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# Modeling and Mitigating Phosphorus Losses from a Tile-Drained and Manured Field Using RZWQM2-P

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## Abstract

Prediction of P losses from manured agricultural fields through surface runoff and tile drainage is necessary to mitigate widespread eutrophication in water bodies. However, present water quality models are weak in predicting P losses, particularly in tile-drained and manure-applied cropland. We developed a field-scale P management model, the Root Zone Water Quality Model version 2–Phosphorus (RZWQM2-P), whose accuracy in simulating P losses from manure applied agricultural field is yet to be tested. The objectives of this study were (i) to assess the accuracy of this new model in simulating dissolved reactive phosphorus (DRP) and particulate phosphorus (PP) losses in surface runoff and tile drainage from a manure amended field, and (ii) to identify best management practices to mitigate manure P losses including water table control, manure application timing, and spreading methods by the use of model simulation. The model was evaluated against data collected from a liquid cattle manure applied field with maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation in Ontario, Canada. The results revealed that the RZWQM2-P model satisfactorily simulated DRP and PP losses through both surface runoff and tile drainage (Nash–Sutcliffe efficiency > 0.50, percentage bias within ±25%, and index of agreement > 0.75). Compared with conventional management practices, manure injection reduced the P losses by 18%, whereas controlled drainage and winter manure application increased P losses by 13 and 23%, respectively. The RZWQM2-P is a promising tool for P management in manured and subsurface drained agricultural field. The injection of manure rather than controlled drainage is an effective management practice to mitigate P losses from a subsurface-drained field.

## Core Ideas

- RZWQM2-P satisfactorily simulated P losses from the manure-applied field.
- A field experiment revealed that the nongrowing season dominated the P losses.
- Particulate P loss dominated the average annual P loss as per the field experiment.
- RZWQM-P adequately simulated seasonal P losses and dominant P loss type.
- Injected manure application was found effective to mitigate P losses.



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Nonpoint-source P pollution of surface water bodies originating from the upstream agricultural lands is becoming a serious environmental concern, degrading the water quality and causing rapid increase in algal population and eutrophication (Guildford and Hecky, 2000). The primary sources of P in an agricultural field are soil, plant materials, and applied fertilizer and manure (Hansen et al., 2002; Heathwaite and Dils, 2000; Withers et al., 2001). Among these, the greatest potential for accelerated P losses occurs with manure application (Duda and Finan, 1983; Eghball and Gilley, 1999; Kleinman and Sharpley, 2003; Moore et al., 2000). Almost all manure produced on Canadian farms is applied to agricultural land (Patni, 1991). In Ontario, animal husbandry generates approximately 16 million $m^3$ of liquid manure and 22 million metric tons of solid manure, which are mainly applied to large areas of farmland (OMAFRA, 2005). According to Statistics Canada data, the area of manure application was ~2.83 million ha (4% of total agricultural area) for all of Canada in 2016, whereas 0.75 million ha (15% of total agricultural area) in Ontario and 0.85 million ha (26% of total agricultural area) in Quebec were applied with manure during the same year. As a primary control of surface water eutrophication, P losses from manured soils have prompted a broad array of guidelines and regulations (USEPA, 1996; OMAFRA, 2002).

In the northern United States and eastern Canada, winter manure application is fairly common and has several advantages. For example, it nullifies the use of manure storage structures, allows more spreading time, and reduces soil compaction (Srinivasan et al., 2006), but at the same time, it is prone to more nutrient loss (Liu et al., 2017a, 2018; Vadas et al., 2017) than spring manure application. However, because of frozen soil, winter-applied manure normally could not be incorporated, and due to nutrient losses under frequent runoff from snowmelt and rain on snow events, governments have restricted winter manure application to prevent loss of manure constituents including P (Srinivasan et al., 2006). Because of the limited number of studies on quantifying nutrient losses from manure on winter

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**Abbreviations**: DRP, dissolved reactive phosphorus; IoA, index of agreement; ICECREAM, ICE-Chemicals Runoff Erosion From Agricultural Management Systems; NSE, Nash–Sutcliffe model efficiency; PBIAS, percentage bias; PP, particulate phosphorus; RZWQM2, Root Zone Water Quality Model version 2; RZWQM2-P, Root Zone Water Quality Model version 2–Phosphorus; USLE, Universal Soil Loss Equation.

application, these government restrictions on winter manure spreading are based more on commonly held perceptions rather than on research (Srinivasan et al., 2006). Therefore, a modeling approach can be used to quantify the effect of winter manure application on P losses.

Agricultural subsurface tile drainage is a commonly used management practice in many parts of the United States and Canada to improve the soil's natural drainage and subsequently to increase crop yield (Evans et al., 1995). Unfortunately, tile drainage can also increase mobile nutrient losses with subsurface flow (Ruark et al., 2012; Rudolph and Goss 1993; Tan et al., 1993, 1998, 2002b; Tan and Zhang, 2011; Zhang et al., 2015b), as it tends to increase total water yield from an agricultural field. This increased nutrient loading pollutes surface and groundwater resources. A modification of a subsurface drainage system, which uses a riser on tile outflows, known as controlled drainage, is now being used to prevent excessive drainage and subsequently nutrient losses. Research indicates that controlled drainage reduces tile drainage water volume (Tan et al., 2002b) and nitrate N loss over a conventional tile drainage system (Drury et al., 2009; Fogiel and Belcher 1991; Tan et al., 1998). For P losses, there were a few studies that investigated this, and they were contradictory. Valero et al. (2007) and Stämpfli and Madramootoo (2006) found that controlled drainage system was not effective to reduce P losses, whereas Tan and Zhang (2011) and Zhang et al. (2015b) found that controlled drainage reduced P losses from an agricultural field.

Nutrient losses are aggravated by conventional surface broadcast applications because the nutrients remain completely exposed to rain and runoff, whereas subsurface injection can be practiced to reduce nutrient losses from an agricultural field (Pote et al., 2006; Watts et al., 2011). However, modeling studies to substantiate this fact are limited.

Kleinman et al. (2015) indicated that computer modeling using measured P data was at the time one of the priorities in improving one's understanding of P dynamics in an agricultural field to mitigate freshwater eutrophication. However, commonly used models such as the Erosion/Productivity Impact Calculator (EPIC; Williams et al., 1983), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS; Leonard et al., 1987), Areal Non-point Source Watershed Environment Response Simulation (ANSWERS; Bouraoui and Dillaha, 1996), and ICE-Chemicals Runoff Erosion From Agricultural Management Systems (ICECREAM; Tattari et al., 2001) do not have dedicated surface manure P pools to simulate P dynamics due to manure application (Pierson et al., 2001; Sharpley et al., 2002). There is also a lack of models that can simulate P losses through tile drainage (Radcliffe et al., 2015), which is one of the major pathways of P loading from agricultural fields to freshwater bodies (Ruark et al., 2012; Tan and Zhang, 2011). Of the available agricultural P management models, ICECREAM seems to be the best at simulating P losses through tile drains (Radcliffe et al., 2015). However, ICECREAM does not have a water table-based tile drainage simulation component. It uses a simple storage routing concepts to simulate matrix flow and macropore flow (Qi and Qi, 2016; Tattari et al., 2001), and these fluxes at first contribute to a groundwater reservoir then from the groundwater reservoir tile flow are initiated when the storage capacity defined by a user-defined threshold value is exceeded (Larsson et al., 2007). This conceptual approach is reported to be less accurate (Larsson et al., 2007). This may be improved by adopting the soil matric potential based Richard's equation (Richards, 1931) to simulate matrix flow, Poiseuille's law-based approach to simulate macro pore flow, and Hooghoudt's equation (Bouwer and van Schilfgaarde, 1963) to simulate tile drainage.

The Root Zone Water Quality Model 2 (RZWQM2; Ahuja et al., 2000) is a field-scale, one-dimensional agricultural process control model that is widely applied in simulating the impacts of agricultural management practices on hydrology, water quality, crop growth, and greenhouse gas emission at locations across the United States (Ma et al., 2007a, 2007b; Qi et al., 2011, 2013) Canada (Ahmed et al., 2007; Jiang et al., 2018), and in China (Fang et al., 2010, 2013; Liu et al., 2017b), but it lacks a P subroutine. We developed a P module for the RZWQM2 model (RZWQM2-P; Sadhukhan et al., 2019) to simulate P dynamics, based on scientific findings regarding the fate and transport of P from tile drained agricultural field. The developed RZWQM2-P is capable of simulating dissolved reactive P (DRP) and particulate P (PP) loss through both tile drainage and surface runoff under inorganic P application (Sadhukhan et al., 2019), but its capability to simulate P losses under manure application is yet to be tested. Further, the impacts of agricultural management practices, such as controlled drainage, winter manure application, and manure injection, on P losses need to be quantified. Therefore, in this study, we calibrated and validated the newly developed RZWQM2-P model against measured hydrologic and P data in a tile drained field with liquid cattle manure application and maize (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation and subsequently applied the calibrated model to quantify the impacts of those agricultural management practices on P losses and to identify the most effective management practice among them to reduce P losses.

# Materials and Methods

## RZWQM2-P Model Overview

Developed by the USDA-ARS, the RZWQM2 model (Ahuja et al., 2000) is a field-scale, one-dimensional agricultural process control model with a daily time step. The model uses the Richards equation (Richards, 1931) to simulate soil water redistribution within the soil profile after infiltration, which is simulated by the Green–Ampt method (Green and Ampt, 1911). Surface runoff is generated when the rainfall rate exceeds the infiltration rate and sediment yield is computed using the Universal Soil Loss Equation (USLE) method (Wischmeier and Smith, 1978). 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 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). The P model within RZWQM2 model is designed with five different soil P pools: three inorganics (namely, labile P, active inorganic P, and stable inorganic P) and two organic pools (namely, fresh organic P pool and stable organic P pool), 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; Vadas et al., 2004, 2007, 2008). The manure P pools are inorganic water-extractable P, inorganic stable P, organic water-extractable P, and organic stable P. The fertilizer P pools were available fertilizer P and residual fertilizer P pools. Among these P pools, a plant can uptake P for its growth from the labile P pool only, and it is considered to be in dissolved form. The simulation of plant P uptake is based on Neitsch et al. (2011). The absorption and desorption of P among the inorganic soil P pools is simulated based on Jones et al. (1984), with advanced dynamic absorption and desorption rates as prescribed by Vadas et al. (2006). Mineralization and immobilization of P is simulated based on Jones et al. (1984), whereas the P decomposition rate from plant residue and soil humus is assumed to be the same as C decomposition, which is simulated based on Shaffer et al. (2000). Applied manure P is distributed within the surface manure P pools according to application depth, type, and properties of manure applied. For the liquid manure application, the model assumed that 60% of the applied manure P immediately infiltrates into the soil as soon as it is applied and added to the soil P pools of the topmost soil layer (labile P, active inorganic P) (Vadas et al., 2007). Leached and decomposed P from the manure P pools is added to the soil P pools. The RZWQM2-P model simulates tile drainage bound DRP and PP loss following Francesconi et al. (2016) and Jarvis et al. (1999), respectively. The model assumes that particle-bound P originates from the first soil layer of the soil profile, and PP through the soil profile is only transported through the macropore flow and contributes directly to the tile system, bypassing the soil matrix. In the model, DRP and PP loss through surface runoff is simulated as per Neitsch et al. (2011) and McElroy et al. (1976), respectively. Labile P, available fertilizer P, and two manure water-extractable P pools contribute to DRP loss, whereas all the P pools contribute to PP loss. The processes of P movement among the fertilizer, manure, organic and inorganic P pools and plant P uptake are described with greater detail in Sadhukhan et al. (2019). Although the P model simulates P dynamics, the RZWQM2 governs the physical, biological, chemical, and hydrological processes that influence the P simulation (i.e., crop growth, runoff, drainage, soil moisture and its flux, soil temperature, sediment yield, macropore flow, plant residue and soil humus decomposition, and agriculture management practices such as tillage). All these components are simulated by RZWQM2 within its original functionalities, and then the P model uses them to simulate P dynamics and P losses through surface runoff and tile drainage.

## Field Experiment

The RZWQM2-P model was assessed against observed DRP and PP loss in both surface runoff and tile drainage water flow from the Honorable Eugene F. Whelan Research Farm near South Woodslee, ON (42.21° N, 82.74° W) for eight cropping years from June 2008 to April 2016. The site was composed of 16 plots (67.1 × 15.2 m) receiving different fertilizer types and drainage treatments. Among these, Plots 4 and 14 were selected for the present study. These plots received liquid cattle manure application and were subject to tile drainage (depth = 0.85 m, spacing = 3.80 m). The crop was rotated between maize and soybean in alternating years. In even years, maize was planted at a density of 79,800 seeds $ha^{-1}$, whereas in odd years, soybean was planted at a density of 486,700 seeds $ha^{-1}$. Liquid cattle manure equivalent to 50 kg P $ha^{-1}$ and 200 kg N $ha^{-1}$ were surface applied in 2008, 2010, 2012, and 2014 before maize planting. Manure water-extractable P content was not measured, so we assumed that in liquid cattle manure, 60% of total P was water-extractable P (Kleinman et al., 2005). Chisel plow tillage was implemented each year before planting and after harvest. The dates of cropping and other management practices are presented in Supplemental Table S1.

The soil type was clay loam, and the measured soil properties for Plots 4 and 14 were averaged (Table 1) and used as the soil input data for the model. The soil profile was divided into six layers. The soil properties such as soil texture, field capacity ($\theta_{fc}$), permanent wilting point ($\theta_{wp}$), soil bulk density ($\rho$), and porosity ($\varphi$) were measured before the start of the experiment. Prior to the onset of the experiment in 2008, soil labile P was measured using the Olsen P method (Olsen et al., 1954), whereas soil total P was measured following the soil testing recommendations by OMAFRA (2009). During growing seasons from 2010 onward, volumetric soil moistures ($\theta$) for the soil layer between 0 and 80 mm was measured twice per week using a portable time domain reflectometry (TDR) probe, whereas soil temperature ($T_{soil}$) at a depth of 50 mm was measured on an hourly basis using sensors. Hourly $T_{soil}$ values were averaged to obtain the daily mean $\underline{T}_{soil}$.

The required weather data (air temperature, precipitation, relative humidity, solar radiation, and wind speed) to run the model were collected for the period of 1 Jan. 2008 to 31 Dec. 2016 from the automated meteorological weather station at the Whelan farm, located <500 m from the experimental plots. In each experimental plot there was a catch basin 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 polyvinyl chloride (PVC) pipes. In the instrumentation building, the flow rate was measured automatically using electronic flowmeters and recorded in a multichannel data logger. Surface runoff and tile drainage were collected at the end of each plot automatically using autosamplers (CALPSO 2000S, Buhler). Surface and tile water samples were collected continuously (year-round), proportionally to flow volume, with samples being taken for every 1000 L of flow during the growing season and for every 3000 L of flow during the nongrowing seasons. After the collection, the samples were analyzed in the laboratory for DRP and total dissolved P using an acidified ammonium persulfate [$(NH_4)_2S_2O_2$] oxidation procedure (USEPA, 1983). Unfiltered water samples were analyzed for total P using the $H_2SO_4$–$H_2O_2$ digestion method (USEPA, 1983). The PP was computed by the difference between total P and total dissolved P.

## Model Calibration and Validation

The RZWQM2-P model was run using the eight crop years (June 2008–April 2016) with the measured surface runoff and subsurface drainage and corresponding DRP and PP loss data as collected from the experimental site. Measured values were used to initialize the labile P pool, whereas all other inorganic and organic P pools were initialized based on measured labile P and total P values following Jones et al. (1984). All the manure and fertilizer P pools were initialed as zero. There were some limitations on flow event separation, so to maintain reality of the P loss, water sample collecting periods were scheduled that resulted in total 34 different periods (Supplemental Table S2) for the study period. Out of these 34 periods, the first 19 periods (1 June 2008 to 9 Nov. 2012) were randomly selected for calibrating the model, whereas the last 15 periods (10 Nov. 2012 to 31 Apr. 2016) were selected for validating the model. During the calibration process, at first, parameters related to soil moisture, surface runoff, and tile drainage simulation were calibrated, as these processes govern P loss from an agricultural field, then the parameters related to P losses were calibrated. The calibration was done manually by trial and error while changing one parameter at a time, within the range as obtained from available literature, following the methods as mentioned by Ma et al. (2011, 2012) for the hydrological calibration and Sadhukhan et al. (2019) for P losses calibration. Three model evaluation statistics such as Nash–Sutcliffe efficiency (NSE), percentage bias (PBIAS), and index of agreement (IoA) were used to evaluate the performance of the model in simulating hydrology, soil moisture, soil temperature, and P losses through surface runoff and tile drainage based on the criteria presented in Moriasi et al. (2007, 2015). The NSE is a normalized statistic that determines the relative magnitude of the variance in simulated data as compared with the measured data, and it is sensitive to peak values. The IoA is a standardized measure of the degree of model prediction error, whereas PBIAS reflects the goodness of model's simulation in respect to the observed data. The model is thought 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).

The soil moisture content simulation within RZWQM2 model is parametrized with air entry pressure ($P_b$) and pore size distribution index ($\lambda$). At the start of the simulation, the values of $P_b$ and $\lambda$ were defaulted as given by Ma et al. (2011), then these values were modified one at a time to match the observed values. Once the soil moisture content was calibrated, the calibration of runoff and tile drainage followed. In the model, runoff is simulated when the rainfall rate exceeds the infiltration rate (Ma et al., 2012), so the parameters such as saturated hydraulic conductivity ($K_{sat}$) of the top soil layer and surface crust hydraulic conductivity ($K_{crust}$) were adjusted to calibrate runoff. Furthermore, the albedo was adjusted for simulation of evapotranspiration, which in turn affected surface runoff. For tile drainage calibration, parameters such as $K_{sat}$, $P_b$, lateral hydraulic conductivity ($K_{lat}$), and macroporosity were adjusted. The $K_{lat}$ had very prominent influence in tile drainage simulation and 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. The DRP loss through surface runoff was calibrated by adjusting the soil P extraction coefficient, whereas DRP loss through tile drainage calibration depended on macroporosity, $P_b$, and $\lambda$ of the deeper soil layers. To control the DRP loading to the tile by macropore flow, the macroporosity value was adjusted, and then the $P_b$ and $\lambda$ of the deeper soil layers were slightly adjusted to control the DRP loading to tile by matrix flow without hampering previous calibration of tile drainage and soil moisture simulations. The PP 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*, whereas the PP loss through tile drainage is governed by parameters like soil replenishment rate coefficient, soil detachability coefficient, soil filtration coefficient, and macroporosity. All these parameters were carefully balanced to get a reasonable simulation with respect to PP loss through tile drainage. At last, to control the plant P uptake from the labile P pool, the P uptake distribution parameter for each crop was adjusted. Calibrated soil hydraulic parameters and their values are presented in Table 1, and all other calibrated parameters are presented in Table 2.

## RZWQM2-P Application

After the RZWQM2-P model was calibrated and validated, it was run to evaluate the impacts of controlled drainage, winter manure application, and injected manure application on P losses under the same agroclimatic situation and for the same simulation period. For a controlled drainage system, the head gate at a depth of 460 mm from the ground level was maintained throughout the simulation period. To simulate winter manure application, each day during the nongrowing periods (1 January–15 May) of the maize planting years was selected as the application date. It resulted in total 136 simulations. Phosphorus losses of all these simulations were subsequently averaged to identify average P losses under winter manure application. Finally, for injected manure application, the liquid cattle manure was assumed to be injected at a depth of 100 mm. For the abovementioned three model applications, crop planting and harvest, tillage, and manure properties remained exactly the same as in the original simulation. The simulated P losses of these three management

**Table 1. Measured and calibrated soil properties.**

| Soil layer depth | Measured soil properties† | | | | | | | | | Calibrated soil properties‡ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\rho$ | Clay | Sand | OM | $\theta_{fc}$ | $\varphi$ | $\theta_{wp}$ | LP | TP | $P_b$ | $\lambda$ | $K_{sat}$ | $K_{lat}$ |
| mm | kg m$^{-3}$ | % | | | m$^3$ m$^{-3}$ | | | g kg$^{-1}$ | | cm | | cm h$^{-1}$ | |
| 0–10 | 1330 | 34.2 | 29.0 | 3.7 | 0.37 | 0.54 | 0.18 | 0.02 | 0.90 | −20.06 | 0.16 | 0.01 | 0.02 |
| 10–100 | 1330 | 34.2 | 29.0 | 3.7 | 0.37 | 0.54 | 0.18 | 0.02 | 0.90 | −29.03 | 0.15 | 0.35 | 0.70 |
| 100–250 | 1390 | 34.2 | 29.0 | 3.7 | 0.36 | 0.54 | 0.18 | 0.02 | 0.90 | −16.64 | 0.20 | 0.55 | 1.10 |
| 250–450 | 1390 | 40.7 | 25.7 | 2.0 | 0.35 | 0.5 | 0.18 | 0.01 | 0.65 | −16.16 | 0.19 | 0.55 | 1.10 |
| 450–800 | 1330 | 40.4 | 27.0 | 0.7 | 0.36 | 0.48 | 0.18 | 0.01 | 0.50 | −25.10 | 0.15 | 0.17 | 0.35 |
| 800–1200 | 1330 | 39.3 | 24.6 | 0.5 | 0.36 | 0.48 | 0.17 | 0.01 | 0.40 | −35.17 | 0.14 | 0.17 | 0.35 |

† $\rho$, soil bulk density; Clay, soil clay content; Sand, soil sand content; OM, soil organic matter content; $\theta_{fc}$, volumetric soil moisture content at field capacity; $\varphi$, soil porosity; $\theta_{wp}$, volumetric soil moisture content at permanent wilting point; LP, soil labile P; TP, soil total P.

‡ $P_b$, air entry pressure; $\lambda$, pore size index; $K_{sat}$, saturated hydraulic conductivity; $K_{lat}$, lateral hydraulic conductivity.

**Table 2. Calibrated parameters and their values.**

| Parameters | Calibrated value | Default (range) |
|---|---|---|
| Surface crust ($K_{crust}$) (cm h$^{-1}$) | 0.01 | 0.01 (0.01–20.00) |
| Albedo | | |
| Dry soil | 0.75 | 0.20 (0.01–0.90) |
| Wet soil | 0.85 | 0.30 (0.02–0.90) |
| Crop at maturity | 0.55 | 0.70 (0.01–0.90) |
| Fresh residue | 0.85 | 0.22 (0.01–0.90) |
| Macroporosity (m$^3$ m$^{-3}$) | 0.03 | – |
| P extraction coefficient (–) | 1.00 | 1.00 (0.10–1.00) |
| USLE coefficients | | |
| Soil erodibility (t ha$^{-1}$) | 1.61 | 0.05 (0.01–1.97) |
| Cover and management factor | 0.55 | 0.50 (0.01–1.00) |
| Support practice factor | 0.55 | 0.50 (0.01–1.00) |
| Manning's N | 0.01 | 0.01 (0.01–0.40) |
| Soil filtration coefficient (m$^{-1}$) | 0.20 | 0.00 (0.00–1.00) |
| Soil detachability coefficient (g J$^{-1}$ mm$^{-1}$) | 0.60 | 0.40 (0.00–1.00) |
| Soil replenishment rate coefficient (gm m$^{-2}$ d$^{-1}$) | 0.01 | 0.20 (0.00–1.00) |
| P uptake distribution parameter | | |
| Corn | 10.00 | 5.00 (1.00–15.00) |
| Soybean | 10.00 | 5.00 (1.00–15.00) |

practices were then compared with original simulation with preplanting manure application, which is generally the conventional management practice, to identify the best management practice to reduce P losses from the field.

# Results

## Soil Moisture and Soil Temperature

Simulated and observed average soil moisture (θ) between 0- and 80-mm depths and soil temperature ($T_{soil}$) at 50-mm depth, along with the simulation statistics for the calibration and validation periods, are presented in Fig. 1a and 1b, respectively. The model satisfactorily simulated θ during calibration period, whereas in the validation period, it was simulated with NSE <0.50 (NSE = 0.47), which is unsatisfactory. During the whole simulation period, however, the model's simulation of θ was satisfactory, with NSE of 0.50, PBIAS of 0.45%, and IoA of 0.81. Simulation of $T_{soil}$ was satisfactory during calibration and validation period (Fig. 1b). During the whole simulation period, simulation of $T_{soil}$ was also satisfactory, with NSE of 0.54, PBIAS of 12%, and IoA of 0.89.

## Hydrology

Overall, the model's performance was very good in simulating runoff (with NSE of 0.80, PBIAS of −3%, and IoA of 0.95) and was good in simulating tile drainage (with NSE of 0.67, PBIAS of 10%, and IoA of 0.90). During the calibration period, simulated runoff showed (Fig. 2a) a high NSE value (NSE = 0.83), and so did simulated tile drainage (Fig. 2b, NSE = 0.70), which are very good and good, respectively, according to Moriasi et al. (2007, 2015). On an annual basis, simulated average runoff and tile flow were close to the observed annual mean values (Supplemental Table S3). During the 8 yr of simulation, simulated average annual evapotranspiration (383 mm) was 42% of the observed annual precipitation (910 mm). This was similar to

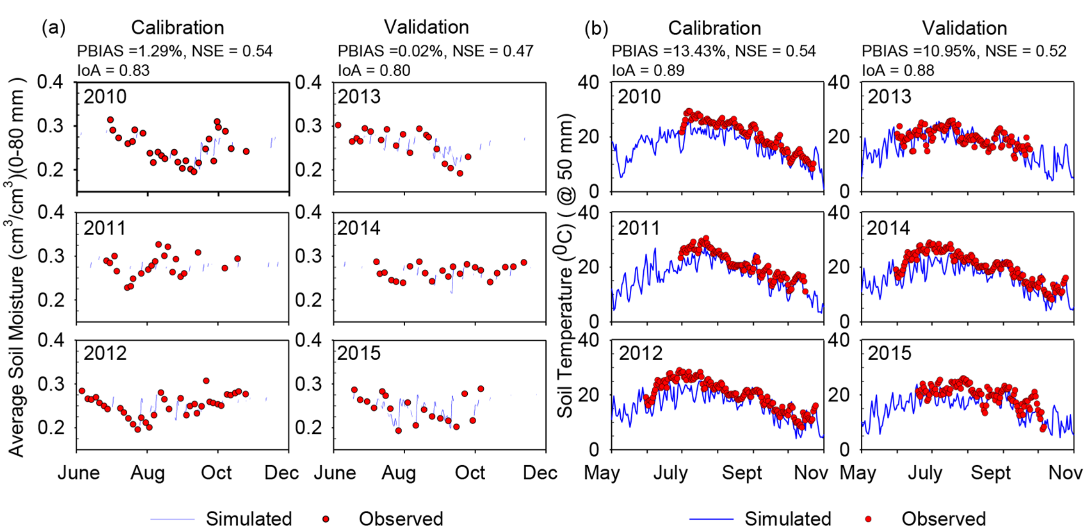


**Fig. 1. Simulated and observed (a) average soil moisture (0–80 mm) (θ) and (b) soil temperature (at 50 mm) ($T_{soil}$). PBIAS, percentage bias, NSE, Nash–Sutcliffe model efficiency; IoA, index of agreement.**

the measured annual evapotranspiration of 45% of the precipitation in the same region reported in Tan et al. (2002a). Between the simulated average annual surface runoff and tile drainage, most of the water (68%) moved out of the field through the tile drainage system.

## Dissolved Reactive and Particulate Phosphorus Loss

The performance of RZWQM2-P in simulating P losses in terms of DRP and PP through surface runoff and tile drainage from a manured agricultural field can be judged as satisfactory (Fig. 3). Model simulation suggested that DRP losses through surface runoff (Fig. 3a) is driven by runoff volume, amount of P in the labile P pool of the topmost soil layer, and the surface manure water-extractable inorganic P pool. The model-simulated annual average DRP loss (Table 3) is 0.29 kg P ha$^{-1}$, and applied manure P contributed 5% of it, meaning that most of the simulated DRP in runoff came from soil P. This conforms to the idea that soil P is an important source of DRP loss through runoff (Wang et al., 2018). The model-simulated average annual DRP loss through tile drainage is 0.53 kg P ha$^{-1}$ (Table 3), which is 83% more than simulated surface runoff associated DRP loss. This substantiates the model's assumption that in the case of liquid manure application, 60% of the applied P immediately infiltrates into the soil as soon as it is applied. This reduces the availability of manure P on the soil surface to be lost through surface runoff but increases DRP loss through tile drainage. The model's simulation suggested that macropore flow is the primary mechanism responsible for the DRP loss through tile drainage, and it contributed 82% of the total DRP load of tile flow. Overall, the simulated DRP loss through both surface runoff and tile drainage closely follows the observed pattern, with NSE of 0.68, PBIAS of 6%, and IoA of 0.93 for surface runoff and NSE of 0.64, PBIAS of 0.11%, and IoA of 0.89 for tile drainage. The simulation identified that 65% of total DRP loss was through tile flow, which conforms to the observed fact that tile flow is the major pathway of the DRP loss from the experimental plot (Table 3). The simulation of PP loss through surface runoff and tile drainage in both the calibration and validation periods agreed well with the observed data (Fig. 3c and 3d). The field experiment showed that 74% of the total P was lost in the form of PP, and tile drainage and surface runoff almost equally contributed toward this loss (Table 3). The model's simulation captured this satisfactorily, with 75% of total simulated P loss being in the form of PP and simulated tile drainage PP loss being half of the total PP loss. This also agrees with the observation of Tan and Zhang (2011), who reported that PP loss accounted majority of total P loss from a tile-drained agricultural field. The model successfully simulated total P loss through both the transport pathways from the field (i.e., the sum of DRP and PP in both runoff and drainage, with high simulation accuracy; NSE = 0.86, PBIAS = −0.46%, and IoA = 0.96).

The RZWQM2-P simulation results were in good agreement with the observed fact that P loss was dominant during nongrowing season in the experimental field. In the present study, observed data showed that nongrowing seasons (December to

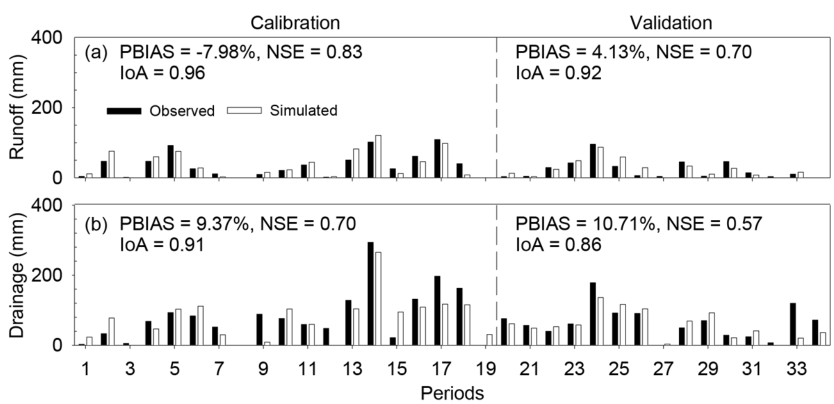


**Fig. 2. Simulated and observed (a) runoff and (b) drainage. PBIAS, percentage bias, NSE, Nash–Sutcliffe model efficiency; IoA, index of agreement.**

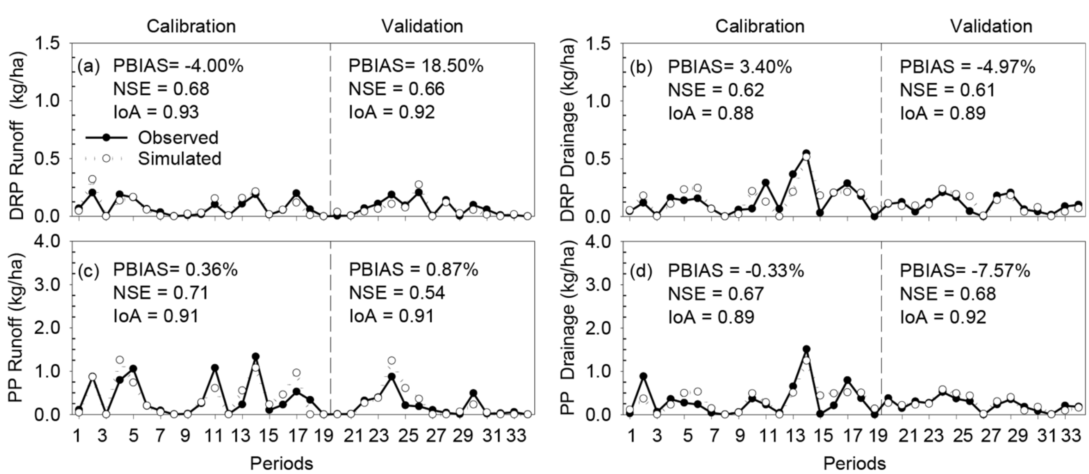


**Fig. 3. Simulated and observed (a) dissolved reactive P (DRP) in runoff, (b) DRP in drainage, (c) particulate P (PP) in runoff, and (d) PP in drainage. PBIAS, percentage bias; NSE, Nash–Sutcliffe model efficiency; IoA, index of agreement.**

May) produced 68% of total drainage volume and 58% of total runoff volume. Subsequently, runoff carried away 53% of the total runoff-bound DRP and 68% of total tile drainage-bound DRP during nongrowing seasons. The same was observed for PP loss, with 56% of total runoff-associated PP and 65% of total drainage-associated PP being lost during the nongrowing seasons. Phosphorus loss in the nongrowing seasons during the whole simulation years comprised 61% of total P loss through surface and subsurface water flow. The RZWQM2-P simulated 61% of total runoff and 65% of total drainage during the nongrowing seasons, whereas simulated P loss during nongrowing seasons represented 65% of the total P lost through surface and subsurface water flow. These simulated results also corresponded well with the review report of King et al. (2015), who reported that the "nongrowing period represents a significant proportion of annual discharge and P loss."

### RZWQM2-P Application

The impact of three different agricultural management practices (controlled drainage, winter manure application, and injected manure application) on P losses as identified by the simulation of RZWQM2-P and comparison with conventional management practices is presented in Fig. 4. Implementation of controlled drainage reduced the average annual tile flow volume (85%), whereas it increased average annual runoff volume (171%) over conventional management practices. Although controlled drainage reduced both DRP and PP loss through tile drainage (both 83%), it overall increased (13%) total P loss because a significant increase in surface runoff volume led to more runoff-associated DRP and PP loss (188 and 110%, respectively). Winter manure application simulation suggested an increase in DRP and PP losses through both the transport pathways, particularly DRP loss through surface runoff (63%), and overall it contributed 23% more total P loss than conventional management practices. Simulation of injected manure application revealed that it is the best management practice among these three, as it reduced DRP and PP losses through both surface runoff and tile drainage, and thus, as a whole, it contributed to less total P loss (17%) from the field.

## Discussion

The RZWQM2-P model responded well in simulation of manure and soil P dynamics, as suggested by P balance over the simulation period (Table 3). An inspection of simulated manure and soil P dynamics on the randomly selected manure application year 2010–2011 with maize planting shows that on the day of manure application, P mass in P pools underwent an addition of 50 kg P ha$^{-1}$, which was reflected by increases in the labile P pool (24 kg P ha$^{-1}$), active inorganic P pool (6 kg P ha$^{-1}$), and surface manure P pool (20 kg P ha$^{-1}$). This sudden increase in the labile P pool created an imbalance between the labile P and active inorganic P pools of and ∼18 kg P ha$^{-1}$ absorbed into the active inorganic P pool from the labile P pool after manure application. During 2010–2011, 49 kg P ha$^{-1}$ from the labile P pool was taken up by the crop, and on the day of harvest, 30 kg P ha$^{-1}$ was left as crop residue while the remaining 19 kg P ha$^{-1}$ was grain harvested. This is comparable with the observed grain P harvested (17 kg P ha$^{-1}$) of maize at a site under a similar P application rate (Qi et al., 2017). During this year, 27 kg P ha$^{-1}$ of mineralized P was added to the system from plant residue and soil humus, whereas a total of 5 kg P ha$^{-1}$ was lost from system through surface runoff and tile drainage. Overall, the simulated P for the all simulation years is balanced (Table 3) out when the annual average P input (25 kg P ha$^{-1}$ from manure, 23 kg P ha$^{-1}$ from plant residue and soil humus) is summed with the annual average P output (43 kg P ha$^{-1}$ of plant P uptake, 3 kg P ha$^{-1}$ of P loss through transport pathways) and annual average change in soil P (increase of 2 kg P ha$^{-1}$).

The RZWQM2-P model is capable of simulating the partition of total P losses through different pathways in tile-drained fields with manure application. Several studies have shown that both surface runoff and tile drainage are important pathways for P loss from agricultural fields (Smith et al., 2015; Tan and Zhang, 2011; Zhang et al., 2015a). Simulation results showed

**Table 3. Phosphorus balance table for the simulation period.**

| Year | Manure P | Residue and humus P release | Plant harvested | Grain harvested | DRP‡ | | | | PP¶ | | | | ΔSP# |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Runoff | | Drainage | | Runoff | | Drainage | | |
| | | SIM† | SIM | SIM | SIM | OB§ | SIM | OB | SIM | OB | SIM | OB | SIM |
| | kg ha$^{-1}$ | | | | | | | | | | | | |
| 1 June 2008–26 May 2009 | 50.00 | 27.67 | 51.44 | 18.25 | 0.70 | 0.68 | 0.81 | 0.62 | 2.81 | 3.02 | 1.71 | 1.83 | 18.34 |
| 26 May 2009–11 June 2010 | 0.00 | 25.96 | 36.39 | 21.21 | 0.05 | 0.06 | 0.30 | 0.19 | 0.31 | 0.36 | 0.66 | 0.46 | −13.51 |
| 11 June 2010–22 June 2011 | 50.00 | 26.69 | 48.65 | 18.58 | 0.53 | 0.41 | 0.83 | 1.26 | 2.15 | 2.64 | 1.98 | 2.42 | 12.34 |
| 22 June 2011–15 May 2012 | 0.00 | 14.13 | 32.27 | 18.73 | 0.20 | 0.32 | 0.77 | 0.69 | 1.58 | 1.18 | 1.89 | 1.39 | −26.16 |
| 15 May 2012–23 May 2013 | 50.00 | 21.42 | 51.38 | 16.54 | 0.04 | 0.01 | 0.25 | 0.23 | 0.01 | 0.02 | 0.60 | 0.52 | 28.27 |
| 23 May 2013–23 June 2014 | 0.00 | 22.82 | 34.73 | 19.80 | 0.28 | 0.45 | 0.61 | 0.54 | 2.39 | 1.79 | 1.49 | 1.46 | −22.71 |
| 23 June 2014–28 May 2015 | 50.00 | 22.18 | 47.92 | 11.05 | 0.43 | 0.35 | 0.49 | 0.43 | 0.40 | 0.33 | 1.11 | 0.89 | 28.77 |
| 28 May 2015–29 Apr. 2016 | 0.00 | 22.39 | 38.53 | 19.89 | 0.09 | 0.18 | 0.22 | 0.30 | 0.26 | 0.58 | 0.50 | 0.65 | −8.86 |
| Total | 200.00 | 183.26 | 341.31 | 144.04 | 2.32 | 2.46 | 4.27 | 4.27 | 9.90 | 9.90 | 9.94 | 9.62 | 16.48 |
| Avg. | 25.00 | 22.91 | 42.66 | 18.01 | 0.29 | 0.31 | 0.53 | 0.53 | 1.24 | 1.24 | 1.24 | 1.20 | 2.06 |

† SIM, simulated.

‡ DRP, dissolved reactive P.

§ OB, observed.

¶ PP, particulate P.

# ΔSP, soil P change.

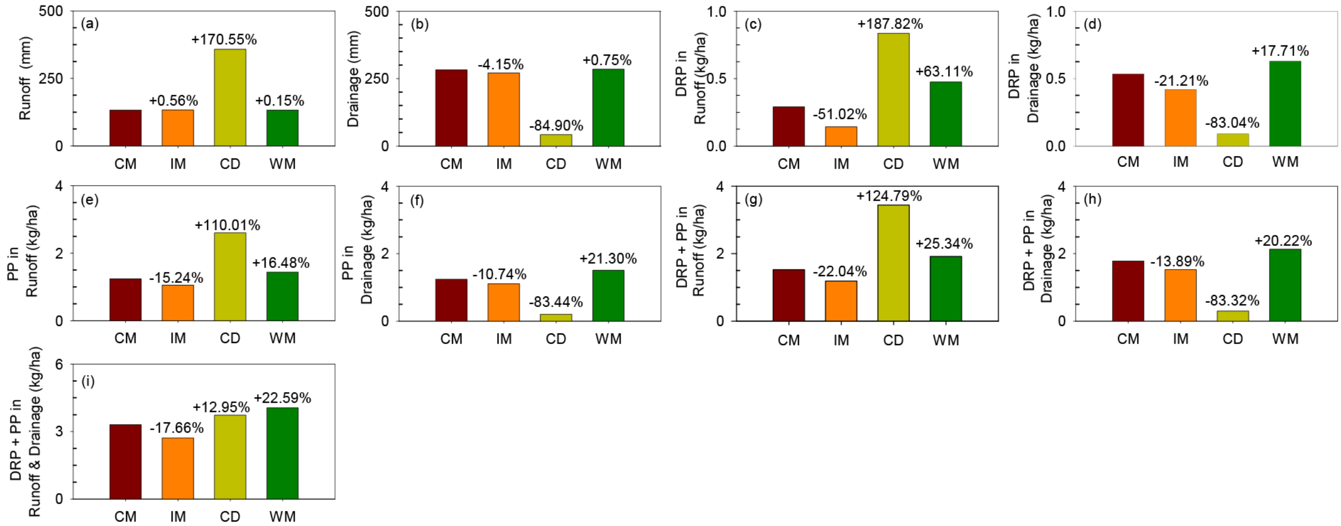


**Fig. 4. Comparison of Root Zone Water Quality Model version 2–Phosphorus (RZWQM2-P) simulation with conventional management practices (CM), injected manure application (IM), controlled drainage (CD), and winter manure application (WM) in terms of (a) runoff, (b) drainage, (c) dissolved reactive P (DRP) loss through surface runoff, (d) DRP loss through drainage, (e) particulate P (PP) loss through runoff, (f) PP loss through drainage, (g) DRP + PP loss through runoff, (h) DRP + PP loss through drainage, and (i) DRP + PP loss through runoff + drainage. The number above each bar represents the percentage increase (+) or decrease (−) compared with conventional management practices.**

that 54% of total annual average total P loss (DRP + PP) was through tile flow, of which 75% was PP (Table 3), and those values were 53 and 74%, respectively, based on observed data. Phosphorus transfer from the soil to tile drainage water occurs by water movement through the soil matrix and/or a preferential flow path. A preferential flow path was earlier identified as a principle mechanism for DRP and PP loss to tiles in the present study area (Tan et al., 2007; Tan and Zhang, 2011; Zhang et al., 2015a, 2015b). Simulation of the RZWQM2-P model identified this fact satisfactorily with 82% of DRP, whereas all of the PP load through tile drainage was transported by the macropore flow. In the RZWQM2-P model, along with water flow volume, DRP loss through surface runoff and tile drainage greatly depends on the amount of labile P. Therefore, a satisfactory simulation of P dynamics will lead to reasonable estimation of labile P, which in turn affects the simulation of DRP loss through surface runoff and tile drainage. In a study at the same site under similar management practices, Wang et al. (2018) reported that measured Olsen P in the 0- to 150-mm soil layer is within the range of 50 to 80 kg P $ha^{-1}$ during the fall period. This value conforms to the RZWQM2-P-simulated average labile P of 76 kg P $ha^{-1}$ for the same soil layer during the fall season. Along with acceptable simulation of P dynamics, the model's capability to simulate P losses through tile flow is attributed to satisfactory soil moisture, soil matrix flux, and macropore flux simulations. Adaptation of Richard's equation to simulate soil moisture and matrix flux and use of the Poiseuille's law-based approach in simulation of macropore flow may have resulted in satisfactory water flux through these flow pathways. The use of Hooghoudt's steady-state equation may have further facilitated tile drainage simulations, which in turn affected P losses through tile drainage. Soil temperature also plays an important role in simulating P dynamics, whereas an acceptable soil temperature simulation may lead to a good estimation of P flow rates among various P pools, decomposition, and mineralization rates of residue and soil organic matter. Finally, the implementation of manure P pools as recommended by Vadas et al. (2007) may have improved the simulation of dynamics and fate of applied manure P while considering leaching, physical assimilation, and decomposition of manure P explicitly. Although RZWQM2-P satisfactorily simulated P losses (DRP, PP) through both surface runoff and tile drainage, further tests are recommended with more observed data in a tile-drained agricultural field.

The management simulation suggested that controlled drainage would reduce total P loss (DRP + PP) through tile flow, but since it increased total P loss through surface runoff, it overall contributed toward 13% more total P loss from the field, considering both surface runoff and tile drainage, than conventional management practices (Fig. 4). Tan and Zhang (2011) found that total P loss was reduced through tile flow and increased through surface runoff. Overall, however, controlled drainage reduced total P loss from the field considering both surface runoff and tile drainage, which conflicted with our study. This may be because greater amount of precipitation during our study period than during the Tan and Zhang (2011) study (910 vs. 781 mm) led to more surface runoff (358 vs. 37 mm), and consequently more P losses through surface runoff, which resulted in more overall total P losses from the field in our study. Thus, for the areas where frequent rainfalls lead to significant amount of surface runoff, controlled drainage is not a recommended management practice to reduce overall P losses from tile-drained fields. Winter manure application leads to more P losses (23% increase) than conventional management practices. This is because during the winter season, the majority of water outflow from the field occurs and winter manure application makes applied P vulnerable for loss under frequent runoff from snowmelt and rain on snow events. This simulation of winter manure application by RZWQM2-P agreed with the study of Liu et al. (2017a), who simulated the impact of fall and winter manure application on total P losses and found that it increased annual total P losses loss by 12 to 16% over the spring application. Finally, simulation of injected manure application with RZWQM2-P indicated that instead of surface application, injected manure application into shallow soil profiles would decrease all forms of P losses from agricultural fields under similar agroclimatic conditions (Fig. 4). This is attributed to the low availability of P on the soil surface for rain and runoff and better incorporation into the soil profile due to injection of manure below the soil surface. These results concurred with the study of Daverede et al. (2004), who reported that injected manure application reduced DRP loading through surface runoff by 90% over the surface application.

Computer simulation models are built on assumptions and simplified versions of very complex real-world phenomena, so they inevitably have some limitations. Accordingly, the RZWQM2-P model is limited to being one dimensional, field scale, and assuming soil as a homogeneous medium. Dissolved unreactive P loss is not simulated under the present model, nor is P loss to groundwater. The model has limited capability in simulation of PP loss, as it assumes that particle-bound P originates from the first 0.01-m soil layer, and only the macropore flow contributes to tile-drainage-bound PP loss while bypassing the soil matrix. Another shortcoming of RZWQM2-P is that, being a field-scale model, it cannot be applied over a large-scale watershed. At present, within RZWQM2-P, the Richard's equation is solved iteratively, which slows down the simulation and calibration process of the model parameter based on the trial and error method. It uses many resources. Therefore, for future improvement, attention should be paid to adopting algorithms to accelerate the speed of solving the Richard's equation and autocalibration of model parameters.

## Conclusions

In this study, the newly developed RZWQM2-P model, a process-based P management tool integrated into the RZWQM2 model, was assessed in simulating agricultural P losses in terms of DRP and PP with 8 yr of data collected from a subsurface-drained field with liquid cattle manure application and maize–soybean rotation in southwestern Ontario, Canada. The simulation results showed that the RZWQM2-P performed satisfactorily in simulating the DRP and PP losses both through surface runoff and subsurface drainage and were consistent with the observed trend that the nongrowing season dominated in P losses over the growing season. The simulation resembles the observed fact that tile drainage and surface runoff both equally contributed toward P losses and most P was lost as PP. The simulation suggested that preferential flow is the main pathway for P losses through tile drainage at the site. Furthermore, the application of RZWQM2-P to quantify the impacts of three agricultural management practices indicated that subsurface manure application rather than controlled drainage is an effective option to mitigate P losses from a tile-drained cropland, whereas winter manure application identified an increase in P losses from the field. Although, the developed RZWQM2-P appears to be a promising tool for P management in subsurface-drained, manured agricultural fields, further tests are recommended with more observed data in a tile-drained agricultural field.

## Supplemental Material

Information regarding crop planting and agricultural management practice dates at the experimental plot, time periods of water flow and P measurement, and the simulated water balance table are included in the supplemental material.

## Conflict of Interest

The authors declare no conflict of interest.

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