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Calibration and Evaluation of Phosphorus Loss in Surface Runoff and Subsurface Drainage Using APEX

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By

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ABSTRACT

Modeling phosphorus (P) loss through surface runoff and subsurface drainage is essential because it helps understand how P transfers to the water bodies in an inexpensive and feasible way. P loss into the Great Lakes leads to eutrophication. APEX (Agriculture Policy/Environmental eXtender) is extended from EPIC (Environmental Policy Integrated Climate model) and can simulate management practices and land use impacts for various land sizes from a field to a small watershed. However, APEX has not been tested in Lake Erie Region. This research, therefore, represents the first effort to use APEX to simulate P loss in this area.

Field data were obtained from experiments conducted at the Agriculture and Agri-Food Canada's Whelan experimental farm in Woodslee, ON, Canada, with corn-soybean rotation. Calibration and evaluation of APEX was executed to test its capability in simulating the impacts of chemical fertilizers and cattle manure on P loss. Different potential evapotranspiration equations (PET) and curve number (CN) equations were used to determine the most suitable one for this study area. Statistical analysis was used to assess the model performance. Satisfactory results were obtained from the simulation of APEX in the Brookstone clay loam soil.

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Chapter I: Introduction

Agriculture is the primary source of non-point source pollution in southwestern Ontario. Every year, significant amounts of phosphorus (P) are lost through surface runoff and subsurface drainage (Wang et al., 2018a), leading to eutrophication and, consequently, toxic cyanobacterial blooming, such as the Lake Erie incident in 2011 (Wang et al., 2018b). Lake Erie experienced largest harmful algal bloom in recorded history. Excessive P application to meet crop needs via chemical fertilizers and animal manure has been the main reason to contribute to the loss of dissolved reactive P into the lakes (Wang et al., 2019). Another contribution is the legacy P that remains in the soil (Wang et al., 2018a). Farmers apply fertilizers/manure based on crop nitrogen requirements that lead to P rising and accumulating in the soil from year to year (Legacy P). Manure contains approximately up to four times more P than that needed by crops based on crop nitrogen requirement for 1:8 of major crops (Wang et al., 2019). The quantity of the dissolved P that gets lost in runoff and the timing of when it gets lost is influenced by a lot of factors, including the quantity of P applied, forms of fertilizer and manure, the application time related to precipitation timing and intensity, soil type, slope, vegetation density and type of vegetation (Wang et al., 2018a). There is a supply and demand approach that is used to estimate how much the crop needs. If there is more demand than supply, there will be nutrient stress; however, when there is more supply than demand, masses of the surplus P are available for loss through the runoff, lateral flow, and percolation in the soil layer (Santhi et al., 2001). Different P sources (fertilizers/manure and P legacy) are available to pass through water systems and reach a main water body, especially when excessive rain occurs. P goes through many transport and transformations that need to be understood, in order to know how to face it.

1.1 Phosphorus in Soil

Phosphorus in soils can be categorized as total, dissolved and particulate phosphorus (Yuan et al., 2005). P is added to the soil by organic or inorganic fertilizers and plant residue. P is lost by plant uptake, runoff, and erosion (Yuan et al., 2005). The mineralization process converts the organic P to inorganic P, which is available to plants. It occurs when the ratio of carbon to P in soil is 200 to 1, and it is also controlled by soil temperature, soil water content, soil pH, P fertilization, the composition of crop residues, and cultivation intensity (Yuan et al., 2005). Mineralization increases with increasing organic P presence; however, regular cultivation helps decrease mineralization with falling organic P amounts. Adsorption and desorption processes determine the supply of P to the plants (Yang et al., 2019). The lower the soil pH and the higher the temperature, the more phosphate is adsorbed. Understanding all these processes is essential in understanding how P reacts within the soil environment to precisely estimate P transport from soil to water resource.

1.2 Background and Literature Review

Various studies have been conducted to estimate factors that would result in P loss in various forms. P loss depends on the quantity and the application forms of fertilizer/manure, the application time relative to the precipitation or runoff events, and precipitation intensity (Wang et al., 2018a). The study by Zhang et al. (2004) conducted in Montreal, Quebec, had one phase with continuous fertilization, and another phase with depletion of P. In the depletion plots where no fertilization P was added, corn yield was still sustained because of the availability of legacy P in the soil added from the previous year. Rehm et al. (1984) showed no changes in the soil test P after five years of corn production with no additional P. Other results by Zhang et al. (2004) showed that adding fertilizer P would enhance the transformation of residual fertilizer from Bicarb inorganic P to inorganic P NaOH, which is less available to plants (Zhang et al., 2004). Inorganic P NaOH decreases P loss from the soils, which prevents water bodies from receiving more P. It was found that it is a slow process to convert residual fertilizer P to stable P, which makes P available to crops for many years even though fertilizer was not applied (Zhang et al., 2004). Wang et al. (2018a) found that direct manure or fertilizer contributes from 31% to 70% of total simulated dissolved reactive P loss in surface runoff from soils amended with solid cattle manure and chemical fertilizers, respectively.

Water management and the presence or absence of cover crop affect the P loss in the soil. In southern Ontario, a study by Zhang et al. (2017) was conducted to test the impacts of different water management on P loss. The results showed that the cover crop through the winter from the previous year's wheat reduced total soil P loss in surface runoff and tile drainage because of the decrease in particulate P loss. Controlled drainage with sub-irrigation further reduced the total soil P loss in combination with cover crop. A study in southern Ontario by Zhang et al. (2017) compared non-tillage to conventional tillage with leaf compost in the P loss. Leaf compost increased dissolved reactive P loss in both conventional and non-tillage processes, but the P loss is more with the non-tillage.

APEX (Agricultural Policy Environmental eXtender) is a flexible and dynamic tool that is used for simulating management and land use impacts for different landscape sizes (Gassman et al., 2010). It is developed as an extender from EPIC (Environmental Policy Impact Climate) software. Both software can model a small field; however, APEX can scale up to a whole farm and small watershed scales. APEX has more enhancements than EPIC, including groundwater sub model, spatial rainfall generator, landscape representation of conservation or best management practices (BMPs), feedlot manure management, and simulation of different grazing density and manure deposition scenarios (Wang et al., 2012). SWAT (Soil and Water Assessment Tool) is another tool used to model the quality and quantity of surface and groundwater and assessing nonpoint source pollution. SWAT is mostly used for watershed scale. National Pilot Project (NPP) made APEX to fill the gaps between SWAT and EPIC. This gap simulates landscape processes at a small farm scale to a small watershed scale (Gassman et al., 2010). Field-scale is used when the whole area has the same soil, slope, and management practices. Landscape or watershed scales are bigger scales and are used when the whole area is divided into subareas, of which each has its own characteristics. APEX simulates the routing of water and pollutants through the channel system in the model. Unlike EPIC, APEX is one of the few models with this functionality (Gassman et al., 2010). APEX was used in this study because it has never been used before in this study area, unlike EPIC and SWAT that have been tested in southwestern Ontario.

APEX has been widely used because modeling is time-saving and cost-effective. Additionally, modelling provides ability to consider different management scenarios and to quantify potential impacts for change. In a study for a field scale using APEX in Columbia, Missouri, Wang et al. (2012) calibrated and evaluated the simulated data by comparing it to the observed data for event runoff and atrazine (herbicide) for corn-soybean rotation. Their results showed runoff, atrazine loads, and plant yields had similar results between simulated and observed data. Gassman et al. (2010) calibrated and validated runoff, total nitrogen and total P losses with different manure types (solid and liquid manure) using APEX in Upper Borth Bosque River watershed in North Central Texas. APEX produced similar results between the observed and the simulated data for the losses of each one. They used APEX and SWAT together to simulate streamflow, nitrate N, and soluble, sediment and total P. The losses of nutrients were all predicted well in the model except for the weakest prediction of sediment P because of the limited data collection.

A study by Wang et al. (2019) used the tools such as EPIC and Surface Phosphorus and Runoff (SurPhos) to model the impacts of manure on P loss in surface runoff and subsurface drainage in Lake Erie region. The study area in Southwestern Ontario is dominated with Brookstone clay loam soil, which is prone to preferential flow through macropores. Macropores form from root channels or earthworm burrows, and they shrink in the dry season (Wang et al., 2019). EPIC has the limitation of assuming a constant crack flow for the whole period. The constant crack flow possibly caused overestimation or underestimation for P loss in drainage (Wang et al., 2019). Crack flow is a coefficient that is used in EPIC and other tools to represent the preferential flow through macropores. Another disadvantage of EPIC is not considering P loss from soil and manure together; it only considers P loss from soil. With these two limitations, EPIC was still reliable for modeling in a Brookstone clay loam soil for crop yield, surface runoff, subsurface drainage, and dissolved reactive P (Wang et al., 2019). SurPhos was more accurate for dissolved reactive P loss because it considers dissolved reactive P loss directly from manure (Wang et al., 2019). It also has improved P sorption-desorption factors. These factors make SurPhos estimation of dissolved reactive P more accurate than EPIC (Wang et al., 2019), but SurPhos does not have a drainage system and cannot simulate crop yield and surface runoff. EPIC worked better for Southwestern Ontario area compared to SurPhos.

1.3 Objectives

It is important to find a suitable model to test, calibrate, and evaluate surface runoff and subsurface drainage in Southwestern Ontario. Many previous studies have performed simulations on surface runoff and subsurface drainage, but no efforts have been made to use APEX on the Brookstone clay loam soil which is prone to preferential flow more than other types of soil.

This study's objective was to calibrate and evaluate the parameters and equations on APEX using the observed data from the field in Southwestern Ontario. This tests how

APEX accurately simulates crop yields, surface runoff, subsurface drainage, and P loss through surface runoff and subsurface drainage from the field.

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Chapter II: Materials and Methods

2.1 APEX Model

APEX features are the landscape representation of best management practices, feedlot manure management and simulation of different grazing density (Wang et al., 2012). APEX simulates the conservative practices, tillage operations, different cropping systems, different nutrient management practices, surface runoff, and losses of fertilizers/sediments/nutrients (Gassman et al., 2010). Depending on the study, these simulations can either be conducted for continuous long-term simulations or for a daily time step. The model consists of many major components including climate, hydrology, crop growth, pesticide fate, nutrient cycling, erosion-sedimentation, carbon-cycling, management practices, soil temperature, plant environment control, economic budget, and sub-area/routing (Gassman et al., 2010).

Surface runoff and infiltration are both results of the partitioning of snowmelt and precipitation. Surface runoff can be estimated by the green-ampt method for infiltration rainfall excess rate and the curve number (CN) (Wang et al., 2012). The curve number has five options for daily adjustments and different conditions; they are discussed in chapter III. Horizontal flow partitions between quick return flow and lateral return flow. Vertical flow percolates through the soil layers and reaches the next layer when the current soil layer exceeds the field capacity for water content (Gassman et al., 2010). Vertical flow and horizontal flow are both used to calculate subsurface flow. Potential evapotranspiration can be calculated in five methods: Penman-Montieth, Penman, Priestly-Taylor, Hargreaves, and Baier-Robertson (Gassman et al., 2010).

Weather driving forces are precipitation, solar radiation, maximum and minimum temperature, wind speed, and relative humidity. Wind speed can be used if wind erosion is going to be considered. APEX has different equations for each P phase and has a loading function for the sediment phase. For the soluble phase, the P runoff is estimated as a function of the concentration of labile P in the topsoil layer, linear adsorption isotherm and runoff volume (Wang et al., 2012). APEX routes water through channels and flood plains, either by daily time step or short time interval complete routing method (Gassman et al., 2010). Short-term interval complete routing method estimates streamflow, whereas daily time step simulates daily water, sediment, nutrient, and pesticide yields, which can be used for the long term. Daily time step was used in this study. Organic P is routed by enrichment ratio approach and transported by sediment (Gassman et al., 2010).

2.2 Methodology

The field experiments were conducted at Woodslee, Ontario, Canada, shown in Figure 1 at the Agriculture and Agri-Food Canada's Hon. Eugene F. Whelan Experimental farm (Wang et al., 2018b) from 2008 to 2011. The field is 0.1 ha with 67.1 m long and 15.2 m wide (Wang et al.,2019). The soil is Brookstone clay loam, consisting of 48.2% sand, 26.4% silt, and 25.4% clay (Wang et al., 2018b). The detailed experiment can be found in the paper by Wang et al. (2019) re modeling the impacts of manure on phosphorus loss in surface runoff and subsurface drainage. The observed data were used for this study.

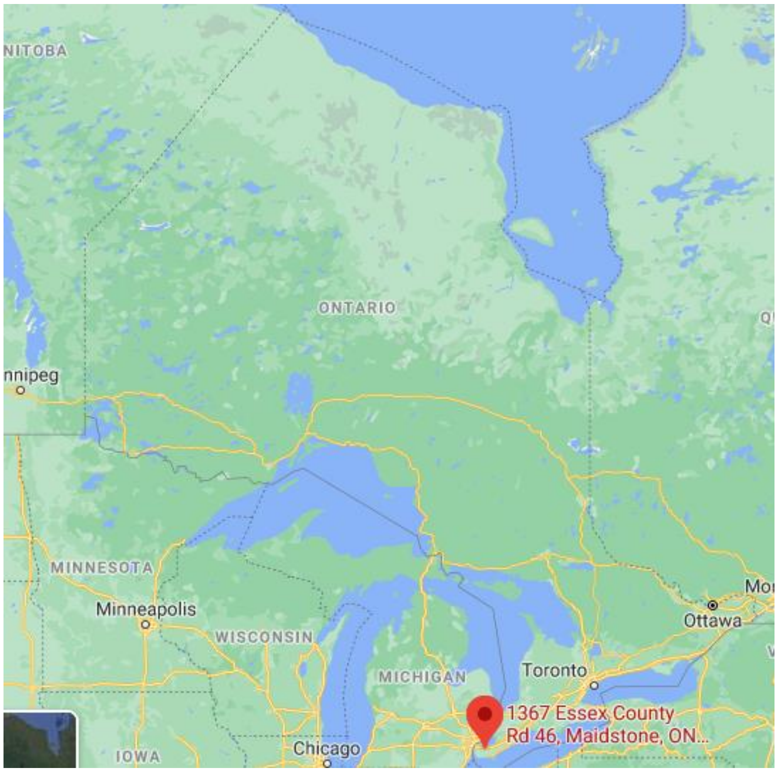

Figure 1: Study area at Woodslee, Ontario (42.2, -82.7). Google. (2020). 1367 Essex County road 46 retrieved from https://www.google.com/maps/place/1367+Essex+County+Rd+46,+Maidstone,+ON+N0R+1K0/@42.2154055,82.7503777,552m/data=!3m2!1e3!4b1!4m5!3m4!1s0x883ad1c50a085883:0xb7822.

Calibration and evaluation of APEX were performed on a field-scale since soil, slope, and management practices are the same for the whole area. The observed data are divided into 17 periods starting from June 1, 2008, until December 22, 2011. The model ran on a daily time step and was evaluated using the 17 periods. Each period has a different time length depending on agronomy practices and forecasted weather (Wang et al., 2018b). The data include the amount of particulate P and dissolved reactive P in surface runoff and in subsurface (i.e., tile drainage) flow, the total runoff and drainage flow volume for each period, the daily weather (temperature, wind speed, solar radiation, relative humidity, and rainfall), management practices (fertilizer application date and corn and soybean plant and harvest dates) and soil characteristics. The observed data was collected daily and are summarized in Tables 1, 2, and 3.

Table 1: Data collected from 2008 to 2011 from Woodslee Ontario, DRP (Dissolved Reactive Phosphorus) and PP (particulate phosphorus).

Period	Start	End	Runoff (mm)	Drainage (mm)	DRP in runoff (g/ha)	DRP in drainage (g/ha)	PP in runoff + drainage (g/ha)
1	2008-06-01	2008-06-16	1.6239	1.7517	5.1	3.1	55.0
2	2008-06-17	2008-07-17	16.1993	27.1885	128.2	96.9	521.8
3	2008-07-18	2008-10-22	0.2287	3.9128	0.3	5.0	6.7
4	2008-10-23	2009-02-11	22.7643	183.6687	131.4	192.2	561.3
5	2009-02-12	2009-03-27	124.2830	165.4812	251.6	420.3	1678.4
6	2009-03-28	2009-05-26	9.5795	88.5310	23.6	349.0	268.2
7	2009-05-26	2009-09-16	5.2483	31.7922	23.7	98.1	242.9
8	2009-09-17	2009-10-23	0.09230	0.0851	0.1	0.09	0.3
9	2009-10-24	2010-04-20	10.8005	79.1595	14.7	173.3	341.6
10	2010-04-21	2010-06-11	13.5812	164.6895	34.8	102.0	776.0
11	2010-06-11	2010-08-05	24.0940	55.5227	227.0	244.6	515.1
12	2010-08-06	2010-12-21	0.1964	8.8452	1.0	11.5	9.6
13	2010-12-22	2011-03-23	26.2210	242.3116	61.5	540.3	553.9
14	2011-03-24	2011-06-22	104.3045	281.8312	300.7	684.1	3874.2
15	2011-06-22	2011-09-07	0.8307	13.8780	1.4	431.4	151.9
16	2011-09-08	2011-11-07	68.2091	151.3841	126.1	348.3	653.9
17	2011-11-08	2011-12-22	108.0915	143.1725	162.0	3567.0	1618.2

Table 2:Management practice from 2008-2011.

Year	Date	Management practices
2008	10-Jun	Inorganic fertilizer
	18-Jun	Maize planting
	05-Nov	Maize harvest
2009	05-Mar	Chisel plow
	22-May	Soybean planting
	20-Oct	Soybean harvest
	01-Nov	Chisel plow
2010	17-Jun	Inorganic fertilizer
	26-Jun	Maize planting
	08-Nov	Maize harvest
	01-Dec	Chisel plow
2011	15-Jun	Soybean planting
	13-Dec	Soybean harvest
	20-Dec	Chisel plow

Table 3:Soil properties of the study site.

Soil Layer depth (m)	ρ (Mg m^{-3})	Clay (%)	Sand (%)	OM (%)	θ_{fc} (m^3m^{-3})	φ (m^3m^{-3})	θ_{wp} (m^3m^{-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	0.9
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	0.9
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	0.9
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	0.7
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	0.5
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	0.4

ρ, soil bulk density; Clay, soil clay content; Sand, Soil Sand Content; OM, Soil organic matter content; θfc, Volumetric soil moisture content at field capacity; φ, Soil Porosity; θwp, 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.

First, two years of data were used for calibration, and the data from the next two years were used for evaluation. Various outputs were compared to ensure the accuracy of calibration and evaluation. The first thing to check is the water and nutrient balance, which should be near 0. Water plays a significant role because it affects crop growth and consequently affects the P loss in runoff and drainage. When the water balance was achieved, the results for crop yields, annual and periodic surface runoff, drainage, and P loss in surface runoff and drainage were checked. In the case where water balance is not close to zero, the potential evapotranspiration (PET) range will be checked (the range needs to be between 700m - 800mm) (Steglich et al., 2018). If PET is not in a reasonable range, crop yield will decrease due to water stress (Wang et al., 2012). The best PET equation was used to calibrate PET, and the corresponding parameter was used to calibrate the equation. For example, if Penman-Monteith were to be chosen, then parameter (1), which is the crop-canopy PET for the Penman-Monteith equation, will be used to calibrate PET. When PET is in range, water balance and crop yields should be closer to the observed values. Option #5 variable daily CN SMI (soil moisture index) of the Curve Number (CN) options is chosen to calibrate surface runoff. Variable daily CN SMI is reliable since it is not sensitive to errors in soil data (Steglich et al., 2018). Parameter 42, the SCS curve number index coefficient, is used to calibrate runoff. To calibrate Particulate P in surface runoff and subsurface drainage, parameters 46 and 47, which are RUSLE (Revised universal soil loss equation) C factor coefficients, were used. To calibrate and evaluate phosphorus in surface runoff, Parameter 8 - soluble phosphorus runoff coefficient and parameter 59 - P upward movement by evaporation coefficient were used. Parameter 84 - coefficient regulating P flux between labile and active pool, and parameter 85 - coefficient regulating P flux between active and stable pool were also used. Preferential flow via cracks, earthworms, and root channels is typical in this area characterized by Brookstone clay loam. Fraction inflow partitioned to vertical/horizontal crack flow will be used to substitute preferential flow (Wang et al., 2018b).

2.3 Statistical analysis

Statistical analysis was accomplished with Nash-Sutcliffe modeling efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS) to evaluate the simulated results (Wang et al., 2012):

$$NSE = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n} O_i}\right]$$

$$R^2 = \frac{\sum_{i=1}^{n}(O_i - \bar{O})\,(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\,\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}$$

where,

n is the total number of observations
O_i is the i^{th} observed value for the parameter being evaluated,
P_i is the i^{th} simulated value for the parameter being evaluated,
$\boldsymbol{\bar{O}}$ is the mean of the observed data for the parameter being evaluated
$\bar{P}$ is the mean of the simulated data for the parameter being evaluated (Wang et al., 2018b).

Statistical analysis was conducted for the 17 periods and it was for the observed vs simulated data. It is essential to do more than one statistical test on the simulated results because one test can show satisfactory results, and the second can show non-satisfactory results (Wang et al., 2012).

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Chapter III: Results and Discussions

3.1 Impacts of PET and CN equations

Potential evapotranspiration equations and curve number equations were used to determine the best combination and evaluate crop yields, potential evapotranspiration, and flow volumes. There are five different methods to evaluate potential evapotranspiration. Penman-Monteith, Penman, Hargreaves, Baier-Robertson, and Priestly-Taylor. Penman-Monteith is considered the most accurate despite the sensitivity to wind speed (Steglich et al., 2018). Penman-Monteith equations are mostly used for windy conditions (Steglich et al., 2018). Penman-Monteith and Penman are the most data-intensive equations; they both require solar radiation, air temperature, wind speed, and relative humidity for inputs (Gassman et al., 2010). Hargreaves is modified to closely match the Penman-Monteith equation with the choice of exponents and equation coefficients (Wang et al., 2018b). It evaluates potential evapotranspiration as a function of extraterrestrial radiation and air temperature (Wang et al., 2018b). Hargreaves has two parameters that can be calibrated (Steglich et al., 2018), and it only requires air temperature as input (Gassman et al., 2010). Baier-Robertson was developed in Canada, and it can provide more accurate results for colder climates (Gassman et al., 2010). Priestly-Taylor requires radiation and temperature as input (Steglich et al., 2018).

Runoff can be calculated using two methods: the curve number equations, and the Green and Ampt infiltration equation. Usually, the Green and Ampt method is used when CN equations are not performing well (Steglich et al., 2018). Green and Ampt use the sub-daily rainfall approach, while CN uses daily rainfall data (Gassman et al., 2010). There are five different options to calculate the curve number for runoff (Table 5). Option number 5 (Variable Daily CN SMI (soil moisture Index)) is most reliable because it is not sensitive to errors in soil data (Steglich et al., 2018). Parameter (42) - SCS curve number index coefficient is used to calibrate option 5 (Steglich et al., 2018). Options 1 and 2 of the CN equations (Table 5), which are the nonlinear options, perform well in several situations (Steglich et al., 2018). Option 1 is the Variable daily CN nonlinear CN/SW with depth soil water weighting, and parameter (92) – Runoff volume adjustment for direct link is used to adjust it if chosen. Option 4 is the Non-varying CN—CN2 used for all storms; is a good method to use in situations where soil water is not dominant (Steglich et al., 2018).

3.1.1 PET Equations

Table 4 shows the impacts of different potential evapotranspiration equations on the crop yield, potential evapotranspiration, surface runoff, and subsurface drainage. The estimated averages for the different equations are as follows: Hargreaves average is 724.65mm, Penman-Monteith average is 1017.5mm, Baier-Robertson average is 805.2mm, and Penman average is 1056.2mm. The acceptable range for the potential evapotranspiration is 732 ± 83mm (Wang et al., 2018b), and it is based on the observed value from the field. The only two that are in range are the Hargreaves and Baier-Robertson. Simulated crop yields had similar results between the different potential evapotranspiration equations. Based on the observed crop yields, the best simulated crop yield result was for the Hargreaves equation. Corn crop (2008 and 2010) yields were affected more by the potential evapotranspiration compared to the soybean crops (2009 and 2011) yields. Simulated surface runoff and subsurface drainage statistical analysis are also shown in Table 4. Hargreaves equation simulated the best periodic runoff and subsurface drainage (Table 4). The second-best performance is the Baier-Robertson and then Penman-Monteith equations, and the worst performance is the Penman equation. Hargreaves was chosen for the calibration as it yielded the best results in terms of crop yield, potential evapotranspiration, surface runoff, and subsurface drainage combined. Priestly-Taylor failed to run using this model, and it could have resulted from the simplification of the equation to 1.28 for the coefficient when the surface areas are wet, and that could be higher under agricultural lands. Another possible reason is that Priestly-Taylor equation does not use wind or relative humidity in the calculation; it requires radiation and temperature. These could be some possible reasons why it failed to run in the model. According to the study by Wang et al. (2018b), it does not accurately simulate crop yield, PET, surface runoff and subsurface drainage as well as the other equations in this study area with clay loam soil.

Table 4:Impacts of different potential evapotranspiration equations on the crop yield, potential evapotranspiration, surface runoff, and subsurface drainage, with the statistical model analysis.

PET Calculation	YEAR	Annual Crop Yield (Mg ha^{-1})	PET (mm)	Periodic Surface Runoff	Drainage
Hargreaves	2008	8.64	735.8		
	2009	3.41	720.1		
	2010	8.06	757.2		
	2011	3.04	685.5		
	R^2			0.80	0.73
	NSE			0.77	0.66
	PBIAS (%)			-4.04	18.61
Penman-Monteith	2008	5.15	1070		
	2009	3.21	978.3		
	2010	5.80	1140		
	2011	3.04	881.8		
	R^2			0.63	0.37
	NSE			0.55	0.09
	PBIAS (%)			25.94	46.34
Baier-Robertson	2008	7.56	826.2		
	2009	3.33	797.3		
	2010	7.54	864.9		
	2011	3.04	732.5		
	R^2			0.70	0.59
	NSE			0.64	0.49
	PBIAS (%)			5.06	28.47
Penman	2008	6.38	1069		
	2009	3.30	1064		
	2010	7.06	1134		
	2011	3.04	957.9		
	R^2			0.57	0.43
	NSE			0.46	0.23
	PBIAS (%)			34.27	38.82

3.1.2 CN Equations

Table 5 shows the impacts of different curve number (CN) equations on the crop yield, potential evapotranspiration, surface runoff, and subsurface drainage. The different CN equations did not impact potential evapotranspiration. For crop yields, option number 5, which is Variable daily CN SMI (Soil Moisture Index), and option number 3, which is Variable daily CN linear C(N/S)W with no depth weighting, simulated the best crop yields, followed by the rest of the options. Simulated surface runoff and subsurface drainage had the best performance with option number 5, followed by option number 1 (Variable daily CN nonlinear C(N/S)W with no depth weighting) and option number 2 (Variable daily CN nonlinear C(N/S)W with no depth weighting), and then the other two options (Table 5). The most accurate equation was option 5, and it was chosen for the model of the clay loam soil with high water storage. Option number 5 can produce most accurate and realistic results over a range of different soil properties than any other CN equation (Wang et al., 2018b). Different parameters were used to calibrate and evaluate the CN equation that was chosen.

Table 5:Impacts of different CN equations on the crop yield, potential evapotranspiration, surface runoff, and subsurface drainage, with the statistical model analysis.

CN Equation	YEAR	Annual Crop Yield ($Mg\ ha^{-1}$)	PET (mm)	Periodic Surface Runoff (mm)	Drainage (mm)
Variable daily CN nonlinear (CN/SW) with soil water depth weighting	2008	6.05	735.8		
	2009	3.41	720.1		
	2010	6.67	757.2		
	2011	3.04	685.5		
	R^2			0.75	0.68
	NSE			0.61	0.58
	PBIAS (%)			-37.91	27.05
Variable daily CN nonlinear (CN/SW) with no depth weighting	2008	6.24	735.8		
	2009	3.41	720.1		
	2010	6.84	757.2		
	2011	3.04	685.5		
	R^2			0.74	0.71
	NSE			0.71	0.64
	PBIAS (%)			-24.92	22.91
Variable daily CN linear (CN/SW) with no depth weighting	2008	8.46	735.8		
	2009	3.41	720.1		
	2010	7.44	757.2		
	2011	3.04	685.5		
	R^2			0.67	0.70
	NSE			0.16	0.48
	PBIAS (%)			-79.69	40.80
Non-varying CN-CN_2 used for all storms	2008	5.89	735.8		
	2009	3.40	720.1		
	2010	6.67	757.2		
	2011	3.04	685.5		
	R^2			N/A	0.61
	NSE			-0.6	0.52
	PBIAS (%)			100	-11.92
Variable daily CN SMI (Soil Moisture Index)	2008	8.64	735.8		
	2009	3.41	720.1		
	2010	8.06	757.2		
	2011	3.04	685.5		
	R^2			0.80	0.73
	NSE			0.77	0.66
	PBIAS (%)			-4.04	18.61

3.2 Calibration and Evaluation

After the PET and CN equations have been chosen, the rest of the equations and parameters mentioned in the methodology section were used to calibrate and evaluate APEX. The calibration was based on 2008 and 2009, and the evaluation was based on 2010 and 2011 data. Both yielded satisfactory results for the surface runoff, subsurface drainage, dissolved reactive P in surface runoff and subsurface drainage, and particulate phosphorus in surface runoff and subsurface drainage, as illustrated in Table 6. Table 6 illustrates the non-cumulative results based on the observed vs simulated data.

Table 6:Calibration and evaluation results for 2008 to 2011.

		Surface Runoff	**Subsurface Drainage**	**P loss in surface Runoff**	**P loss in subsurface drainage**	**P loss with sediment**
Calibration	R^2	0.88	0.60	0.60	0.87	0.84
	NSE	0.84	0.57	0.54	0.75	0.58
	PBIAS (%)	-14.97	17.30	11.14	-18.12	8.50
Evaluation	R^2	0.71	0.76	0.61	0.75	0.82
	NSE	0.68	0.62	0.51	0.75	0.68
	PBIAS (%)	2.00	19.32	21.39	-0.42	26.69

When PBIAS has a higher value (e.g., 19.32%), that indicates the quantity was not as accurately simulated as the lower PBIAS (e.g., 2.00%). Low NSE (e.g., 0.57) indicates that the pattern is not as well estimated compared to higher NSE (e.g., 0.88). The higher PBIAS and lower R^2 and NSE values in Table 6 could be contributed from (i) high drainage rates due to excessive precipitation and snow melting from fluctuating temperatures in the Spring and Fall, (ii) constant crack flow coefficient on APEX, (iii)

APEX simplification of subsurface drainage, and (iv) application date for fertilizer/manure followed by precipitation results in some loss of P with precipitation. More details of the over and underestimations of the periods are provided in sections 3.4 and 3.5. Phosphorus loads were based on concentration of phosphorus in soil and flow volume of runoff and subsurface drainage. Phosphorus loads were more accurate for this study because the average of the phosphorus concentration was taken instead of the peak concentration.

The cumulative analysis was used to visualize the trends/graphs before and after the model was calibrated and evaluated. Cumulative analysis could be misleading sometimes as it could show there is an underestimation or overestimation for all the periods if there was an under or over estimation early on. Figures 2a and 2b show the cumulative results for the surface runoff pre-calibration and evaluation (2a) and post-calibration and evaluation (2b). In both graphs, the simulated data is greater than the observed data, and both graphs show the same trend between observed and simulated data. Figure 2a has a larger variation between observed and simulated data, while the values for Figure 2b are closer to each other after the calibration and evaluation of the model.

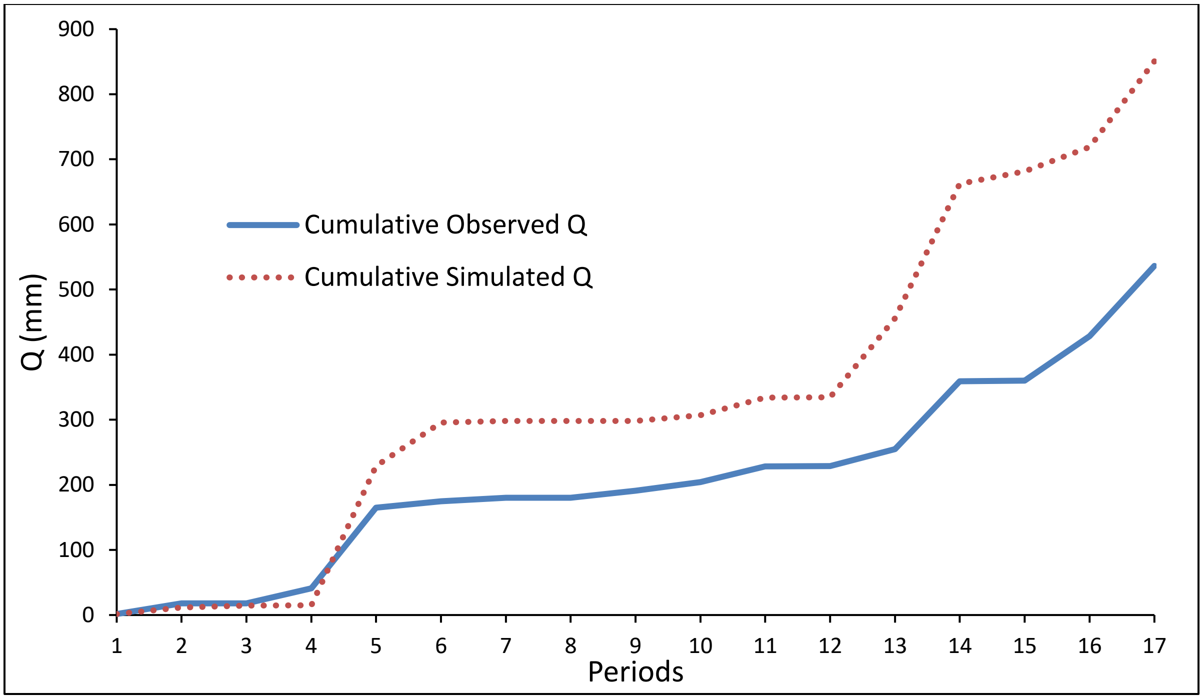

Figure 2a: Cumulative results before calibration and evaluation for surface runoff (Q).

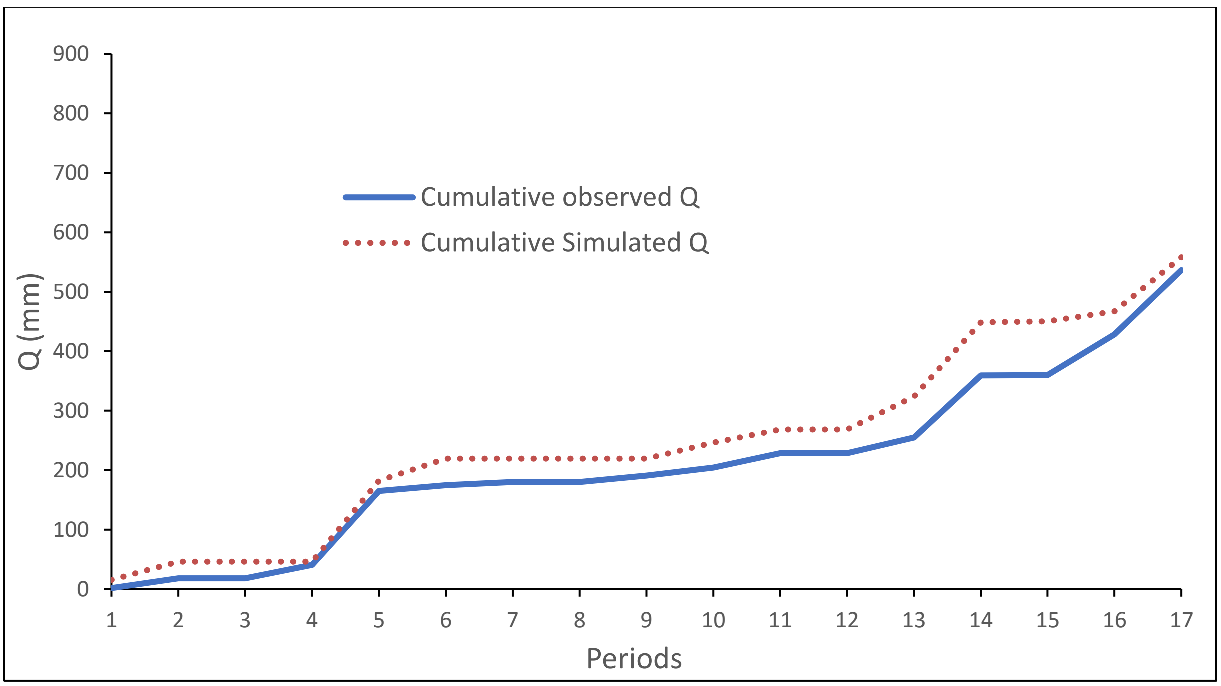

Figure 2b: Cumulative results after calibration and evaluation for surface runoff (Q).

Figures 3a and 3b show the cumulative results for the subsurface drainage pre-calibration and evaluation (3a) and post-calibration and evaluation (3b). There is a considerable difference between the observed and simulated values in Figure 3a. The simulated data do not have the same fluctuations as the observed data; it is a straight line compared to the observed data. Period 17 is around 200 mm, while the observed data is around 1600 mm. Post calibration and evaluation in Figure 3b show the observed and simulated data have the same trends and the values are closer to each other. Period 17 is at around 1400 mm compared to 200 mm for pre-calibration and evaluation. For Both graphs, the simulated data were underestimated.

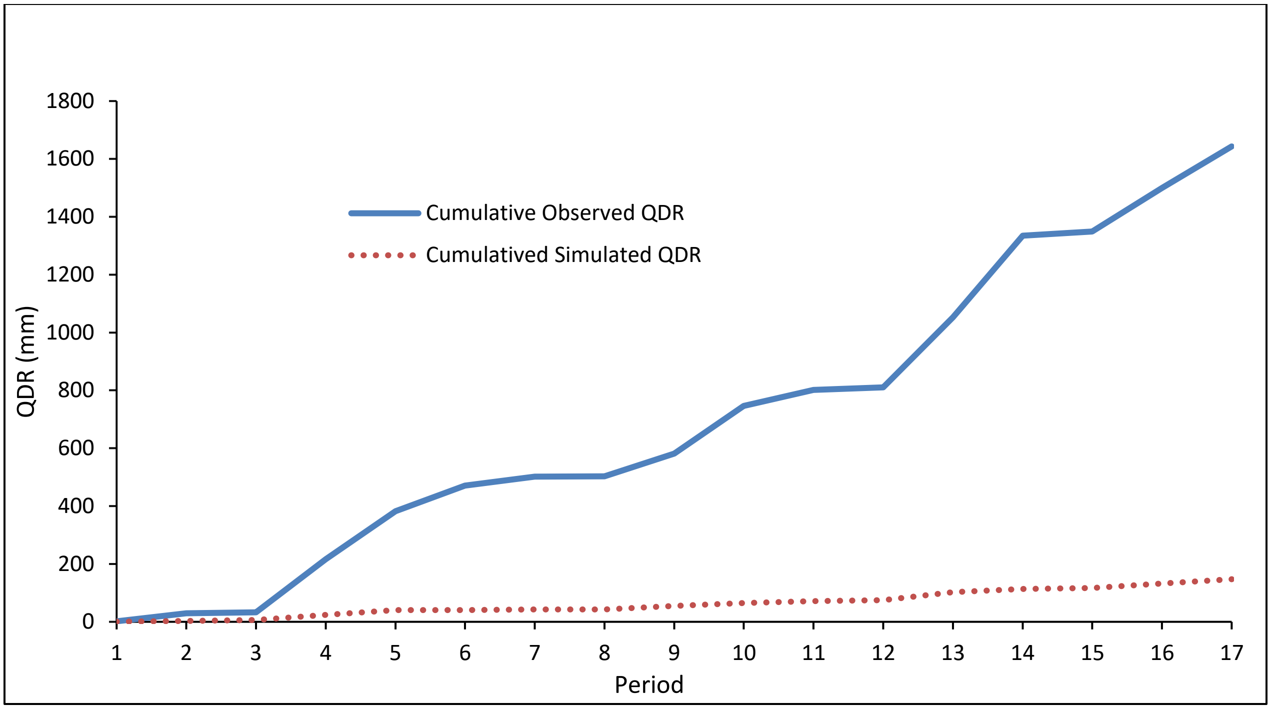

Figure 3a: Cumulative results before calibration and evaluation for subsurface drainage (QDR).

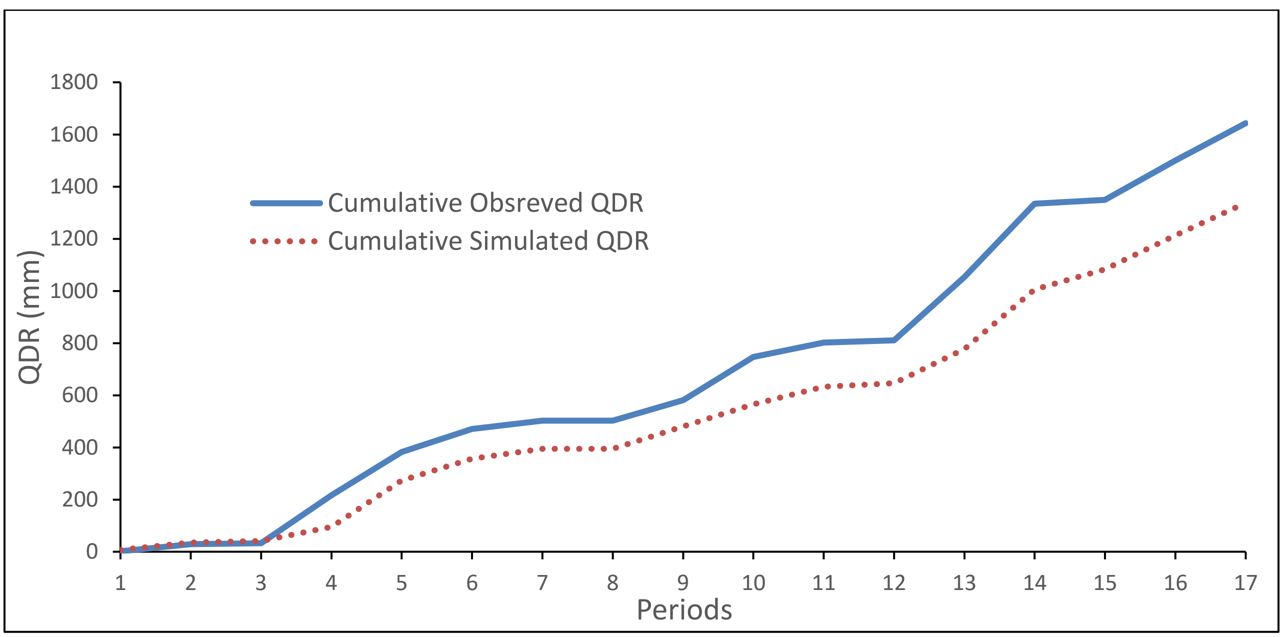

Figure 3b: Cumulative results after calibration and evaluation for subsurface drainage (QDR).

Figures 4a and 4b show the cumulative analysis for the dissolved reactive phosphorus in surface runoff pre-calibration and evaluation (4a) and post-calibration and evaluation (4b). In figure 4a, observed and simulated data have the same values for the first four periods, but then the gap gets more significant between them. The simulated data does not have the same trends as the observed data, and the data is overestimated. Figure 4b indicates that the simulated and the observed data have a smaller gap and have the same trend between them after calibration and evaluation. The dissolved reactive phosphorus was underestimated after period 3.

Figures 5a and 5b show the cumulative analysis for the dissolved reactive phosphorus in subsurface drainage (QDRP) pre-calibration and evaluation (5a) and post-calibration and evaluations (5b). In Figure 5a, QDRP is overestimated, and the difference between the observed and simulated values gets more significant with the periods. In Figure 5b, QDRP is overestimated as well, but the values between the observed and simulated data are similar, and the gap is much smaller after calibration and evaluation.

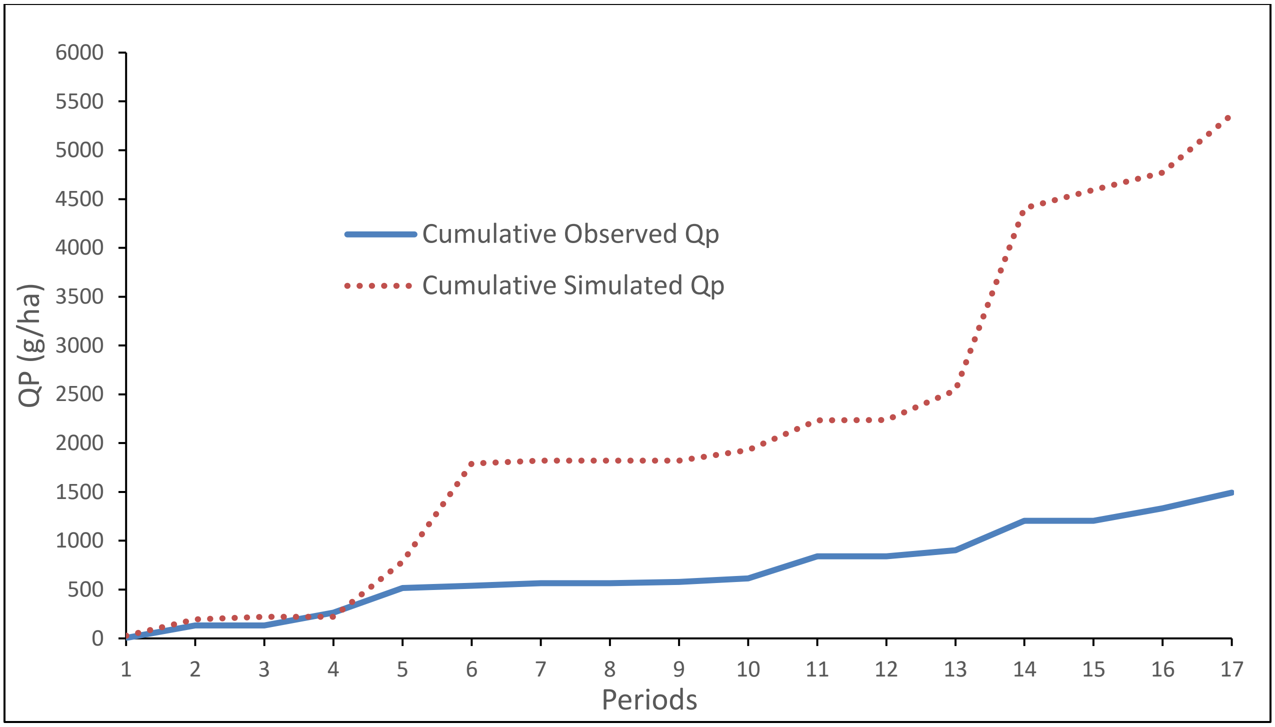

Figure 4a: Cumulative results before calibration and evaluation for dissolved reactive phosphorus in surface runoff (QP); results in g/ha.

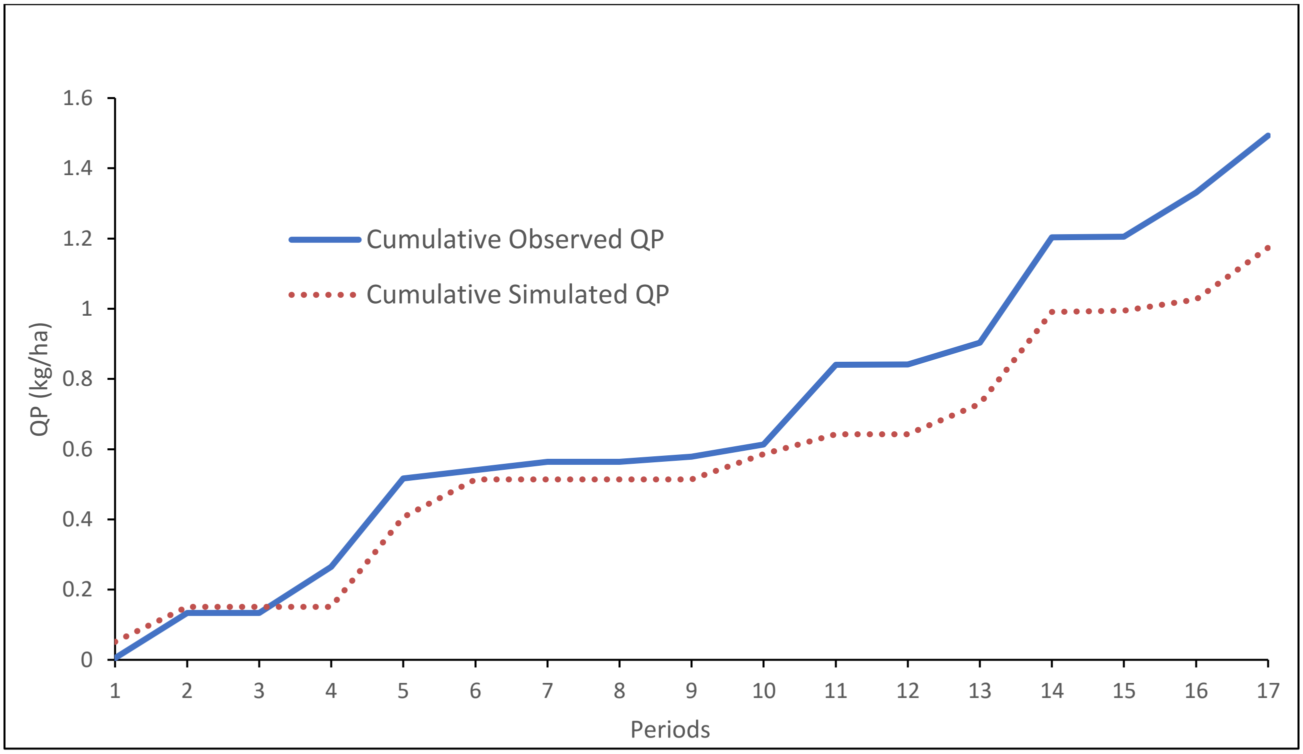

Figure 4b: Cumulative results after calibration and evaluation for dissolved reactive phosphorus in surface runoff (QP), results in Kg/ha.

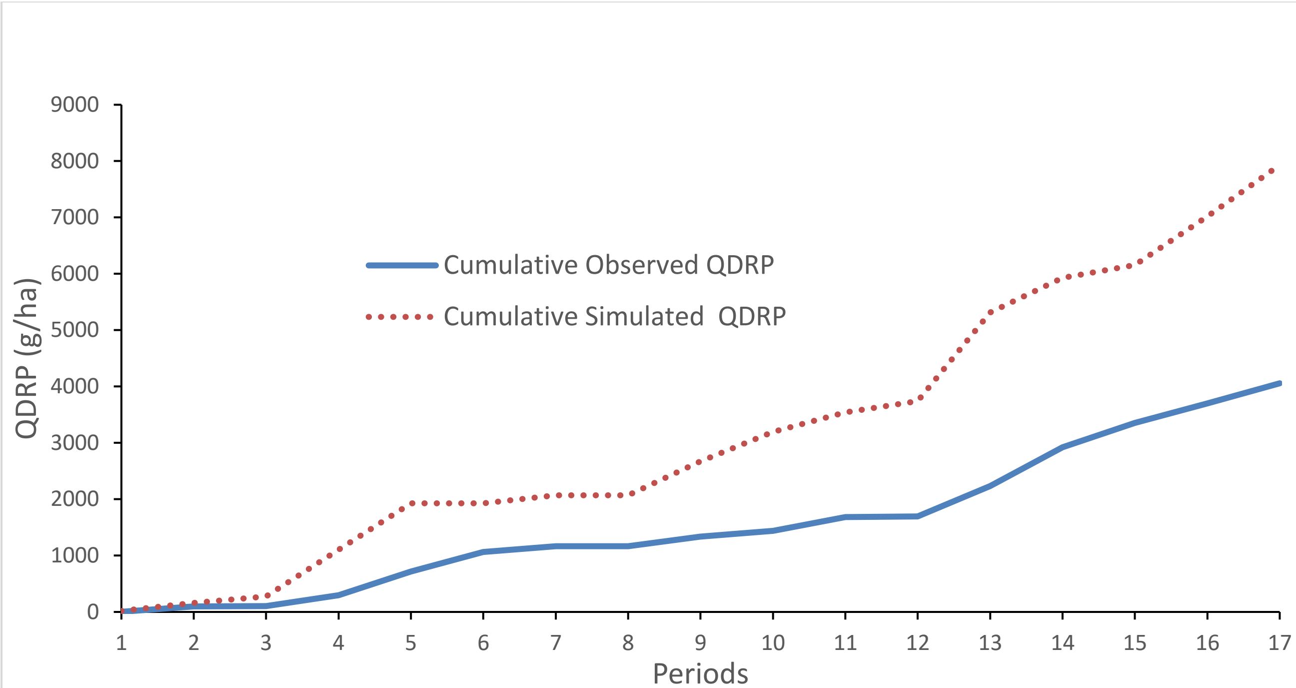

Figure 5a: Cumulative results before calibration and evaluation for dissolved reactive phosphorus in subsurface drainage (QDRP); results in g/ha.

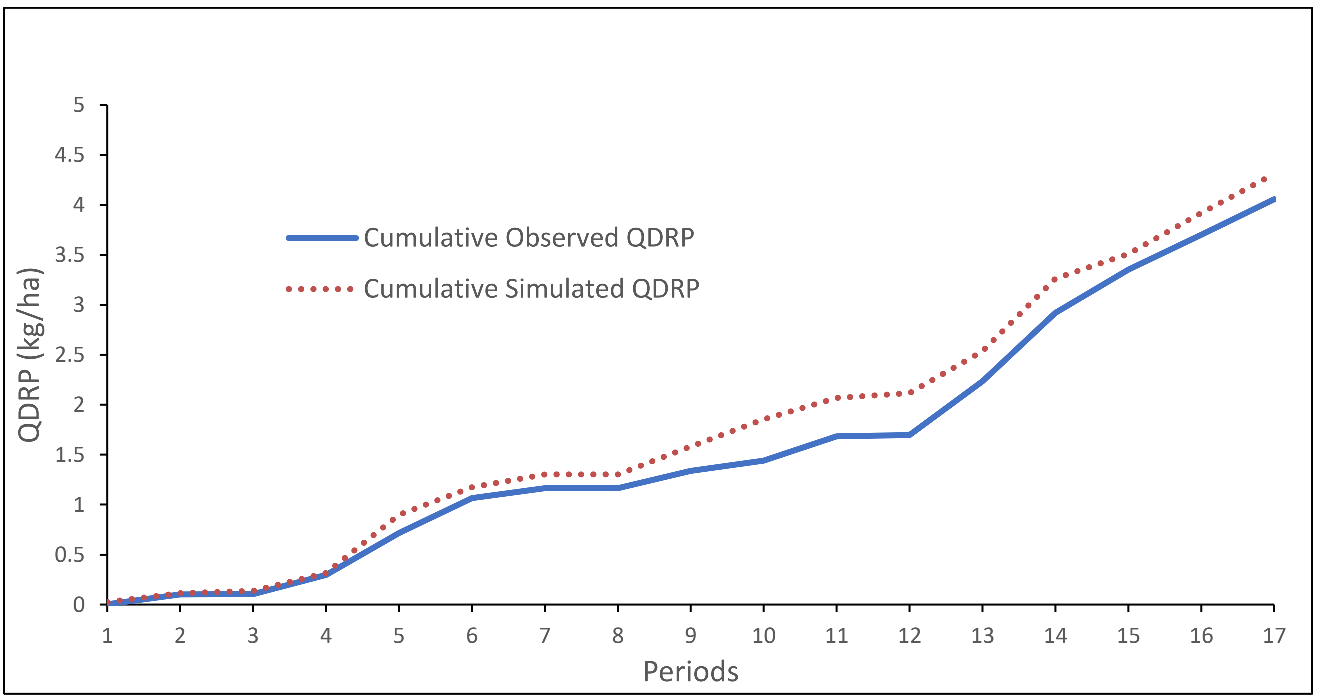

Figure 5b: Cumulative results after calibration and evaluation for dissolved reactive phosphorus in subsurface drainage (QDRP), results in Kg/ha.

Figures 6a and 6b show the cumulative analysis for the particulate phosphorus in surface runoff and subsurface drainage (YP) pre-calibration and evaluation (6a) and post-calibration and evaluation (6b). The simulated and observed YP are closer in values after the calibration and evaluation (Figure 6b) compared to before (Figure 6a). In Figure 6b, the simulated data has same results as the observed data until period 9. In both situations, YP was underestimated.

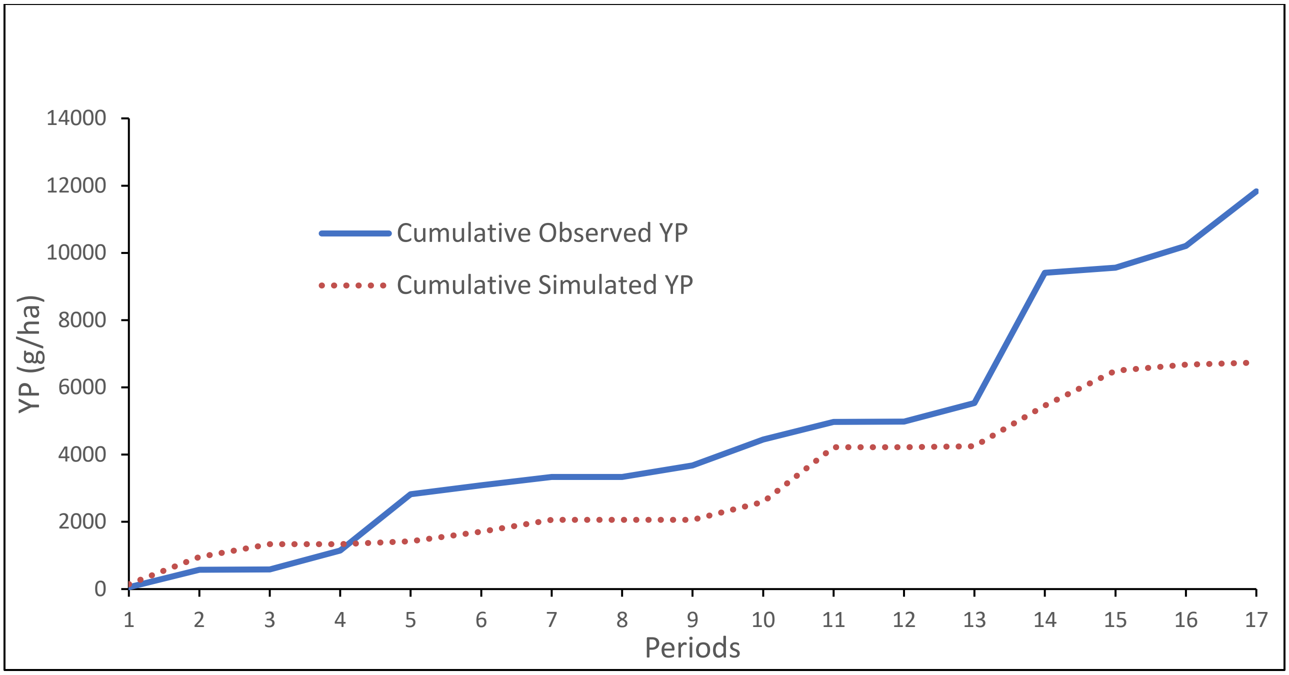

Figure 6a: Cumulative results before calibration and evaluation for particulate phosphorus in surface runoff and subsurface drainage (YP); results in g/ha.

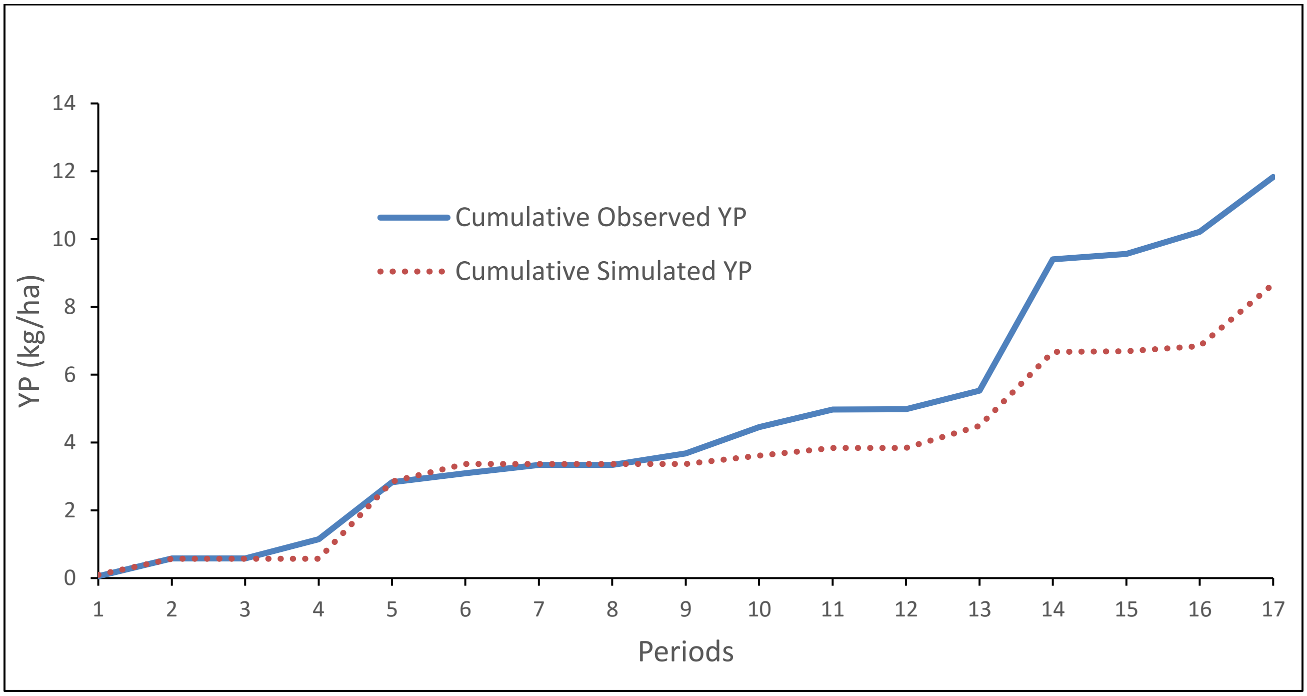

Figure 6b: Cumulative results after calibration and evaluation for particulate phosphorus in surface runoff and subsurface drainage (YP); results in kg/ha.

3.3 Crop Yields

Crop yields results after calibration and evaluation are shown in this section. As shown in Table 7, the model did not simulate any nutritional stress. The temperature stress does not affect the yield as APEX calculates temperature stress at harvest date, not at the crop maturity date. The simulated crop yield and the potential evapotranspiration shown in Table 8 are the results of analyzing and choosing the most accurate combinations between CN equations and the potential evapotranspiration equations, and that is option number 5 and Hargreaves equation. Potential evapotranspiration fell into the satisfactory range (732±83mm) (Wang et al., 2019). The mean for the simulated corn and soybean crop yield is 5.78 Mg/ha, which is 4.6% lower than the mean for the observed corn and soybean crop yield, 6.05 Mg/ha. Statistical analysis shows that the crop yield had satisfactory results (Table 8). The crop yields were analyzed separately to get a better idea for each year.

In 2008 the simulated corn yield (8.64 Mg/ha) was 2.46% higher than the observed corn yield (8.43 Mg/ha). In 2009 the simulated soybean yield (3.41 Mg/ha) was 19.33% lower than the observed soybean yield (4.14 Mg/ha). In 2010 the simulated corn yield (8.06 Mg/ha) was 1.48% lower than the observed corn yield (8.18 Mg/ha). In 2011 the simulated soybean yield (3.04 Mg/ha) was 12.63% lower than the observed soybean yield (3.45 Mg/ha). Many reasons could have affected the simulated crop yields. Water is the most crucial factor that affects crop yields. For example, in 2011, the simulated soybean was 12.63% lower than the observed value, which can be affected by the potential evapotranspiration as it was the lowest compared to the other years. Another possible reason is the model could have over or underestimated the drought stress days and the excess water stress days. On the field, the water stressors could have been a little bit different. Another reason could be the over and underestimation of surface runoff, which effects potential evapotranspiration, drought stress days, and excess water stress days. Soybean had a more significant percentage difference between the simulated and observed crop yields than the corn crop yields, which could be caused of the underestimating of nitrogen stress compared to the field nitrogen stress.

Table 7:Simulated drought stress (WS), nitrogen stress (NS), phosphorus stress (PS), temperature stress (TS) and excess water stress (AS).

Year	WS (Days)	NS (Days)	PS (Days)	TS (Days)	AS (Days)
2008	0.08	0.0	0.0	38.7	0.0
2009	0.0	0.0	0.0	44.4	0.0
2010	0.14	0.0	0.0	47.7	0.0
2011	0.0	1.0	0.0	47.5	0.0

Table 8:Simulated crop yield and potential evapotranspiration.

	YEAR	Crop Yield (Mg/HA)		PET (mm)	
		Observed	Simulated	Observed	Simulated
Corn	2008	8.43	8.64		735.8
Soybean	2009	4.14	3.41		720.1
Corn	2010	8.18	8.06		757.2
Soybean	2011	3.45	3.04	732±83	685.5
R^2		0.99			
NSE		0.96			
PBIAS		4.34%			

3.4 Surface Runoff and Subsurface Drainage

Calibrated and evaluated surface runoff and subsurface drainage results are presented in this section. Simulated surface runoff had a satisfactory result of R^2=0.80, NSE=0.77, and PBIAS=-4.04%, even though some over and underestimations have occurred (Figure 7a). The overestimations that occurred in some of the periods for runoff were tied to the underestimation that occurred for the same period for the subsurface drainage. The periods were April 21, 2010, to June 10, 2010, December 22, 2010, to March 23, 2011, and March 24, 2010, to June 22, 2011. In the first two periods, there was an overestimation. One possible reason is the amount of precipitation of 45mm in one day. Another possible reason is the constant crack flow coefficient that is constant on APEX, but in the field, it changes based on different conditions. The overestimation that occurred for the period March 28, 2009, to May 25, 2009 could be because the model assumed that snow melting has occurred as the temperature fluctuates from the negative temperatures to positive temperatures.

Simulated subsurface drainage had satisfactory results when modeled (R^2=73, NSE= 0.66, and PBIAS = 18.61%), although there were some overestimations and underestimations for some periods (Figure 7b). The overestimation that occurred for the subsurface drainage could be from the constant crack flow coefficient modeled in APEX. Another reason is the simplification of the subsurface drainage in APEX, since it considers all the subsurface flow above the subsurface drainage as subsurface drainage flow. An underestimation occurred on October 23, 2008, to February 11, 2009. The reason behind it could be from the fluctuation of temperature around zero degrees, resulting in the snow melting and the precipitation to saturate the soil. Which led to high drainage rates on the field, but it was not accurately simulated on APEX. Precipitation, temperature, constant crack flow coefficient, crop interception, and simplifying subsurface drainage are some of the possible reasons why some periods can be over or underestimated compared to the observed values on the field.

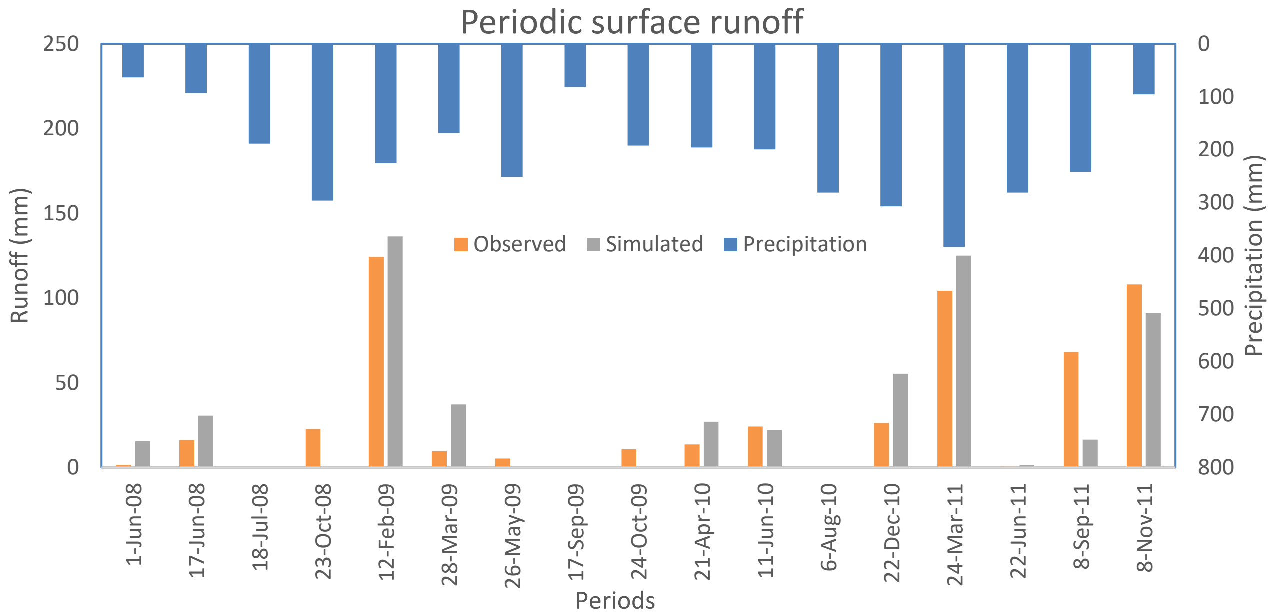

Figure 7a: Observed vs. simulated results for the periodic surface runoff with the precipitation.

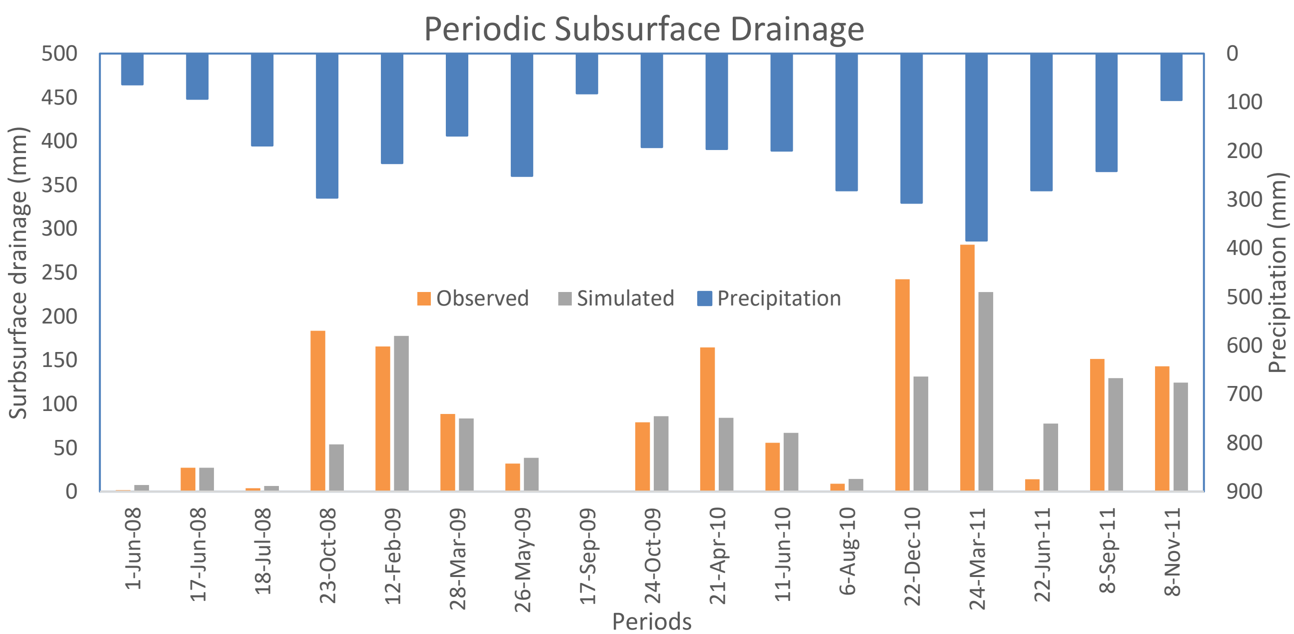

Figure 7b: Observed vs. simulated results for the periodic subsurface drainage with the precipitation.

3.5 Phosphorus Loss Surface Runoff and Subsurface Drainage

Calibrated and evaluated results for P loss in surface runoff and subsurface drainage are presented in this section. Simulated soluble phosphorus loss in surface runoff (QP) had satisfactory results (R^2= 0.60, NSE=0.55 and PBIAS= 21.39%). There are three overestimated periods (June 1, 2008 to June 16, 2008; March 28, 2009 to May 25, 2009; and December 22, 2010 to March 23, 2011). The three overestimated periods were tied to the overestimation of runoff in Figure 7a. Similarly, if there is any underestimation in QP, it could be tied to the underestimation of surface runoff for that period. From October 23, 2008 to February 11, 2009, for example, there was no simulated surface runoff, leading to no P loss simulated in the surface runoff. Another underestimated period is September 8, 2011 to November 7, 2011, where surface runoff was underestimated; consequently, QP was underestimated as well. Both underestimations that occurred on June 17, 2008 to July 17, 2008 and June 11, 2010 to August 5, 2010 are caused by the precipitation after applying solid cattle manure (Wang et al., 2019). Solid cattle manure was applied on June 2nd and 3rd of 2008, and a precipitation event of 45 mm occurred on June 21, 2008. The second solid manure application was on June 11, 2010; and a heavy precipitation of 73.8 mm followed on July 23, 2010. Precipitation after manure application can result in heavy losses of QP. Another underestimation occurred from March 24, 2011 to June 21, 2011. One possible reason for the underestimation is that the model did not simulate the leaf cover that occurred before harvesting, which could be another phosphorus source. Another possible reason is the higher crack flow coefficient on the field, leading to more QP moving to subsurface drainage or deep percolation (Wang et al., 2019).

Simulated soluble phosphorus loss in subsurface drainage (QDRP) had satisfactory results (R^2= 0.82, NSE=0.81, and PBIAS= -6.26 %). Similar to QP, over and underestimation of QDRP is tied to over and underestimation of subsurface drainage. The overestimated period from February 12, 2009 to March 27, 2009 in QDRP is tied to the overestimation in subsurface drainage for the same period. The underestimated periods from March 28, 2009 to May 25, 2009 and December 22, 2010 to March 23, 2011 in QDRP were tied to underestimation of subsurface drainage. The other periods of over- and underestimation could result from the constant crack flow, which is not as realistic as the change of crack volume on the field. Another possible reason is the crop cover before harvesting that can cause more phosphorus added to the soil. The third possible reason is that some parameters (such as parameter 84-coefficient regulating P flux between labile and active pool and parameter 85-coefficient regulating P flux between active and stable pool) are assumed constant in the model, while they fluctuate in reality.

Simulated particulate phosphorus loss in surface runoff and subsurface drainage (YP) had satisfactory results (R^2= 0.74, NSE=0.70, and PBIAS= 26.69 %). Similar to QP and QDRP, from February 12, 2009 to March 27, 2009 and from March 28, 2009 to May 25, 2009, overestimation occurred, which is likely because both surface runoff and subsurface drainage were overestimated for these periods. From October 23, 2008 to February 12, 2009 and from September 8, 2011 to November 7, 2011, underestimation occurred, which is tied to the underestimation of both surface runoff and subsurface drainage. June 11, 2010 to August 5, 2010 was underestimated, which could be from the heavy precipitation event of 73.8 mm that occurred on July 23, 2010 after the solid manure application on June 11, 2010. The other underestimated periods could result from the crop cover during the growing season and the residue after harvesting, which stays during the winter. This results in crop protection from soil erosion and from breaking down of phosphorus from the soil particles (Wang et al., 2018).

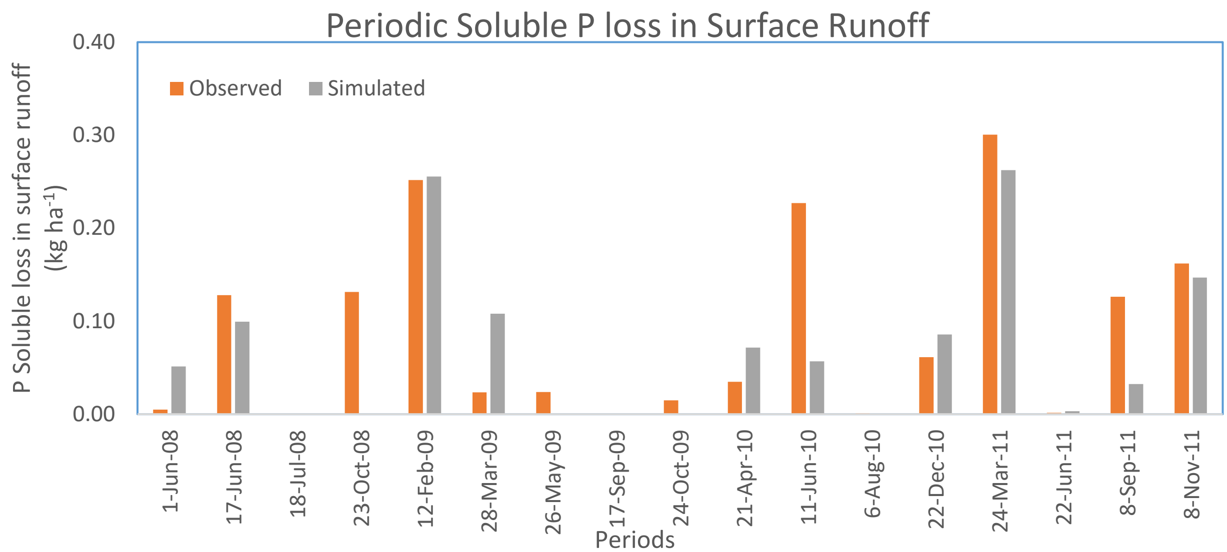

Figure 8a: Observed vs. simulated results for the periodic soluble P loss in surface runoff.

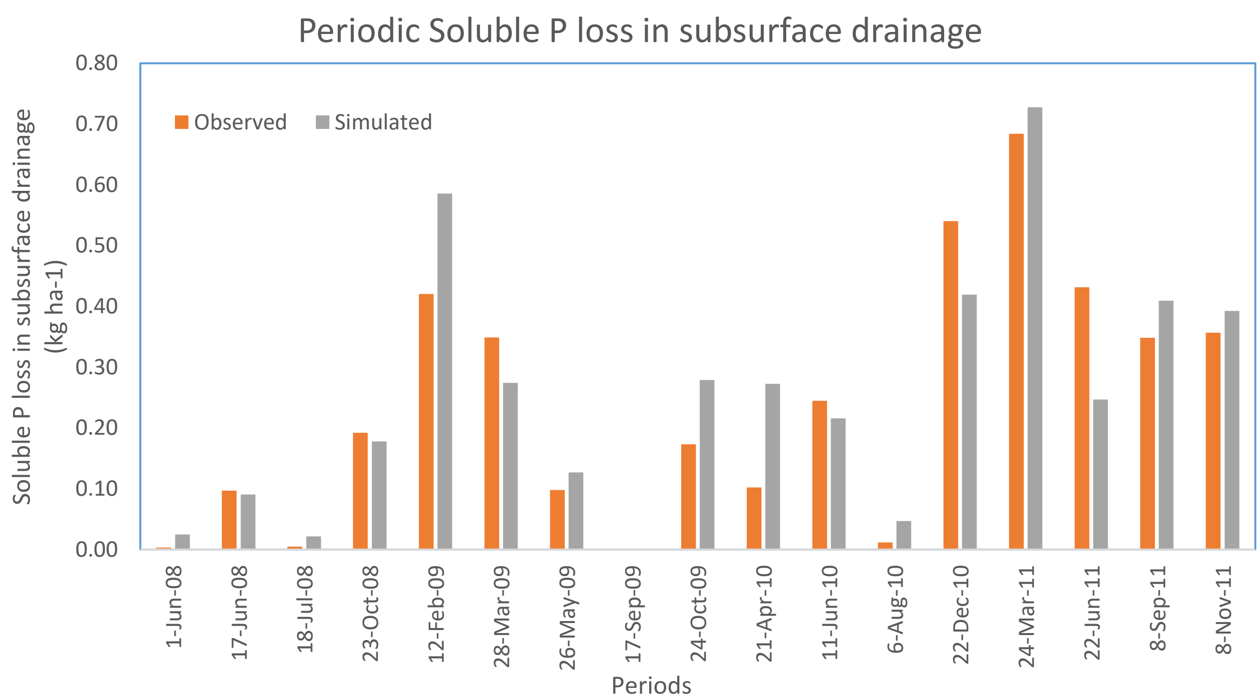

Figure 8b: Observed vs. simulated results for the periodic soluble P loss in subsurface drainage.

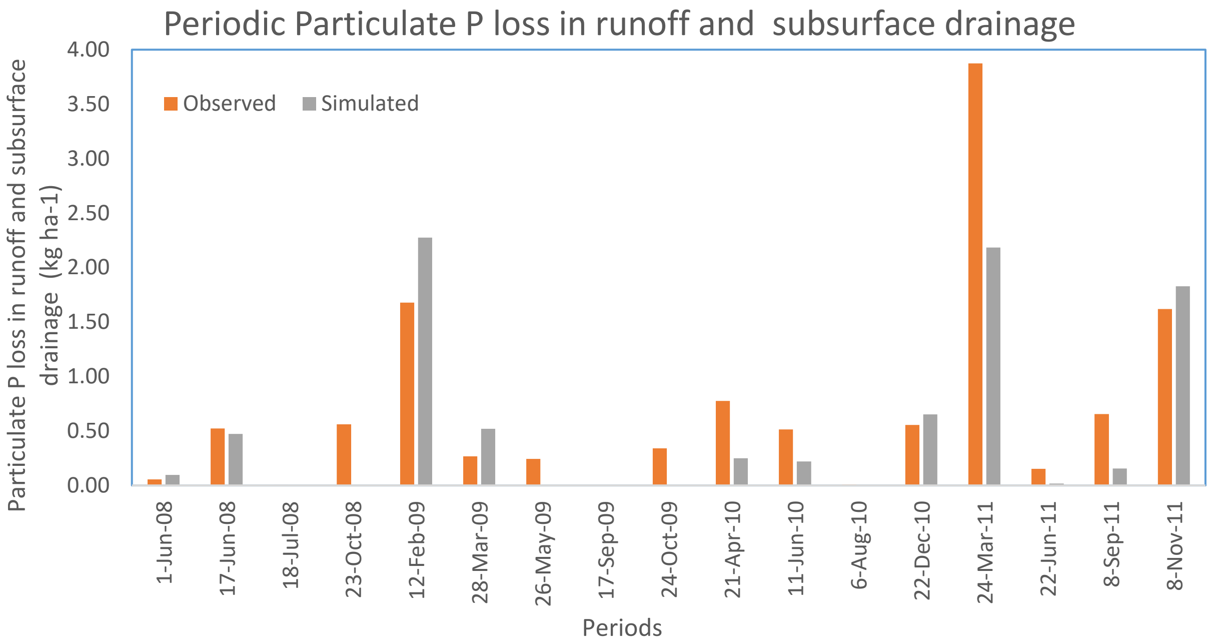

Figure 9: Observed vs. simulated results for the periodic Particulate P loss in runoff and subsurface drainage.

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Chapter IV: Conclusions and Future Work

4.1 Conclusions

This study represents the first investigation into testing APEX on a clay loam soil in southwestern Ontario. APEX was calibrated and evaluated to successfully simulate the crop yields, potential evapotranspiration, surface runoff, subsurface drainage, and phosphorus loss in surface runoff and subsurface drainage in the study area. However, there were some underestimations and overestimation for some periods because of some limitations from the model. The cumulative analysis graphs showed the differences in results between the pre-calibration and evaluation and post-calibration and evaluation. It showed how APEX was successfully calibrated the first two years (Corn-2008, and soybean-2009) and evaluated in the last two years (Corn-2010 and Soybean-2011). The results also showed the different impacts of potential evapotranspiration equations and curve number equations on crop yields, potential evapotranspiration, surface runoff, and subsurface drainage. The combination of the Hargreaves equation and Variable Daily CN soil moisture index curve number equation had the best results for the model's calibration and evaluation process for this study area. The results showed how the solid manure was impacted by precipitation, crop cover, and crack flow coefficient, which affects phosphorus loss to Lake Erie. Therefore, APEX proved to be applicable to the Brookstone clay loam soil of Southwestern Ontario in the Lake Erie Region. This study will help Ontario government in their Ontario’s Action plan project to reduce phosphorus loadings by 2025 to the lake (Ontario Government, 2018). It will serve as a base study for many future studies and projects using APEX or other models in Ontario or Canada. It will also help develop best management practice for agriculture and researchers to set a target to decrease phosphorus loss, and help implement a strategic planning for a sustainable future to save the water bodies from eutrophication.

APEX's limitation is the assumption of a constant crack coefficient that does not represent the changing volume size of crack flow in real life. Another limitation is the assumption of constant parameters for the four-year period, which does not represent the realistic conditions as well. Better assumptions of precipitation, snowmelt, and crop cover would lead to better results in simulating runoff, subsurface drainage, and phosphorus loss. The data only included the average P loads because the average phosphorus concentrations were taken on the field, not the daily peak concentrations.

4.2 Future Work

1) More work will need to be done with APEX to predict phosphorus loss by changing some management practices as follows:

1) Changing planting dates
2) Changing the tillage practices
3) Changing fertilizer rates
4) Changing the type of manure

This work will help develop a better idea of how the different management practices impact the phosphorus loss to Lake Erie, and hence help tackle the problem.

2) More effort will need to be placed on resolving APEX's limitations in order to deal with realistic field conditions

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