

Research article

Source contribution to phosphorus loads from the Maumee River watershed to Lake Erie

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ABSTRACT

Coastal eutrophication is a leading cause of degraded water quality around the world. Identifying the sources and their relative contributions to impaired downstream water quality is an important step in developing management plans to address water quality concerns. Recent mass-balance studies of Total Phosphorus (TP) loads of the Maumee River watershed highlight the considerable phosphorus contributions of non-point sources, including agricultural sources, degrading regional downstream water quality. This analysis builds upon these mass-balance studies by using the Soil and Water Assessment Tool to simulate the movement of phosphorus from manure, inorganic fertilizer, point sources, and soil sources, and respective loads of TP and Dissolved Reactive Phosphorus (DRP). This yields a more explicit estimation of source contribution from the watershed. Model simulations indicate that inorganic fertilizers contribute a greater proportion of TP (45% compared to 8%) and DRP (58% compared to 12%) discharged from the watershed than manure sources in the March–July period, the season driving harmful algal blooms. Although inorganic fertilizers contributed a greater mass of TP and DRP than manure sources, the two sources had similar average delivery fractions of TP (2.7% for inorganic fertilizers vs. 3.0% for manure sources) as well as DRP (0.7% for inorganic fertilizers vs. 1.2% for manure sources). Point sources contributed similar proportions of TP (5%) and DRP (12%) discharged in March–July as manure sources. Soil sources of phosphorus contributed over 40% of the March–July TP load and 20% of the March–July DRP load from the watershed to Lake Erie. Reductions of manures and inorganic fertilizers corresponded to a greater proportion of phosphorus delivered from soil sources of phosphorus, indicating that legacy phosphorus in soils may need to be a focus of management efforts to reach nutrient load reduction goals. In agricultural watersheds around the world, including the Maumee River watershed, upstream nutrient management should not focus solely on an individual nutrient source; rather a comprehensive approach involving numerous sources should be undertaken.

1. Introduction

In 2014, toxins from a Harmful Algal Bloom (HAB) in the Western Basin of Lake Erie entered the drinking water plant in Toledo, Ohio, forcing the city to issue a drinking water advisory to its citizens (Jetoo et al., 2015). Negative consequences of HABs such as drinking water

advisories (Ho and Michalak, 2015; Jetoo et al., 2015), depressed housing prices (Smith et al., 2019; Wolf and Klaiber, 2017), and toxin bioaccumulation in fish (Bi et al., 2019; Wituszynski et al., 2017), have affected waterbodies and their surrounding watersheds throughout the world (Huisman et al., 2018). Coastal cultural eutrophication, the process in which human activities accelerate eutrophication of water bodies

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through nutrient discharge, is a leading cause of the development of HABs worldwide (Glibert, 2019; Paerl et al., 2018). In marine systems, the primary focus has been on reducing nitrogen inputs to lessen the occurrence of HABs (Paerl et al., 2018), while in freshwater systems, such as Lake Erie, the major focus has turned to phosphorus, as it is typically the limiting nutrient in HAB production there (Schindler et al., 2016).

The Great Lakes Water Quality Agreement (GLWQA), signed in 1972 between the United States and Canada, aimed to address the occurrence of HABs as well as other water chemistry and pollution issues within the Great Lakes (Botts and Muldoon, 2005). The initial agreement focused on reducing point sources of nutrients, particularly phosphorus, which resulted in improved water quality throughout the Great Lakes, including a reduction in the size and occurrence of HABs in Lake Erie (Botts and Muldoon, 2005; DePinto et al., 1986). However, in the 2000s, HABs reemerged within the lake (Kane et al., 2014; Scavia et al., 2014) with increasing severity over time (Stumpf et al., 2016). In response, the United States and Canada agreed to a revised GLWQA in 2016 that includes targets to reduce total phosphorus (TP) and dissolved reactive phosphorus (DRP) loads by 40% entering the lake by 2025 (US EPA, 2018).

The Maumee River watershed is the largest contributor of phosphorus to the Western Basin of Lake Erie (Maccoux et al., 2016). A recent mass-balance study of the watershed has found that approximately 88% of the TP load discharged from the watershed originates from non-point sources dominated by agriculture (Ohio EPA, 2018). Few studies of the watershed assess the individual role of legacy phosphorus (Muenich et al., 2016), manure (IJC, 2018; Robertson et al., 2019), and inorganic fertilizers (IJC, 2018; Robertson et al., 2019) on phosphorus discharge from the watershed. Within the watershed, media attention and legislation have focused on contributions from manure management (ORC, 2014); however, questions remain on the relative impact this and other sources have on phosphorus discharged to Lake Erie.

Watershed models are commonly used to analyze the contribution of various sources of nutrients on downstream water quality (Hua et al., 2019; Liu et al., 2019a; Robertson et al., 2019; Zhou et al., 2018; Collick et al., 2015). The Soil and Water Assessment Tool (SWAT), is a leading watershed model that has been extensively used across the globe for this purpose (Pulighe et al., 2020; Abbasi et al., 2019; Nazari-Sharabian et al., 2019; Tan et al., 2019), including in the Maumee River watershed (Yuan et al., 2020; Scavia et al., 2017; Martin et al., In Press). Using local manure nutrient information and improving how manure applications are represented in SWAT models of the Maumee River watershed are of particular importance because policies and plans designed to control or reduce nutrient discharge from the watershed rely, in part, on watershed modeling results from SWAT models of the watershed (Ohio Lake Erie Commission, 2020; US EPA, 2018).

Numerous studies have focused on simulating and improving SWAT simulation of manure and inorganic fertilizer sources and transport (Menzies Pluer et al., 2019; Knighton et al., 2017; Liu et al., 2017; Malagó et al., 2017; Collick et al., 2016; Gildow et al., 2016). Recent SWAT improvements related to manure applications include utilizing local manure nutrient information in regional simulations (Liu et al., 2017) and developing new soil phosphorus routines to improve how manure nutrients are simulated in the soil (Collick et al., 2016). However, these improvements have yet to be incorporated into the supported SWAT source code, and so are not commonly used in SWAT assessments, nor are they included in this study.

This study aims to apportion contributions of phosphorus discharged from the Maumee River watershed to Lake Erie by source type, including manure applications, inorganic fertilizer applications, point sources (e.g. wastewater treatment plants and combined sewer overflows), and soil sources. In this work, soil sources of phosphorus include the residual phosphorus initialized within the calibrated model and legacy nutrients stored within the soil profile. This study has two objectives, 1) to simulate the source contributions of phosphorus discharged from the

Maumee River watershed using a SWAT model of the basin, and 2) to estimate the delivery fractions of inorganic fertilizer and manure sources within the watershed to Lake Erie.

2. Methods

2.1. Study area

This study was performed in the Maumee River watershed (Fig. 1) which drains into the Western Basin of Lake Erie. The Maumee River watershed spans over 17,000 square kilometers of which approximately 80% of the land use is agricultural (Ohio EPA, 2010). The watershed's flat topography and clayey or poorly drained soils (Ohio EPA, 2014) have led to subsurface ("tile") drainage being heavily employed across the agricultural landscape (Muenich et al., 2016). The watershed is the largest source of TP loading to the Western Basin of Lake Erie (Maccoux et al., 2016).

2.2. SWAT model and model phosphorus cycling

The Soil and Water Assessment Tool (SWAT, revision 635; modified according to Kalcic et al., 2016) was used to simulate hydrologic and nutrient dynamics within the Maumee River watershed. SWAT is a process-based, semi-distributed hydrological model developed by the United States Department of Agriculture (USDA) Agricultural Research Service (ARS). The SWAT model has been used in many watersheds across the world (e.g. Bauwe et al., 2019; Tan et al., 2019; Cibir et al., 2016) including in the Maumee River watershed (e.g. Scavia et al., 2017). Among watershed model options for the Maumee River watershed, the SWAT model has been identified as the most suitable watershed model, partly because of the ability to simulate impacts of agricultural practices on nutrient runoff (Gebremariam et al., 2014).

SWAT considers soil phosphorus cycling in two broad pools: inorganic or mineral soil phosphorus and organic soil phosphorus (Neitsch



Fig. 1. The Maumee River Watershed spans parts of Indiana, Michigan, and Ohio and drains into Lake Erie's Western Basin.

et al., 2011). Within each of these two broad pools, three sub-pools are present and used to store various forms of phosphorus in the simulation. In the inorganic phosphorus pool, the sub-pools include active, stable, and solution, while in the organic phosphorus pool, the sub-pools include active, stable, and fresh. Fertilizers and crops can affect the gross amount of phosphorus that is cycled through soil within the model. Manure applications affect both the inorganic and organic phosphorus pools while inorganic fertilizer affects only the inorganic soil phosphorus pool. In addition to these external sources of phosphorus addition or drawdown, the concentration of solution phosphorus in the inorganic phosphorus pool, otherwise known as labile phosphorus, is set within all soil layers within the model prior to beginning a simulation. Soil phosphorus cycling described above only affects nutrients applied on hydrologic response units (HRUs), the smallest spatial unit within the model. Unlike manure and inorganic phosphorus fertilizer inputs, which have the opportunity for binding or loss along the transport pathway to the reach, nutrients discharged from point sources directly enter the reach of each subbasin, being loaded directly into the main channel of the simulated watershed, and are thus governed by in stream nutrient processes. This has ramifications on the interpretation of delivery fractions. Once nutrients are in the main channel, all are then governed by in stream nutrient processes, regardless of source.

2.3. SWAT model parametrization and calibration

The time-periods for model calibration and validation were 2005–2015 and 2000 to 2004, respectively. The calibration period occurred after the validation period in part to account for the two most severe harmful algal blooms that occurred in Lake Erie in 2011 and 2015 (NOAA, 2019a) as well as due to better available spatial and temporal data relating to agricultural land management and point source discharges in the study area. Calibration and validation was performed to best simulate stream flow, sediment, and nutrient loads. Stream flow and water quality data used for calibration and validation were obtained from the USGS gauge #04193500 from the National Center for Water Quality Research at Heidelberg University, which collects daily samples. Nutrient loads were calculated at the gauge by multiplying river discharge by nutrient concentration (Williams et al., 2016). Model calibration showed that the model satisfactorily predicted hydrology and nutrient loads (Table 1; Moriasi et al., 2015; Arnold et al., 2012). Two labile P values were initialized in the model baseline: 24.7 mg/kg and 5 mg/kg. The top 20 cm of soil in agricultural row crop lands received a labile P value of 24.7 mg/kg based on regional soil test phosphorus values (Culman et al., 2019; Williams et al., 2015; Sharpley et al., 1984), while lower soil layers and all other land uses received the SWAT default value of 5 mg/kg. These two labile P values in the model baseline were set uniformly across HRUs based on land use within the watershed. For more information on model parameterization see the Supplemental Information.

Table 1

Daily and monthly calibration and validation statistics for the Maumee River SWAT model. ‘Satisfactory’ performance metrics are based off Moriasi et al. (2015) and Arnold et al. (2012). All entries met the minimum criteria for ‘Satisfactory’ performance except daily and monthly sediment PBIAS validation. See the Supplemental Information as well as Apostel et al. (In Press) for more information and detail on model development and calibration.

	Statistic	Metric for Satisfactory Performance	Daily Calibration (2005–2015)	Monthly Calibration (2005–2015)	Daily Validation (2000–2004)	Monthly Validation (2000–2004)
Flow	NSE	>0.5	0.87	0.95	0.82	0.86
	PBIAS	< ±15%	−0.83	−0.88	−10.03	−10.11
Total Phosphorus	NSE	>0.35	0.58	0.52	0.46	0.44
	PBIAS	< ±30%	−3.76	−3.23	−18.53	−18.35
Dissolved Reactive Phosphorus	NSE	>0.35	0.62	0.67	0.63	0.73
	PBIAS	< ±30%	2.03	1.51	−9.89	−10.22
Total Nitrogen	NSE	>0.35	0.55	0.69	0.68	0.71
	PBIAS	< ±20%	−1.24	−6.44	−6.44	−6.73
Sediment	NSE	>0.45	0.65	0.75	0.58	0.70
	PBIAS	< ±20%	1.62	2.06	−27.21	−26.09

2.4. Representing watershed manure applications

Manure application dates (Supplemental Information - Manure Application Timing), manure application methods (Supplemental Information - Manure Application Methods), and manure nutrient contents (Supplemental Information - Manure Nutrient Compositions) were derived from local manure analyses and practices of northwest Ohio Concentrated Animal Feeding Operations (CAFOs; Kast et al., 2019). These data were used to inform HRU level manure application procedures throughout the watershed. In the model set-up, approximately 18% of the total agricultural cropland in the watershed received manure application at least once every six years, with approximately 7.5% of the agricultural cropland receiving manure each year (Supplemental Information - Manure Application Locations). Manure applications occurred every year on alfalfa rotations (1.2% of agricultural cropland), once every two years on continuous corn, continuous soybean, soybean-corn, wheat-corn, and soybean-wheat rotations (52.0% of agricultural cropland), and once every three years on corn-soybean-wheat, corn-corn-soybean, corn-soybean-soybean, corn-corn-wheat, wheat-soybean-wheat, and soybean-soybean-wheat rotations (46.8% of agricultural cropland). Swine manure generated from livestock housed in permitted CAFOs was applied within a 2.01 km radius from the livestock barn while cattle manure generated from livestock housed in these operations were applied within a 3.07 km radius off the livestock barn (Kast et al., 2019). Manure application rates varied by county, livestock type, and the permitted-status of the livestock (Supplemental Information - Manure Application Rates and Supplemental Information - Livestock Population Estimates). Manure application rates varied between 46.6 kg/ha and 13,605.7 kg/ha for swine manure, between 534.9 kg/ha and 14,927.7 kg/ha for cattle manure, and between 1,892.1 kg/ha and 5,741.6 kg/ha for poultry manure. An irrigation operation was applied concurrently with liquid manure applications in SWAT to better represent the high moisture content of liquid manure. The irrigation operation and corresponding characteristics varied based on the method in which manure was applied in the model (Supplemental Information - Irrigation Operation).

2.5. Scenarios simulated

Twenty-one scenarios were simulated in SWAT (Table 2) to estimate the impacts of phosphorus source on loads discharged from surface runoff and subsurface drainage in the Maumee River watershed, as well as to assess the sensitivity of the model to changing soil phosphorus concentrations and of the inclusion of an irrigation operation applied concurrently with liquid manure applications.

2.6. Simulation approaches and scenario descriptions

The general approach to modeling was to eliminate or ‘turn off’ specific inputs of phosphorus in each scenario (Scenario1-5; 16–19; and

Table 2
Descriptions of scenarios evaluated (PS- Point Sources, P- Phosphorus).

Scenario Category	Scenario Number	Scenario	Description
–	BAS	Baseline	Calibrated Baseline model. Labile P concentrations were set to 24.7 mg/kg for the top 20 cm of agricultural row crop lands and 5 mg/kg for all other land uses and lower soil layers.
1	1	No PS	All point sources in the watershed were removed.
1	2	No Manure P	All phosphorus in manure applications in the watershed were removed. Nitrogen in manure applications was maintained to support crop growth.
1	3	No Inorganic Fertilizer P	All sources of inorganic phosphorus fertilizers were removed.
1	4	No Inorganic Fertilizer or Manure P	All sources of inorganic phosphorus fertilizer and all phosphorus in manure applications in the watershed were removed. Nitrogen in manure applications was maintained to support crop growth.
1	5	No PS or Inorganic Fertilizer or Manure P	All point sources, all sources of inorganic phosphorus fertilizer, and all phosphorus in manure applications in the watershed were removed. Nitrogen in manure applications was maintained to support crop growth.
1	6	No Irrigation	All irrigation operations applied in the Baseline concurrently with liquid manure applications were removed.
1	7	Uniform Urban Soil P	Labile P concentrations in all agricultural lands, across soil layers, in the Baseline were set to 5 mg/kg, the SWAT default value, to be consistent with other land uses.
1	8	25% Initialized Soil P	Labile P concentrations in all agricultural lands were reduced to 25% of the initialized values in the Baseline.
1	9	50% Initialized Soil P	Labile P concentrations in all agricultural lands were reduced to 50% of the initialized values in the Baseline.
1	10	75% Initialized Soil P	Labile P concentrations in all agricultural lands were reduced to 75% of the initialized values in the Baseline.
1	11	125% Initialized Soil P	Labile P concentrations in all agricultural lands were increased to 125% of the initialized values in the Baseline.
1	12	150% Initialized Soil P	Labile P concentrations in all agricultural lands were increased to 150% of the initialized values in the Baseline.
1	13	175% Initialized Soil P	Labile P concentrations in all agricultural lands were increased to 175% of the

Table 2 (continued)

Scenario Category	Scenario Number	Scenario	Description
1	14	200% Initialized Soil P	initialized values in the Baseline. Labile P concentrations in all agricultural lands were doubled from the initialized values in the Baseline.
2	15	75% Fertilizer and Manure Application Rates	Inorganic fertilizer and manure application rates were reduced by 25% from the baseline rates.
2	16	75% & No PS	All point sources from the 75% Fertilizer and Manure Rates application scenario (15) were removed.
2	17	75% & No Manure P	All phosphorus in manure applications in the 75% Fertilizer and Manure Rates application scenario (15) were removed. Nitrogen in manure applications was maintained to support crop growth.
2	18	75% & No Inorganic Fertilizer P	All inorganic phosphorus fertilizer applications in the 75% Fertilizer and Manure Rates application scenario (15) were removed.
2	19	75% & No PS or Inorganic Fertilizer or Manure P	All point sources, inorganic phosphorus fertilizer and manure phosphorus applications in the 75% Fertilizer and Manure Applications Rates application scenario (15) were removed. Nitrogen in manure applications was maintained to support crop growth.
3	20	300% Manure Application	Manure application rates were tripled from the baseline scenario.
3	21	300% Manure Application & No Manure	All phosphorus in manure applications in the 300% Manure Application scenario (20) were removed. Nitrogen in manure applications was maintained to support crop growth.

21), and then compare results to a baseline scenario (Scenario BAS; 15; and 20) to determine impacts on phosphorus discharged from the watershed due to various sources of upstream phosphorus. This approach was also followed to assess the impact of adding an irrigation function applied with liquid manure (Scenario 6) and of varying the initialized soil phosphorus levels of agricultural HRUs (Scenarios 7–14). However, for assessing the impact of adding an irrigation function applied with liquid manure (Scenario 6), rather than “turning off” a specific input of phosphorus the irrigation operation was “turned off.”

The twenty-one scenarios were categorized into three bins: 1) evaluation of baseline fertilizer and manure application rates, and soil phosphorus levels, 2) 75% fertilizer and manure application rates, and 3) baseline fertilizer application and 300% manure application rates. Scenarios in this first bin aim to apportion the impact of various individual sources of upstream phosphorus (1–5) as well as varying levels of soil phosphorus assigned to agricultural HRUs on phosphorus discharge from the watershed (7–14) and to evaluate the impact of including an irrigation function applied concurrently with liquid manure applications (6). The second bin, 75% fertilizer and manure application rates, utilizes fertilizer and manure rates at 75% of those in the calibrated baseline. Scenarios in this category (15–19) aim to investigate how depressed fertilizer and manure applications affect the relative importance of various individual sources of phosphorus on phosphorus discharge from

the watershed. The third category, baseline fertilizer application and 300% manure application rates, utilizes fertilizer rates in the calibrated baseline and manure rates at 300% of those in the calibrated model. Scenarios in this category (20–21) aim to assess how over-application of manures would affect the phosphorus delivery fraction from the watershed.

In the 25% Initialized Soil P, 50% Initialized Soil P, and 75% Initialized Soil P scenarios, the initialized HRU-level labile P for all agricultural HRUs were reduced by 75%, 50%, and 25%, respectively from the baseline values of 24.7 mg/kg and 5 mg/kg values. In the SWAT model, labile P is a parameter representing the soluble phosphorus within the soil profile that is available for transport through surface and subsurface pathways (Neitsch et al., 2011). In the 125% Initialized Soil P, 150% Initialized Soil P, 175% Initialized Soil P, and the 200% Initialized Soil P scenarios, the initialized HRU-level labile P for all agricultural HRUs were increased from the baseline values by 25%, 50%, 75%, and 100% respectively. Percent changes for March–July TP (Equation (1)) and DRP (Equation (2)) for each scenario compared to the calibrated baseline were calculated to assess the impact of each scenario, and thus individual sources of phosphorus, on phosphorus discharged from the watershed.

$$\text{Percent Change} = (\text{March-July TP Baseline} - \text{March-July TP Scenario}) / (\text{March-July TP Baseline}) \quad (1)$$

$$\text{Percent Change} = (\text{March-July DRP Baseline} - \text{March-July DRP Scenario}) / (\text{March-July DRP Baseline}) \quad (2)$$

2.7. Model simulation and data analysis

The 21 scenarios were simulated from 2005 to 2015 with a five-year warm-up period. Although model processes were run on the daily time-scale, results were generated on the monthly time-scale. Nutrient loads were analyzed during the March–July period, as this is the critical time for phosphorus loading and HAB development in Lake Erie (Wilson et al., 2019; Stumpf et al., 2012). Delivery fractions were calculated by dividing the estimated mass of TP and DRP discharged from the Maumee River and attributed to manure or inorganic fertilizer sources by the mass of that phosphorus source applied in the model on an annual basis (Fig. 2). Phosphorus delivery fractions used in this study are based on the conceptual understanding of sediment delivery ratios (Streeter et al., 2018) that estimate exported soil sediment from a given watershed and can be expanded to account for phosphorus (Schiling et al., 2018). In effect, the phosphorus delivery fraction estimates the percent of

phosphorus applied as either a given source that reaches Lake Erie each year.

3. Results

3.1. Source contributions of discharged March–July total phosphorus and dissolved reactive phosphorus

Inorganic fertilizers contributed the greatest proportion of DRP March–July loads (58%) and the second largest proportion of TP March–July loads (42%). Soil sources contributed the largest proportion of TP loads (45%) and the second largest proportion of DRP loads (18%). Manure sources of phosphorus contributed 8% of the TP load and 12% of the DRP load from the watershed (Fig. 3) while accounting for between 13% and 15% of the total phosphorus land applied in the watershed (Supplemental Information Table S12). Removing phosphorus from manure applications and inorganic fertilizer applications resulted in a 52% decrease in TP loads and a 65% decrease in DRP loads. Due to the routing of phosphorus in the SWAT model (i.e., movement from the active to stable pool), removing phosphorus from manure and inorganic fertilizer separately did not correspond to an additive effect in the No Inorganic Fertilizer or Manure P scenario. In the No Inorganic Fertilizer

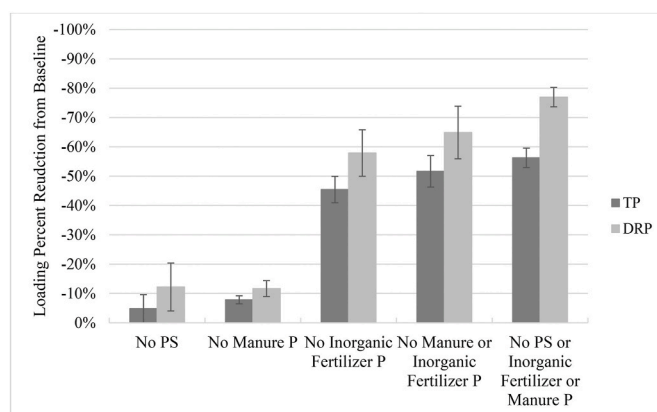


Fig. 3. Average March–July TP and DRP loading percent reduction from the Baseline. Whiskers represent annual March–July variation in TP and DRP discharges from 2005 to 2015. Note: Fractions of TP and DRP load may not add to 100% due to the interaction effect of manure and inorganic fertilizer applications and their distributions into various phosphorus pools within the SWAT model.

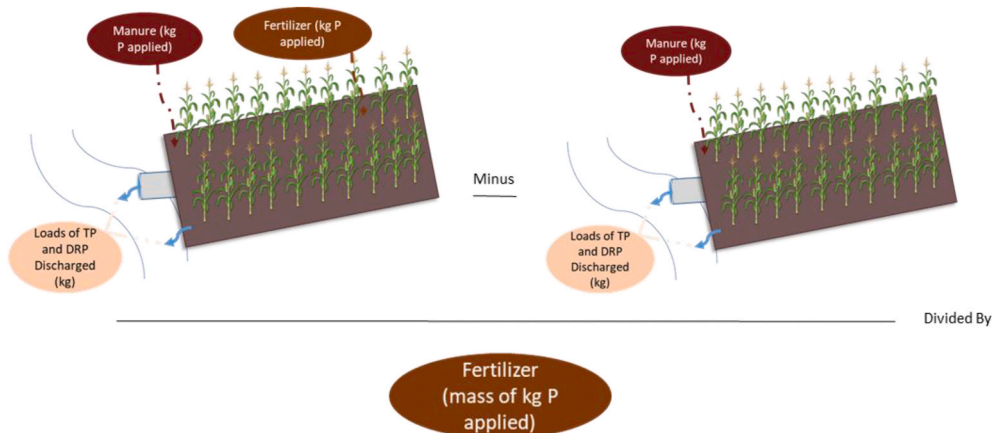


Fig. 2. Calculating the TP and DRP delivery fractions for inorganic fertilizer phosphorus. In this example, annual TP and DRP loads from the No Inorganic Fertilizer P scenario were subtracted from the annual TP and DRP loads from calibrated baseline. This value was then divided by the mass of inorganic fertilizer P applied. This process was repeated in calculating TP and DRP delivery fractions of manure phosphorus using the respective model scenario and mass of manure P applied.

or Manure P scenario, TP loadings increased by 1.6% compared to the load reductions achieved by summing the TP load reductions for the No Manure P and No Inorganic Fertilizer P scenarios, while DRP loadings decreased by 4.7%.

Point sources contributed 5% and 12% of the TP and DRP load, respectively (Fig. 3). Point sources showed the greatest year-to-year variation in the proportion of TP and DRP of all the sources, given that they are less driven by climate than are the others. Point sources had their greatest influence on total TP and DRP load in 2005, the year with the third-least amount of precipitation and their lowest influence on total TP and DRP load in 2011, the year with the highest amount of precipitation as compared to the other sources of phosphorus in the watershed (Table 3). Similar to point sources, soil sources varied yearly in their fractional share of discharged TP and DRP. Annual proportions of TP and DRP loading attributed to soil sources ranged between 39% and 49%, and 19% and 27%, respectively (Table 3).

Applying less inorganic fertilizer and manure decreased the proportional contributions from inorganic fertilizer and manure to TP and DRP loadings. Accordingly, point sources and soil sources contributed a greater fraction of TP and DRP discharged from the watershed when less manure and inorganic fertilizers were applied (Table 4).

3.2. Annual phosphorus delivery fractions from manure and inorganic fertilizers

Average delivery fractions (Table 5) were similar for manure as for inorganic fertilizers for both TP (3.0% for manure and 2.7% for inorganic fertilizer) and DRP (1.2% for manure and 0.7% for inorganic fertilizer). These results indicate that manures, when applied at similar rates to inorganic fertilizers, contribute similarly to Lake Erie.

Manure applied at 300% rates of that in the baseline increased the delivery fractions for TP and DRP approximately to 123% and 165%, respectively, from the baseline TP and DRP phosphorus delivery fractions (Fig. 4). In 2011, the wettest year in the simulation, the delivery fractions for TP and DRP for both manure (5.0% and 4.3%, respectively) and inorganic fertilizers (1.9% and 1.1%, respectively) were the largest. In 2012, the driest year in the simulation, the delivery fractions for TP and DRP for both manure (1.2% and 0.5%, respectively) and inorganic fertilizers (1.1% and 0.3%, respectively) were the smallest (Fig. 4). In 2012, point sources contributed 13% of the TP and 27% of the DRP load discharged from the watershed, Table 3. These fractional TP and DRP load contributions for point sources combined with the small yearly manure and inorganic fertilizer TP and DRP delivery fractions indicate

Table 3

Fraction of the simulated March–July phosphorus loads contributed by sources and discharged to Lake Erie between 2005 and 2015 based on scenario simulation results. “Land Applied P” refers to the combination of inorganic fertilizer phosphorus and manure sources of phosphorus applied in the watershed simulation. Annual inorganic and manure phosphorus fertilizers applied are estimated from county-level fertilizer sales and livestock animal counts, respectively (Apostel et al., In press; Kast et al., 2019).

Year	Fraction of total TP (DRP) load (%) from each source				
	Point Sources	Inorganic P Fertilizer	Manure P Fertilizer	Land Applied P	Soil Sources
2005	18 (33)	35 (40)	5 (6)	39 (44)	44 (24)
2006	11 (22)	39 (46)	6 (8)	44 (51)	46 (27)
2007	5 (14)	41 (53)	7 (10)	46 (59)	49 (27)
2008	4 (11)	43 (56)	7 (11)	49 (64)	46 (25)
2009	6 (16)	42 (51)	6 (9)	47 (57)	47 (27)
2010	6 (13)	43 (53)	8 (11)	49 (61)	45 (27)
2011	3 (7)	46 (64)	8 (12)	53 (71)	45 (23)
2012	13 (27)	42 (47)	8 (10)	49 (54)	39 (21)
2013	4 (12)	47 (59)	8 (12)	54 (66)	42 (23)
2014	4 (10)	49 (62)	9 (16)	56 (71)	41 (19)
2015	4 (9)	51 (65)	9 (13)	57 (72)	39 (19)
Average	8 (16)	43 (54)	7 (11)	49 (61)	44 (24)

Table 4

Fraction of the simulated March–July phosphorus loads contributed by sources and discharged to Lake Erie between 2005 and 2015 with 75% of Inorganic Fertilizers and Manure Application Rates based on scenario simulation results. Land Applied P refers to the combination of inorganic fertilizer phosphorus and manure sources of phosphorus applied in the watershed simulation. Annual inorganic and manure phosphorus fertilizers applied are estimated based off county-level fertilizer sales and livestock animal counts (Apostel et al., In press; Kast et al., 2019).

Year	Fraction of total TP (DRP) load (%) from each source				
	Point Sources	Inorganic P Fertilizer	Manure P Fertilizer	Land Applied	Soil Sources
2005	20 (38)	28 (32)	4 (4)	32 (35)	49 (28)
2006	12 (26)	32 (37)	5 (6)	36 (42)	53 (33)
2007	5 (17)	34 (43)	5 (8)	38 (49)	57 (34)
2008	5 (14)	36 (47)	6 (9)	41 (54)	54 (32)
2009	7 (20)	34 (42)	5 (7)	39 (46)	55 (34)
2010	7 (16)	36 (45)	6 (8)	41 (51)	52 (33)
2011	3 (9)	39 (55)	7 (9)	44 (61)	53 (30)
2012	15 (33)	35 (38)	6 (7)	40 (43)	46 (25)
2013	5 (15)	40 (49)	7 (9)	45 (55)	50 (30)
2014	4 (13)	41 (53)	8 (13)	47 (61)	49 (26)
2015	4 (12)	43 (56)	7 (10)	48 (62)	47 (25)
Average	8 (19)	36 (45)	6 (8)	41 (51)	51 (30)

Note: Fractions of TP and DRP load may not add to 100% due to the interaction effect of manure and inorganic fertilizer applications and their distributions into various phosphorus pools within the SWAT model.

Table 5

Annual TP and DRP delivery fractions for inorganic phosphorus fertilizer and manure.

Year	TP Delivery Fraction (%)		DRP Delivery Fraction (%)	
	Inorganic P Fertilizer	Manure	Inorganic P Fertilizer	Manure
2005	2.6	2.6	0.7	1.0
2006	1.6	1.5	0.5	0.6
2007	2.7	2.9	0.7	1.2
2008	4.2	4.1	1.0	1.5
2009	2.7	2.9	0.7	1.1
2010	1.2	1.3	0.4	0.6
2011	4.3	5.0	1.1	1.9
2012	1.1	1.2	0.3	0.5
2013	3.8	4.4	0.9	1.7
2014	2.9	3.3	0.7	1.4
2015	2.8	3.4	0.8	1.5
Average	2.7	3.0	0.7	1.2

that phosphorus land applied in a dry year will have smaller proportional effect on discharged water quality from the watershed as compared to wetter years. In wetter years, such as 2011, higher manure and inorganic fertilizer TP and DRP delivery fractions corresponded with smaller point source fractional TP and DRP load contributions (Table 3; Fig. 4).

3.3. Sensitivity of adding an irrigation function with liquid manure applications and of varying initialized soil P concentrations

Removing the irrigation operation applied concurrently with liquid manure applications had a negligible impact on nitrogen and phosphorus loadings from the watershed (Supplemental Information - Table S5). Annual Total Nitrogen and Nitrate loadings from the watershed were both reduced 0.2% respectively when the irrigation operation was removed from the simulation. TP and DRP loadings decreased marginally (<0.1%) when the irrigation operation was removed. Although watershed outlet nutrient loadings were not largely affected by the removal of the irrigation operations, more variability on their impact was present in the 2082 HRUs (10% of modeled agricultural HRUs), which received the operations (Supplemental Information - Tables S9 and S10).

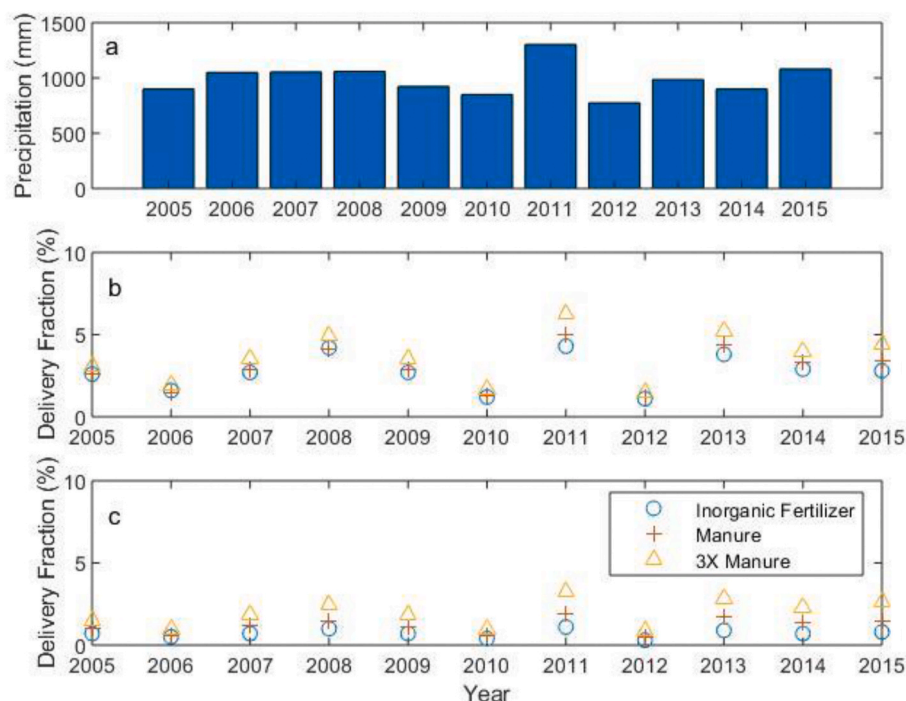


Fig. 4. Results for a) simulated annual precipitation, b) annual TP delivery fraction and c) annual DRP delivery fraction for baseline inorganic phosphorus fertilizer, baseline manure, and manure applied at three times the baseline rate.

Increasing or reducing the initialized concentration of labile P within agricultural HRUs in the model affected DRP more than TP (Fig. 5). Increasing the initialized labile P concentrations by 25% in agricultural HRUs resulted in increases of March–July TP loads by 6% and DRP loads by 9% while doubling the labile P concentration in these HRUs resulted in increases of March–July TP loads by 22% and DRP loads by 34%. Reducing the initialized labile P concentration by 50% resulted in reductions of March–July TP loads by 15% and DRP loads by 19% while

reducing labile P concentrations to a uniform 5 mg/kg level resulted in reductions of March–July TP loads by 25% and DRP loads by 31% (Fig. 5).

3.4. Scenario impacts on crop yields

Baseline average watershed-level corn yield was 8.94 kg/ha, average watershed-level soybean yield was 2.47 kg/ha, and average watershed-

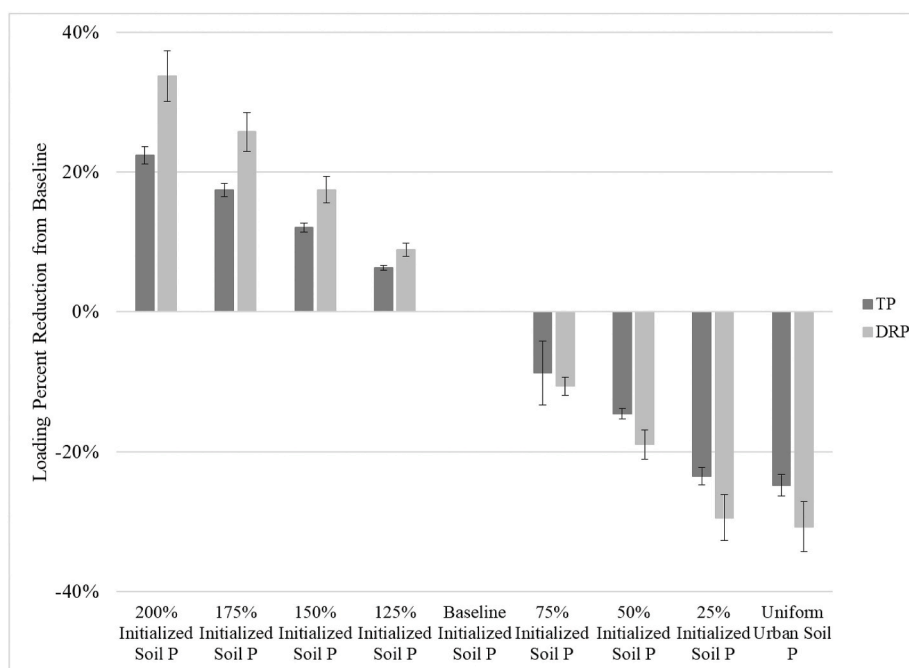


Fig. 5. Average TP and DRP percent change in TP and DRP loads from the Baseline due to changes in initial soil P levels. Whiskers represent yearly variation in TP and DRP discharges from 2005 to 2015. Labile P values of soils in agricultural HRUs were increased to 200%, 175%, 150%, or 125% of baseline or reduced to 75%, 50% or 25% of baseline, or to a uniform value initialized in all non-agricultural HRUs.

level wheat yield was 3.23 kg/ha. Crop yields for corn, soybean, and wheat were only marginally affected by altering the application rates of inorganic fertilizer and manure, the initialized labile phosphorus, and by removing individual sources of phosphorus within the watershed (Supplemental Information- Table S11).

4. Discussion

4.1. Source contributions of discharged total phosphorus and dissolved reactive phosphorus

As expected, the proportions of estimated TP loads discharged to Lake Erie from the Maumee River watershed were similar to results of mass balances completed for this watershed, confirming that agricultural inputs are the dominant source of phosphorus loading from the watershed (Robertson et al., 2019; Ohio EPA, 2018; Ohio EPA, 2016). Novel results compared to these mass-balance studies include the impact of soil sources of phosphorus as well as manure sources of phosphorus on nutrient loading from the watershed. On average, manure contributed similar masses of TP and DRP discharged from the watershed as did point sources while contributing 8-times less TP than inorganic fertilizers or soil sources and 7-times less DRP than inorganic fertilizers and 2.5-times less DRP than soil sources. This indicates that although current applications of manure play an important role in phosphorus discharge from the watershed, other sources of phosphorus in the watershed contribute larger masses of TP and DRP.

Legacy sources of phosphorus contribute to impaired downstream water quality across the world (Zhu et al., 2018; Sharpley et al., 2013) including watersheds throughout the United States (Guo et al., 2019; Sharpley et al., 2013) and in the Maumee River watershed (King et al., 2017; Muenich et al., 2016). Legacy nutrients are particularly important in the Maumee River watershed, where in multiple sub-basins of the watershed these sources contribute more than 34% of the riverine discharged phosphorus (Stackpoole et al., 2019). In the calibrated baseline model, soil sources of phosphorus contributed between 39% and 49% of the annual TP and 19% and 27% of the annual DRP discharged from the watershed (Table 3). These results indicate that soil sources of phosphorus within the watershed play an increased role in nutrient discharge with decreasing agricultural inputs. Soil sources of phosphorus contribute over 7% more of the total proportion of TP and DRP discharged from the watershed when manure and inorganic fertilizer rates are reduced by 25%. This increase indicates that focusing management on reducing the impact of some sources of phosphorus can lead to a shift in the importance and role of other sources in phosphorus discharges from the watershed. For instance, even though only 91%–96% of corn and 75%–83% of soybean acres in Indiana, Michigan, and Ohio were planted through June 2019 (USDA-NASS, 2019a; USDA-NASS, 2019b; USDA-NASS, 2019c), and less inorganic fertilizer and manure were likely applied within the watershed, the HAB in Lake Erie was substantial (NOAA, 2019b). The severity of the HAB was likely driven in part by large amounts of precipitation in the region leading to an increased contribution of phosphorus discharged from the soil in the watershed.

Although our results indicate the importance of phosphorus discharged from soil stores in the watershed, there is uncertainty surrounding the spatial locations of fields with high and low soil phosphorus within the watershed. Our assumption that all agricultural row crop lands had the average soil phosphorus concentration could have led to an under-estimate of the contribution of manure phosphorus, if fields receiving manure applications in reality have greater soil stores than fields receiving inorganic fertilizers. In the majority of simulations (BAS, 1–6, and 15–21), agricultural row crop HRUs had uniform soil phosphorus values of 24.7 mg/kg in top the 20 cm of soil. When these uniform values were reduced by 75%, March–July TP and DRP loads from the watershed were reduced by 24% and 29%, respectively (Fig. 5), which is greater than the combined effect of removing phosphorus from

manure applications and point sources individually from the watershed (Fig. 3). Similarly, our assumption that nutrient applications were based on crop need and county-level fertilizer sales constrained the behavioral heterogeneity in fertilizer application practices.

4.2. Phosphorus delivery fractions from manure and inorganic fertilizers

The proportion of total and dissolved reactive phosphorus discharged from the watershed originating in manure applications was similar to that of phosphorus originating in inorganic fertilizer applications (Table 5). McDowell and Sharpley (2004) found that in low-flow lysimeters in Pennsylvania the estimated load of DRP and TP for dairy manure and superphosphate were similar while poultry manure resulted in DRP loads 90% greater than superphosphate and TP loads 29% greater than superphosphate values. In contrast to our results a column experiment with a sandy soil, described by Kang et al. (2011), found adding inorganic sources of phosphorus led to significantly more DRP leaching than manure sources such as dairy lagoon and swine lagoon liquids. A potential explanation for this discrepancy is that the manure nutrient compositions simulated in the model were based on manure nutrient analyses from manure storage pits in Ohio (Kast et al., 2019) and that the watershed is comprised of predominantly clay soils (Muenich et al., 2016).

Although manure and inorganic fertilizers were found to have similar TP and DRP delivery fractions when the baseline manure and fertilizer application rates were applied, tripling manure application rates and maintaining inorganic fertilizer rates resulted in manure delivery fractions increasing more than three-fold. This indicates that over-application of manure may contribute a disproportionately greater load of phosphorus than manure applied at lower rates. Field studies conducted by Smith et al. (2001) and Tarkslon and Mikkelsen (2010), similarly found that as the rate of manure application increased the phosphorus losses from the soil increased. Therefore, estimates from most of the scenarios (BAS, 1–5, and 15–19) of the phosphorus load from manure applications are likely conservative, as just 12% of manure applications were over-applied, as compared to crop phosphorus needs. In the states encompassing the watershed, manure can be legally applied on fields with soil test phosphorus values up to 150 ppm or 200 ppm, which is 3.8–5 times the 40 ppm range for maintenance applications for corn and soybeans, or even higher if certain conditions are met (Kast et al., 2019). This indicates that manure is potentially applied on fields in the watershed that do not agronomically need the phosphorus for optimal crop growth (Vitosh et al., 1995). Future watershed modeling work in this region could improve with a greater understanding of manure application practices from livestock operations within the watershed, particularly from operations with animal units below permitted thresholds (Kast et al., 2019).

4.3. Representing manure applications in SWAT

A challenge faced by watershed models, including SWAT, is incorporating relationships related to phosphorus losses from mathematical equations and observations (Collick et al., 2016). In a typical SWAT model, when manures are applied, the manure nutrients are applied in the top 1 cm of soil and soil nutrient processes and cycling drive the movement of manure phosphorus (Collick et al., 2016). Using new phosphorus routines developed for the 2012 version of SWAT, including specific routines for manure phosphorus, Collick et al. (2016) found improved sensitivity of phosphorus losses to manure applications where annual phosphorus losses approximately doubled with these new phosphorus routines compared to standard phosphorus routines in SWAT. This paper aims to build on this work improving default phosphorus movement in the SWAT model by introducing an alternative way of accounting for liquid manure moisture contents, which can be greater than 95% (Davis et al., 1999), using irrigation operations that represent the liquid nature of dairy and swine manures. Further, we used manure

nutrient compositions based on manure analyzes taken in the region (Kast et al., 2019) rather than standard SWAT values for swine, cattle, and poultry manures. While these changes better represent the actual moisture and nutrients applied to the soil via manure, there were no noticeable differences in the results compared to conventional SWAT methods (Fig. 3), suggesting more field studies are needed to verify these new approaches.

4.4. Reaching water quality targets in the watershed

Although these scenarios may be unrealistic and infeasible due to economic and technical challenges, they provide insight into where opportunities exist to reduce phosphorus loading from the watershed. Scavia et al. (2017) and Martin et al. (In Press) indicate that multiple best management practices and increased adoption rates are needed to reach a 40% reduction in TP and DRP loading from the watershed. Results from this study further this conclusion. In order to reach the 40% reduction target, addressing multiple sources of phosphorus sources (inorganic fertilizer, manure, point sources, soil) need to be addressed.

We found that the two largest sources of TP and DRP discharged to Lake Erie in the watershed are inorganic phosphorus fertilizer and soil sources of phosphorus (Fig. 3). Reducing the impact of inorganic phosphorus fertilizer on TP and DRP loading from the watershed can occur in multiple ways. These methods include reducing the amount of inorganic phosphorus fertilizer used (Martin et al., In Press; Scavia et al., 2017), placing the fertilizer below the soil surface (Yuan et al., 2018; Smith et al., 2017), and with edge-of-field practices (King et al., 2018; Pease et al., 2018). A key challenge in reducing the effect of soil sources of phosphorus on downstream water quality in the watershed is identifying the fields within the watershed that contribute the highest loads of TP and DRP. Once these fields are identified management practices such as soil phosphorus drawdown (Liu et al., 2019b; Vadas et al., 2018) can be guided to these fields.

5. Conclusion

To better estimate the contributions of various sources of phosphorus runoff reaching the Western Lake Erie Basin from the Maumee River watershed a SWAT model was used to identify the role of manure, inorganic fertilizer, point, and soil sources of nutrient loadings. Inorganic fertilizers and soil sources were found to contribute the largest loads of TP from the watershed, with each source contributing approximately 45% of the load at the watershed outlet. Inorganic fertilizers contributed approximately 60% of the DRP discharged from the watershed. Manure, a leading concern among stakeholders in the region, contributed 8% and 11% of the TP and DRP, respectively, discharged from the watershed. Although manure sources of phosphorus contributed less mass of TP and DRP discharged from the watershed they had similar TP and DRP delivery fractions to inorganic fertilizers. On average, 3.0% of the total phosphorus and 1.2% of the dissolved reactive phosphorus applied as manure was discharged from the watershed each year while 2.7% of the total phosphorus and 0.7% of the dissolved reactive phosphorus from inorganic fertilizers applied did the same. As manure application rates increased the TP and DRP delivery fractions increased as well indicating that at greater applications rates higher TP and DRP loads would be delivered from the watershed. Although manure had similar TP and DRP delivery fractions to that of inorganic phosphorus fertilizer, inorganic phosphorus fertilizers and soil sources of phosphorus contributed the largest March–July TP and DRP loads discharged from the watershed. This indicates that focusing phosphorus reductions from these two sources of phosphorus within the watershed may yield the greatest gain in phosphorus reductions to Lake Erie.

This research identified the specific sources of phosphorus in the watershed that result in the largest loads to Lake Erie. While this can be used to prioritize management towards these sources to realize larger reductions, completely removing each source from the watershed is

unrealistic. Future work can address this limitation by developing scenarios focused on sources with the largest loadings that are economically and physically amenable to producers in the region. This could build upon Scavia et al. (2017) and Martin et al. (In Press), which utilized a stakeholder group to design scenarios including those considered feasible by agricultural groups in the region. Working with stakeholders in this respect can not only aid in developing scenarios but also in generating knowledge among the agricultural community on the effects of various best management practices on discharged water quality. Future work can focus on calibrating the SWAT model at the field-level, which would allow for analyses on the accuracy of the SWAT model in simulating field-level manure and inorganic fertilizer applications and lead to improved calibration statistics upstream in the watershed.

Credit author statement

Jeffrey Kast, Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Visualization, Anna Apostel, Methodology, Software, Margaret Kalcic, Methodology, Software, Validation, Writing – review & editing, Supervision, Funding acquisition, Rebecca Logsdon Muenich, Methodology, Software, Writing – review & editing, Awoke Dagne, Methodology, Software, Colleen Long, Methodology, Grey Evenson, Methodology, Software, Writing – review & editing, Jay Martin, Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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