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Water and phosphorus Dynamics predictions in subsurface (tile) drained watersheds

Vinayak Shedekar, Margaret Kalcic, Fariba Babaeian, Lourdes Arrueta, Asmita Murumkar, Kevin King, and more…

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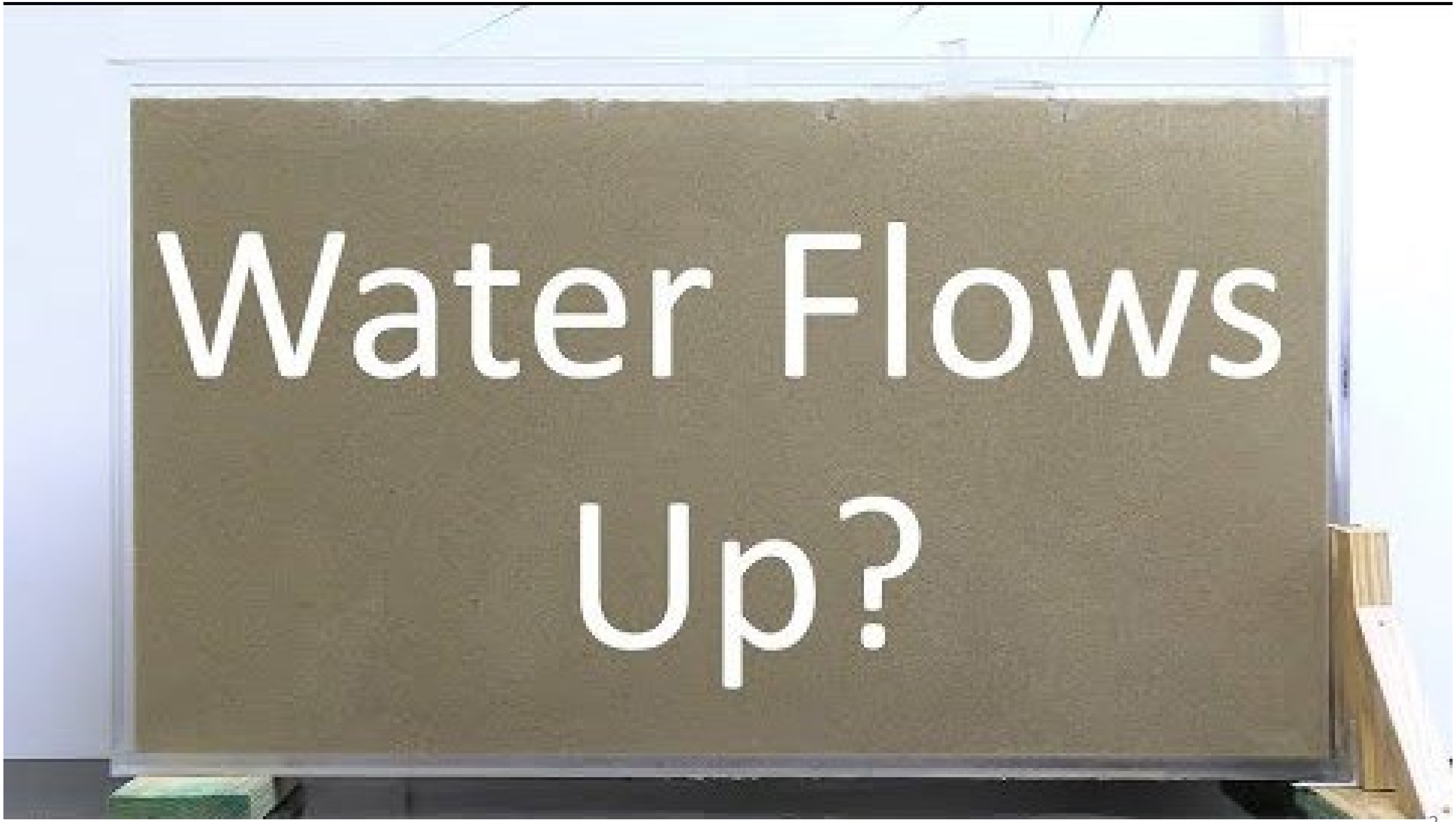
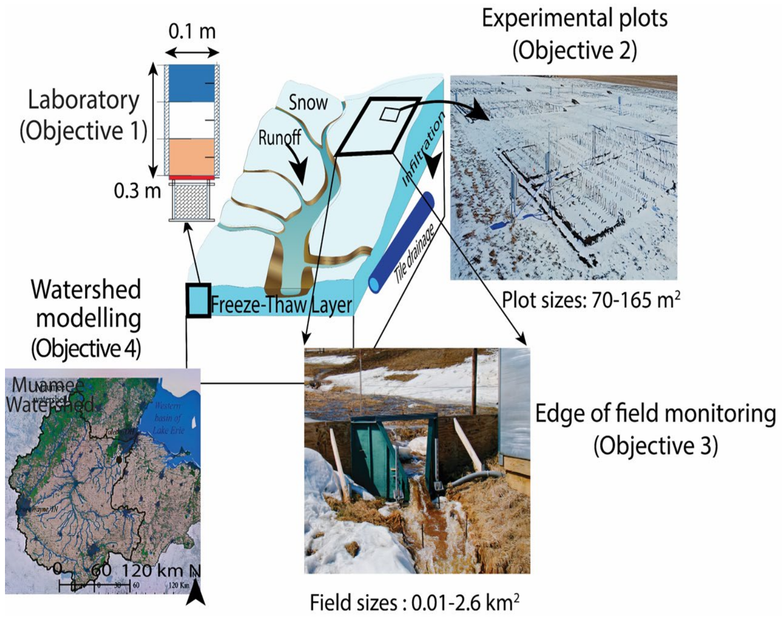
How does water move towards drains?

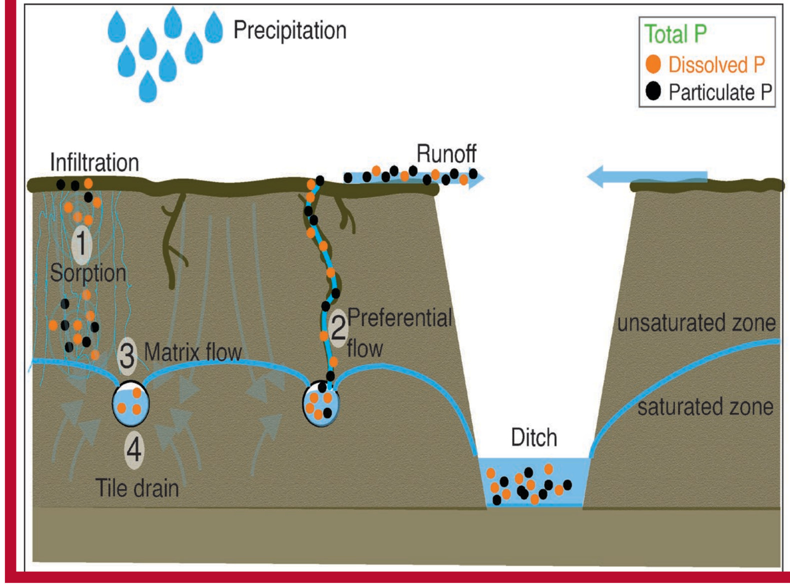


Current Watershed Modeling Projects

❑ Cold season process hydrology



❑ phosphorus dynamics in tile drained landscapes



❑ Soil Health

Team: The Ohio State University, University of Wisconsin-Madison, USDA-ARS (Columbus), USDA-ARS (National Soil Erosion Research Laboratory

Project Teams & Collaborators

THE OHIO STATE UNIVERSITY

- **Vinayak Shedekar**
- Michael Brooker
- Fariba Babaeian
- **Asmita Murumkar**
- Jay Martin
- Grey Evenson
- Sushant Mehan

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UNIVERSITY OF WISCONSIN-MADISON

- **Anita Thompson**
- **Margaret Kalcic**
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- Francisco Arriaga
- Lourdes Arrueta
- Shyanee Lee
- Laxmi Prasad

USDA ars

- **Soil Drainage Research Unit, Columbus OH**
- **National Soil Erosion Research Laboratory**
- Kevin King & Will Osterholz
- Chad Penn & Mark Williams

Acknowledgments

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Maumee Watershed Modeling Stakeholder Advisory group

United States Department of Agriculture National Institute of Food and Agriculture

Maumee River Watershed(MRW)

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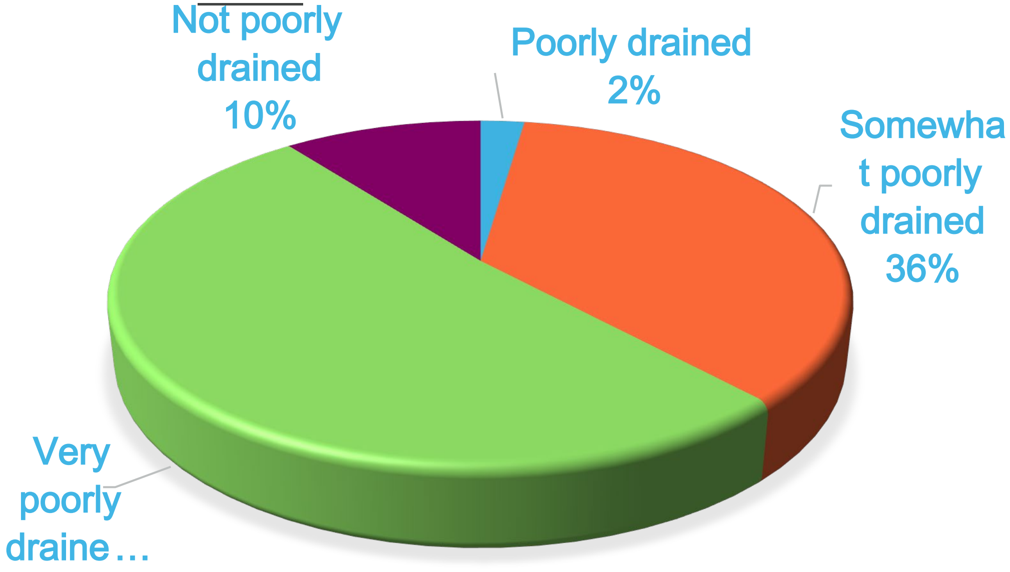
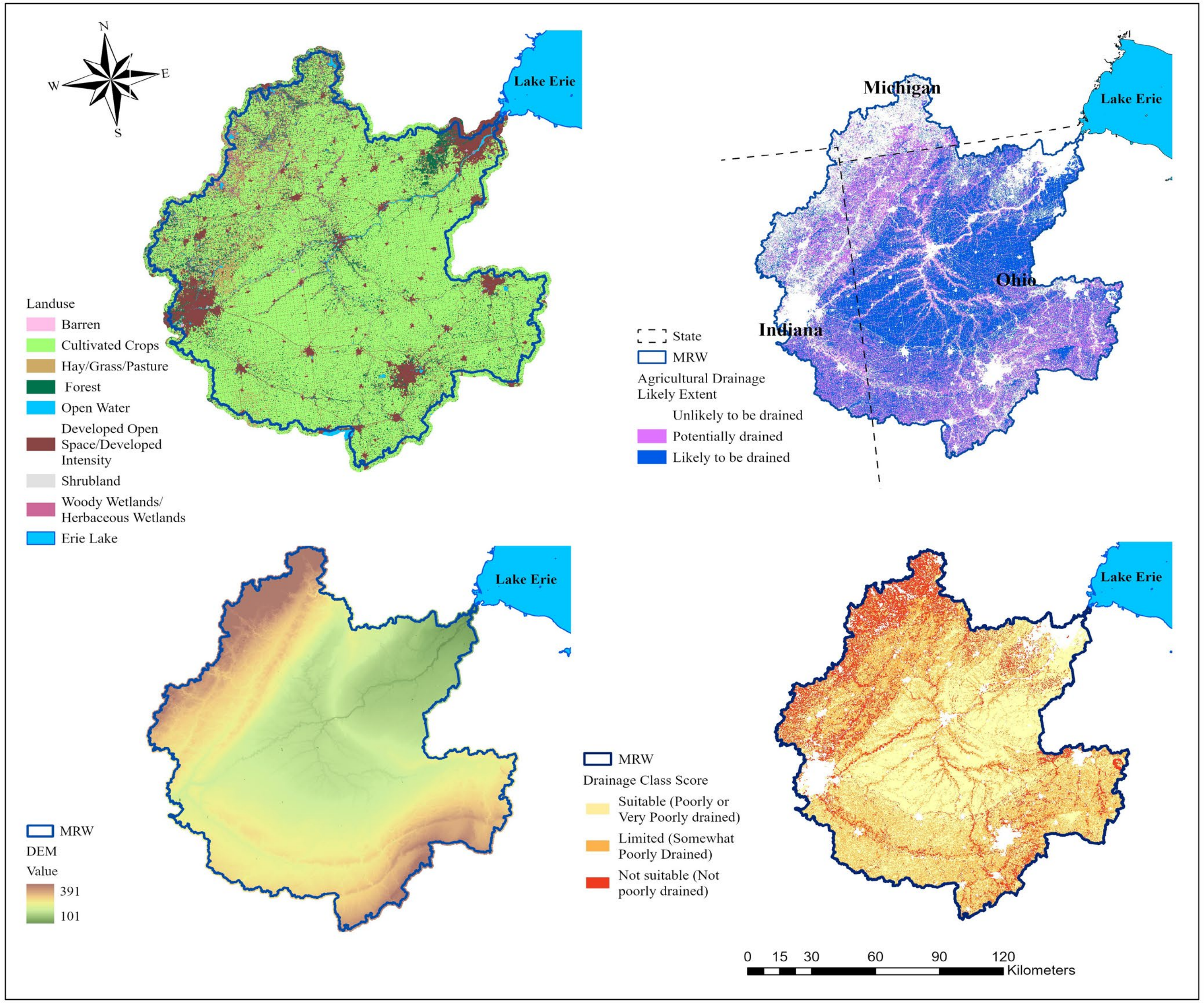
- 76% of the MRW land use is row-crop agriculture
- Characterized by very poorly drained soils

89.6% of Agr Watershed Area



Of Agr Watershed Area with subsurface drainage systems: 71.5%



(Frankenberger et al., 2022; Annual the National Land Cover Database (NLCD), 2023)

Drainage spacing refinements in SWAT model – effects on field - and watershed -scale hydrology & nutrient loss

Fariba Babaeian, Asmita Murumkar, Margaret Kalcic, Kevin King, Ahmed Awad, and Vinayak Shedekar

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Objectives

1. To enhance the representation of drainage intensity in a field-scale SWAT model using the recommendations from Ohio Drainage Guide
2. To assess the performance of the SWAT model with improved drainage intensity representation
3. To assess the sensitivity of the SWAT model at watershed and field scales to different drain spacing configurations

Data and Methods

SWAT Model

(Apostel et al., 2021)

MRW

Field-scale HRU Delineation

→

Ohio Drainage Guide

Drain Spacing

Soil Type, Parent Materials, Landscape Features

→

Improved SWAT Model

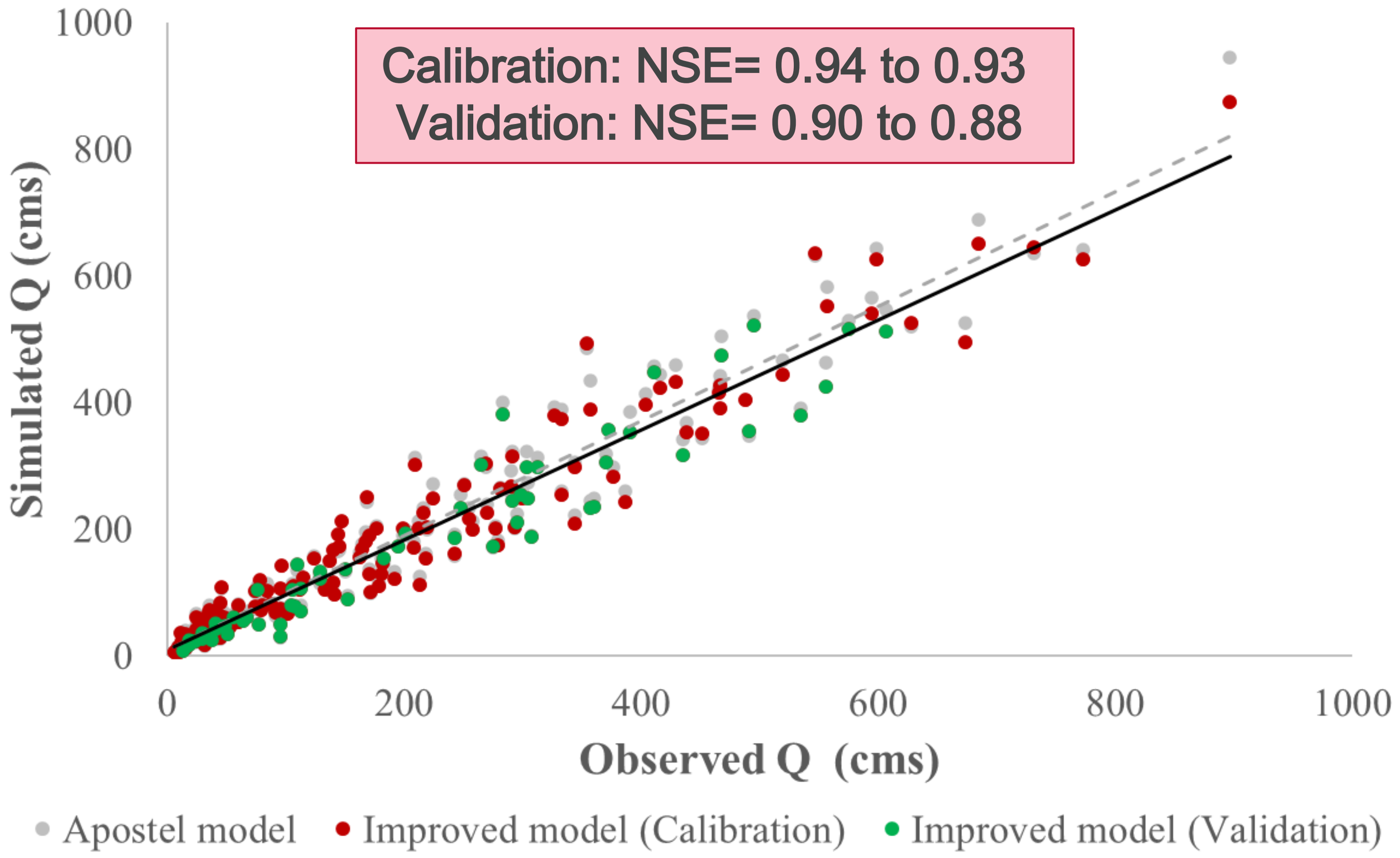
MRW

Drainage Intensity representation

Summary of drainage intensity representation

	Drain Spacing (ft (m))	Drain depth (ft (m))	Area (km^2)	% of Agr Watershed Area	Drainage Coefficient (mm/day)	Number of HRUs	% of Agr Watershed Area
Apostel et al. (2021)	15 (4.6)	3.3 (1)	5384.3	41.1	12.7	-	-
					25.4	7072	41.1
	35 (10.7)		3979.9	30.4	12.7	5603	30.4
					25.4	-	-
Improved Model	30 (9.1)	2.92 (0.89)	2947	22.5	12.7	186	1
					25.4	3777	21.5
	35 (10.7)		1260.2	9.6	12.7	646	3.3
					25.4	1076	6.4
	40 (12.2)		5003.1	38.2	12.7	4736	26
					25.4	2035	12.2
	50 (15.2)		24.3	0.2	12.7	16	0.1
					25.4	26	0.1
	60 (18.3)		129.5	1	12.7	19	0.1
					25.4	158	0.9

Watershed -Scale Performance (Monthly)



Watershed -Scale Performance (Monthly)

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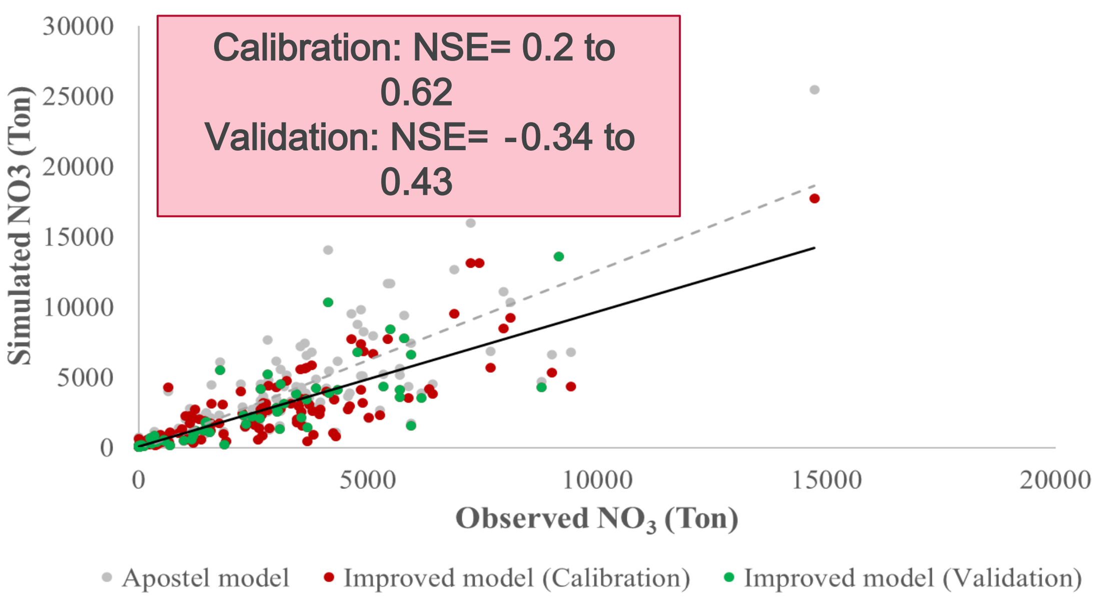
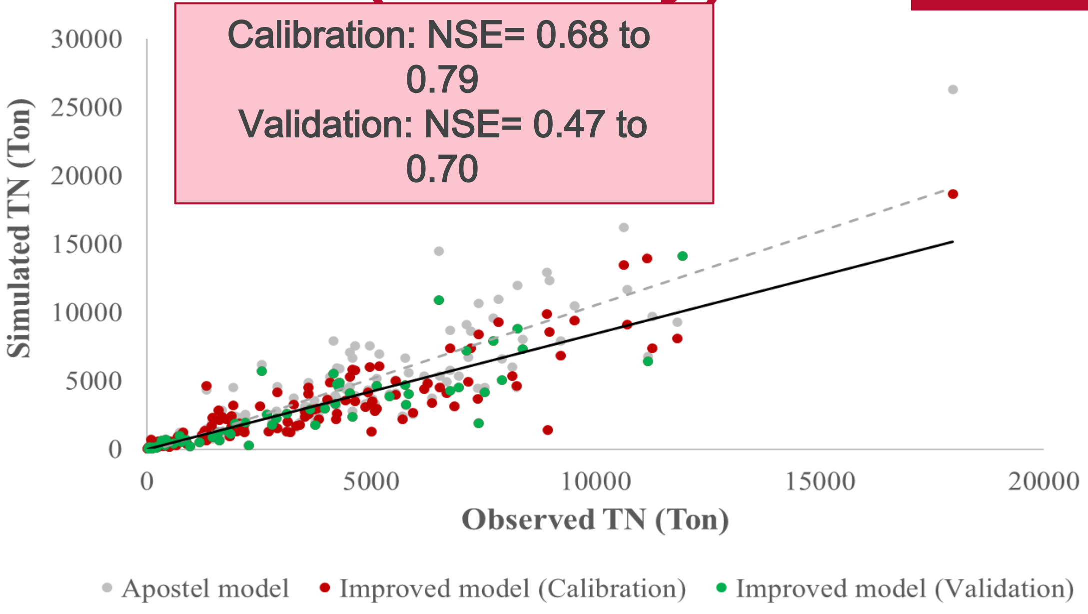
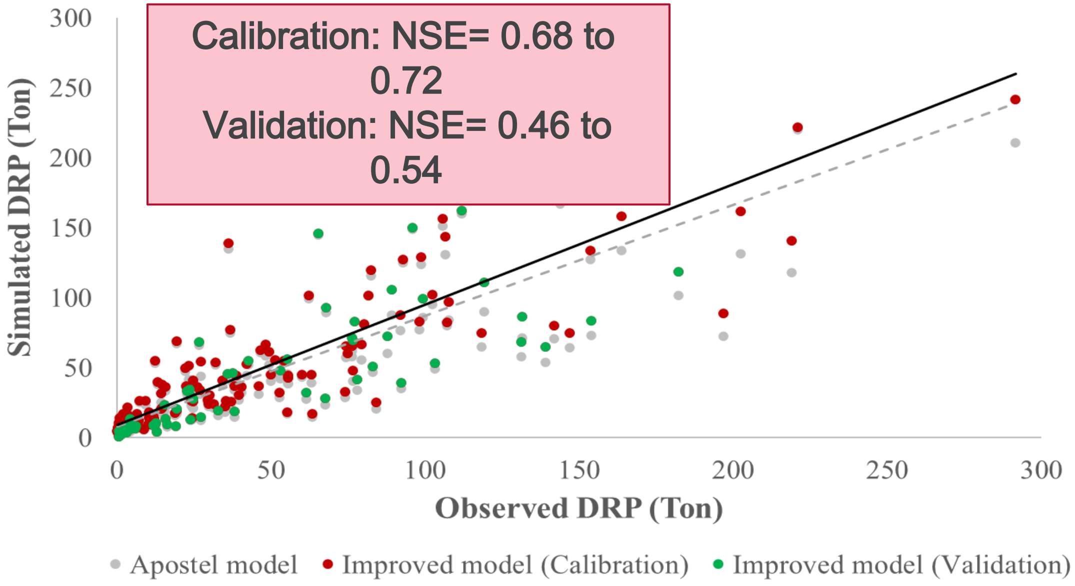
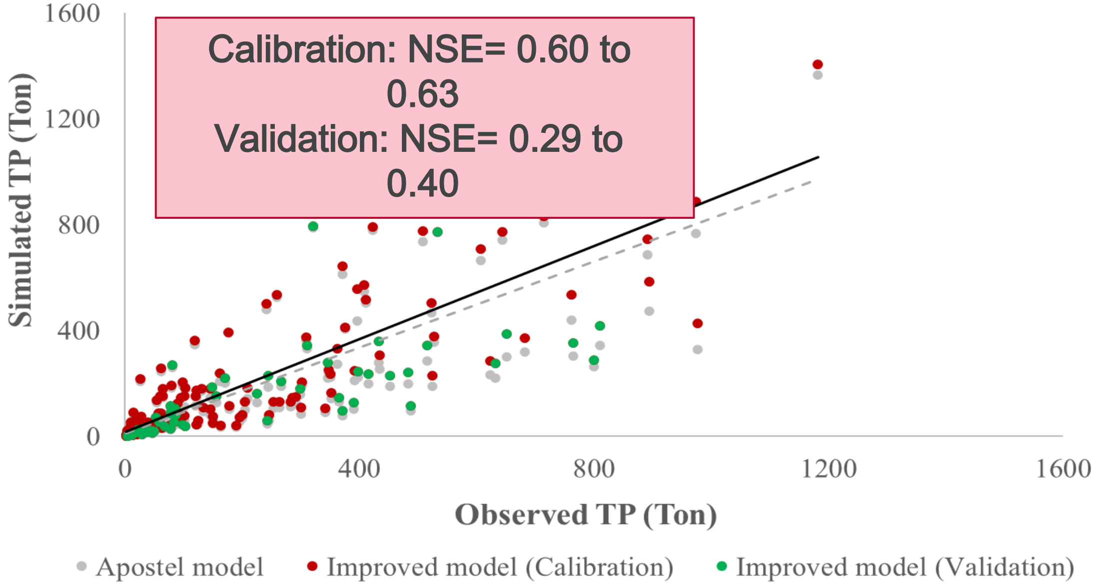




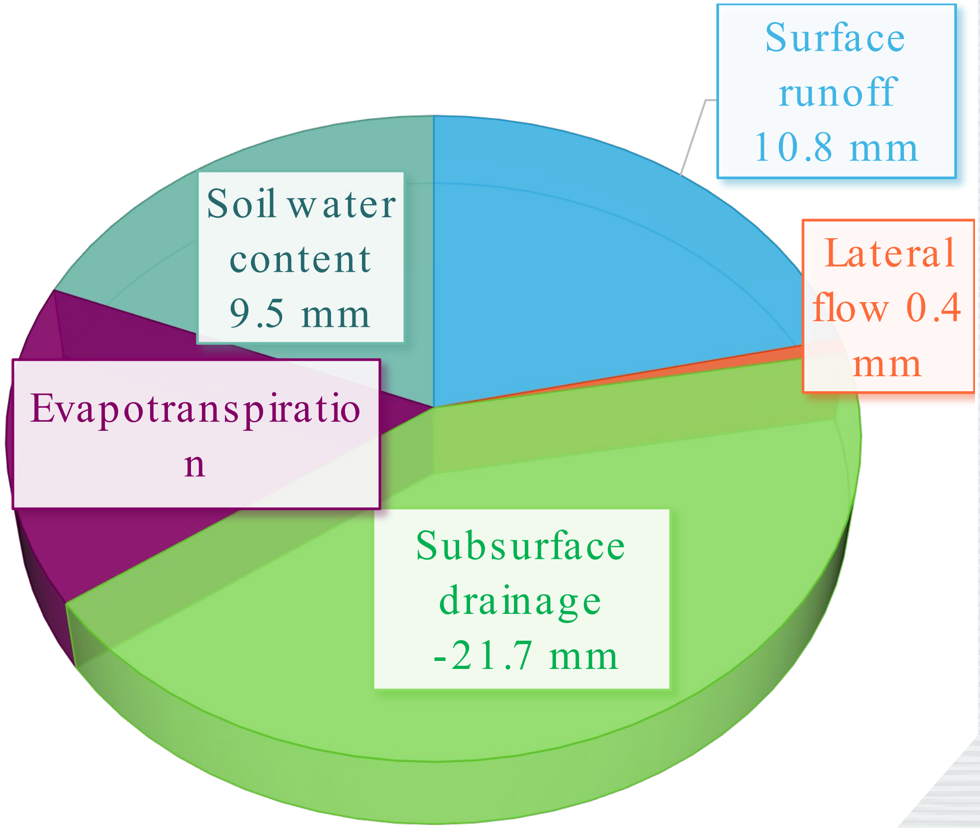




Watershed -Scale Sensitivity of the SWAT to Drainage Intensity

Average Annual Water Balance (2005 -2021)

Balance components (mm)	Apostel et al., 2021	Improved model	Changes (mm)	Changes (%)
Precipitation	1004.9	1004.9	-	-
Surface Runoff	184.2	195	10.8	6 ↑
Lateral Flow	25.2	25.6	0.4	1.5
Subsurface drainage	135.8	114.1	-21.7	-16 ↓
Evapotranspiration	647.9	656	8.1	1.3
Soil water content	212.8	222.2	9.5	4.5



Watershed -Scale Sensitivity of the SWAT to Drainage Intensity

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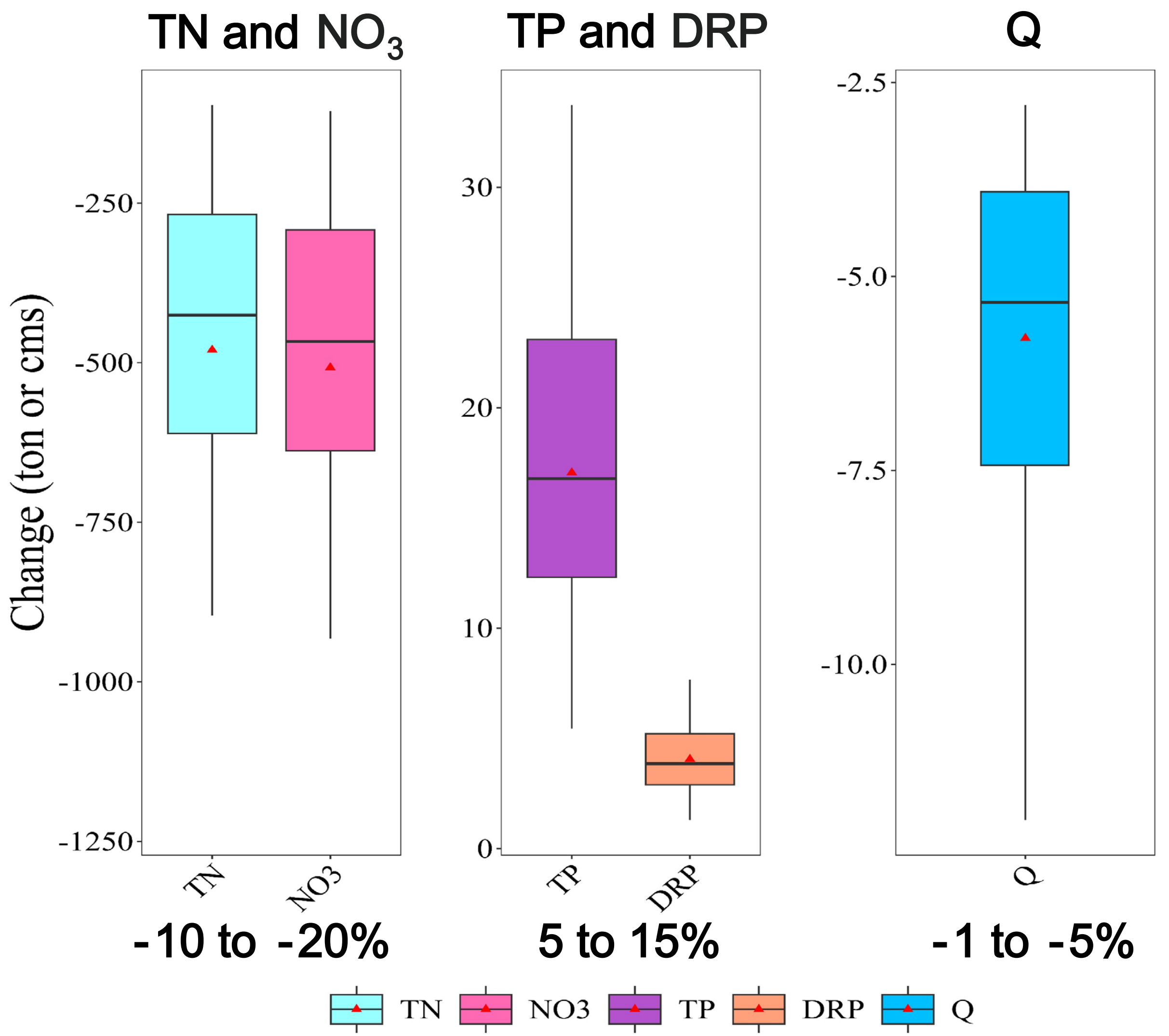
Annual Sensitivity (2005 - 2021)



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Watershed -Scale Performance (Monthly)

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- The SWAT -MRW model performance in the calibration and validation periods

	Monthly Calibration (2005 -2016)						Monthly Validation (2017 -2021)					
	Apostel et al., 2021			Improved model			Apostel et al., 2021			Improved model		
	R^2	NSE	PBIAS	R^2	NSE	PBIAS	R^2	NSE	PBIAS	R^2	NSE	PBIAS
Q	0.94	0.94	2.13	0.94	0.93	5.12	0.92	0.90	10.57	0.92	0.88	13.70
NO_3	0.70	0.20	-18.79	0.71	[illegible]	[illegible]	0.5[illegible]	-[illegible]	-25.06	0.62	0.43	-0.87
TN	0.78	0.68	1.57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.73	0.75	0.70	16.39
DRP	0.7[illegible]	0.68	-2.93	0.75	0.72	-[illegible]	0.5[illegible]	0.46	16.33	0.61	0.5[illegible]	6.44

Satisfactory range (Moriasi et al., 2015)

Q: |PBIAS| < 15

TN, NO_3, TP, DRP: |PBIAS| < 30

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Field -Scale Sensitivity of the SWAT to Drain Spacing

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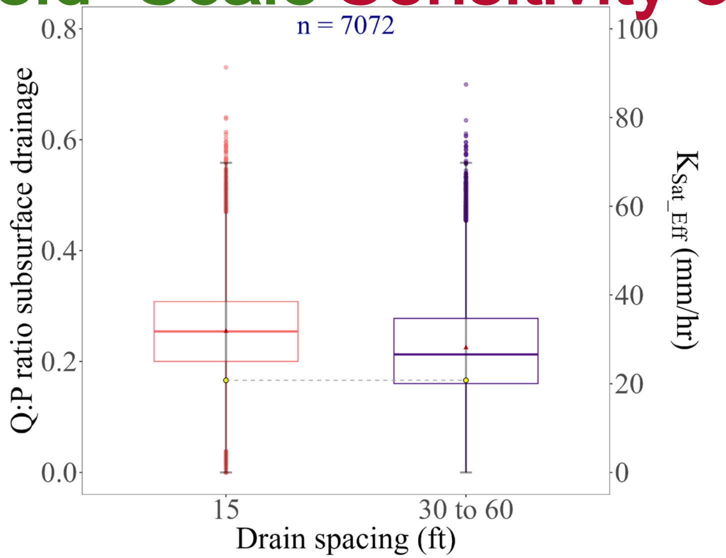
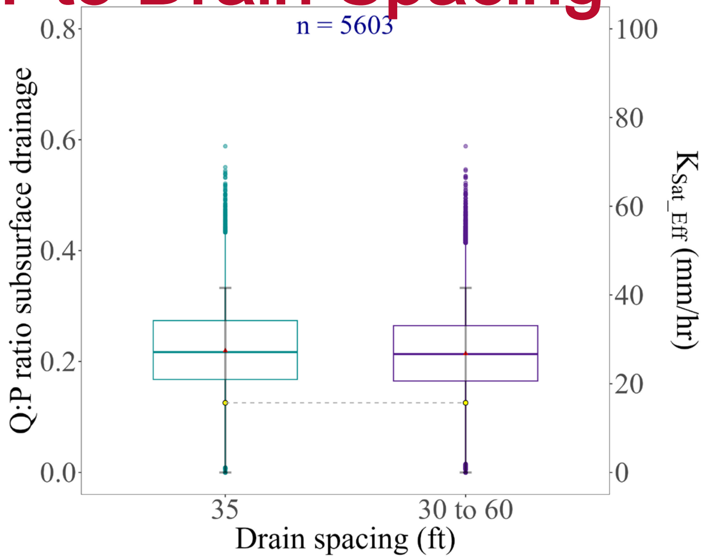
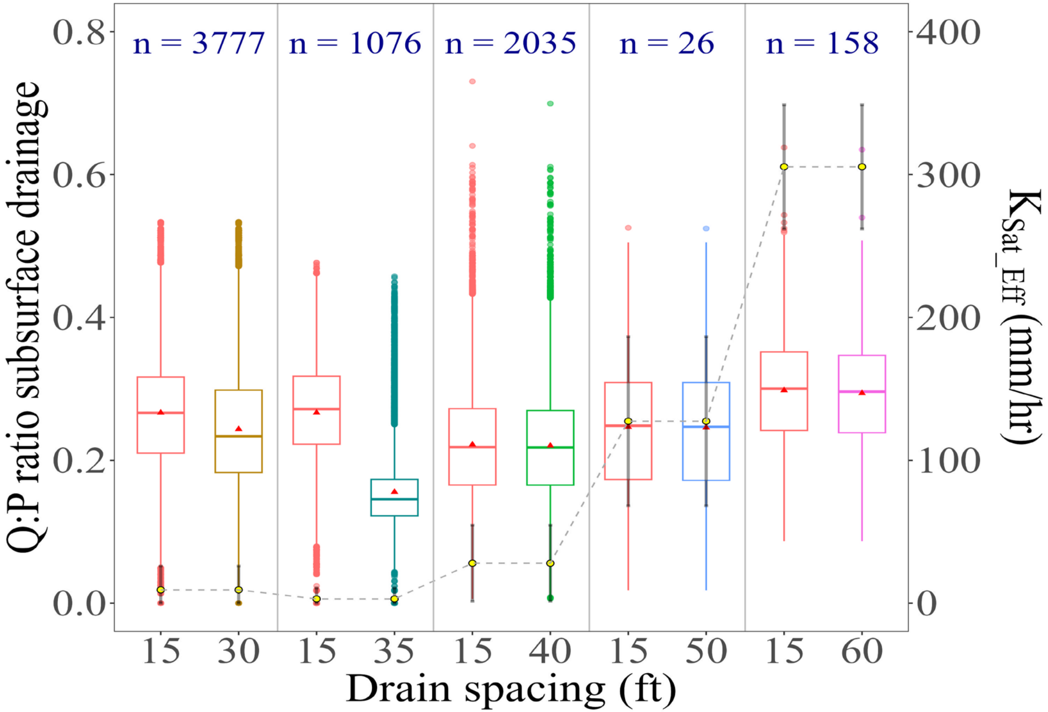
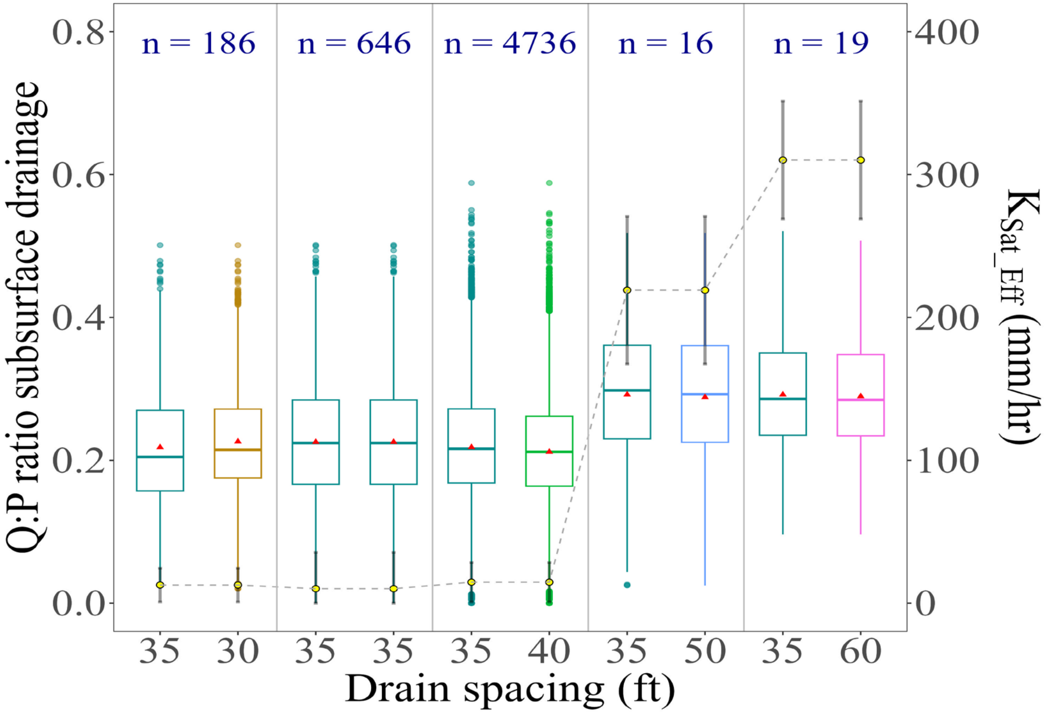
Q:P Ratio
Subsurface Drainage









Field -Scale Sensitivity of the SWAT to Drain Spacing

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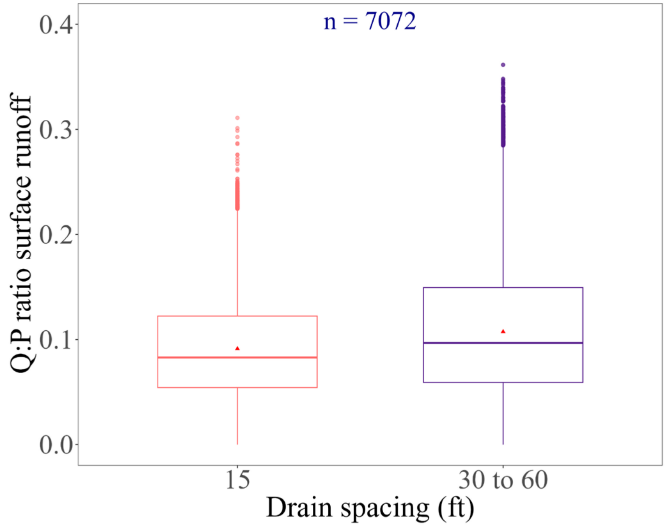
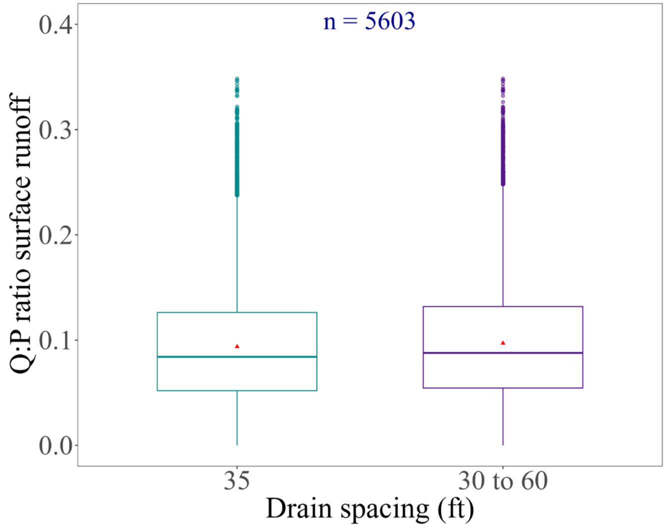
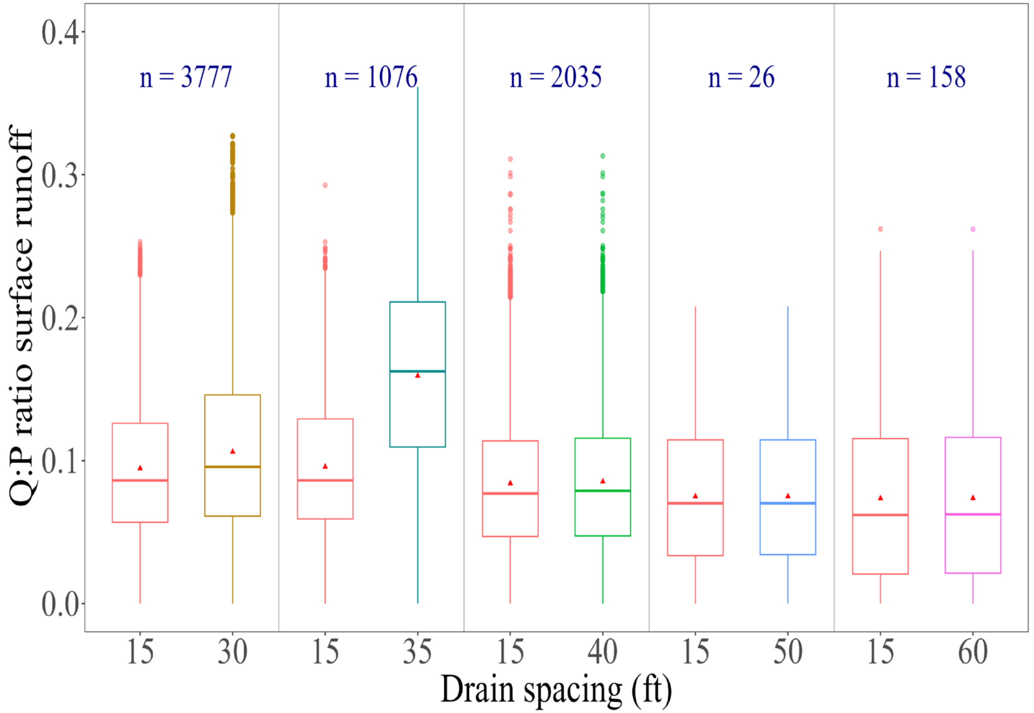
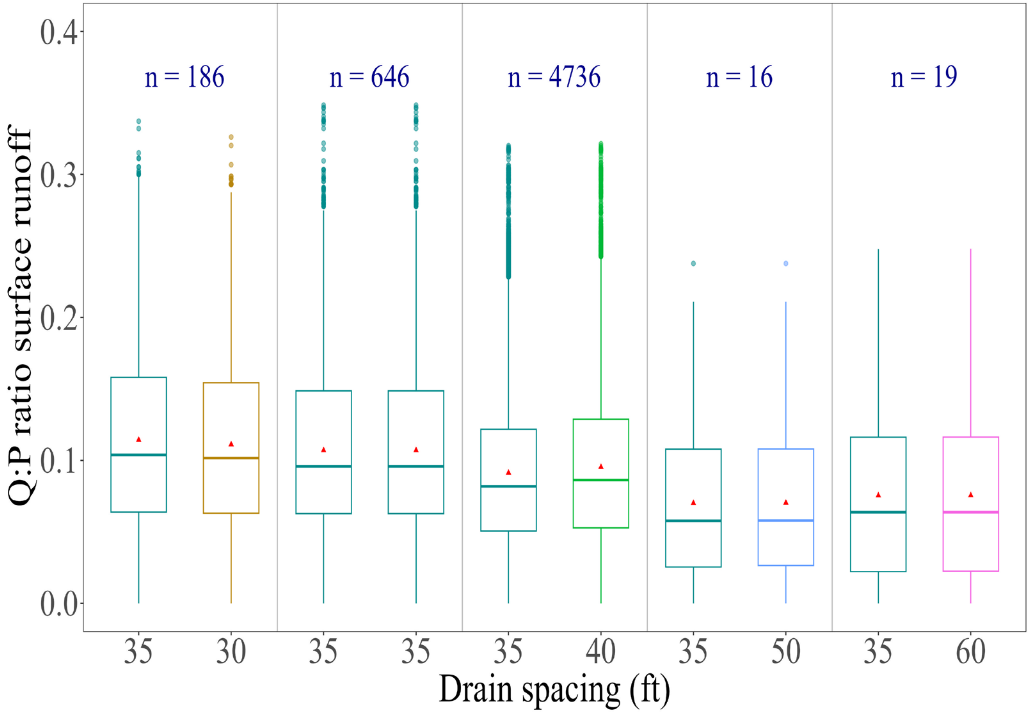
Q:P Ratio
Surface Runoff









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Conclusions

- Watershed -scale sensitivity of the SWAT to enhanced drainage intensity representation
  - Significantly improved the model performance in water quality predictions
  - Annual discharge: a slight decrease in (5%)
  - Annual nitrate and total nitrogen losses: 10–20% reductions
  - Annual DRP and TP losses increased: 5 to 15%

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Conclusions

- Field-scale sensitivity of the SWAT to enhanced drainage intensity representation

  - Drain spacings from 15 to 30-60 ft: Reduction in subsurface drainage mainly due to wider drain spacings of 30 and 35 ft
  - Drain spacings of 40, 50, and 60 ft: Negligible changes in subsurface drainage
  - Wider drain spacings of 50 and 60 ft: Higher subsurface drainage and lower surface runoff due to higher effective hydraulic conductivity

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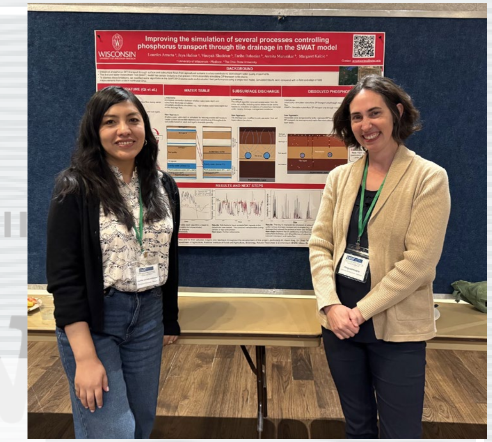

Phosphorus Dynamics

predictions in subsurface (tile) drained watersheds

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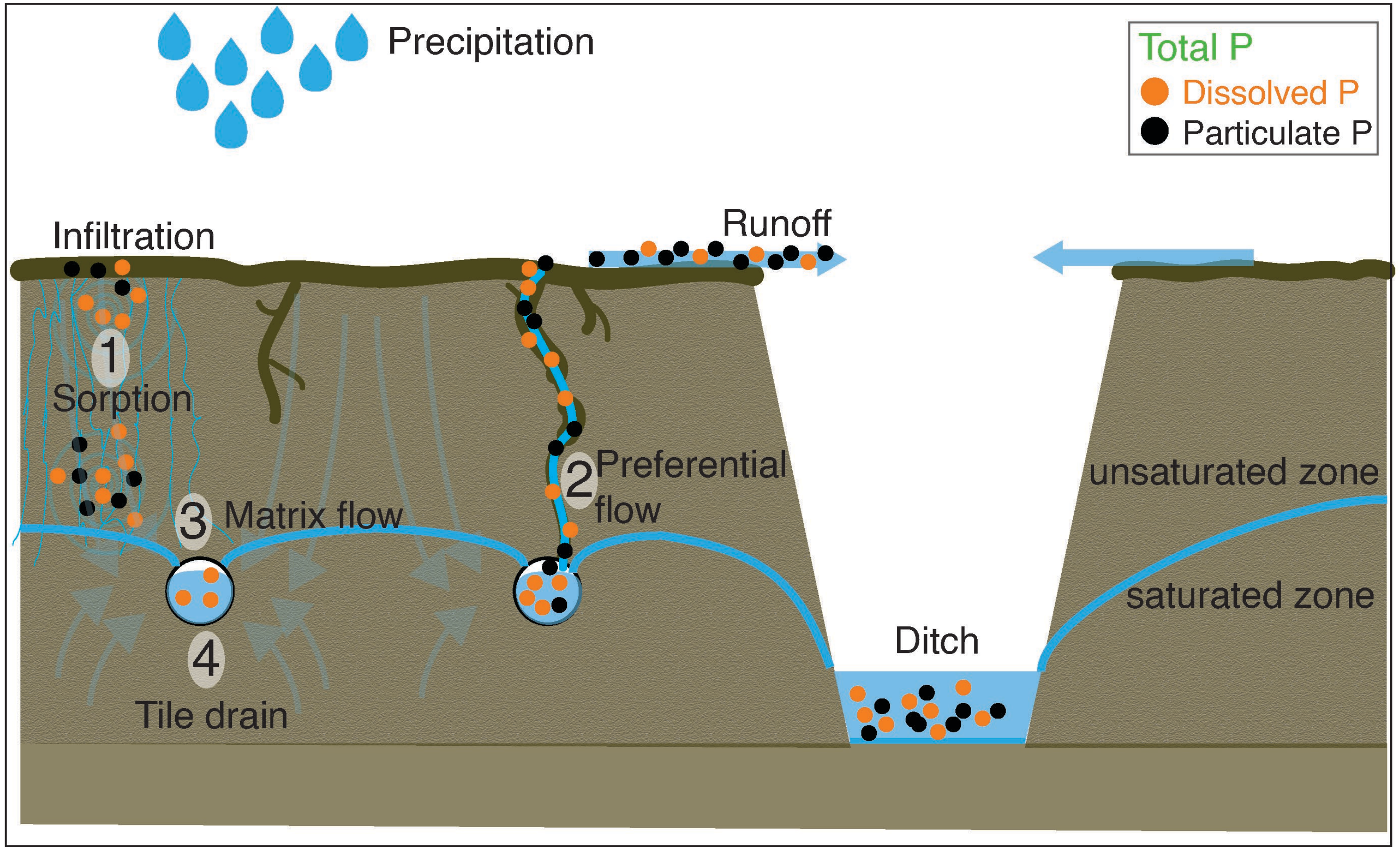
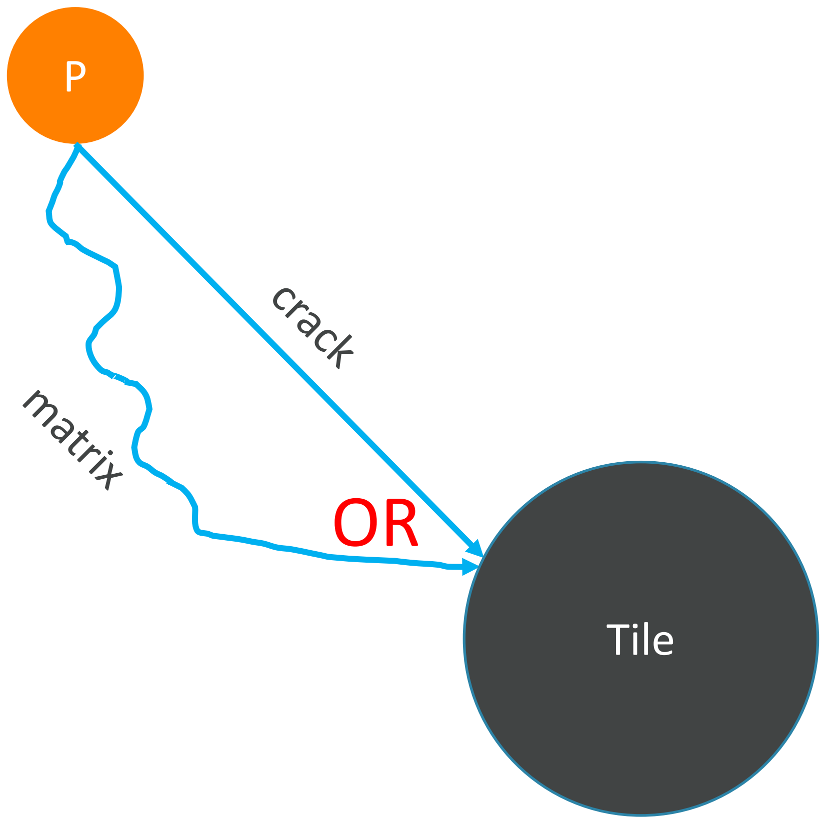
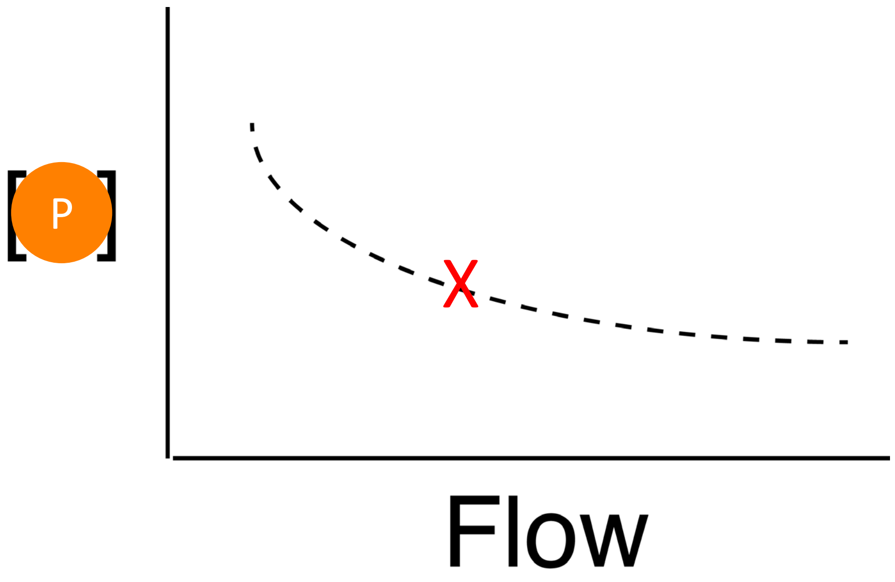
Phosphorus dynamics in tile drained landscapes



P transport associated with drainage discharge



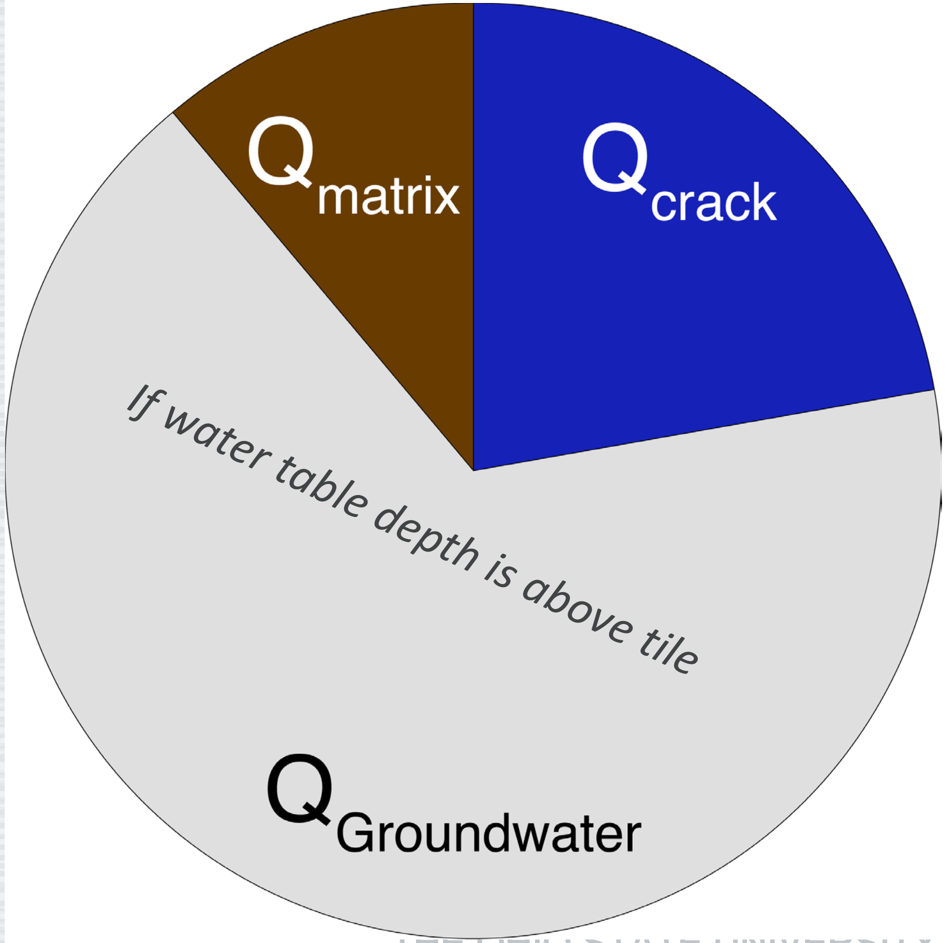
- P transport associated with matrix, crack, and groundwater flow



- P concentration should increase during larger flow events

Hydrology – partitioning of subsurface drainage water

- Pie chart of Tile Q (or Tile P) may look more like:



Proposed

Allow SWAT to calculate the Q_{crack}

Remaining water balance $(Q_{tile}-Q_{crack})=Q_{remain}$

Partition Q_{remain} as 80% Groundwater and 20% Matrix

Input parameter?
Dynamic?
Field specific (tile spacing…)

Assume one GW P concentration (0.005? <- calibrate)
Fast flow represents crack flow desorption
Slow flow represents matrix flow desorption

ORIGINAL solp algorithm in **SWAT2012**	**SWAT+** solp algorithm
Step – 1 Calculate soluble P lost in surface runoff	**Step – 1** Calculate soluble P lost in surface runoff
Step – 2 Calculate the amount of soluble P Leached using w_{perc}	**Step – 2** Calculate the amount of soluble P Leached using w_{perc} GLEAMS equation
Step – 3 Estimate soluble p in tiles due to crack flow using $min(1, w_{crk}/3)$	**Step – 3** Estimate soluble p in tiles using TileQ and the GLEAMS equation

Modified solp algorithm

New Approach:

- Processes were reorganized to better represent DP transport.
- DP transport via macropore and matrix flow were calculated on a layer-by-layer basis.

ORIGINAL solp algorithm in **SWAT2012**

Step – 1 Calculate soluble P lost in surface runoff

Step – 2 Calculate the amount of soluble P Leached using w_{perc}

Step – 3 Estimate soluble p in tiles due to crack flow using $min(1, w_{crk}/3)$

NEW solp algorithm

Step – 0 Calculate soluble p transport via **crack flow** for each soil layer using w_{crk}.

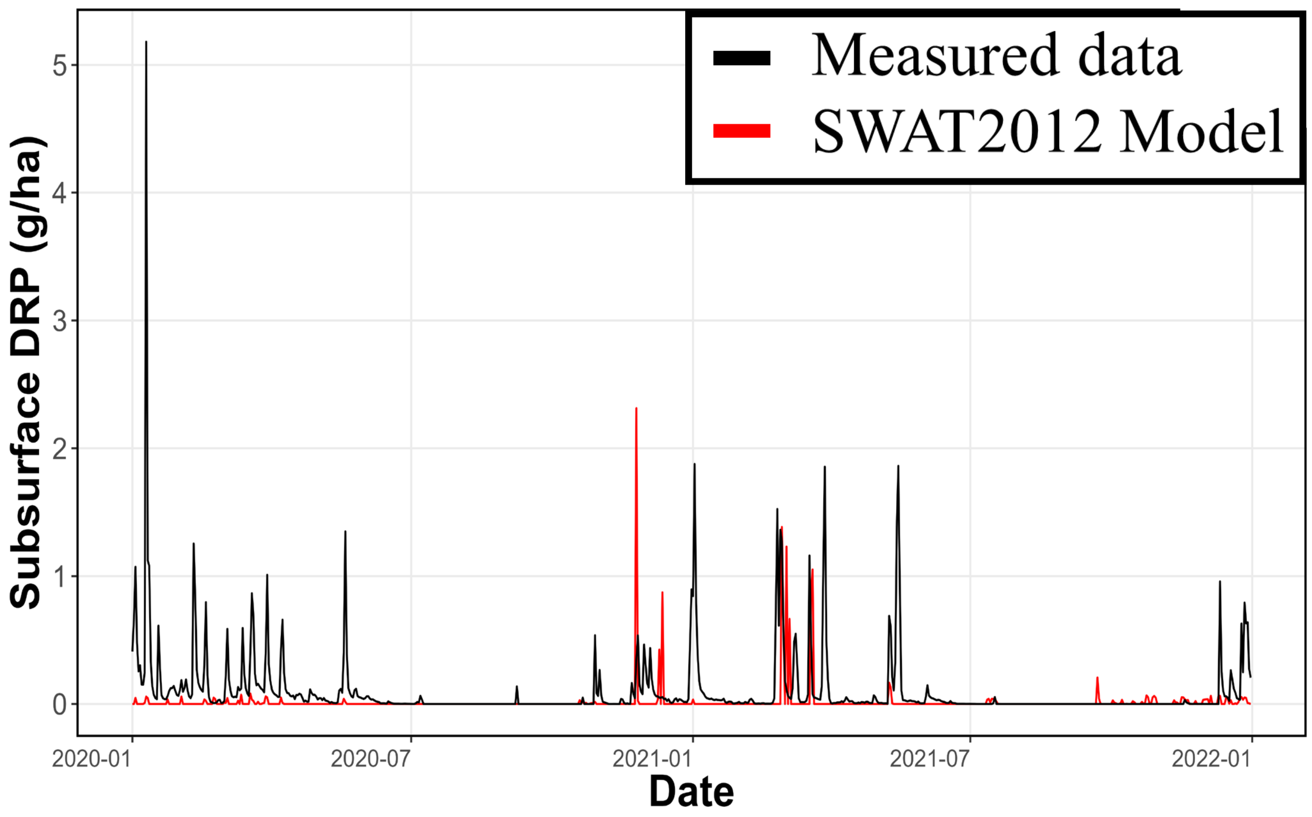
Step – 1 Calculate soluble P lost in surface runoff.

Step – 2 Calculate the amount of soluble P leached using **matrix flow** for each soil layer (w_{perc}-w_{crk}).

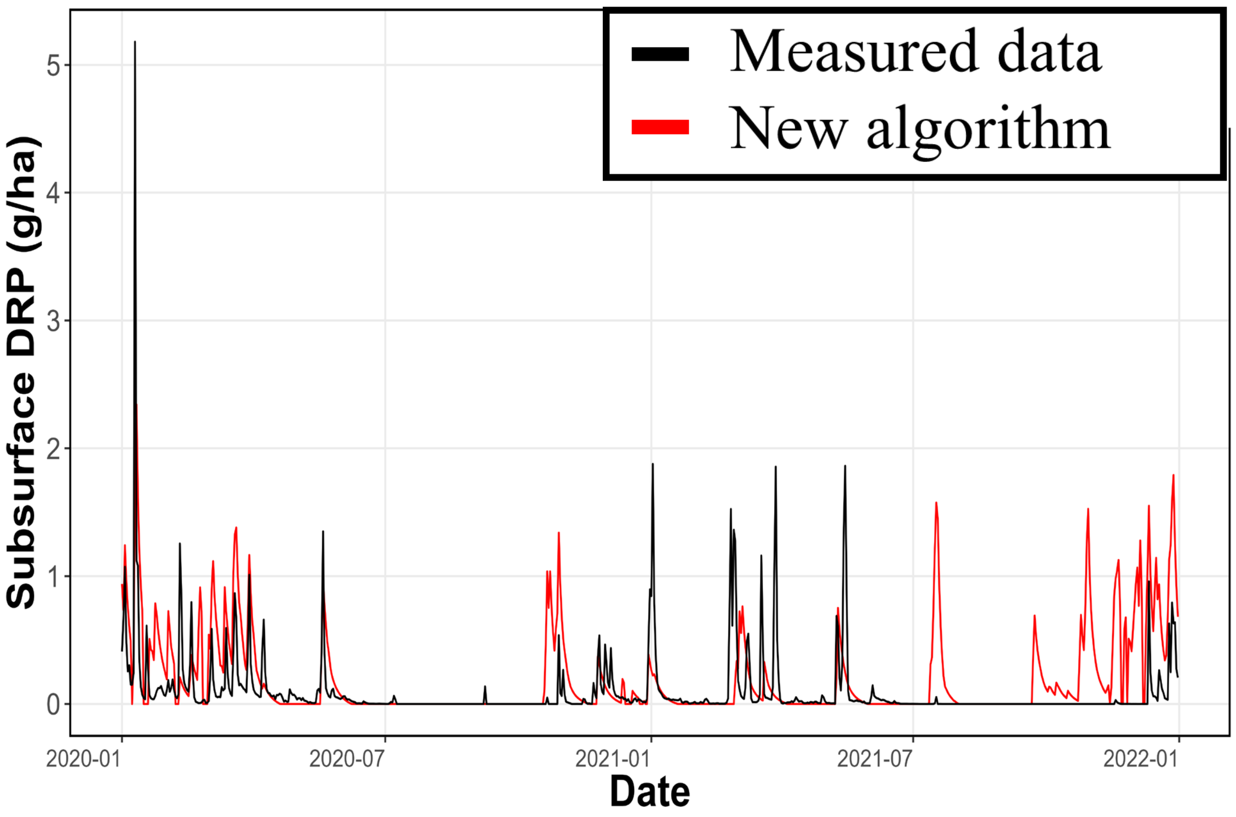
Step – 3 Calculate soluble p in tile drainage using *TileQ*.

Subsurface Dissolved Phosphorus

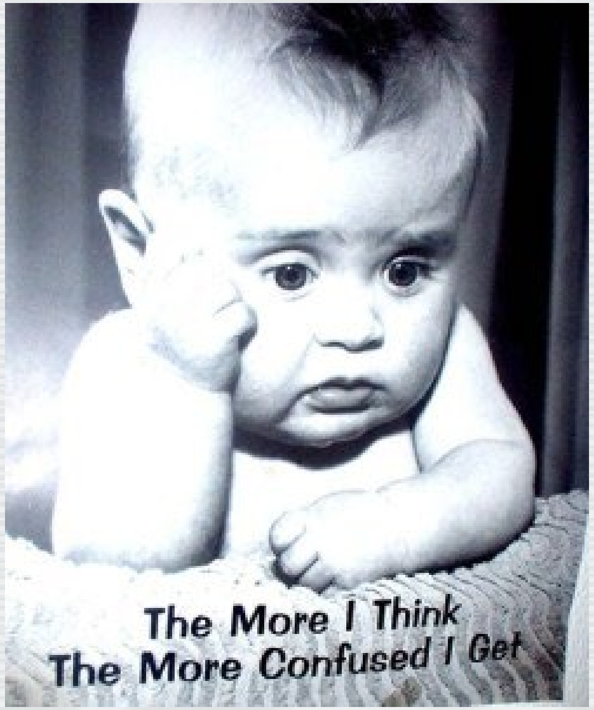
SWAT 2012 solp algorithm



New solp algorithm



Future & ongoing improvements…



How Dissolved Phosphorus (DP) transport is impacted by soil properties and hydrology

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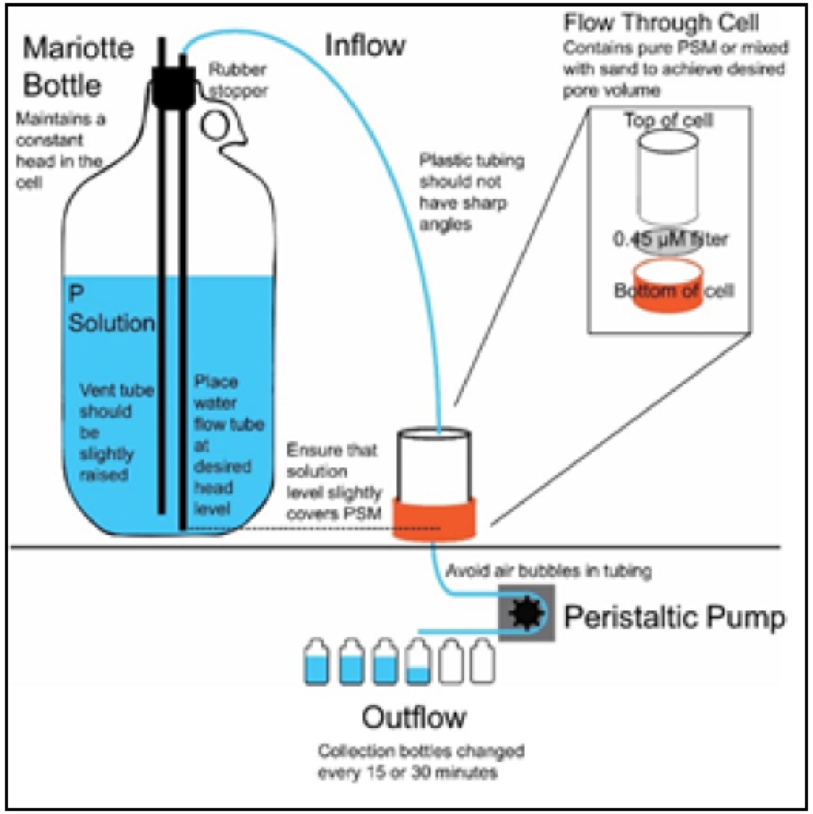
Flow-through P sorption and desorption tests

- Collected topsoil and corresponding subsoil samples (26 soil types)
- Two flowing conditions :
  - Slow Flow rate (0.5 cm/hr)
  - Fast Flow rate (25 cm/hr)



Flow-through system for studying sorption and desorption under flowing conditions

(Laboratory study by Chad Penn, USDA-ARS)

How Dissolved Phosphorus (DP) transport is impacted by soil properties and hydrology

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Slow Flow (Matrix Flow)

Desorption of P from topsoil

$$FWMC = m \times Q + C$$

$$m = -0.0001 \times M3P + 0.0038$$

$$C = 0.0039 \times M3P + 0.0314$$

Fast Flow (Crack Flow)

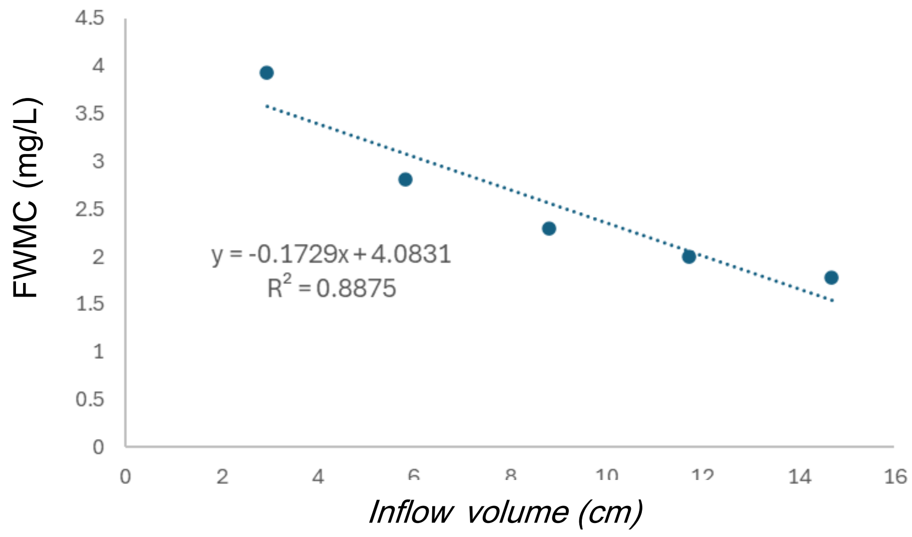
Desorption of P from topsoil

$$FWMC = m \times Q + C$$

$$m = -0.00003 \times M3P - 0.0001$$

$$C = 0.0015 \times M3P + 0.0374$$

Example relationship for one of the soils



FWMC: Flow Weighted Mean Concentration (mg/L)
Q: Volume of flow (cm)
m: Slope
C: Intercept
M3P: Soil test P (STP) concentrations (soil M3-P level) of the topsoil layer (mg/kg)

Equilibrated Groundwater

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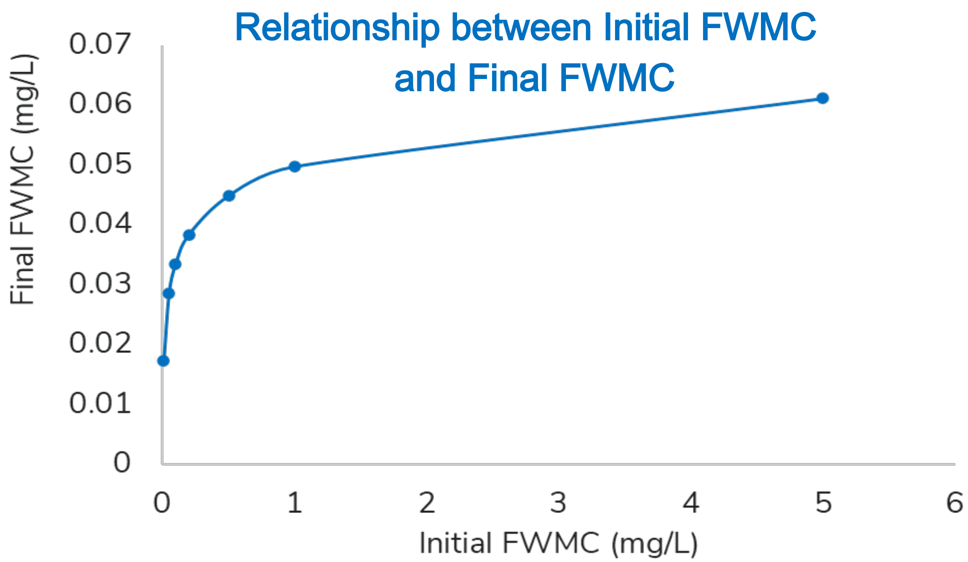
$$WSP = 0.0056 \times M3P_i \times 10$$

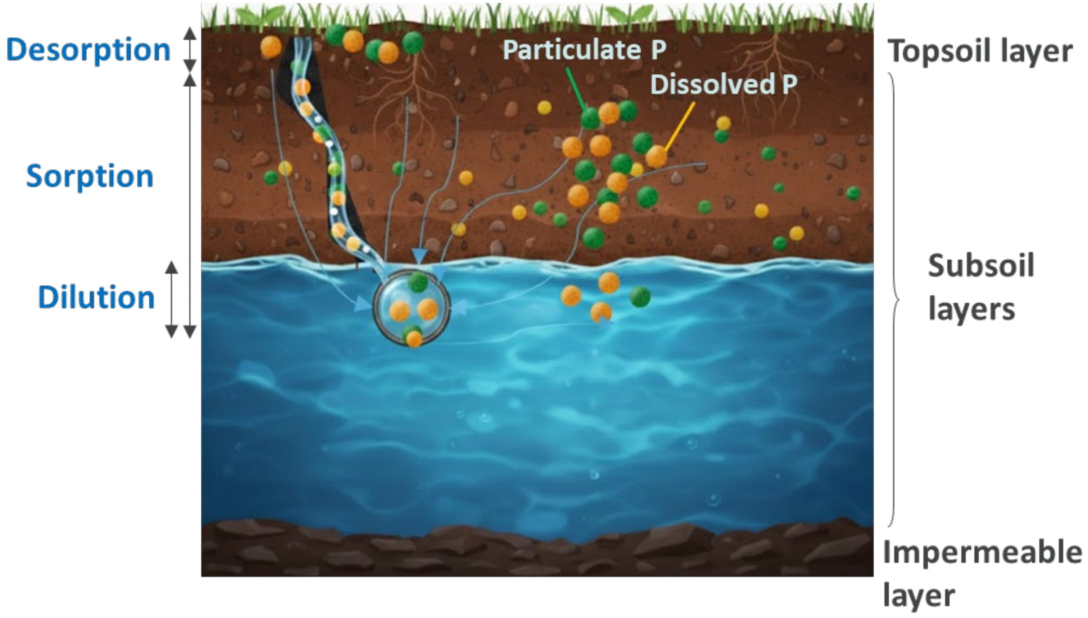
$$m = 0.0126 \times WSP$$

$$C = 0.0889 \times WSP$$

$$\boxed{FWMC_{EQ} = LN(IF(FWMC_{Initial} < 0.01, 0.01, (FWMC_{Initial} \times m + C))}$$

m: Slope
C: Intercept
WSP: Groundwater soluble P (mg/kg)
M3P: soil test P (STP) concentrations (soil Mehlich-3 P level) in the soil layer corresponding to the groundwater depth (mg/kg)
FWMC Initial: DP concentration moving from the soil layer with tile drain (mg/L)
FWMC EQ: Equilibrium DP concentration (Final DP in outflow from the tile drain (mg/L)





Proposed Workflow of DP concentration for SWAT

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Slow Flow (Matrix Flow)

$FWMC_{topsoil}$

Desorption of P from topsoil

$$FWMC = m \times Q + C$$
$$m = -0.0001 \times M3P + 0.0038$$
$$C = 0.0039 \times M3P + 0.0314$$

Adsorption/sorption by subsoil

$$m = -0.8088 \times FWMC_{topsoil} + 0.0043 \times M3P - 1.604$$
$$C = -0.0019 \times M3P + 0.8342$$
$$DP_{add} = \frac{FWMC_{topsoil} \times Q}{Z_{subsoil} \times BD_{subsoil}}$$
$$FP_{Sorption} = -10^{m} \times DP_{add} + C$$
$$FWMC_{subsoil} = (1 - FP_{Sorption}) \times FWMC_{topsoil}$$

$FWMC_{subsoil}$

Adsorption/sorption by subsoil

$$m = -0.8088 \times FWMC_{subsoil\ layer\ above} + 0.0043 \times M3P - 1.604$$
$$C = -0.0019 \times M3P + 0.8342$$
$$DP_{add} = \frac{FWMC_{subsoil\ layer\ above} \times Q}{Z_{subsoil} \times BD_{subsoil}}$$
$$FP_{Sorption} = -10^{m} \times DP_{add} + C$$
$$FWMC_{subsoil} = (1 - FP_{Sorption}) \times FWMC_{subsoil\ layer\ above}$$

Adsorption/sorption by subsoil

$$m = -0.8088 \times FWMC_{subsoil\ layer\ above} + 0.0043 \times M3P - 1.604$$
$$C = -0.0019 \times M3P + 0.8342$$
$$DP_{add} = \frac{FWMC_{subsoil\ layer\ above} \times Q}{Z_{subsoil} \times BD_{subsoil}}$$
$$FP_{Sorption} = -10^{m} \times DP_{add} + C$$
$$FWMC_{subsoil} = (1 - FP_{Sorption}) \times FWMC_{subsoil\ layer\ above}$$

Continue through the layer with tile drain

Equilibrated Groundwater

$$WSP = 0.0056 \times M3P_i \times 10$$
$$m = 0.0126 \times WSP$$
$$C = 0.0889 \times WSP$$
$$FWMC_{EQ} = LN(IF(FWMC_{Initial} < 0.01, 0.01, (FWMC_{Initial} \times m + C))$$

Fast Flow (Crack Flow)

Desorption of P from topsoil

$$FWMC = m \times Q + C$$
$$m = -0.00003 \times M3P - 0.0001$$
$$C = 0.0015 \times M3P + 0.0374$$

DP Tile



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Water and phosphorus Dynamics predictions in subsurface (tile) drained watersheds

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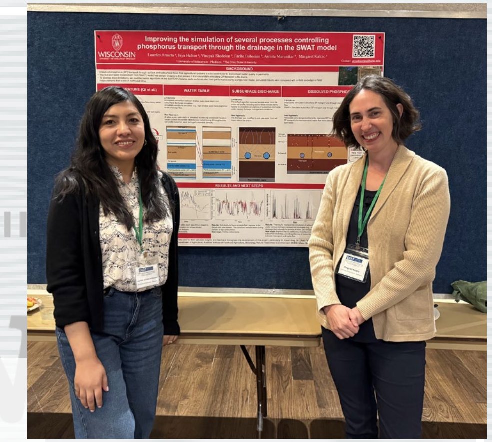

Phosphorus Dynamics

predictions in subsurface (tile) drained watersheds

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Step – 0 Estimate soluble p transport via crack flow for each soil layer

$$drp\_crk(lyr, hru) = \frac{Sol\_solP_{solution,surface} . crk(lyr,hru)}{(\rho_{b(lyr,hru)} . depth_{(lyr,hru)} . k_{d,surface})+1}$$

$$drp_{crk(lyr,hru)} = soluble\ P\ due\ to\ crack\ flow\ for\ each\ soil\ layer, kg/ha$$

$$crk(lyr, hru) = percolation\ due\ to\ crack\ flow\ for\ each\ soil\ layer, mm$$

$$Sol\_solP_{solution,surface} = amount\ of\ phosphorus\ in\ solution\ in\ the\ top\ 10mm, \frac{kg}{ha}$$

$$\rho_b(lyr, hru) = soil\ bulk\ density\ for\ each\ soil\ layer$$

$$depth_{surface} = depth\ of\ the\ surface\ layer, 10\ mm$$

$$k_{d,surface} = Phosphorus\ soil\ partitioning\ coefficient, m3/Mg$$

Step – 1 Calculate soluble P lost in surface runoff

$$P_{surf} = \frac{P_{solution,surface} . Q_{surface}}{(\rho_b . depth_{surface} . k_{d,surface})}$$

$$P_{surf} = \frac{Sol\_solP_{solution,surface} . Q_{surface}}{(\rho_b . depth_{surface} . k_{d,surface}) + 1}$$

$$P_{surf} = amount\ of\ soluble\ P\ lost\ in\ the\ runoff, \frac{kg}{ha}$$

$$Sol\_solP_{solution,surface} = amount\ of\ phosphorus\ in\ solution\ in\ the\ top\ 10mm, \frac{kg}{ha}$$

$$Q_{surface} = amount\ of\ surface\ runoff\ on\ a\ given\ day, mm$$

$$depth_{surface} = depth\ of\ the\ surface\ layer, 10\ mm$$

$$k_{d,surface} = Phosphorus\ soil\ partitioning\ coefficient, m3/Mg$$

Step – 2 Calculate the amount of soluble P leached via matrix flow for each soil layer.

$$P_{perc} = \frac{P_{solution,surface} . w_{perc,surface}}{10 . \rho_b . depth_{surface} . k_{d,perc}}$$

$$P_{perc} = \frac{Sol_{solP_{(lyr,hru)}} * (prk_{(lyr,hru)} - crk_{(lyr,hru)})}{(conv_{wt\,(lyr,hru)}/1000) * Pperco\_sub_{(lyr,hru)}}$$

$P_{perc} = amount\ of\ phosphorus\ leached\ from\ soil\ layer.$

$Sol_{solP_{(lyr,hru)}} = amount\ of\ phosphorus\ stored\ in\ solution.$

$prk_{(lyr,hru)} = percolation\ from\ soil\ layer\ on\ current\ day, mm.$

$crk_{(lyr,hru)} = percolation\ due\ to\ crack\ flow\ for\ each\ soil\ layer, mm$

$conv_{wt\,(lyr,hru)} = factor\ which\ converts\ \frac{kg}{kg}\ soil\ to\ \frac{kg}{ha}$

$Pperco\_sub_{(lyr,hru)} = Phosphorus\ percolation\ coefficient$

Step – 3 Estimate soluble p in tile drainage

$$TileP_{crk} = P_{perc} * \min(1, \frac{sol_{crk}}{3})$$

$$TileP = \frac{Sol_{solP_{(lyr,hru)}} * qtile}{(conv_{wt\,(lyr,hru)}/1000) * Pperco\_sub_{(lyr,hru)}}$$

$$tilep = soluble\ phosphorus\ in\ tile\ drainage, \frac{kg}{ha}.$$

$$Sol_{solP_{(lyr,hru)}} = amount\ of\ phosphorus\ stored\ in\ solution.$$

$$qtile = tile\ discharge, mm.$$

$$conv_{wt\,(lyr,hru)} = factor\ which\ converts\ \frac{kg}{kg}\ soil\ to\ \frac{kg}{ha}$$

$$Pperco\_sub_{(lyr,hru)} = Phosphorus\ percolation\ coefficient$$

Field -Scale Sensitivity of the SWAT to Drainage Intensity

CFAES

Average annual changes in water balance components (2005 -2021)

Model	Drain Spacing (ft)		Precipitation (mm)	Surface runoff (mm)	Subsurface drainage (mm)	Evapotranspiration (mm)	Lateral Flow (mm)
Apostel et al., 2021	15		1007±50	93±16	265±42	646±49	2±5
	35		1020±48	98±21	234±37	676±34	7±7
Improved Model	15	30	998± 43	120±48	220±94	650±41	0.4±1
		35	1001±42	20±54	72±77	707±23	0.8±2
		40	1030±58	90±16	236±33	697±37	6±6
		50	954±25	72±31	241±56	626±71	15±27
		60	963±27	71±41	289±27	581±27	20±18
	35	30	1002±38	127±54	196±91	666±33	2±2
		35	1000±34	132±43	191±74	662±43	3±4
		40	1023±50	101±19	225±31	681±29	9±7
		50	953±19	67±36	281±48	577±57	27±33
		60	970±29	75±43	287±30	580±17	29±24

Conclusions

- Field-scale sensitivity of the SWAT to enhanced drainage intensity representation

  - The SWAT model may not accurately predict the effects of drain spacing at the field scale, highlighting the need for additional source code modifications

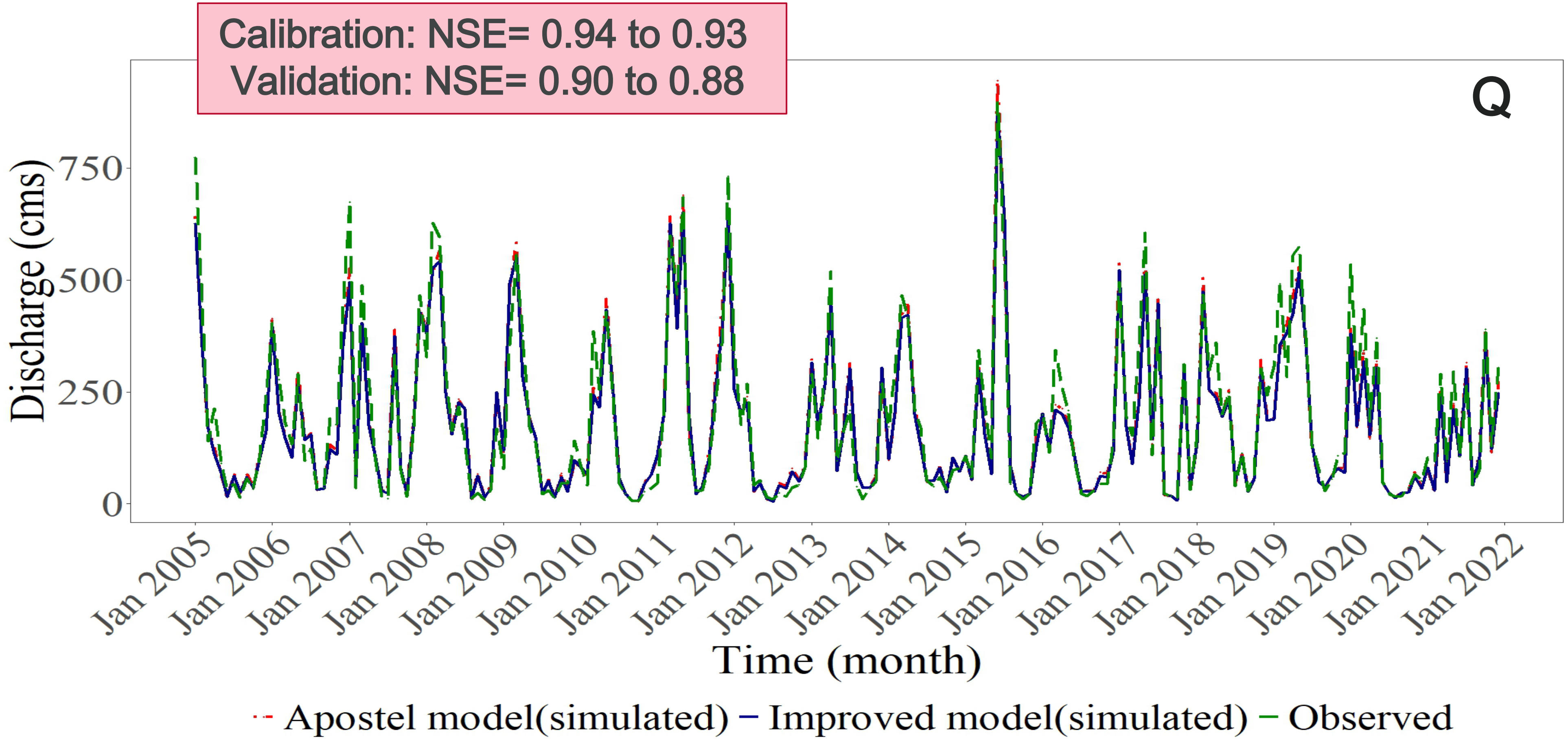
Conclusions

❑ Next Steps

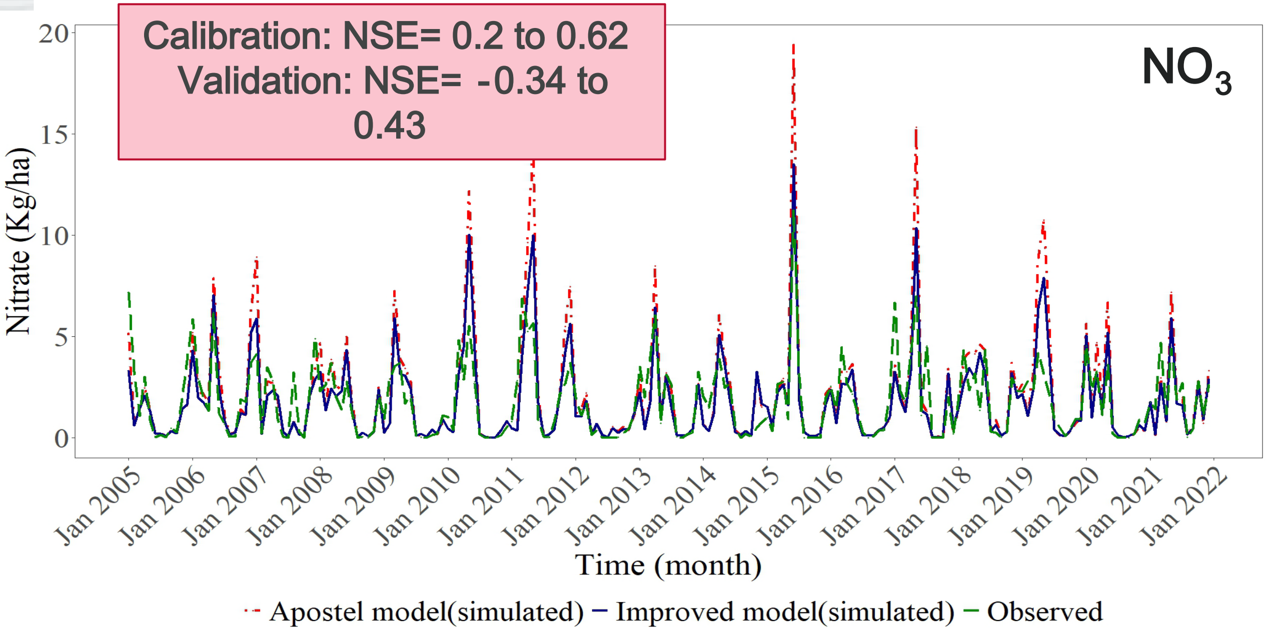
- Compare SWAT simulations with DRAINMOD
- Analyze water quality and crop yields at the field scale
- Test Drainage Water Management across all suitable HRUs

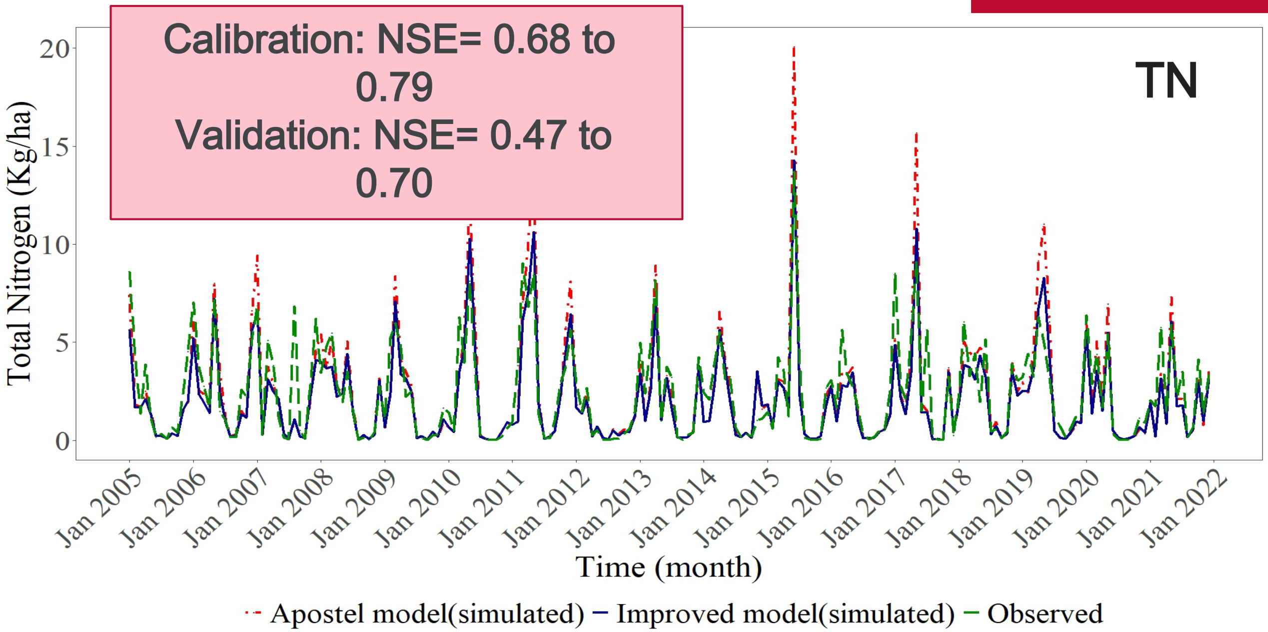
Watershed -Scale Performance

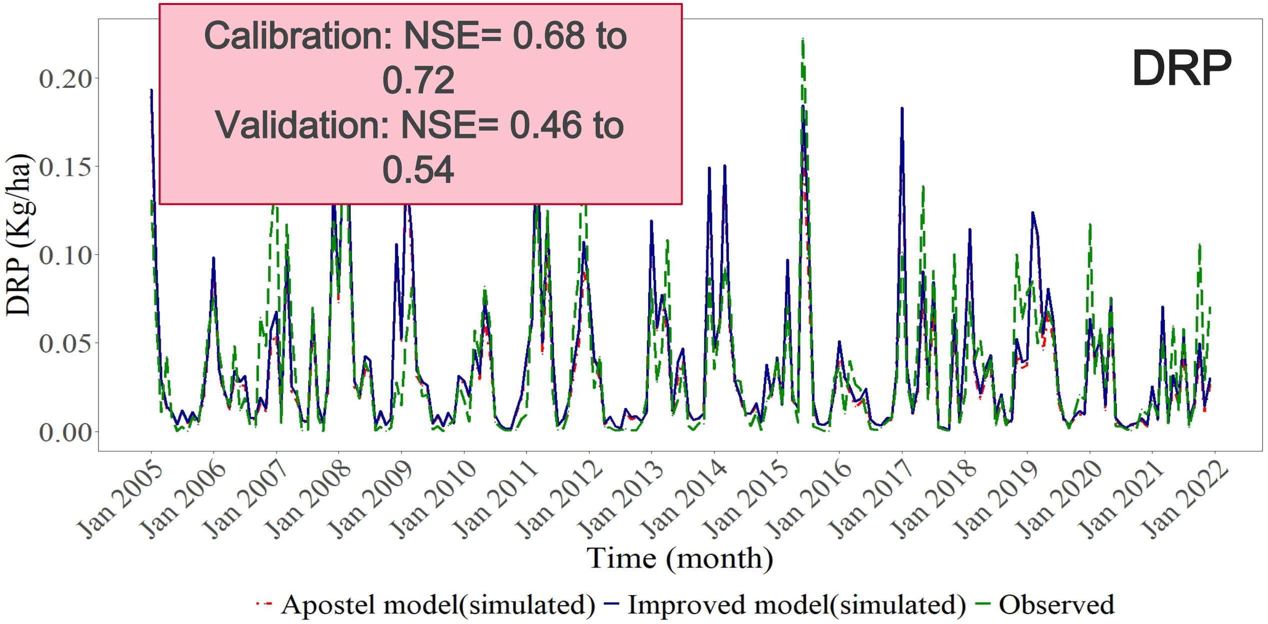
- Improving drainage intensity had minimal impact on discharge

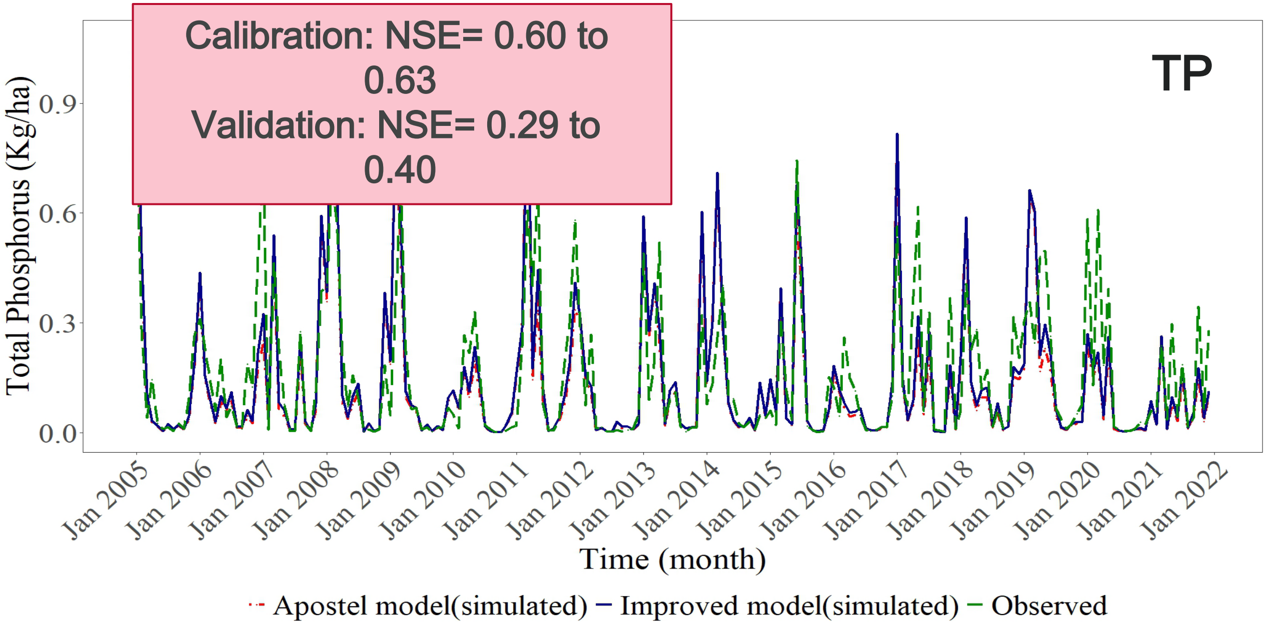


Watershed -Scale Performance





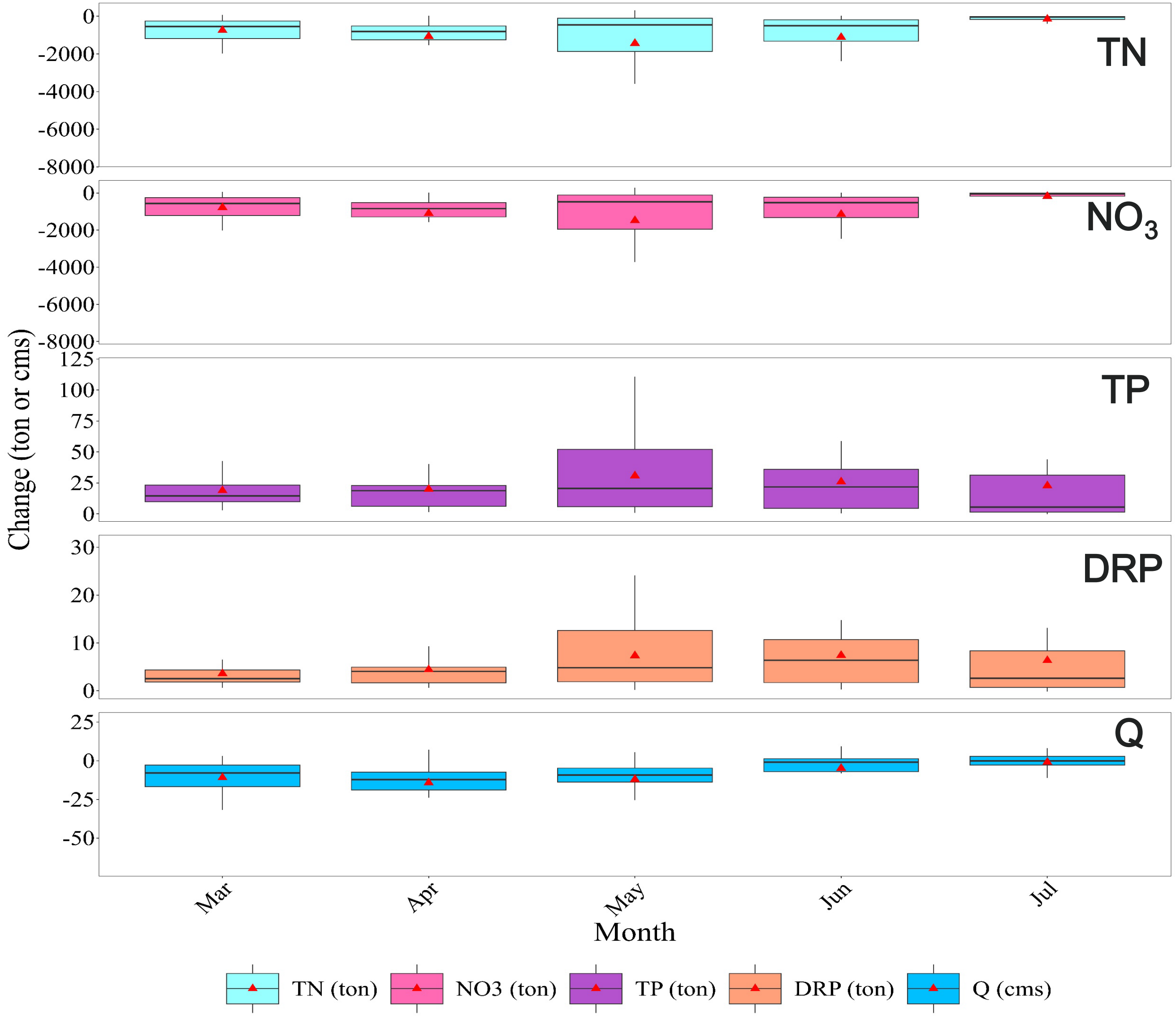




Watershed -Scale Sensitivity of the SWAT to Drainage Intensity

CFAES

Monthly Sensitivity (March-July) (2005 -2021)



Field -Scale Sensitivity of the SWAT to Drain Spacing

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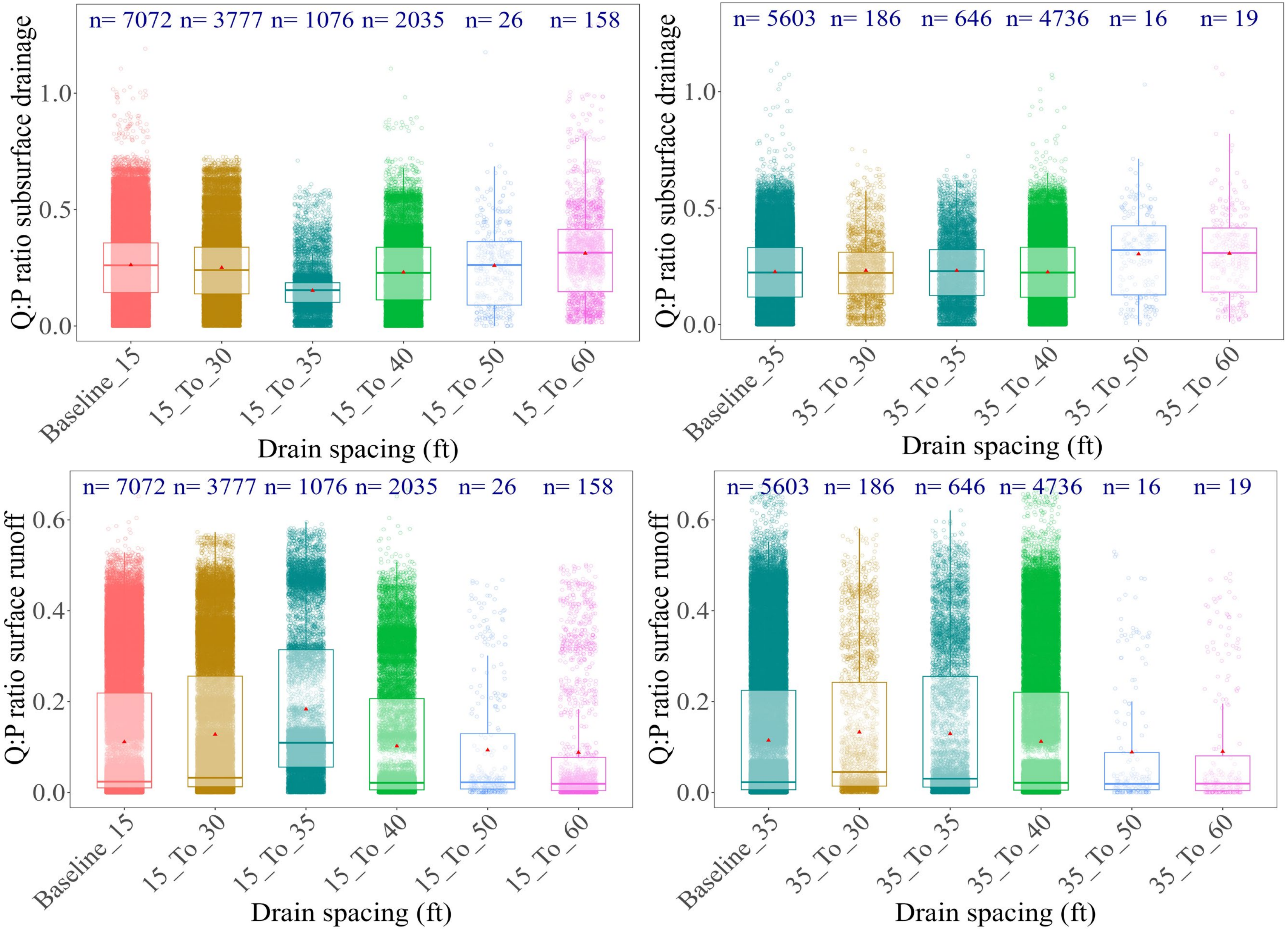
Q:P Ratio Subsurface Drainage

Q:P Ratio Surface Runoff



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