40	0.00	31.49
Average (mm y-1)	947.71	449.73	129.57	124.50	375.43	404.49	8.76	0.00	7.00

OB, Observed; SIM, Simulated; ET, Evapotranspiration; ΔS, Soil water change.

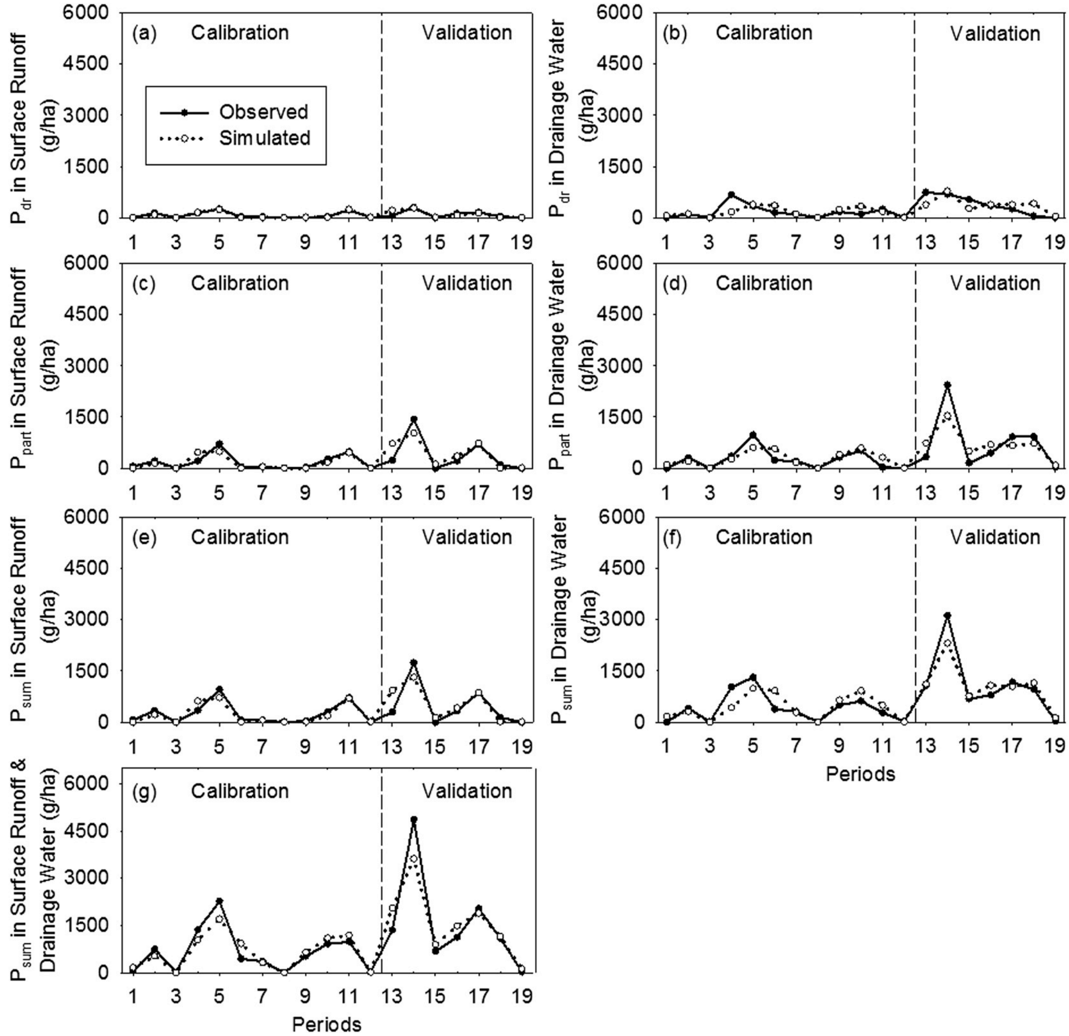

Fig. 5. Comparison between simulated vs. observed mass of (a) P_{dr} in surface runoff, (b) P_{dr} in drainage water (c) P_{part} in surface runoff, (d) P_{part} in drainage water, (e) P_{sum} in surface runoff, (f) P_{sum} in drainage water, (g) P_{sum} in surface runoff + drainage water. P_{dr}, Dissolved Reactive Phosphorus; P_{part}, Particulate Phosphorus; P_{sum}, Sum of P_{dr}, P_{part}; Periods are the time periods as mentioned in Table 3.

Table 9
P balance table for the simulation period (all values in kg/ha).

Year	Fertilizer	Residue & Humus P Release	GH		P_{dr}				P_{part}				ΔSP
					Runoff		Drainage		Runoff		Drainage		
			SIM	OB	SIM	OB	SIM	OB	SIM	OB	SIM	OB	
06/01/08–05/26/09	50.00	21.50	19.56	15.30	0.47	0.54	1.07	1.27	1.08	1.22	1.73	1.87	34.46
05/26/09–06/11/10	0.00	33.11	20.12	18.26	0.03	0.07	0.68	0.37	0.21	0.32	1.15	1.04	−10.24
06/11/10–06/22/11	50.00	33.68	18.12	16.77	0.75	0.59	1.33	1.68	2.20	2.15	2.59	2.80	11.09
06/22/11–05/15/12	0.00	18.08	18.48	21.23	0.22	0.33	1.44	1.18	1.19	1.01	2.58	2.43	−21.27
05/15/12-12/09/12	50.00	11.60	16.93	15.01	0.00	0.00	0.04	0.01	0.01	0.00	0.08	0.02	17.03
Total	150.00	117.97	93.20	86.57	1.46	1.53	4.56	4.51	4.70	4.70	8.12	8.17	31.07
Average	33.33	26.22	20.71	19.24	0.32	0.34	1.01	1.00	1.04	1.04	1.81	1.82	6.90

OB, Observed; SIM, Simulated; ΔSP, Soil P change; P_{dr}, Dissolved Reactive Phosphorus; P_{part}, Particulate Phosphorus; GH, Grain Harvested.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2018.12.007.

References

Ahmed, I., Rudra, R., McKague, K., Gharabaghi, B., Ogilvie, J., 2007a. Evaluation of the root zone water quality model (RZWQM) for southern Ontario: Part I. Sensitivity analysis, calibration, and validation. Water Qual. Res. J. Can. 42 (3), 202–218.

Ahmed, I., Rudra, R., McKague, K., Gharabaghi, B., Ogilvie, J., 2007b. Evaluation of the root zone water quality model (RZWQM) for southern Ontario: Part II. Simulating long-term effects of nitrogen management practices on crop yield and subsurface drainage water quality. Water Qual. Res. J. Can. 42 (3), 219–230.

Ahuja, L., Rojas, K., Hanson, J., Shaffer, M., Ma, L., 2000. Root Zone Water Quality Model. Water Resour. Publ., Highlands Ranch, CO.

Al-Abed, N., Ng, H.Y.F., Tan, C.S., Drury, C.F., Gaynor, J.D., Soultani, M., Welacky, T.W., 1997. Modelling nitrate in a tile-drained field using RZWQM. Environnement Canada, Institut national de recherche sur les eaux. Collection de l'INRE, Burlington, Ontario, pp. 97–187.

Bouwer, H., Van Schilfgaarde, J., 1963. Simplified method of predicting fall of water table in drained land. Trans. ASAE (Am. Soc. Agric. Eng.) 6 (4), 288–291.

Brooks, R.H., Corey, A.T., 1964. Hydraulic properties of porous media and their relation to drainage design. Trans. ASA. 7 (1), 26–0028.

Fang, Q.X., Ma, L., Halvorson, A.D., Malone, R.W., Ahuja, L.R., Del Grosso, S., Hatfield, J.L., 2014. Simulating Greenhouse Gas emission in irrigated corn field using RZWQM. Environ. Model. Software 72, 56–70.

Flerchinger, G.N., 1987. Simultaneous Heat and Water Model of a Snow-residue-soil System. PhD. Dissertation. Program in Engineering Science, Washington State University.

Francesconi, W., Williams, C., Smith, D., Williams, J., Jeong, J., 2016. Phosphorus modeling in tile drained agricultural systems using APEX. J. Fertil. Pestic. 7, 166.

Gillette, K.R., Malone, W., Kaspar, T.C., Ma, L., Parkin, T.B., Jaynes, D.B., Fang, Q.X., Hatfield, J.L., Feyereisen, G.W., Kersebaum, K.C., 2018. N loss to drain flow and N2O emissions from a corn-soybean rotation with winter rye. Sci. Total Environ. 618, 982–997.

Grant, C.A., Flaten, D.N., Tomasiewicz, D.J., Sheppard, S.C., 2001. The importance of early season phosphorus nutrition. Can. J. Plant Sci. 81 (2), 211–224.

Green, W.H., Ampt, G., 1911. Studies on soil phyics. J. Agric. Sci. 4 (1), 1–24.

Guildford, S.J., Hecky, R.E., 2000. Total nitrogen, total phosphorus, and nutrient limitation in lakes and oceans: is there a common relationship? Limnol. Oceanogr. 45 (6), 1213–1223.

Hanson, J., 2000. Generic crop production. In: Ahuja, L.R., Rojas, K.W., Hanson, J.D., Shaffer, M.J., Ma, L. (Eds.), Root Zone Water Quality Model. Water Resour. Publ. LLC, Highlands Ranch, Colorado.

Hanson, J.D., Rojas, K.W., Shaffer, M.J., 1999. Calibration and evaluation of the root zone water quality model. Agron. J. 91, 171–177.

Hegman, W., Wang, D., Borer, C., 1999. Estimation of Lake Champlain Basinwide Nonpoint Source Phosphorus Export. Lake Champlain Basin Program Technical Report No. 31.

Jarvis, N., Villholth, K., Ulen, B., 1999. Modelling particle mobilization and leaching in macroporous soil. Eur. J. Soil Sci. 50 (4), 621–632.

Jiang, Q., Qi, Z., Madramootoo, C., Singh, A., 2018. Simulating hydrologic cycle and crop production in a subsurface drained and sub-irrigated field in Southern Quebec using RZWQM2. Comput. Electron. Agric. 146, 31–42.

Jones, C., Cole, C., Sharpley, A., Williams, J., 1984. A simplified soil and plant phosphorus model: I. Documentation. Soil Sci. Soc. Am. J. 48 (4), 800–805.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3), 235–265.

King, K.W., Williams, M.R., Macrae, M.L., Fausey, N.R., Frankenberger, J., Smith, D.R., 2015. Phosphorus transport in agricultural subsur-face drainage: a review. J. Environ. Qual. 44, 467–485.

Kleinman, P.J.A., Smith, D.R., Bolster, C.H., Easton, Z.M., 2015. Phosphorus fate, management, and modeling in artificially drained systems. J. Environ. Qual. 44 (2), 460–466.

Larsson, M.H., Persson, K., Ulén, B., Lindsjö, A., Jarvis, N.J., 2007. A dual porosity model to quantify phosphorus losses from macroporous soils. Ecol. Model. 205 (1–2), 123–134.

Ma, L., Ahuja, L., Nolan, B., Malone, R., Trout, T., Qi, Z., 2012. Root zone water quality model(RZWQM 2): model use, calibration, and validation. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 55 (4), 1425–1446.

Ma, L., Ahuja, L.R., Saseendran, S.A., Malone, R.W., Green, T.R., Nolan, B.T., Hoogenboom, G., 2011. A Protocol for Parameterization and Calibration of RZWQM2 in Field Research. Methods of Introducing System Models into Agricultural Research. SSSA Book Series, Madison,WI, pp. 1–64.

Ma, L., Malone, R.W., Heilman, P., Jaynes, D.B., Ahuja, L.R., Saseendran, S.A., Ascough, J.C., 2007a. RZWQM simulated effects of crop rotation, tillage, and controlled drainage on crop yield and nitrate-N loss in drain flow. Geoderma 140 (3), 260–271.

Ma, L., Malone, R.W., Heilman, P., Karlen, D.L., Kanwar, R.S., Cambardella, C.A., Ahuja, L.R., 2007b. RZWQM simulation of long-term crop production, water and nitrogen balances in Northeast Iowa. Geoderma 140 (3), 247–259.

Ma, Q., Don Wauchope, R., Ma, L., Rojas, K.W., Malone, R.W., Ahuja, L.R., 2004. Test of the Root Zone Water Quality Model (RZWQM) for predicting runoff of atrazine, alachlor and fenamiphos species from conventional-tillage corn mesoplots. Pest Manag. Sci. 60 (3), 267–276.

Madani, A., Gordon, R., Akhand, N., Burney, J., Caldwell, K., 2002. Performance of RZWQM in atlantic Canada. In: Proceedings of the World Congress of Computers in Agriculture and Natural Resources. ASAE Publication No. 701P030, pp. 850–856.

Malone, R.W., Nolan, B.T., Ma, L., Kanwar, R.S., Peterson, C., Heilman, P., 2014. Tillage and application rate affects atrazine transport to subsurface drainage with macropore flow: evaluation of RZWQM using a long-term field study. Agric. Water Manag. 132, 10–22.

Ministère de la santé et des services sociaux du Québec (MSSS), G. d. Q, 2007. Liste régionale des avis de santé publique reliés aux lacs et rivières affectés par les algues bleu-vertes en 2007. Québec, QC.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 50 (3), 885–900.

Murphy, J., Riley, J.P., 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27, 31–36.

Moriasi, D.N., Gitau, W.M., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 58 (6), 1763.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute.

Oehmen, A., Lemos, P.C., Carvalho, G., Yuan, Z., Keller, J., Blackall, L.L., Reis, M.A., 2007. Advances in enhanced biological phosphorus removal: from micro to macro scale. Water Res. 41 (11), 2271–2300.

Olsen, S.R., Legg, J.O., Goring, C.A.I., Dean, L.A., 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. USDA Circular 939.

Qi, H., Qi, Z., 2016. Simulating phosphorus loss to subsurface tile drainage flow: a review. Environ. Rev. 25, 150–162.

Qi, H., Qi, Z., Zhang, T., Tan, C.S., Sadhukhan, D., 2017. Modeling phosphorus losses through surface runoff and subsurface drainage using ICECREAM. J. Environ. Qual. 47 (2), 203–211.

Qi, Z., Bartling, P.N., Jabro, J.D., Lenssen, A.W., Iversen, W.M., Ahuja, L.R., Evans, R.G., 2013. Simulating dryland water availability and spring wheat production in the northern Great Plains. Agron. J. 105 (1), 37–50.

Qi, Z., Helmers, M.J., Malone, R.W., Thorp, K.R., 2011. Simulating long-term impacts of winter rye cover crop on hydrologic cycling and nitrogen dynamics for a corn-soybean crop system. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 54 (5), 1575–1588.

Radcliffe, D.E., Reid, D.K., Blombäck, K., Bolster, C.H., Collick, A.S., Easton, Z.M., King, K., 2015. Applicability of models to predict phosphorus losses in drained fields: a review. J. Environ. Qual. 44 (2), 614–628.

Rawls, W.J., Brakensiek, D.L., Saxton, K.E., 1982. Estimation of soil water properties. Trans. ASAE (Am. Soc. Agric. Eng.) 25, 1316–1320.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. J. Appl. Phys. 1 (5), 318–333.

Schaap, M.G., Leij, F.J., van Genuchten, M.Th, 2001. ROSETTA: a computer programfor estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251, 163–176.

Shuttleworth, W.J., Wallace, J., 1985. Evaporation from sparse crops-an energy combination theory. Q. J. Roy. Meteorol. Soc. 111 (469), 839–855.

Steenhuis, T.S., Bodnar, M., Geohring, L.D., Aburime, S.-A., Wallach, R., 1997. A simple model for predicting solute concentration in agricultural tile lines shortly after application. Hydrol. Earth Syst. Sci. 1 (4), 823–833.

Surampalli, R.Y., Banerji, S.K., Pycha, C.J., Lopez, E.R., 1995. Phosphorus removal in ponds. Water Sci. Technol. 31 (12), 331–339.

Syers, J.K., Johnston, A.E., Curtin, D., 2008. Efficiency of Soil and Fertilizer Phosphorus Use. Reconciling Changing Concepts of Soil Phosphorus Behaviour with Agronomic Information. FAO Fertilizer and Plant Nutrition Bulletin No. 18. Rome, Italy.

Tattari, S., Bärlund, I., Rekolainen, S., Posch, M., Siimes, K., Tuhkanen, H.R., Yli–Halla, M., 2001. Modeling sediment yield and phosphorus transport in Finnish clayey soils. Trans. ASAE (Am. Soc. Agric. Eng.) 44 (2), 297–307.

Tan, C.S., Drury, C.F., Gaynor, J.D., Welacky, T.W., Reynolds, W.D., 2002. Effect of tillage and water table control on evapotranspiration, surface runoff, tile drainage and soil water content under maize on a clay loam soil. Agric.Water Manage. 54, 173–188.

Thorp, K.R., Jaynes, D.B., Malone, R.W., 2008. Simulating long-term performance of drainage water management in midwestern United States. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 51 (3), 961–976.

USEPA, 1983. Total Kjeldahl nitrogen method 351.1 (colorimetric, automated phenate). In: Methods for Chemical Analysis of Water and Wastes. EPA-600/4-79-020. off. Res. Dev., Environ. Monitoring and Support Laboratory, Cincinnati, OH.

Vadas, P., Krogstad, T., Sharpley, A., 2006. Modeling phosphorus transfer between labile and nonlabile soil pools. Soil Sci. Soc. Am. J. 70 (3), 736–743.

Vadas, P.A., 2014. Surface Phosphorus and Runoff Model, Theoretical Documentation Version 1.0. U.S. Dairy Forage Research Center, USDA, Madison, Wisconsin, USA.

Wang, Z., Qi, Z., Xue, L., Bukovsky, M., Helmers, M.J., 2015. Modeling the impacts of climate change on nitrogen losses and crop yield in a subsurface drained field. Climatic Change 129 (1), 323–335.

Zhang, T.Q., Tan, C.S., Welacky, T., Zheng, Z.M., 2013. Soil phosphorus losses in surface runoff and tile drainage as related to organic amendment addition and water management. In: The 7th International Phosphorus Workshop, Uppsala, Sweden. Programme and Book of Abstracts 160 Swedish Univ. Agric. Sci., Uppsala.