A LIMITATION OF THE PREDICTIVE CAPACITY OF THE SWAT MODEL: MODELING P LOSSES FROM DAIRY MANURE SPREADING SCHEMES IN TEMPERATE CLIMATES

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ABSTRACT

The Soil and Water Assessment Tool (SWAT) is a widely used watershed-scale model employed to simulate streamflow and nutrient fluxes, including phosphorus (P), from nonpoint sources to surface water bodies. A number of both lab and field studies have shown that manure spread on fields has high potential for nutrient loss in surface runoff directly following application. We evaluated the ability of P routines in the current version of SWAT to capture this labile period and simulate P losses from dairy manure spread fields. SWAT immediately incorporates P applied as manure into soil P which we believe is not an accurate representation of P cycling. We compared results of the SWAT model to a simpler semi-empirical model, JoFlo. We found that JoFlo was better equipped to simulate patterns of P losses from manure-spread fields. Our results provide valuable information to the many who use SWAT to study dairy manure management.

BIOGRAPHICAL SKETCH

Erin Menzies grew up near Chautauqua Lake in Lakewood, NY with her parents, David and Priscilla Menzies, and her twin brothers, Allan and Griffin Menzies. Erin attributes her love of the natural world to the ten summers she spent in Algonquin Park, Ontario attending and working at Northway Lodge, a wilderness camp for girls. Erin received a Bachelor’s of Science in 2010 in the field of Environmental Engineering from the University of Vermont in Burlington, Vermont. In 2011 Erin began service in the United States Peace Corps in Ecuador. She served in a small rural community named La Esmeralda in the province of Los Rios. She was a Sustainable Agriculture volunteer and worked primarily with a Cocoa Growers cooperative and a few local women’s groups. Erin loves to ski, hike, play outside with her dog, and cook over the top complicated meals.

To my family and my soon to be family, who always support me.

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I would also like to thank my family and my soon to be family, you are the best anyone could hope for.

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LIST OF ABBREVIATIONS

CAFO	Concentrated Animal Feeding Operation
DD	Degree Days above -8°C since manure application
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
HRU	Hydrologic Response Unit
M_o	Average manure WEP
MRLC	Multi-Resolution Land Characteristics
NED	National Elevation Dataset
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Association
NSE	Nash-Sutcliffe Efficiency Coefficient
NYS	New York State
PHOSKD	Phosphorus Soil Partitioning Coefficient
PP	Particulate Phosphorus
SRP	Soluble Reactive Phosphorus
SWAT	Soil and Water Assessment Tool
P	Phosphorus
SWCD	Soil and Water Conservation District
TDP	Total Dissolved Phosphorus and SWAT Simulated In-Stream Mineral Phosphorus
TSS	Total Suspended Solids
US	United States
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture Agricultural Research Service
USGS	United States Geological Survey
VSA	Variable Source Area
WEP	Water Extractable Phosphorus

PREFACE

Manure management is important in areas of the globe where agriculture includes meat production or the manufacture of animal products. The issue is particularly relevant in areas of the United States, such as New York State (NYS), where runoff comes in contact with dairy manure from concentrated animal feeding operations (CAFOs) and is a primary contributor to nutrient pollution to surface waters. Milk is New York's primary agricultural product with half of all agricultural receipts attributed to milk and the state is the fourth largest producer of milk in the United States (USDA, 2012a). In 2012, 13.2 billion pounds of milk were produced with a preliminary value of 2.41 billion dollars (USDA, 2012a). This quantity of milk is produced by the approximately 625,000 cows in NYS (USDA, 2012b). The dairy cow population found on NYS dairy farms generates approximately 50 million pounds of manure each day. That massive quantity of manure needs to be managed and stored or disposed of every day. With an immense quantity of manure being generated each day proper management of manure spread for waste disposal may be the most effective means of limiting the total mass of P (P loading) entering fresh water systems (King et al., 2015; Zhang, 2015; Schoumans et al., 2014; Van Es et al., 2004; Sharpley and Barton, 2000).

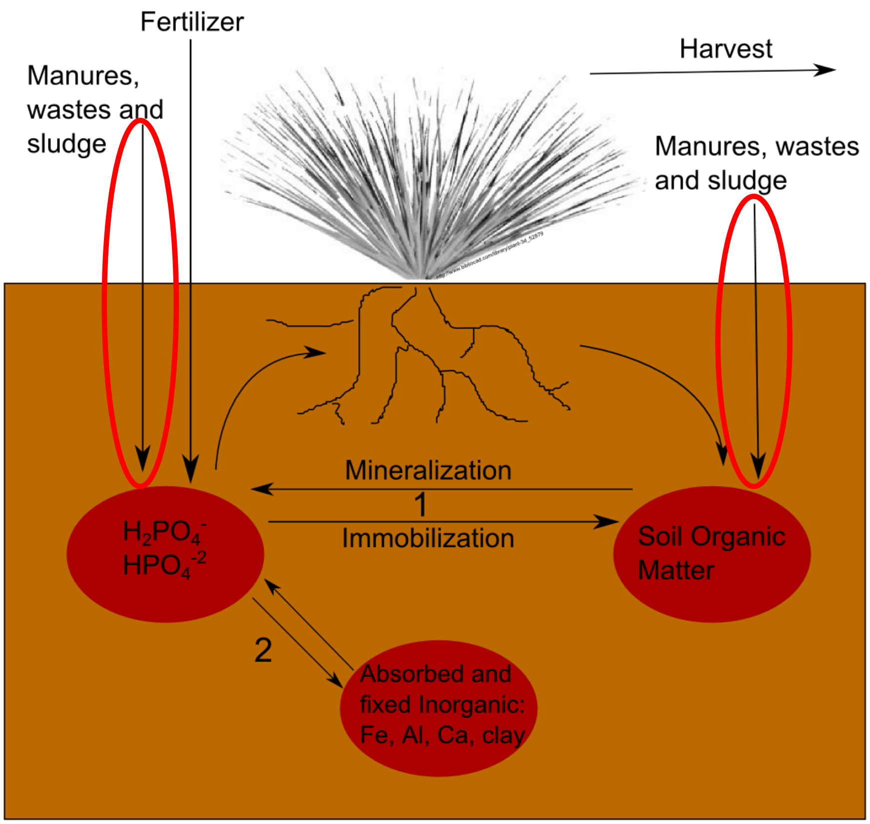
Introduction

Eutrophication conditions in fresh water systems are frequently controlled by phosphorus (P) pollution, which commonly stems from agricultural land use (Prestigiacomo et al., 2016; O'Neil et al., 2012; Carpenter et al., 1998). Excess P, from anthropogenic sources such as fertilizers and animal manures are primarily carried away from fields and into surface waters through surface runoff (Collick et al., 2016; Carpenter et al., 1998; Skaggs et al., 1994; Osborne and Kovacic, 1993). Developing reliable strategies for managing agricultural P is a persistent challenge.

Watershed scale models are commonly used to quantify the impacts of agriculture on surface water bodies and to test management strategies for controlling nutrient loads. The Soil and Water Assessment Tool (SWAT) is one such quasi-spatially distributed watershed scale hydrologic model that is widely used in scientific research as well as by policy makers and conservationists (Neitsche, 2011). The SWAT has been used to predict flow, sediment, P, and nitrogen loads to surface water bodies (Collick et al., 2015; Me et al., 2015; Easton et al., 2011; Chaubey et al., 2006; Kirsch et al., 2002). The SWAT is frequently used when conservation and management are at the forefront of project goals due to the relative ease of model initialization and availability of inputs (e.g. Francesconi et al., 2016; Dennedy-Frank et al., 2016; Keeler et al., 2013; Arnold et al., 1998). The SWAT is commonly used to simulate P fate and transport in order to facilitate decision making at the policy level. (Lu et al., 2015; Boluwade and Madramootoo, 2013; Pezet et al., 2013).

Weather and landscape characteristics are important factors in SWATs representation of watershed hydrology. Several recent modifications to SWAT may allow it to better represent the P transport processes in the Northeast United States (US) including runoff in frozen soils (Han et al., 2010), soil erosion under snow cover conditions (Han et al., 2010), and P-transport via tile drains (US) (Lu et al., 2015).

Given the widespread and growing use of SWAT worldwide it is important to understand the shortcomings and limitations to the models use. Despite potential improvements, weaknesses in the P cycling routines found in the currently available version of the SWAT (SWAT 2012 Rev. 637) have recently been examined by Collick et al. (2016); the routines' details are described in Chaubey et al. (2006). With respect to dairy agriculture in the Northeast US, we are concerned that SWATs immediate incorporation of manure P into soil P pools (Figure 1) (Neitsche et al., 2011) is a conceptual shortcoming that does not properly represent the soil-surface partitioning of P applied as fertilizer and, more specifically, animal manure. In the current release of SWAT, P applied as manure is immediately partitioned into either the plant available soluble soil P pool of orthophosphates or incorporated into the pool of organic P found in the soil organic matter. In the case of dairy manure, the mass fraction of manure that is added to the organic P pool is 0.003 and the mass fraction that is considered mineral P (soluble P) is 0.005 (Neitsche et al., 2011). These values are not fractions of the total P found in the manure but rather, fractions of the total mass of manure that is P. We suspect this immediate incorporation into soil P pools unrealistically buffers the transport potential of P from field-applied animal manures.



1

$$P_{minf,ly} = 0.8 \cdot \delta_{ntr,ly} \cdot orgP_{frsh,ly}$$

2

$$P_{sol|act,ly} = 0.1\left(P_{solution,ly} - \min P_{act,ly} \cdot \left(\frac{pai}{1-pai}\right)\right)$$

$$\text{if } P_{solution,ly} > minP_{act,ly} \cdot \left(\frac{pai}{1-pai}\right)$$

$$P_{sol|act,ly} = 0.6 \cdot \left(P_{solution,ly} - minP_{act,ly} \cdot \left(\frac{pai}{1-pai}\right)\right)$$

$$\text{if } P_{solution,ly} < minP_{act,ly} \cdot \left(\frac{pai}{1-pai}\right)$$

Figure 1. Soil phosphorus (P) cycling processes modeled in the SWAT. P applied as manure or fertilizer is immediately incorporated into the soil P pools and does not remain on the surface for any period of time. The red circles highlight this process. Net mineralization (1) is calculated in SWAT and includes immobilization. It is dependent on the residue decay rate constant and the size of the organic P pool. Net sorption (2) is also calculated by SWAT and is dependent on the phosphorus availability index and the size of the mineral P pools. (Figure adapted from S.L. Neitsch et al., 2001)

Previous studies have used models to assess the potential for reducing P by applying manure to parts of a watershed with low risks of generating storm runoff (Walter el al., 2000; 2001; Easton et al., 2008b). Here we want to explore the possibility that changing the timing of manure applications can help mitigate nonpoint source P pollution from agriculture. The impact of timing of manure applications has been shown to be an important factor in determining the magnitude of P losses in Northeast US agricultural settings (Collick et al., 2016; Archibald, 2015; Komiskey et al., 2011; Lewis and Makarewicz, 2009; Hergert et al., 1981). Previous studies have found that labile P found in surface applied manure does not behave as soil P does (Archibald et al., 2015; Kleinman and Sharpley, 2003). These studies have concluded that P losses decrease with successive rain events after application (Vadas et al., 2011). Others have found that surface applied P decays exponentially with time after application (Gerard-Marchant et al., 2005; Kleinman et al., 2004). All of these studies highlight the need for P cycling in models which includes decay of available P in surface applied manure which the current SWAT routines do not include. We anticipate that SWAT will not generate the types of P transport that these studies have shown because the model immediately incorporates surface applied P in the form of dairy manure into soil P pools.

The high degree of complexity of models like SWAT is not necessarily an indication of its ability to reproduce observed fluxes in the environment (e.g. Baveye and Boast, 1999; Schaefli et al., 2011). In many cases, simple models can be more effective tools. JoFlo (Archibald et al., 2014; Archibald, 2015) is one such model. JoFlo is a semi-empirically based model developed specifically for use in the

Northeast US (Archibald, 2015). JoFlo uses mechanistic routines for some processes, e.g., snowmelt and potential evapotranspiration, and empirical routines for others, e.g., storm runoff and P transport. The P transport equations were based on empirical lab experiments conducted by Archibald (2015) and plot experiments by Easton et al. (2007b). Unlike SWAT, which explicitly simulates P transformations among different pools (Figure 1), JoFlo simulates an exponential decline in P mobility following manure spreading as a function of "degree days". So, one question being asked in this project is "can this very simple model provide as useful information for manure management as the relatively complex SWAT model?".

The question of how timing of manure applications influences P transport is particularly relevant in areas of the country like New York State (NYS), with shallow, marginal soils, which experience strong seasonality of their hydrology, including frozen winter conditions. Karl Czymmck, a Senior Extension Associate in the Department of Animal Science at Cornell University and a staff member with the state-wide PRO-DAIRY Program, is an expert on the regional dairy industry. Czymmek and his colleagues (personal communication, May 2015) note the challenges NYS dairy farmers face in disposing of manures, specifically noting the perception of animal manure being as much a waste product as a fertilizer. Small farms, in particular, generally have very limited capacity to store manure and, therefore, must dispose of it regularly regardless of the season. On the other hand, relatively large farms, typically Concentrated Animal Feeding Operations (CAFOs), have the capacity to store animal wastes for part of each year, but they then need to dispose of large volumes of manure (usually liquid manure) over a very short time period.

Winter manure disposal is particularly worrisome. It is well established that frozen soils impact P loading in runoff due to changes to infiltration (Edwards et al., 1995; Zuzel et al., 1990; Zuzel and Pikul, 1987; Steenhuis et al., 1981; Storey, 1955), nutrient availability in soils (Herrmann and Witter, 2002; Vaz et al., 1994), and nutrient accumulation in snowpack (Rascher et al., 1987). Srinivasan et al. (2006) and Han et al. (2010) demonstrate the extent of the importance of winter hydrology on nutrient fate and transport.

1.1 Objective.

The ultimate objective of this study is to evaluate how changing the timing of manure applications will alter nonpoint source P loads. Embedded in this objective is evaluating the capability of SWAT to simulate expected changes in P loads. As part of this evaluation, we will compare SWAT results to predictions made by JoFlo. This analysis will prove useful in determining the applicability of the SWAT to temperate agricultural watersheds where manure is frequently spread year round, during the growing season as well as on snow and frozen ground. We demonstrate the sensitivity of stream P loading with respect to the timing of manure application within SWAT and JoFlo.

Materials and Methods

2.1 Watershed Description.

The Fall Creek watershed encompasses approximately 33,000 ha and is located in the Great Lakes basin of NYS (Lat: 42º 27’ 12”, Long: -76º 28’ 22”) (Figure 2).

Fall Creek and its tributaries flow into Cayuga Lake which is part of the Lake Ontario and St. Lawrence River watersheds. Fall Creek has a robust history of monitoring making it an ideal watershed in which to validate a watershed scale model. A USGS stream gage (04234000) has been in place since 1925, continuously monitoring daily stream flow (USGS, 2015). Bouldin (2007) performed rigorous water quality sampling of many parameters from 1972 to 1995. These data were used to corroborate model output with respect to flow, TSS, and TDP loads between the years 1972 and 1989 when TSS and TDP were among measured parameters.

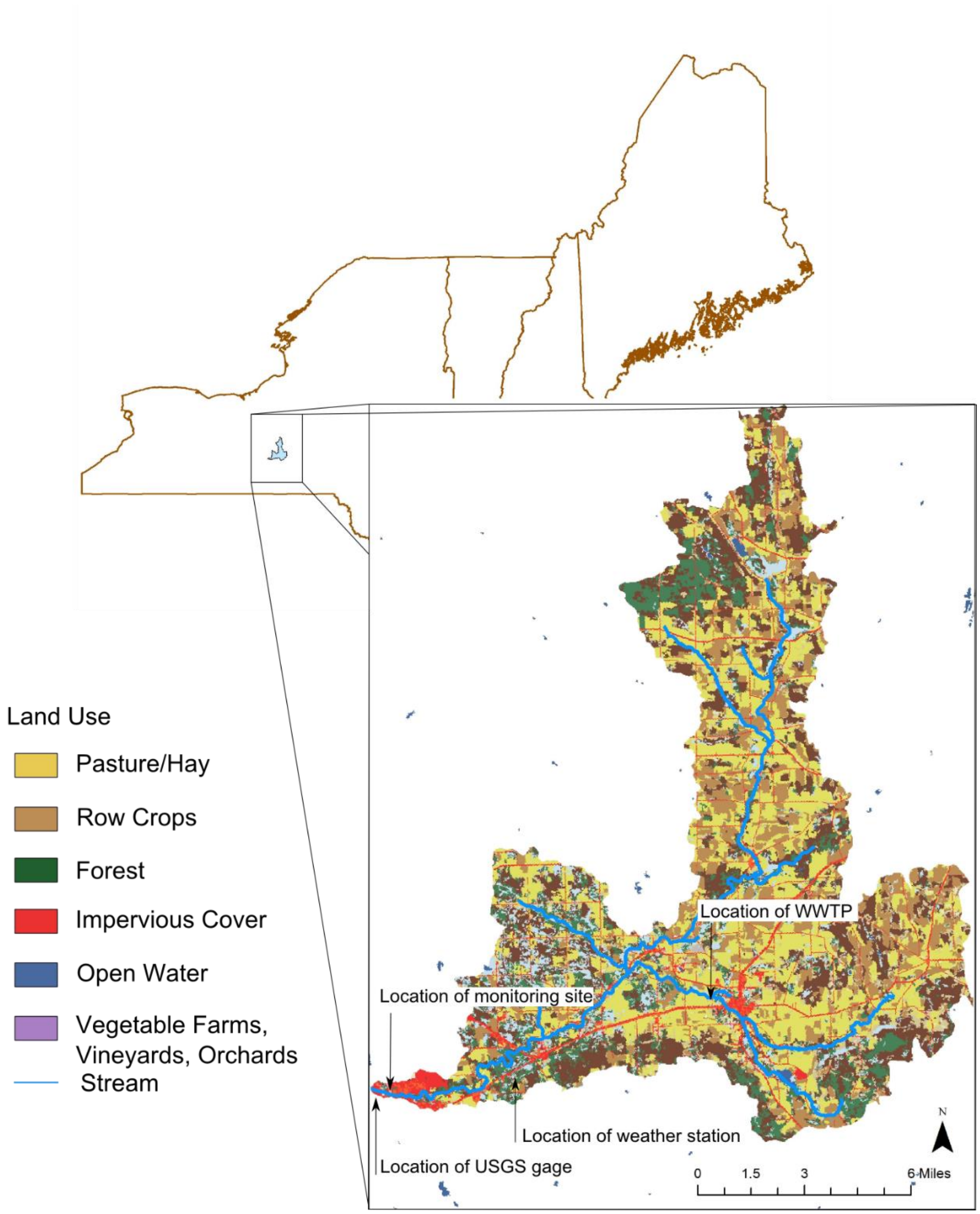


Figure 2. The study watershed is located within the Northeastern United States. The inset displays the watershed in more detail including the 2011 NLCD land uses. Key land uses for this study are highlighted in the legend, pasture and row crops dominate the watershed. The locations of the USGS stream gage used for model calibration as well as the weather station whose data was used to inform the model are indicated.

The Fall Creek watershed is dominated by agricultural land (46.7%), the large majority of which can be found in pasture and hay lands (29.8%) as well as row crops (16.7%) (Fry et al., 2011). Other agricultural land uses in the area include vegetable farms, vineyards, and orchards totaling 0.2% of the total land cover. A number of animal operations exist within the watershed as well; the Pro Dairy program located at Cornell University estimates that more than 2,000 ha or 60%, of pasture land are managed by CAFO dairy farms within the watershed bounds (K. Czymmck et al., personal communication, May 2015). The remaining land use consists primarily of forest (32.9%), wetlands (7.2%), and developed lands (5.8%).

The soils are primarily silt loams and much of the region is poorly drained due to a fragipan (Dahlke et al., 2012). This dense restricting layer is usually found within 30 to 60 cm of the soil surface and limits percolation of water causing soils above the fragipan to saturate quickly during rain events. As a result, storm runoff generation in this region is dominated by saturation excess rather than infiltration excess (Easton et al., 2007a; McDonnell, 2005; Needelman et al., 2004; Srinivasan et al., 2002; Beven, 2001; Dunne and Leopold, 1978; Dunne and Black, 1970); The area is located in a humid continental climate and the weather varies seasonally with freezing temperatures persisting for 4 to 5 months of the year; snow cover is frequent from December to March. Precipitation (rainfall + snow water equivalent) in the region averages 94.7 centimeters per year, with slightly higher precipitation in the summer than winter. (Cornell NRCC, 2015).

2.2 SWAT Description.

2.2.1 Model Overview. The SWAT is a watershed scale, semi-distributed, quasi-physically-based model (Neitsch et al., 2011). Spatial data required for initialization include elevation, soils, and land cover. The model uses these data to categorize the landscape into unique hydrologic response units (HRUs); this reduces computational requirements, but also reduces the accuracy of the spatial representation of features and processes within a subbasin. The SWAT was used with an adaptation, referred to as SWAT-VSA, to more accurately represent the runoff generating processes of the region referred to as variable source area (VSA) hydrology (Easton et al., 2008).

2.2.2 SWAT P Routines. In the SWAT the user can add P to the soil pools in either mineral (soluble) or organic forms. As previously mentioned, the current version of SWAT assumes that manure applied to soils is immediately incorporated into the soil P pools in organic or mineral forms as illustrated by Figure 1.

2.2.3 Input Data. We used the following datasets in ArcSWAT, a geographic information system (GIS) interface. A digital elevation model (DEM) from the United States Geological Survey (USGS) National Elevation Dataset (NED) at a resolution of 1 arc-second (approximately 30 meters) (Gesch, 2007; Gesch et al., 2002) was used. Land use data from the National Land Cover Database (NLCD, 2006) by the Multi-Resolution Land Characteristics (MRLC) Consortium at a resolution of approximately 30 meters (Fry et al., 2011) were used. This dataset was modified to include more specific agricultural land uses common to the Finger Lakes region of NYS such as vineyards, orchards, and vegetable farms. These additional agricultural data were obtained from the 2009 New York Cropland Data Layer at a resolution of 30 meters (USDA et al., 2010). One land use data set was used for the entire modeling period (1970-2010). Shaw et al. (2011) found only a 2% increase in total roadway miles in the Fall Creek watershed since 1954. Population growth in the watershed is consistent with this small increase in roadways; between 1950 and 1980 population increased by 10% each decade and from 1980 to present there has been a 5% increase in population in each decade (Forstall, 1995). Based on these data we can assume that land use has not appreciably changed over the modeling period (1970-2010). A soils layer was built using TopoSWAT (Fuka and Easton, 2016). TopoSWAT is an automated ArcMap tool that calls upon the Digital Soil Map of the World and includes a soil wetness class to give a more accurate representation of soil type and its propensity to generate runoff as defined by VSA hydrology (Fischer et al., 2008).

Forcing data sets are required by the SWAT to simulate specific environmental conditions, these include: meteorological, land management, and point source emissions data. In all SWAT simulations, the watershed model was forced with daily precipitation and daily minimum and maximum temperatures. Relative humidity, solar radiation, and wind speed were solved internally by SWATs weather generator. These weather data are available from National Oceanic and Atmospheric Association (NOAA) Global Historical Climatology Network (GHCN) of weather stations. For this model we used the meteorological station (Number USC00304174) located at Cornell University in Ithaca, NY (NOAA, 2015) because of its location in the watershed and its long term data record. An estimation of current land management practices was used to create baseline inputs to the model. Fertilization routines for vegetable farms, orchards, and vineyards were determined based on recommendations commonly made to farmers growing each aforementioned crop in the form of a 10-10-10 fertilizer (Cornell Gardening, 2016).

We applied manure spreading schedules that capture the current state of manure management to row crops and pasture land to the model. These schedules were determined after discussions with experts from a number of county Soil and Water Conservation Districts (SWCDs) in the Finger Lakes region (K. Czymmck et al., personal communication, May 2015). In these discussions we outlined three manure spreading schedules for pasture land and one for row crops. In total, 9.03 million kg of manure are applied to 2,020 ha of pasture land and 30.8 million kg of manure are applied to 5,320 ha of row crops (Table 1). In order to incorporate these schedules into the SWAT framework, we assigned random HRUs, whose land use designation is Pasture, to 19 groups of three spatial sizes; 108 ha, 54 ha, and 400 ha. Twelve groups of 108 ha were assigned to Schedule 1; six groups of 54 ha were assigned to Schedule 2; and one group of 400 ha was assigned to Schedule 3 (Table 2). Each group under Schedules 1 and 2 were assigned a different month in which manure would be applied to them. As a result, each HRU received manure applications in only one month of the year. With this method we simulate the common practice of rotating the fields in which manure is spread. All HRUs designated as Row Crops were assigned to Schedule 4. We then applied manure to these groups as specified by the SWCD experts (Table 1).

Table 1. Manure application schedules applied to pasture and row crops to simulate current conditions. Includes details concerning area of land managed under each schedule, manure quantity applied, the total mass of dry manure applied each year, the total mass of P applied each year, and the time of year in which manure is applied.

	Land use	**Ha**	**Kg/Ha**	**Total kg/year**	**Total kg P/year**	**Timing**
Schedule 1	Pasture	1,300	3,300	4,290,000	33,920	Year round
Schedule 2	Pasture	320	3,300	1,056,000	8,480	May-October
Schedule 3	Pasture	400	4,600	3,680,000	14,840	May, October
Schedule 4	Row Crops	5,320	2,900	30,865,000	123,420	May, October

Table 2. Grouping of land for manure application schedules. Includes schedule names, land use in each schedule, total number of hectares in each schedule, the number of groups that schedule is broken into, and the number of hectares in each group.

	Land use	**Ha**	**Groups**	**Ha/Group**	**Timing**
Schedule 1	Pasture	1,300	12	108	Year round
Schedule 2	Pasture	320	6	54	May-October
Schedule 3	Pasture	400	1	400	May, October
Schedule 4	Row Crops	5,320	1	5,320	May, October

The Fall Creek watershed contains two wastewater treatment plants which discharge directly into the stream. The flow from both plants was considered to be one singular point source as the two plants share an effluent pipe. Daily rates of sediment (0.015 metric tons/day) and P discharges (4.4 kg/day) were obtained from the Environmental Protection Agency's (EPA) Enforcement and Compliance History website (USEPA, 2015a; USEPA, 2015b).

2.3 JoFlo Description.

2.3.1 Model Overview. JoFlo is a simple, empirically-based model developed by Archibald (2015) for use in the northeastern US. The model is made up of separate hydrology and P modules that are executed in R version 3.0.2 (2013-09-25) (R Development Team, 2008). The hydrology module is conceptually similar to STOPMODEL (Walter et al., 2002). Outputs from the hydrology module of the model become inputs for the P module. The hydrology portion of the model is a lumped water budget model based on the soil water budget as proposed by Thornthwaite and Mather (1955) (Figure 3). JoFlo distributes the soil moistures and storm runoff throughout the landscape via wetness classes that are based on the soil topographic index of Walter et al. (2002) and Lyon et al. (2004). The hydrology portion of JoFlo was developed and parameterized using 10 watersheds in New York, New Jersey, and Pennsylvania. Fall Creek, the watershed we examine in this study, was one of the watersheds used to parameterize and corroborate JoFlo. Despite the largely empirical basis of JoFlo, the model uses energy budget approaches to simulate snowmelt (Walter et al., 2005) and potential evapotranspiration (Archibald and Walter, 2014b)

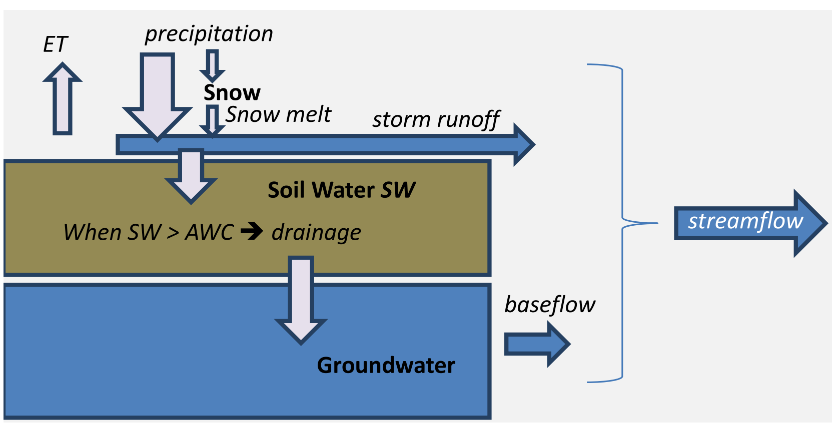


Figure 3. Figure from Archibald (2015) with permission. The hydrology model of JoFlo is based on a lumped water budget model. *SW* is soil water and *AWC* is available water capacity.

2.3.2 JoFlo P Routines. JoFlo simulates soluble reactive phosphorus (SRP) loading based on availability of SRP in a given wetness class and the amount of storm runoff for that wetness class as determined by the hydrology module (Archibald, 2015). The relationships employed in JoFlo are empirically based on experiments conducted by Archibald (2015) and, partially, by Easton et al. (2007b). The P module of the model was parametrized and tested in the Fall Creek watershed. To simulate SRP concentration in overland flow from manured areas, JoFlo employs an empirical relationship:

$$SRP = \left(\frac{WEP}{M_o}\right) 16.04\, DD^{-0.68}$$

Where *WEP* is the water extractable P (mg/m2) applied as manure; M_o is the average manure WEP (767 mg/m2); *DD* is the number of degree days above -8°C since manure application. This relationship allows for an exponential decay of SRP available for loss in surface runoff. By including this component, growing degree days since manure application, JoFlo simulates a labile period in which P can be easily lost in significant quantities to surface runoff.

2.3.3 Input Data. JoFlo requires several data sets to initialize the hydrology module. These data include daily meteorological data, precipitation (rain + snow melt), and maximum and minimum temperatures. JoFlo also requires the location of the watershed in latitude in degrees. The P portion of the model requires results from the hydrology module as well as the percent of the watershed area spread with manure and the WEP (mg/m2) applied.

Daily meteorological data were obtained from the NOAA GHCN weather stations. We used the meteorological station (Number USC00304174) located at Cornell University in Ithaca, NY (NOAA, 2015). The weather data used in JoFlo is identical to those used in the SWAT initialization. The current manure spreading strategies outlined in section 2.2.3 were applied to JoFlo.

Other sources of P that were included in the SWAT model, such as vineyards, orchards, and vegetable farms, as well as point sources of P were not included in JoFlo. This is due to the simplicity of the model and its inability to accept such inputs. Unlike SWAT, JoFlo's hydrology module has been regionally calibrated by Archibald et al. (2014) and the P routine uses empirically derived parameters (Archibald, 2015) so there is no calibration of this model.

2.4 Model Corroboration.

2.4.1 SWAT Model Corroboration. The SWAT model was forced with observed daily precipitation, daily minimum, and daily maximum temperatures (NOAA, 2015) and then calibrated and parameterized against observed stream flow measurements from USGS gage 04234000 located at the Fall Creek watershed outlet (USGS, 2015). The Nash-Sutcliffe model efficiency (NSE) coefficient (Nash and Sutcliffe, 1970) was used as the model performance objective function. The DEOptim R package was used to automate model parameter adjustments for parameters controlling the hydrology (Mullen et al., 2011). Model simulations were conducted from 1970 to 2010. Objective function calculations were performed from 1973 to 2010, using a 3 year warm up period to establish initial hydrologic and biogeochemical conditions. A list of calibrated parameters and brief explanations for each parameter can be found in Table 3. The values resulting from the calibration for each parameter are listed in Table 4.

Table 3. Description of parameters adjusted to improve the models predictive capacity of streamflow in Fall Creek.

ID Number	Parameter	Units or Limits	File	Brief Explanation
1	GW_Delay	days	gw	The lag between the time that water exits the soil profile and enters the shallow aquifer
2	Alpha_BF	1/days	gw	Base flow recession constant
3	GWQMN	mm H_2O	gw	Depth of water in the aquifer needed to generate return flow
4	GW_Revap	0 to 1	gw	Ease of movement of water from shallow aquifer to root zone
5	Revapmn	mm H_2O	gw	Depth of water in shallow aquifer for percolation to deep aquifer to occur
6	Rchrg_dp	0 to 1	gw	Fraction of percolation from the root zone that recharges the deep aquifer
7	SFTMP	°C	bsn	Air temp at which precipitation is equally likely to be rain as snow
8	SMTMP	°C	bsn	Threshold temperature value at which snow pack will begin to melt
9	SMFMX	mm/°C-day	bsn	June 21 melt factor
10	SMFMN	mm/°C-day	bsn	December 21 melt factor
11	TIMP	0 to 1	bsn	Snow pack temperature dependence on previous days temperature
14	SURLAG	1 to 12	bsn	Surface runoff lag coefficient
32	ESCO	0.01 to 1	hru	Soil evaporation compensation factor
33	EPCO	0.01 to 1	hru	Plant uptake compensation factor

Table 4. Values for each adjusted parameter resulting in an NSE for streamflow in Fall Creek of 0.57.

ID Number	**Parameter**	**Units or Limits**	**File**	**Fall Creek**
1	GW_Delay	days	gw	82.410
2	Alpha_BF	1/days	gw	0.152
3	GWQMN	mm H_2O	gw	29.154
4	GW_Revap	0 to 1	gw	0.192
5	Revapmn	mm H_2O	gw	443.955
6	rchrg_dp	0 to 1	gw	0.107
7	SFTMP	°C	bsn	-0.424
8	SMTMP	°C	bsn	3.286
9	SMFMX	mm/°C-day	bsn	1.843
10	SMFMN	mm/°C-day	bsn	3.611
11	TIMP	0 to 1	bsn	0.553
14	SURLAG	0.01 to 12	bsn	0.246
32	ESCO	0.01 to 1	hru	0.583
33	EPCO	0.01 to 1	hru	0.955
NSE				0.57

The model was next calibrated and parameterized to TSS and TDP. Parameters were adjusted manually and results were evaluated based on comparisons to model predictions. Observed TSS was compared to simulated sediment. Sediment calibration is important to P calibration and simulation because P is commonly bound to sediment and in Fall Creek particulate P (PP) concentrations are two orders of magnitude higher than soluble P concentrations (Prestigiacomo et al., 2016). In order to predict P loads we must be sure we are simulating sediment loads as accurately as possible. Observed TDP was compared to SWAT simulated mineral P. Comparisons of forms of SWAT simulated P to forms of observed P can be difficult and many studies interpret SWAT outputs differently (Zeckoski et al., 2015; Pezet et al., 2013). Numerous studies have compared TDP and mineral P to calibrate their models (Woodbury et al., 2014; Dechmi et al., 2012; Tolson and Shoemaker, 2007) and we believe this interpretation to be the most accurate. Observed data were gathered by Bouldin (2007) at a location near the outlet of Fall Creek (Lat: 42° 27' 10", Long: -76° 28' 14"). Observations of TSS and TDP occurred between 1972 and 1989.

2.4.2 JoFlo Corroboration. For this study, no parameterization was conducted on either the hydrology or P modules of JoFlo. A rigorous corroboration of the model performance in Fall Creek was carried out by Archibald (2015). Simulated streamflow from the model was compared to streamflow measurements at the USGS gage 04234000 located at the Fall Creek watershed outlet from 1990 to 2010 (USGS, 2015) (NSE=0.70) (Figure 4a). Simulated SRP loads were compared to measurements taken by Dave Bouldin (NSE=0.57) (Figure 4c).

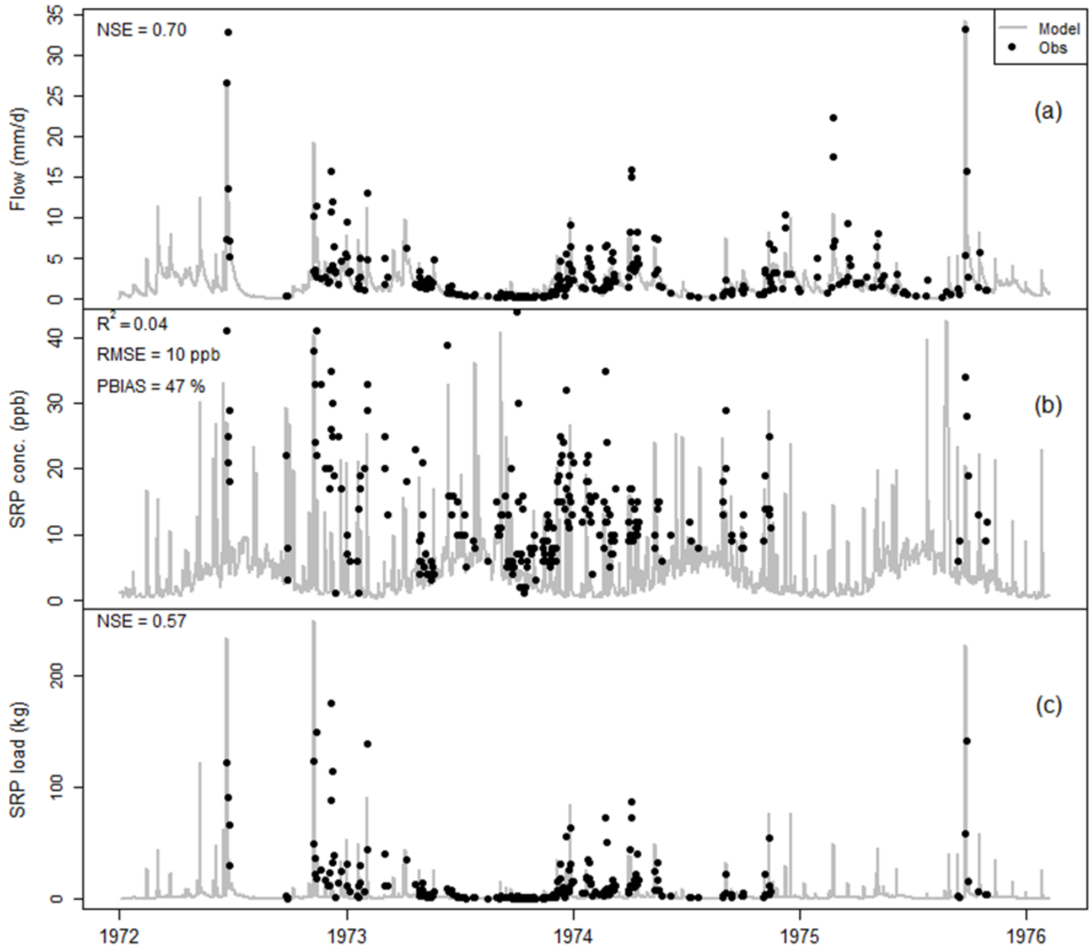


Figure 4. Figure from Archibald (2015) with permission. Model (grey line) SRP and measured (black circle), (a) streamflow at the Fall Creek outlet (mm/day) (NSE=0.70) (b) SRP concentrations (ppm), and (c) SRP load (kg/day) (NSE=0.57).

A number of manure spreading schedules were applied to both the SWAT and JoFlo including both real and hypothetical scenarios. The development of these hypothetical schedules focused on the month of the year in which the manure was applied in an attempt to isolate the impacts of manure spread during each respective season. As previously mentioned, the current spreading strategy was determined through discussions with local experts (K. Czymmck et al., personal communication, May 2015). Based on these discussions, fertilized pasture land was broken up and assigned to one of three schedules and fertilizer was applied to simulate current practices (Tables 1 and 2).

We tested the current spreading strategy as a baseline for comparing a number of hypothetical schedules. We developed these schedules with the intention of examining the pattern of soluble P losses from fertilizer applied throughout the year.

2.6 Hypothetical Manure Spreading Scenarios.

1. No manure: This scenario represents an idealized situation in which no manure is spread in the watershed and all manure produced is exported. As a result, simulated sources of P export in SWAT are point sources (0.05 kgP/ha/yr), soil P (initially 5 kgP/kg soil), and inorganic fertilizers (0.066 kgP/ha/yr) on vegetables, vineyards, and orchards. The only P source in JoFlo is base flow which ranges from 0.02 to 0.09 kg/ha/yr.
2. Current: This scenario approximates the current and historical manure spreading strategies found in this region of NYS. In this scenario, 9.03 million kg of manure are applied to 2,020 ha of pasture land in each year of the simulation. In addition, to pasture, 30.9 million kg of manure are applied to 5,320 ha of row crops. Additional details can be found in Tables 1 and 2.
3. Monthly: This is a series of hypothetical scenarios in which all of the manure spread in a year under Scenario 2 is all applied in one month of the year. Specifically, each hectare of land receives the same quantity of manure it would have in scenario 2 but rather than applying it over the course of a year, it was uniformly applied over the course of one month.

In scenarios 2 and 3, we simulated manure application to the same HRUs in SWAT, that is, the manure was applied to the same geographical area. This eliminated the effect that the location of manure spread relative to Fall Creek might have had on our SWAT results. All scenarios include the same inputs from other sources of P such as point source discharges and the inorganic fertilizers applied to vegetables, vineyards, and orchards. The results of the scenarios were evaluated by examining P loading to Cayuga Lake at the stream gage location which is slightly upstream from where Fall Creek discharges into Cayuga Lake. We intend to compare simulated P loading from the SWAT to P loading simulated by JoFlo.

All analyses were conducted in R version 3.0.2 (2013-09-25) (R Development Team, 2008), using the EcoHydRology (Fuka et al., 2014), data.table (Dowle et al., 2014), and lubridate (Grolemund and Wickham, 2011) packages.

Results

3.1 SWAT Model Corroboration.

The SWAT model employed in this analysis, based on the NSE coefficient for daily flow values (NSE=0.57) at the location of the USGS stream gage close to the watershed outlet (USGS, 2015), resulted in a satisfactory representation of the hydrology of the Fall Creek watershed (Moriasi et al., 2007). SWAT tended to underestimate streamflow during larger events and base flow between events. Also, the simulated time required for the stream to return to base flow was shorter than observed (Figure 5).

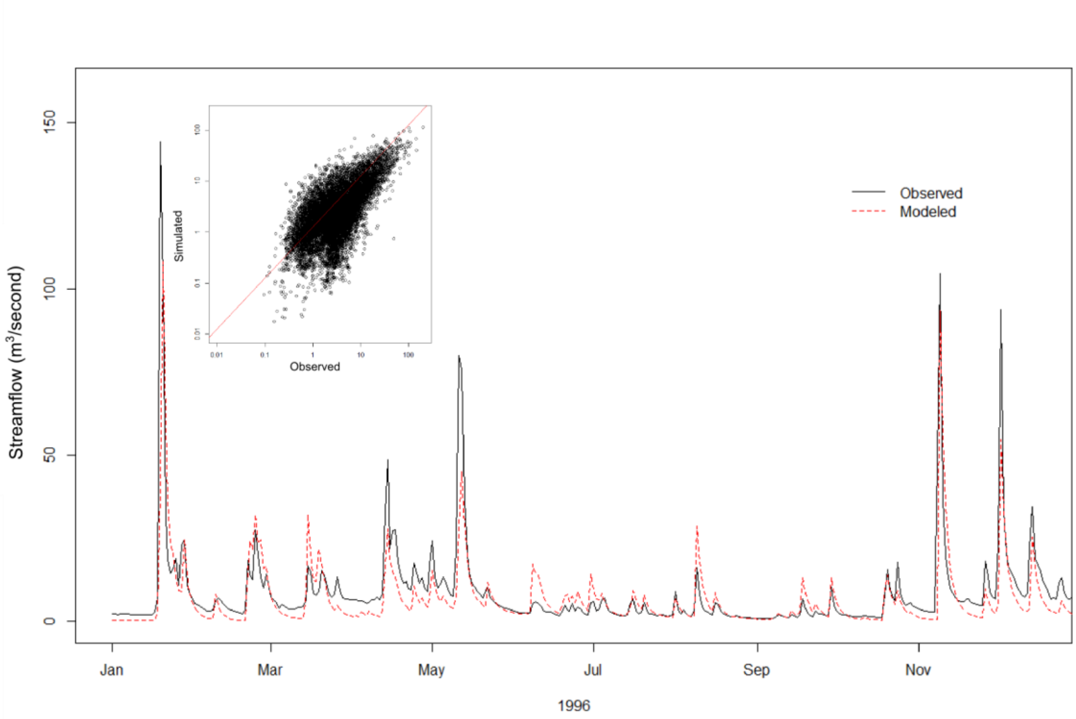


Figure 5. Comparison of daily streamflow during a randomly selected year (1996). Daily streamflow as measured by USGS gage 04234000 in units of m^3/s is denoted by the black line. Model predictions also in cubic meters per second are marked by the red line. The Nash Sutcliffe Efficiency coefficient for this model is 0.57. The model effectively predicts streamflow, the SWAT overestimates streamflow during storm events and requires more time to return to base flow.

Model output of sediment and TDP were compared to measured data aggregated to flow weighted averages of measured TSS and TDP (Bouldin, 2007). A time series of these data show that the model predicts larger loads of both TSS and TDP than the observed values during the wet winter and spring months and lower loads than observed in the fall (Figure 6). Comparisons of the modeled and observed in-stream water quality constituents show a noisy fit to the observed data. The SWAT model over predicts both TSS and TDP more often than it under predicts but data points clustered around the 1:1 line (Figure 7a, b). An examination of the comparison between the cumulative load simulated by the model and the observed cumulative load reveals that the model is predicting relatively well over the course of the simulation period for both TSS and TDP, except for the early portion of the simulation (Figure 7c, d). We attribute some of the uncertainty in daily TDP loading to the model structure which we are evaluating.

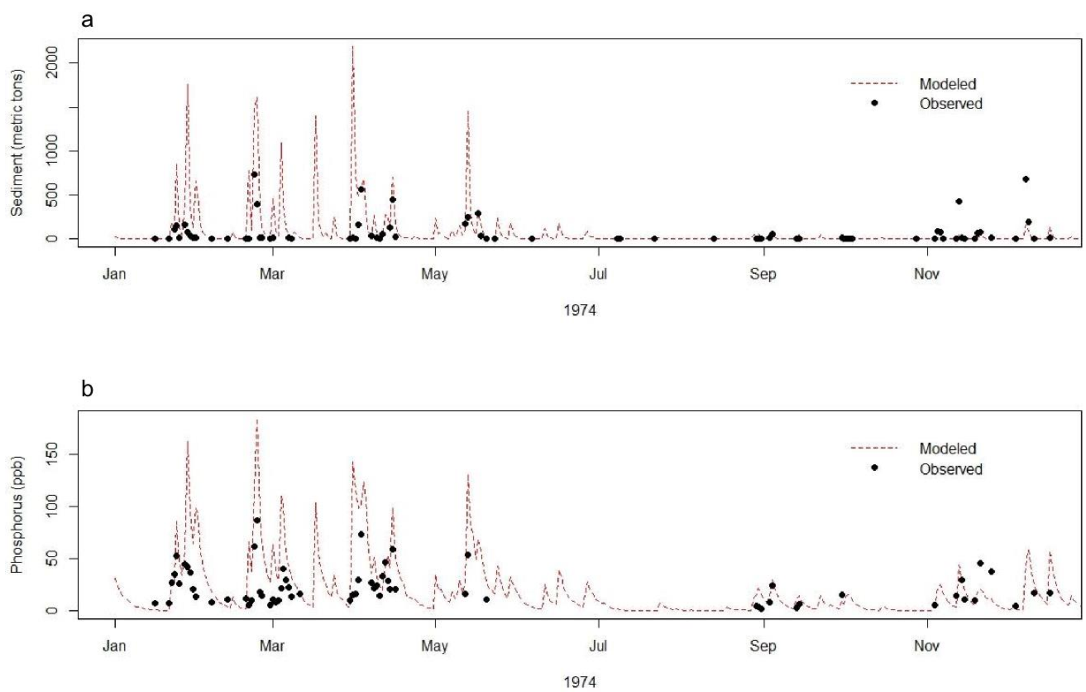


Figure 6. Comparisons between SWAT-simulated and observed (a) sediment loads and (b) phosphorus concentrations. The red dotted line represents SWAT-simulated values and black circles represent observed data by Bouldin (2007).

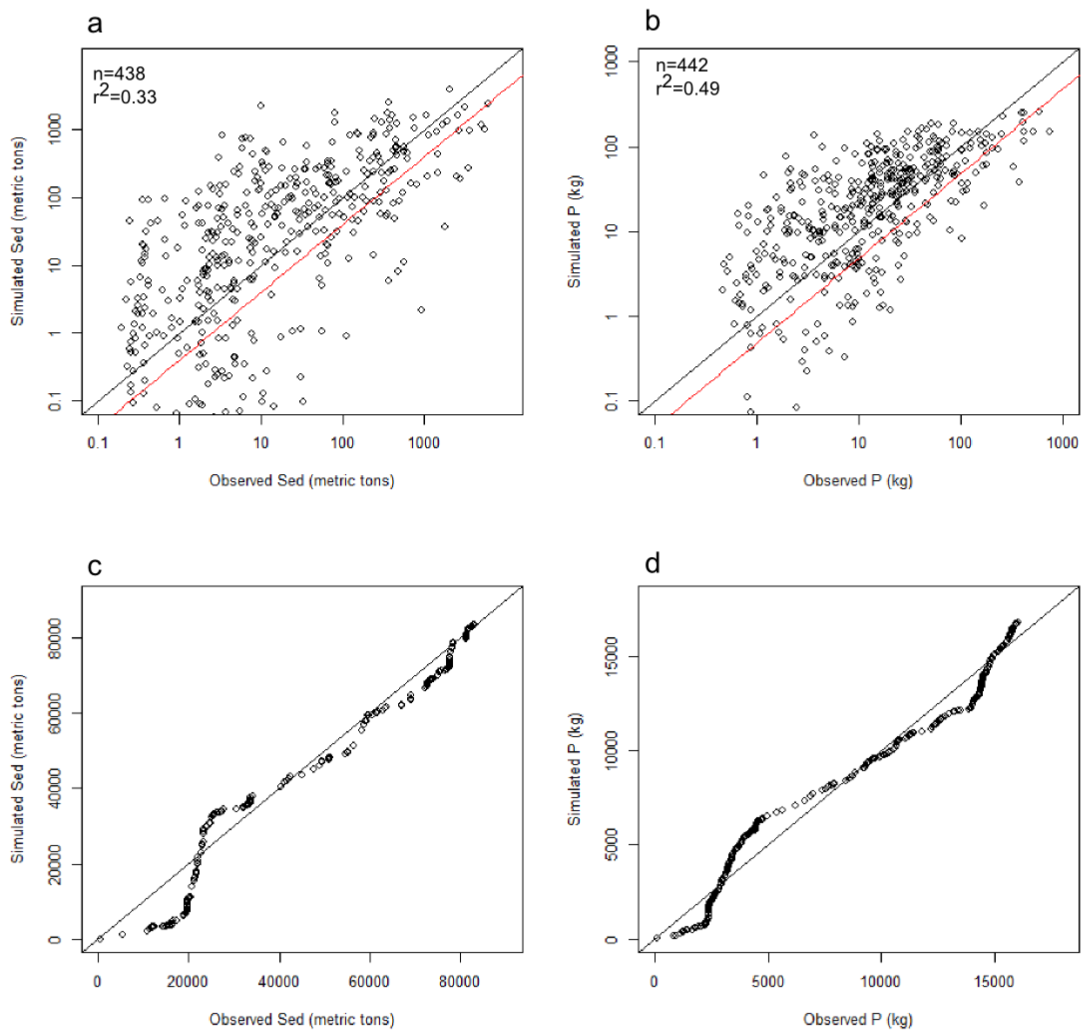


Figure 7. Comparisons between SWAT-simulated and observed (a) sediment loads and (b) phosphorus loads. Notice plots (a) and (b) are plotted on a log-log scale. Comparison between SWAT-simulated and observed cumulative (c) sediment and (d) phosphorus loads. Observed data are flow weighted averages of measurements taken by Bouldin (2007). The black line on all plots is a 1:1 reference line. The red lines on plots (a) and (b) are linear models fitted to the data. The r^2 value for the linear model can be found on the plot as well as the number of data points on each plot.

3.2 Effect of the Timing of Fertilizer P Application on P Stream Loading.

3.2.1 The SWAT. There was no statistical difference observed in P loading from the series of hypothetical monthly spreading scenarios outlined as scenario 3 (Figure 8). This finding was consistent when P loading over the seasons was examined, as well as types of in stream P (SWAT simulated total P and organic P). Similarly, when we examine SWAT simulated TDP over the course of a year we saw no difference in the pattern of TDP loading only small changes in the magnitude of TDP loading during a given storm event (Figure 9). This finding is independent of the amount of precipitation in a given year.

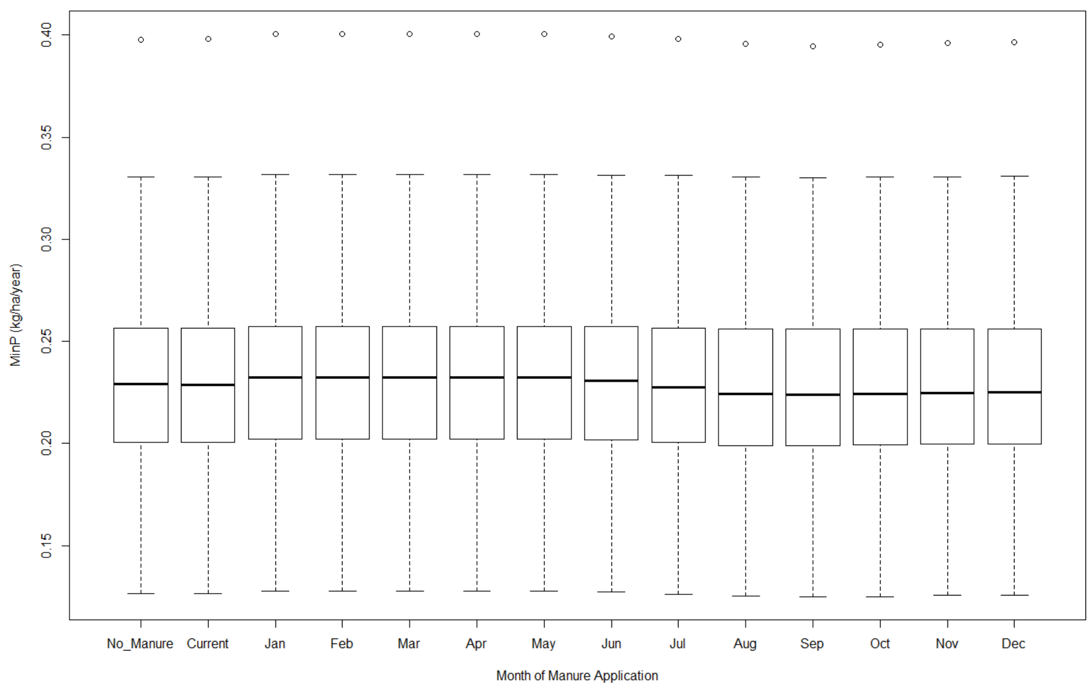


Figure 8. Annual loading of mineral phosphorus reaching the outlet of the Fall Creek watershed as predicted by the SWAT model in kilograms of mineral P per hectare per year. No_Manure refers to the no manure scenario, Current refers to the current spreading strategies, and the boxes labeled Jan through Dec represent annual mineral P loading when all manure is applied in the specified month of that year as part of the monthly scenarios.

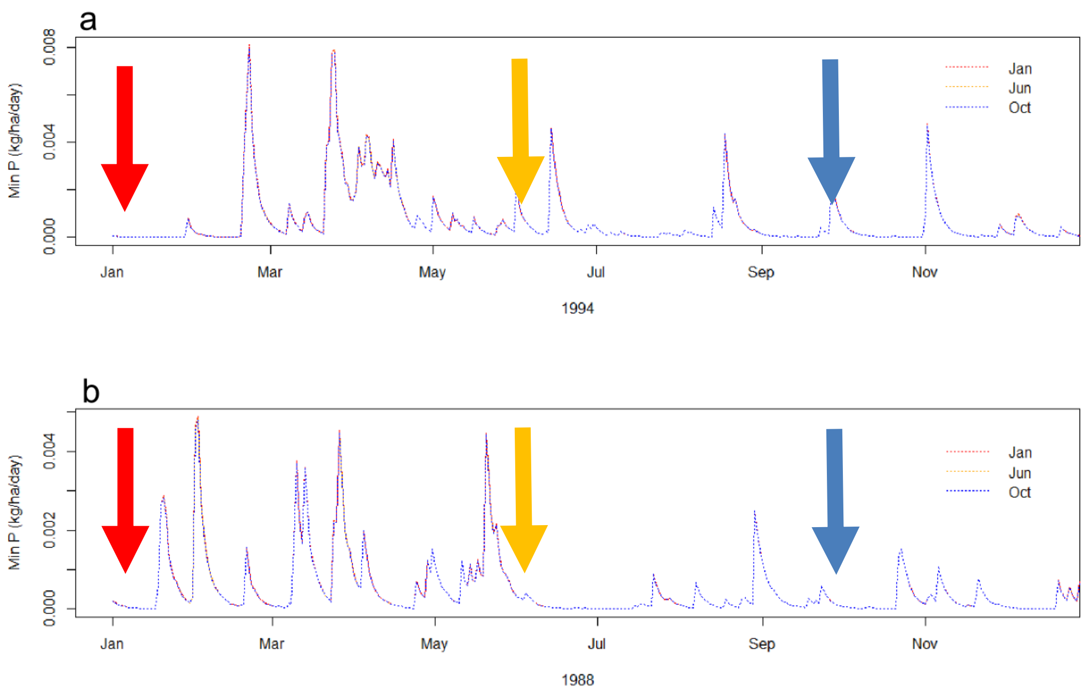


Figure 9. Comparison of seasonal spreading predictions by SWAT in a (a) wet year with 1100 mm of precipitation and a (b) dry year with 800 mm of precipitation. All lines on the plot describe the daily mineral P load from the Fall Creek watershed. The red, yellow, and blue arrows each denote 4 manure applications in the months of January, June, and October respectively. The red, yellow, and blue lines denote daily simulated mineral P loading when manure is applied in January, June, and October, respectively. At some points in the plot not all lines can be seen as they are directly on top of one another. The pattern of P loading is the same regardless of timing of manure applications.

These results indicate that the ability of the SWAT to predict differences in P loading under different manure spreading schedules is limited. Other recent studies have come to similar conclusions regarding the efficacy of the SWAT P cycling routines Vadas and White (2010) examined P cycling routines in SWAT and concluded that the model under predicts total soil P which could lead to under prediction of dissolved inorganic P loss in runoff soon after application to soils. Very recently, Collick, et al. (2016) documented this limitation as well when examining the proximity of manure spread to rain events. They found no change in timing or magnitude of soluble P loading when manure was spread either 1, 5, or 10 days before a precipitation event. The inability of SWAT to produce changes in P loading due to the timing of manure spread has impacts on the efficacy of SWAT as a predictive tool for water resources management.

3.2.2 JoFlo. In contrast to SWAT, JoFlo demonstrated statistically significant differences in SRP loading from the series of hypothetical monthly spreading scenarios outlined as scenario 3 (Monthly) (Figure 10). The winter and early spring months (Dec, Jan, Feb, and Mar) were not statistically significantly different from each other or the current scheme. When manure was applied in summer months annual loading decreased by more than 75% from the current scenario in some cases. These iterations were not statistically significantly different from each other or the no manure scenario (Scenario 1) indicating that these months might be the best months to apply manure in to reduce the impact on freshwater bodies. A time series of SRP loading reveals a pattern consistent with empirical findings; SRP loads increase in the month in which manure is applied or the following month (Figure 11). The effect is magnified in wet years (Figure 11a) but is still present in dry years (Figure 11b).

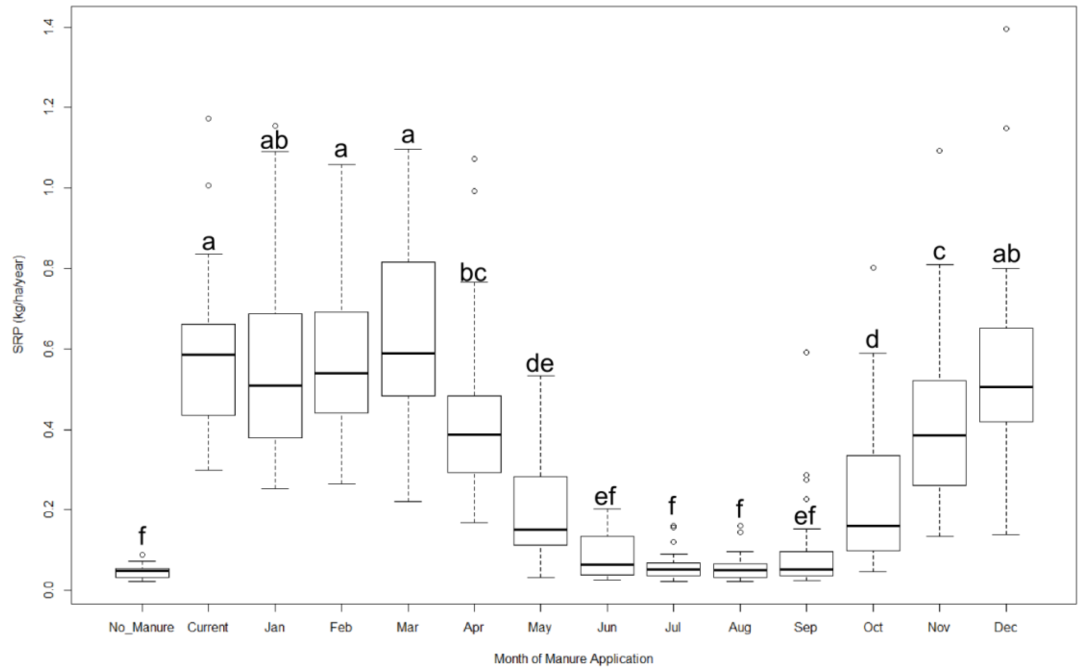


Figure 10. Annual loading of soluble reactive phosphorus (SRP) reaching the outlet of the Fall Creek watershed as predicted by JoFlo (Archibald, 2015). No_Manure refers to the no manure scenario. Current refers to the current spreading strategies, and the remaining boxes represent annual SRP loading when all manure is applied in that specified month. Letters denote statistically significant differences ($p<0.05$). Significant differences were seen between the months. Annual SRP loading is drastically reduced during summer growing season.

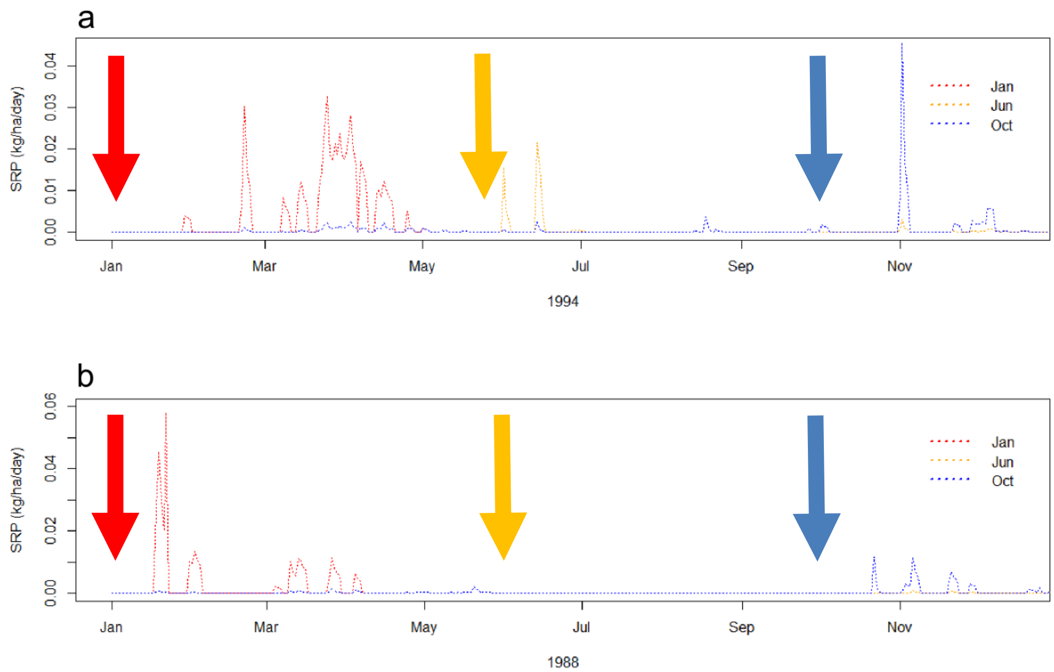


Figure 11. Comparison of seasonal spreading predictions by JoFlo in a (a) wet year with 1100 mm of precipitation and a (b) dry year with 800 mm of precipitation. All lines on the plot describe the daily SRP load from the Fall Creek watershed. The red, yellow, and blue arrows each denote 4 manure applications in the months January, June, and October respectively. The red, yellow, and blue lines denote daily SRP loading when manure is applied in January, June, and October, respectively. The pattern of SRP loading is sensitive to the timing of manure application.

Discussion

The importance of accurately simulating P losses from manure spread fields at the watershed scale cannot be overstated. Archibald (2015) and other researchers have consistently observed that there is a highly labile period immediately prior to a rain event, such that manure application at this time results in a significant percentage being transported away in runoff (Komiskey et al., 2011; Hergert et al., 1981; Klausner et al., 1976; Young and Mutchler, 1976). Our results confirm that the SWAT is limited in its ability to capture this critical process during the labile period, and therefore is unable to capture seasonal differences associated with the timing of manure spreading relative to the time of year. These limitations stem from the current P cycling routines in the SWAT model. In the current version, P added to the system as manure is immediately incorporated into the soil P pools. This abrupt incorporation of P into the soil eliminates the labile period shown to be important by empirical studies (Archibald et al., 2015; Gerard-Marchant et al., 2005; Kleinman et al., 2004). This time in which P could be carried away from the field and into the stream is crucial to correctly predicting P loading to surface waters.

We observed changes in soil P pools that begin to explain the results we observed. Soil P and movement into the stable mineral P pool increased as manure was applied. Soil P pools and movement into the stable mineral P pool were slightly larger in the iterations of Scenario 3 (Monthly) than in scenario 2 (Current). This implies that by applying more manure in one application we increase soil P pools rather than increasing P found in the stream. When manure is applied in SWAT the soil acts as a large sink of P and prevents changes to instream P loading. When manure is not applied as in Scenario 1 (No Manure) we see P moving out of the stable mineral P pool and into solution resulting in the same P load found in the stream. This movement of P within the soil P pools dampens the impact manure spreading might have on in stream P.

The SWAT is an extensive and complicated model with many parameters and many options for inputs or modifications to the model. We have demonstrated that P loading from manure spreading is a case in which model complexity has not resulted in more realistic predictions. A simpler model, JoFlo, developed by

Archibald (2015), is capable of capturing this labile period and producing a pattern of P loading that reflects current knowledge concerning P loss from soil over time. JoFlo simulations resulted in decreased P loads when manure was applied in the summer months during the growing season. This was what we had expected to see based on current knowledge of P cycling with respect to seasonal changes in hydrology and nutrient cycling.

By examining a short time period in 1996 with a few rain events the differences between predicted P loading from SWAT and from JoFlo are highlighted. Output from JoFlo displays a difference in loading magnitude and timing depending on when the manure was applied while output from the SWAT model displays identical magnitude and time of P loading regardless of when manure was applied to the landscape (Figure 12). By comparing these two models we highlight the differences between the patterns of loading. A direct comparison of loading values is not possible as SWAT output is TDP while Archibald's model outputs SRP.

Interpretation of these results for manure management would be drastically different between the two models. SWAT results indicate that not only is the timing of manure spread not important for pollution reduction but also that the rates that are currently applied are not having a significantly greater impact than the no manure scenario. This indicates that no changes to manure spreading need to be made. The results of JoFlo tell a very different story for manure management. To reduce P loading to Cayuga Lake farmers should apply manure in June, July, August, and September. These months have the lowest loading rates and are not statistically significantly different from the no manure scenario. This means dairy farmers can safely apply manure to their fields in these months without risk of large P fluxes to adjacent water bodies.

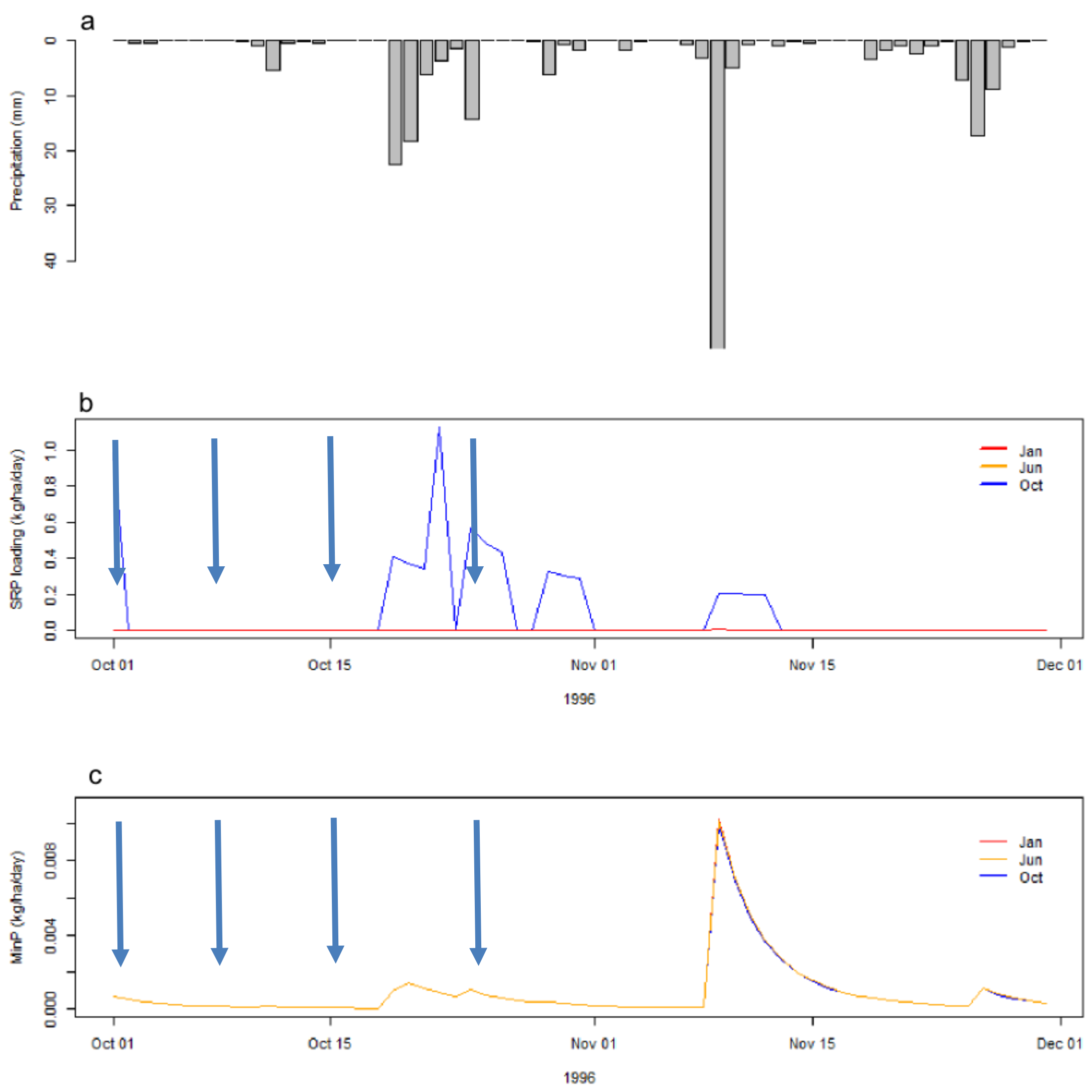


Figure 12. Comparison of precipitation (a) and predicted SRP loading from JoFlo (b) and TDP loading from the SWAT (c) over the course of two months and two appreciable rain events. The blue arrows denote manure applications in January. The red, yellow, and blue lines denote daily soluble P loading when manure is applied in January, June, and October, respectively. The pattern of P loading from the two models is drastically different. Output from JoFlo display sensitivity to manure application and precipitation events. The SWAT is sensitive only to precipitation events that are sufficiently large.

Conclusion

The empirical relationship between the timing of manure application and P losses to waterways has been established by many studies (Archibald et al., 2015; Archibald, 2015; Komiskey et al., 2011; Vadas et al., 2011; Gerard-Marchant et al., 2005; Kleinman et al., 2004; Kleinman and Sharpley, 2003; Hergert et al., 1981; Klausner et al., 1976; Young and Mutchler, 1976). The P routines carried out by SWAT do not reflect these empirical relationships; this greatly limits its ability to evaluate manure spreading scenarios. However, simpler models, such as JoFlo, are capable of accurately reproducing empirical patterns. We conclude, based on our findings, that the SWAT routines must be modified to more accurately reflect empirical knowledge of how P losses vary with the timing of manure spreading. Modifications should include adding labile pools of mineral and organic P applied to the soil surface or lightly incorporated (Figure 13). P in manures and other fertilizers would be added to these pools upon application. Movement of P out of these pools would be through losses in surface runoff and incorporation of labile P into soil P pools. P would move from the surface labile pools into the soil P pools as a function of time since application. Work is currently being done at the United States Department of Agriculture Agricultural Research Service (USDA-ARS) to modify SWAT P routines and rectify this problem, it is unknown at this time if their modifications are similar to the solution we propose.

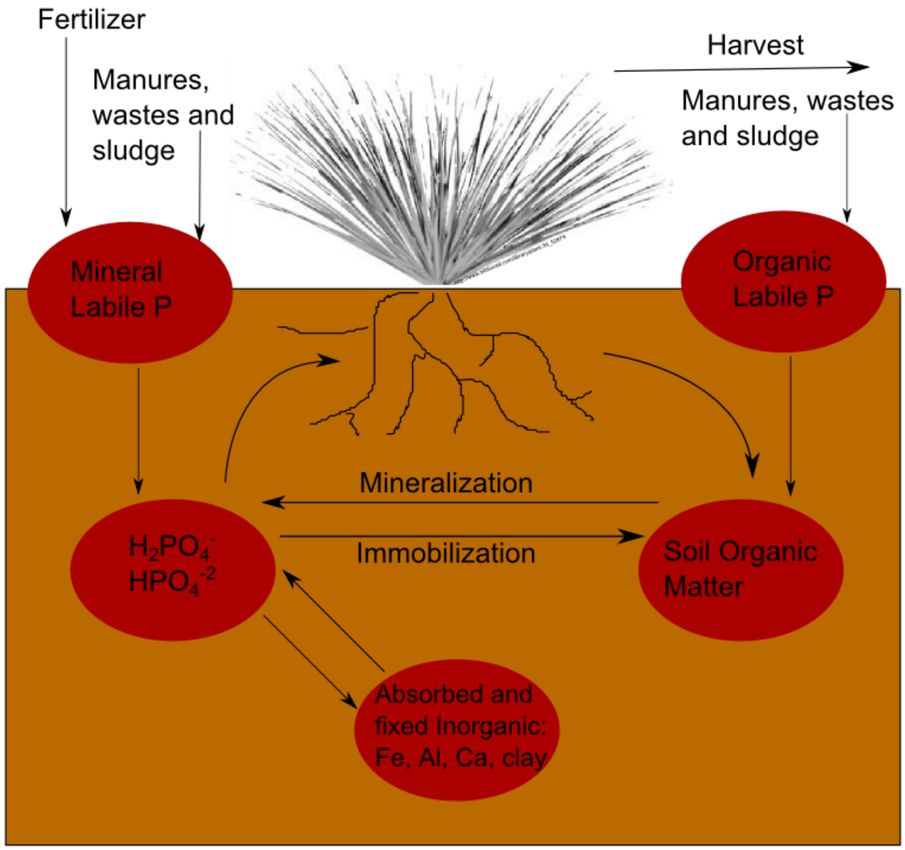


Figure 13. Proposed modifications to the soil P cycling routines in the SWAT model. Fertilizers, manures, wastes, and sludge would be partitioned into mineral and organic labile P pools which would be easily washed away in surface runoff. P would move from these pools into the existing mineral and organic soil P pools as a function of time since application.

Our findings should be of use to decision makers and conservationists as the SWAT is commonly used in projects where pollution mitigation and conservation are primary goals. Those who are using SWAT to answer applied questions must be fully aware of the limitations of the model and formulate questions accordingly. In its current state the SWAT cannot be used to provide information or recommendations to dairy farmers about when to dispose of manure waste to minimize their impact on adjacent fresh water bodies. Similarly, any previous studies which attempted to do so must be reexamined and reevaluated. The results of this study explore a flaw in SWAT P cycling that has important management and conservation implications and must be taken into account if the SWAT is to be used to model P loading from agriculture.

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