Introduction of ArcNLET-Py Phosphorus modelling

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2 Conceptual Model of Phosphorus

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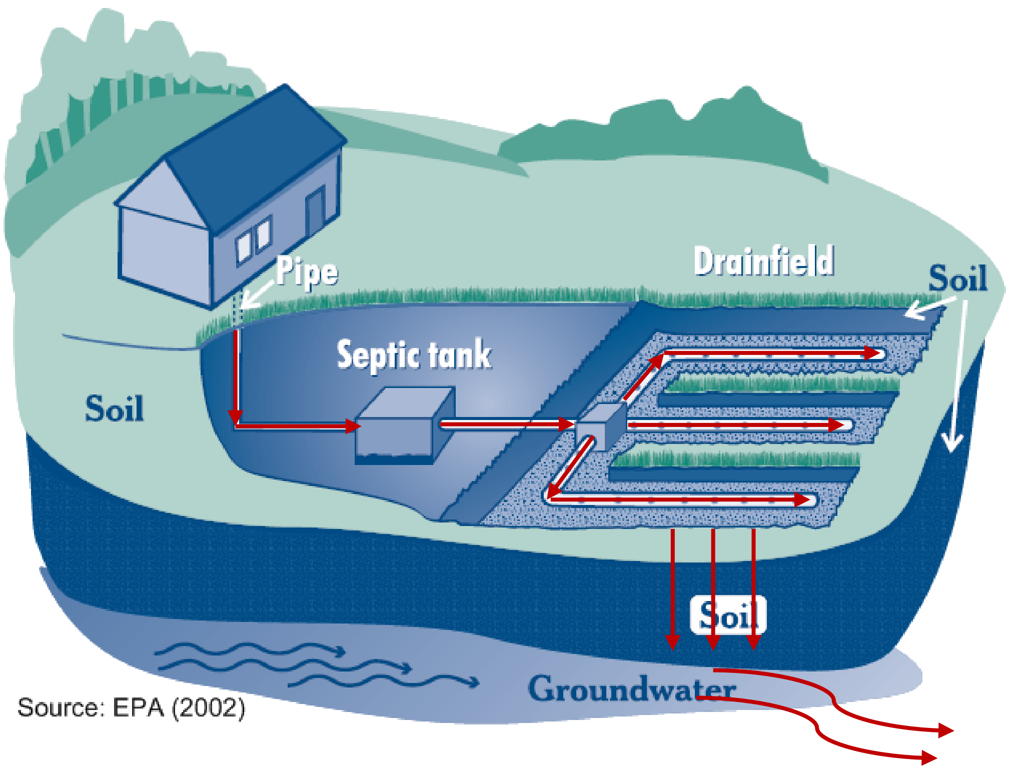
1. Brief Introduction of ArcNLET-Py

1.1 Background

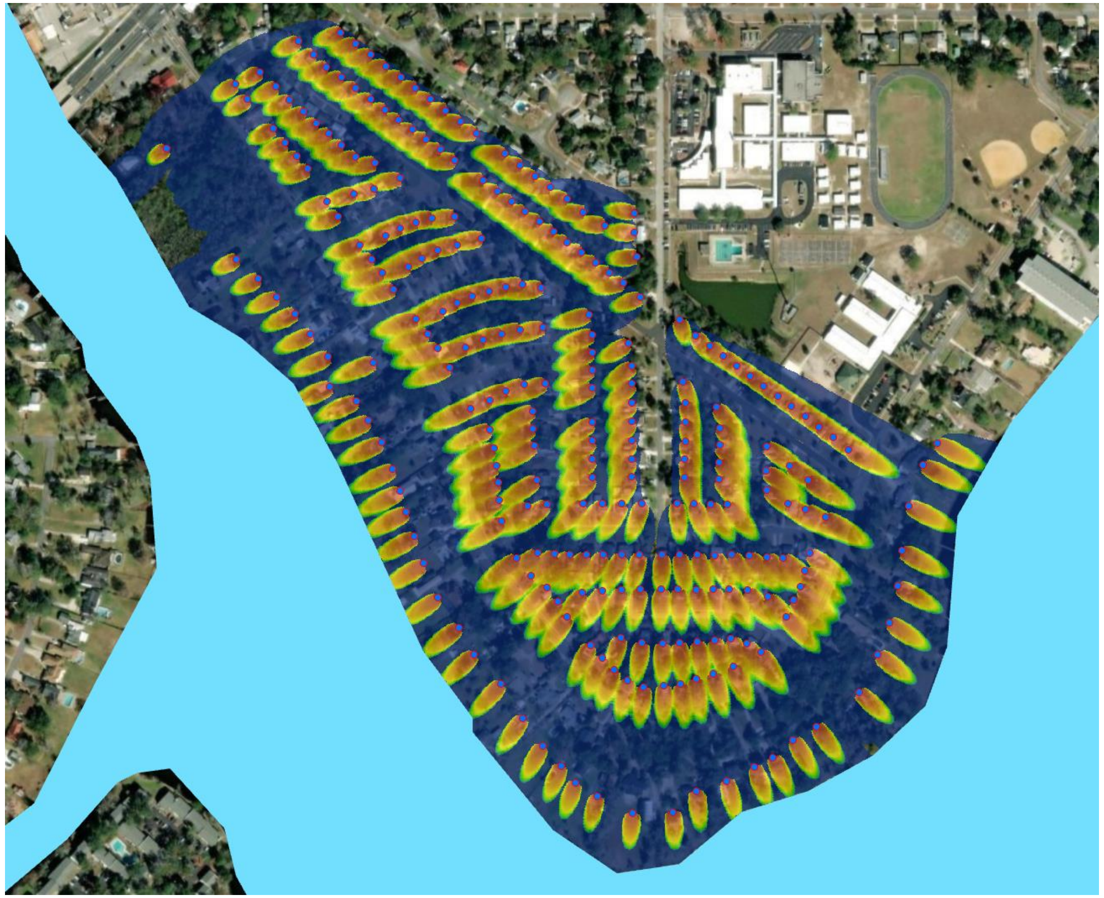


- OSTDS (Onsite Sewage Treatment and Disposal Systems) are currently used by more than 20% of the U.S. population (US EPA, 2024a).
- Sewage from OSTDS is recognized as a significant source of nitrogen and phosphorus in groundwater (US EPA, 2024b).

ArcNLET was developed to estimate both nitrogen and phosphorus loads from OSTDS to groundwater and, subsequently, to surface waterbodies.

1.2 ArcNLET introduction

- ArcNLET, an ArcGIS-based Nutrient Load Estimation Toolbox.
- The development of ArcNLET has lasted for more than 10 years, led by Dr. Ye, Dr. Rios, Dr. Wang, Dr. Zhu, and others.
- Since last year, we have significantly redeveloped the toolbox, creating a new version called ArcNLET-Py. This version is rewritten in Python and integrated with ArcGIS Pro.



1.3 ArcNLET-Py resources

- Source code on GitHub and online User's manual:

  https://github.com/ArcNLET-Py/ArcNLET-Py

- Training videos on YouTube:

  https://www.youtube.com/@mingye9168/videos

- FSU Website:

  https://atmos.eoas.fsu.edu/~mye/ArcNLET/

1.4 Overview

- Section 2 Conceptual Model of Phosphorus

  Conceptual model and mathematical models used to develop OSTDS phosphorus functionality in ArcNLET-Py.

- Section 3 Case Study

  The Lakeshore example was used to demonstrate the application of the phosphorus function.

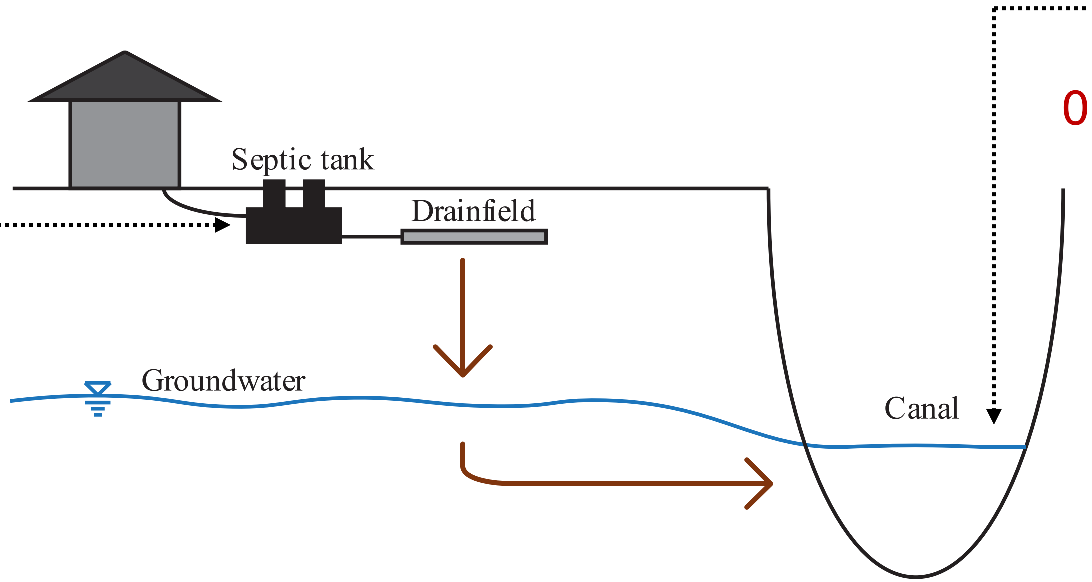
For users who are new to ArcNLET-Py, it is recommended to watch the introductory video and follow the tutorial to become familiar with the toolbox and its features before proceeding.

2. Conceptual Model of Phosphorus

2.1 Background

- Phosphorus loss from septic tanks can impact water quality at much lower concentrations compared to nitrogen.
- Phosphorus in wastewater comes from human waste, detergents, food waste, etc.

Total phosphorus
in wastewater
nearly 10 mg/L



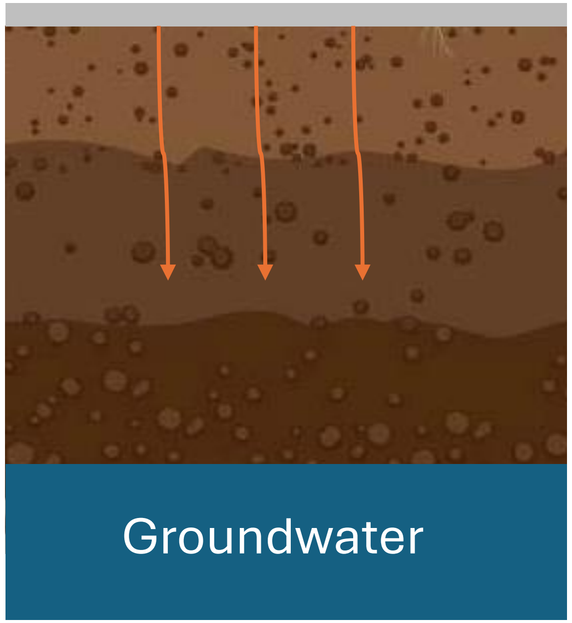
EPA criteria (1986)
0.1 mg/L for flowing water
0.05 mg/L for stream entering lakes

2.2 Phosphorus concentration in wastewater

- Total phosphorus concentrations in septic tank wastewater range from 0.2 to 32 mg-P/L (Robertson et al., 2019; Lowe et al., 2009; McCray et al., 2005), with an average around 9-10 mg-P/L.
- In septic tank wastewater, about 85% of the phosphorus is in the form of inorganic phosphorus, while the remaining 15% is organic phosphorus (Lusk et al., 2017; McCray et al., 2005; Tchobanoglous and Schroeder, 1985). Additionally, most organic phosphorus is mineralized into inorganic phosphorus in the soil (Lusk et al., 2017).
- Therefore, we assume total phosphorus concentrations in septic tank wastewater are roughly equal to inorganic phosphorus (Orthophosphate) if data is absent.

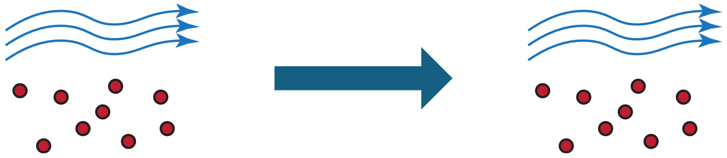
2.3 Phosphate reactive transport

Drainfield



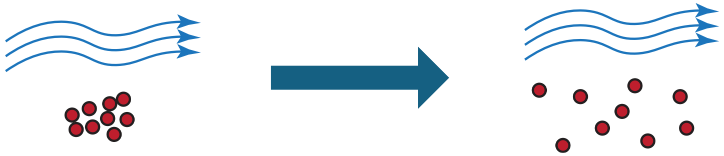
Reactive transport of phosphate

Advection



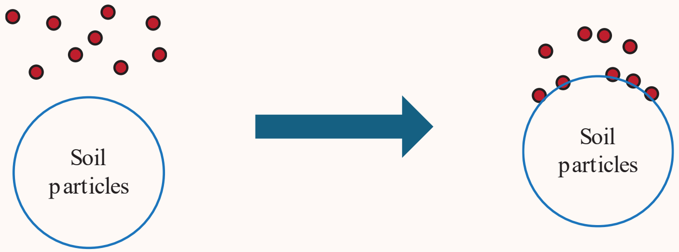
Solutes move with water

Dispersion



Hydrodynamic dispersion and molecular dispersion

Reaction

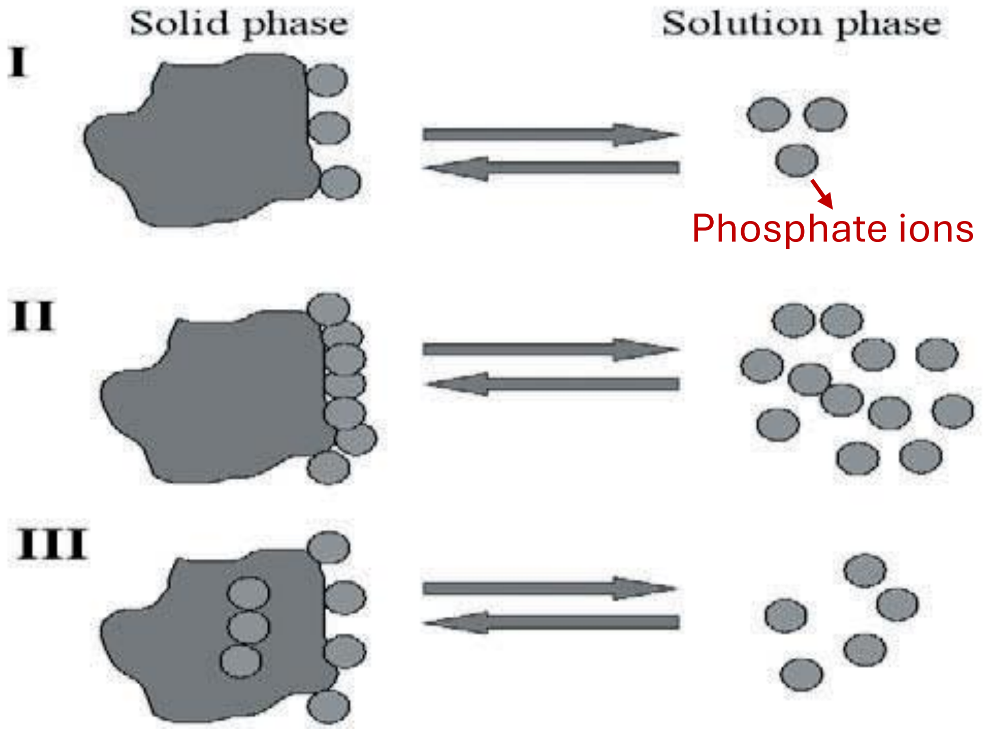


Sorption process

2.4 Phosphate sorption

Phosphate Sorption

Two-step process



I: Initial equilibrium

II: Increase in solution P concentration --- Rapid adsorption to solid surface (seconds to minutes)

Quick, reversible process

III: Diffusion to solid phase (hours to days)

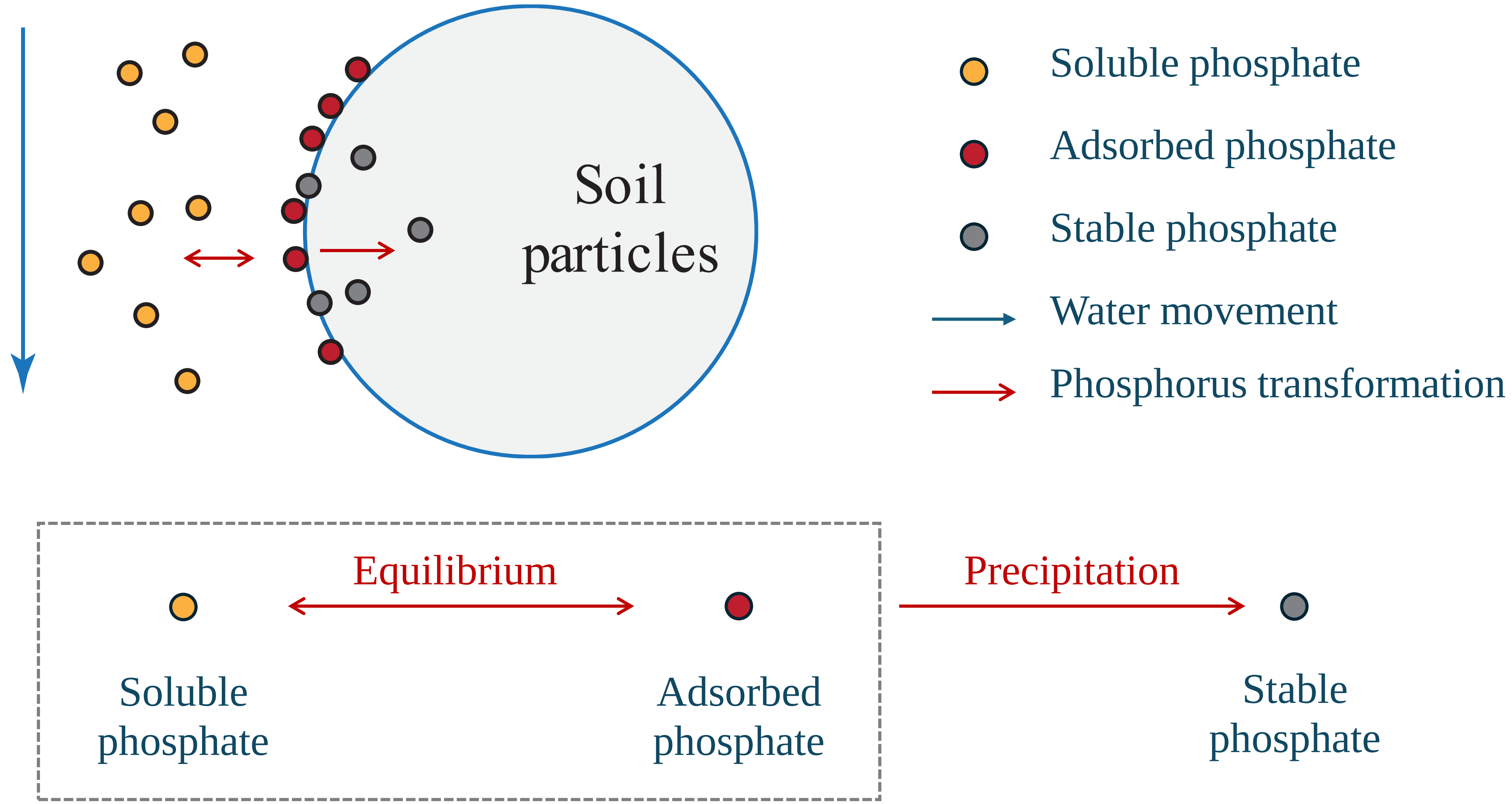
Slow, irreversible processes

Sims, J.T., Sharpley, A.N., 2005. Phosphorus: agriculture and the environment. American Society of Agronomy.

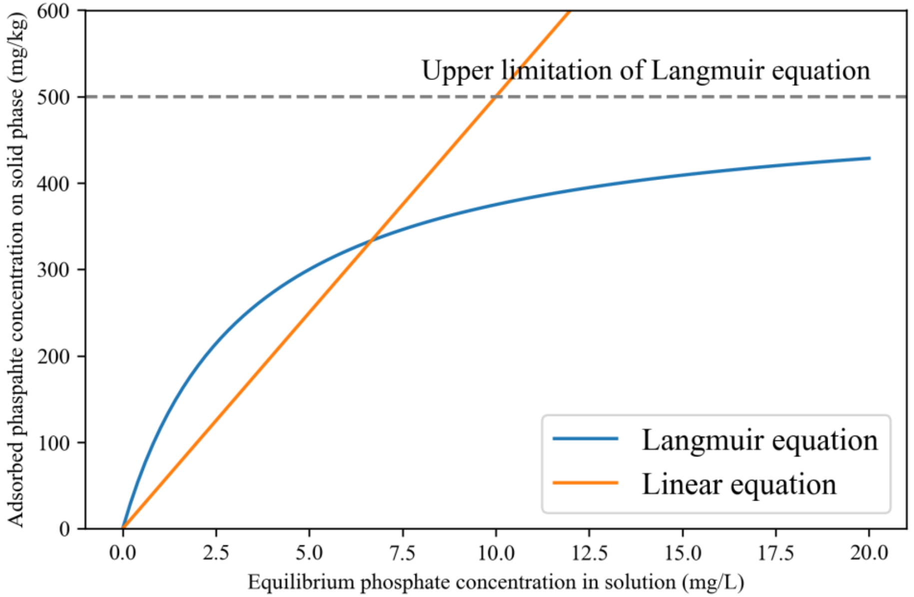
2.4 Phosphate sorption

- Phosphate sorption is a complex process, including a combination of several processes, and it can be influenced by factors such as soil texture, soil organic matter, pH, mineralogy, temperature, and degree of soil P saturation.
- Generally, phosphate sorption is divided into a fast reversible process, and a range of slower, irreversible processes (This division is somewhat arbitrary).
- These slower processes are more complex and have been described by various authors using terms such as “precipitation”, “deposition”, “slow adsorption”, “the slow reaction”, “fixation”, or “solid-state diffusion” (McGechan and Lewis, 2002).

2.5 Phosphorus conceptual model



2.5 Phosphorus conceptual model



- Soluble P and adsorbed P are in equilibrium, indicating a fast and reversible process.
- Both the Langmuir equation and the linear equation are used to describe this process.
- The linear equation is recommended when phosphate concentration varies from less than 1 mg/L to less than10 mg/L (McCray et al., 2005).
- The Langmuir equation is recommended for larger phosphate concentrations (Lusk et al., 2017).
- Precipitation is calculated by first-order reaction rate.

2.4 Governing Equations Vadose zone

Dispersion | Precipitation process

- Linear sorption

$$0 = D\frac{\partial^2 C}{\partial z^2} - \frac{q}{\theta}\frac{\partial C}{\partial x} - R_{precip}\left(1 + \frac{\rho k}{\theta}\right)C$$

- Langmuir sorption

$$0 = D\frac{\partial^2 C}{\partial z^2} - \frac{q}{\theta}\frac{\partial C}{\partial x} - R_{precip}\left(1 + \frac{\rho}{\theta}\frac{KQ_{\max}}{1 + KC}\right)C$$

Advection | Equilibrium adsorption

The finite different method is used to solve the equation.

2.5 Governing Equations Groundwater

Dispersion | Precipitation process

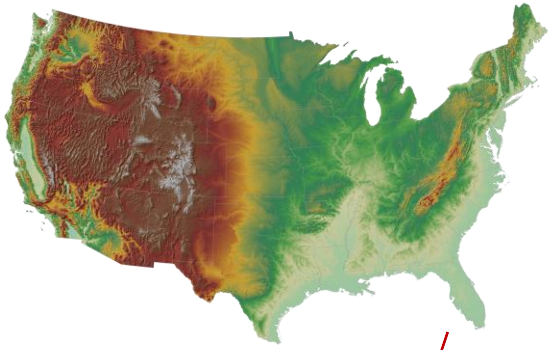
$$0 = \underbrace{D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2}}_{\text{Dispersion}} - \underbrace{v \frac{\partial C}{\partial x}}_{\text{advection}} - \underbrace{R_{precip}}_{\text{Precipitation process}} \underbrace{\left(1 + \frac{\rho k}{\theta}\right) C}_{\text{Equilibrium adsorption}}$$

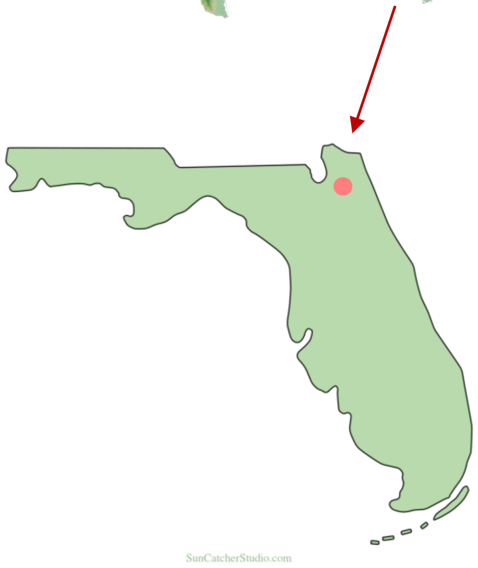
advection | Equilibrium adsorption

Linear sorption is recommended for groundwater transport because phosphorus concentrations in groundwater are likely to be considerable < 10 mg/L (McCray et al., 2005).

3. Case Study

3.1 Study area





265 septic tanks

3.2 Data preparation

- ➢Study area – shapefile with one polygon
- ➢DEM – raster
- ➢Location of septic tanks – multi-point shapefile
- ➢Waterbodies – shapefile

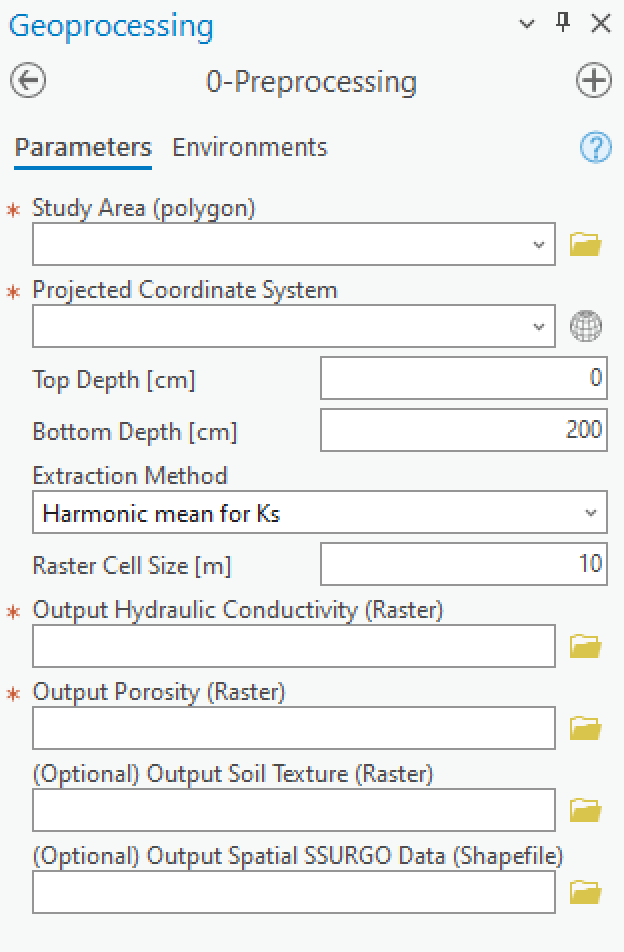
This case extends a previous example by incorporating the phosphorus calculation component.

The objective is to show the procedures for using ArcNLET-Py to estimate the loading of nitrogen (ammonium and nitrate) and phosphorus from OSTDS to surface waterbodies.

3.3 Procedure 1, preprocessing module

Objective: Extract data from the online SSURGO database for subsequent calculations.

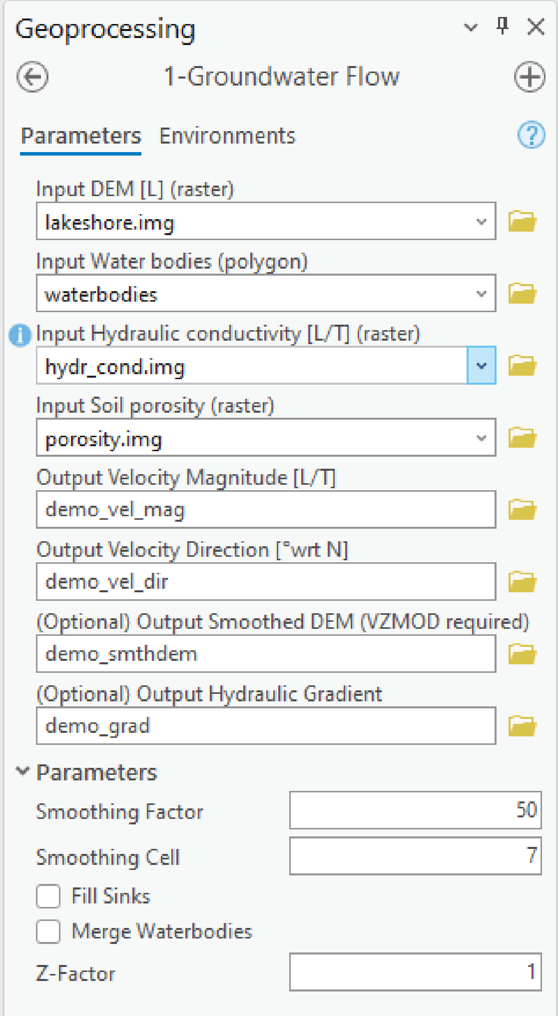
- Inputs
  - Study area
- Outputs
  - Hydraulic conductivity
  - Porosity
  - Soil types



3.4 Procedure 2, groundwater flow module

Objective: calculate groundwater velocity and velocity direction based on DEM and soil data.

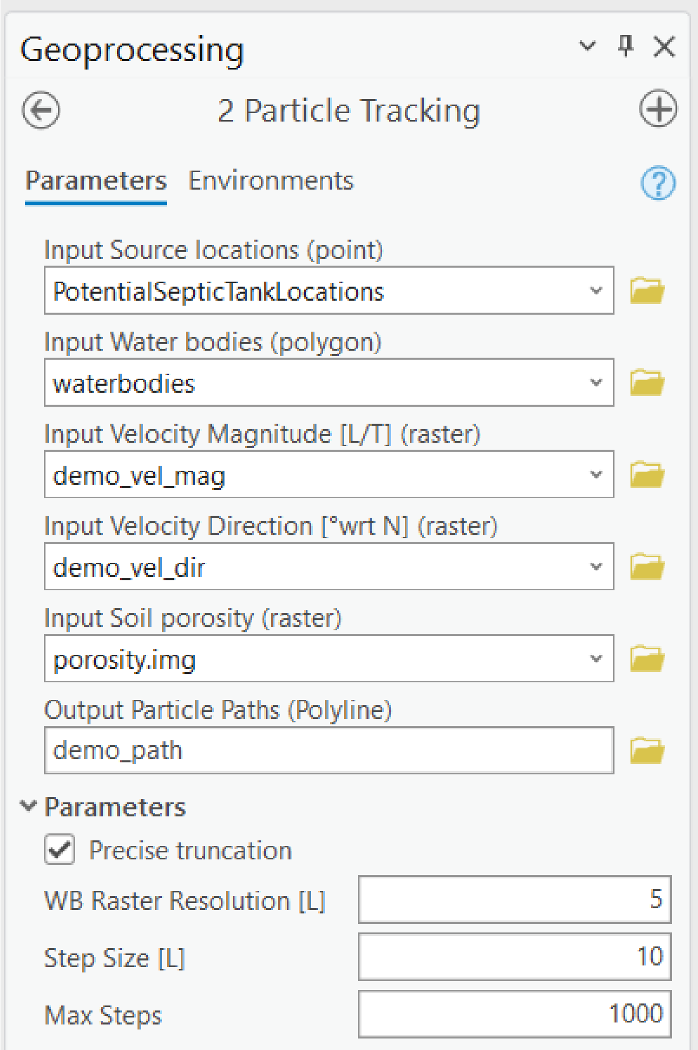
- Inputs
  - DEM
  - Waterbodies
  - Hydraulic Conductivity
  - Porosity
- Outputs
  - Velocity Magnitude
  - Velocity Direction
  - Hydraulic Gradient
  - Smoothed DEM



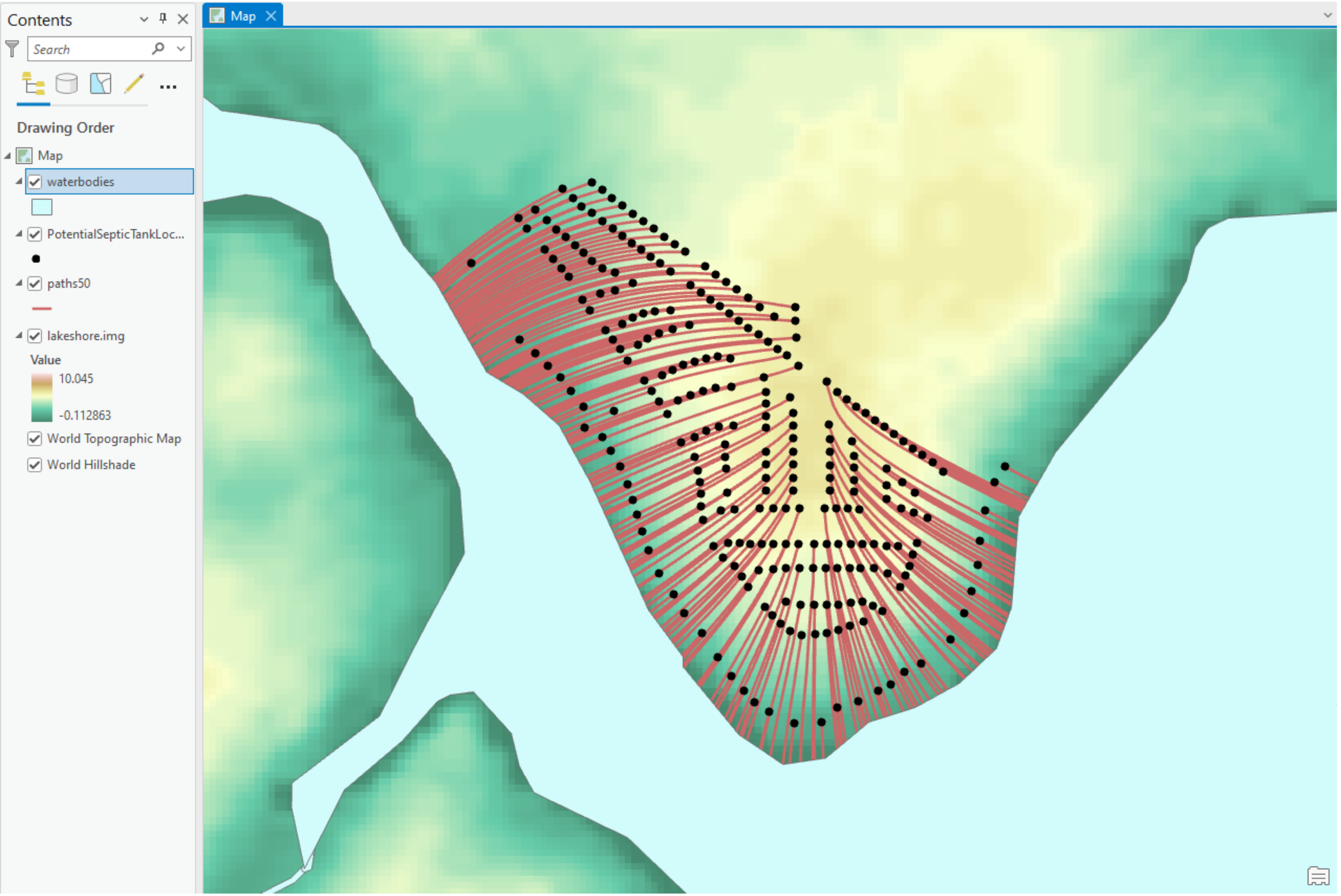
3.5 Procedure 3, particle tracking module

Objective: simulate water particle movement from sources (septic tanks) to surface waterbodies.

- Inputs
  - Velocity Magnitude and Direction
  - Locations of septic tanks
  - Waterbodies
  - Porosity
- Outputs
  - Particle paths



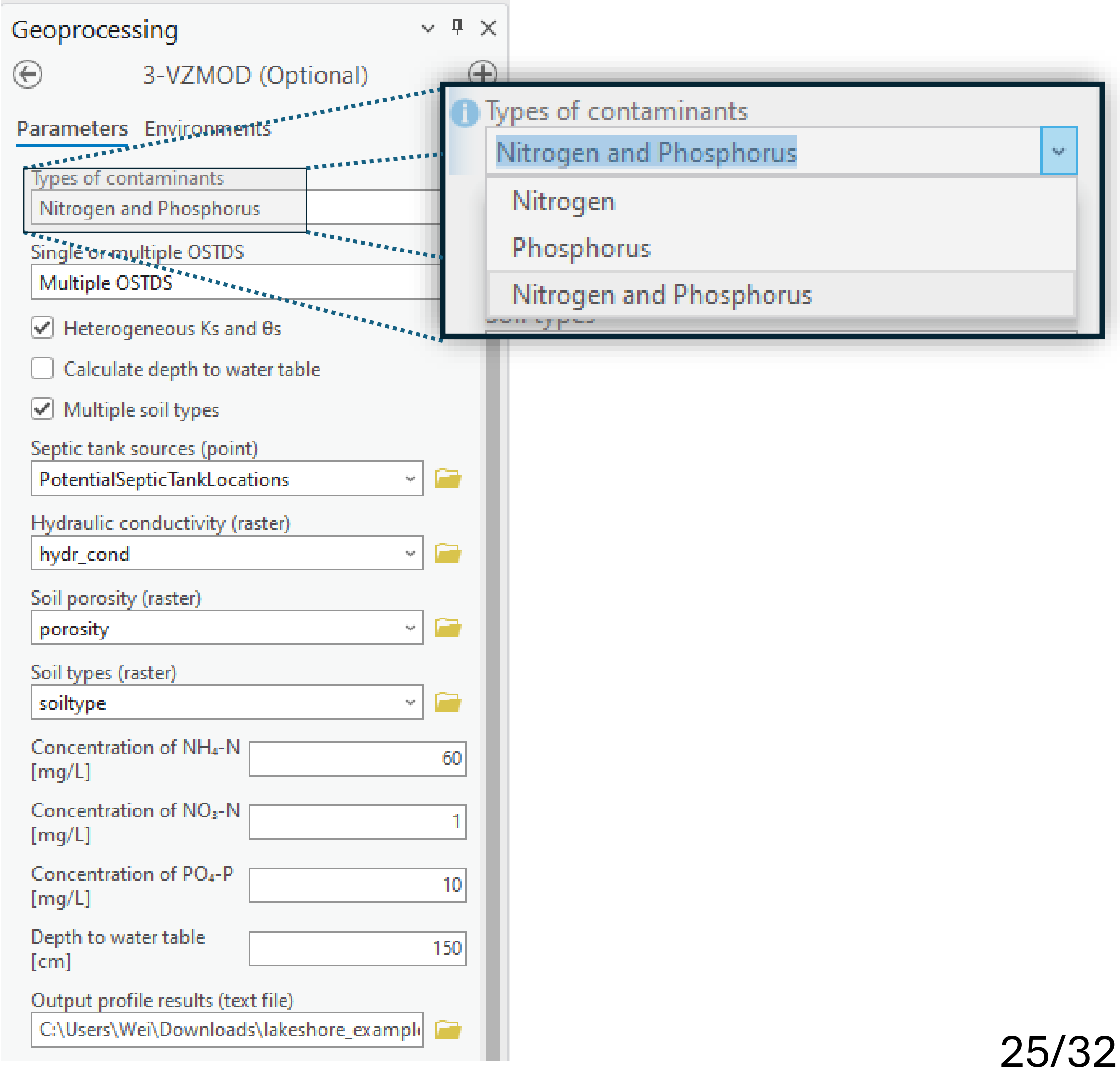
3.5 Procedure 3, particle tracking module



3.6 Procedure 4, VZMOD

Objective: Model nitrogen and phosphorus reactive transport in the vadose zone.

- Inputs
  - Regional scale hydraulic parameters
  - Initial concentration values
  - Depth from drainfield to water table
  - Reactive transport parameters
- Outputs
  - Nitrogen and phosphate concentrations entering groundwater



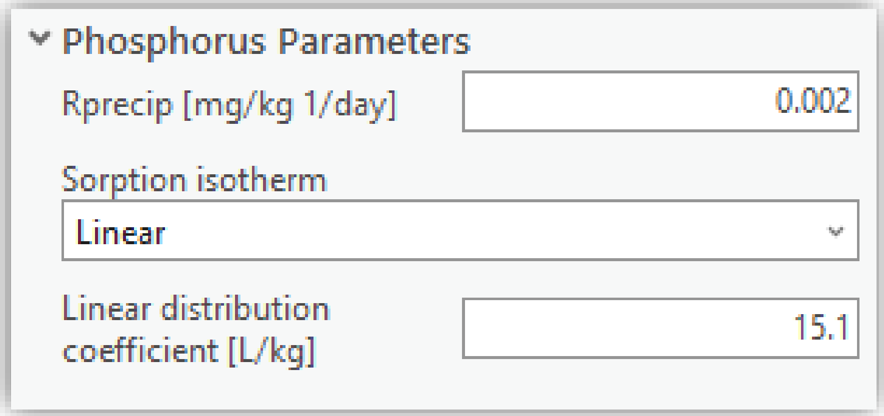
3.6 Procedure 4, VZMOD

- Linear sorption

Precipitation rate

Linear distribution coefficient

$$0 = D\frac{\partial^2 C}{\partial z^2} - \frac{q}{\theta}\frac{\partial C}{\partial x} - R_{precip}\left(1 + \frac{\rho k}{\theta}\right)C$$



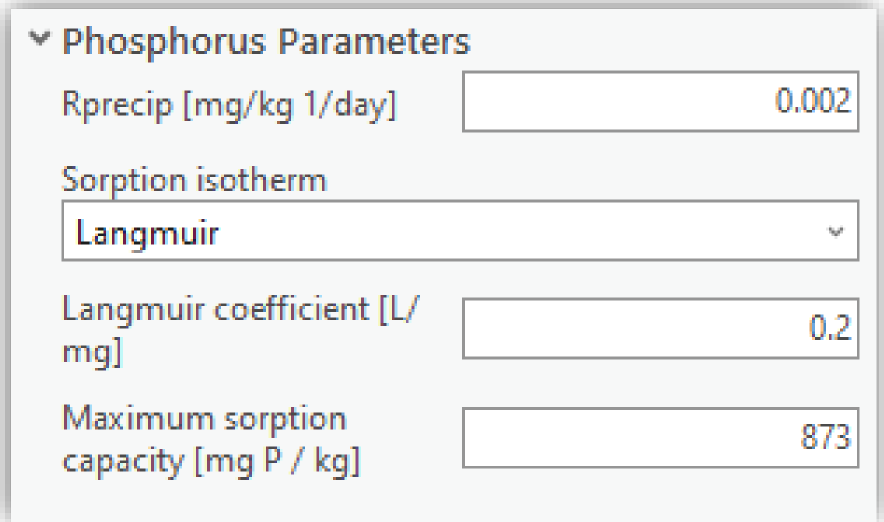
- Langmuir sorption

Precipitation rate

Langmuir coefficient

$$0 = D\frac{\partial^2 C}{\partial z^2} - \frac{q}{\theta}\frac{\partial C}{\partial x} - R_{precip}\left(1 + \frac{\rho}{\theta}\frac{KQ_{max}}{1 + KC}\right)C$$

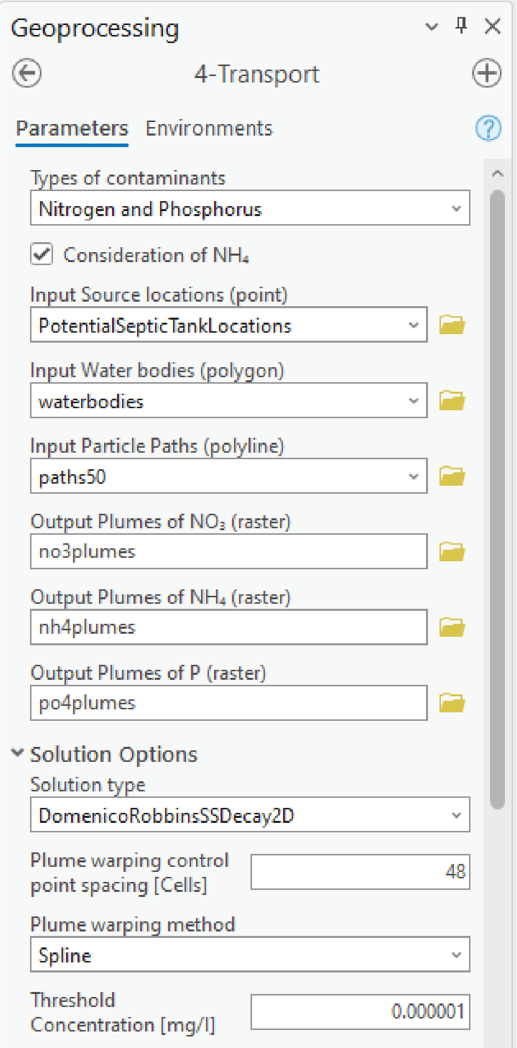
Maximum sorption capacity



3.7 Procedure 5, transport module

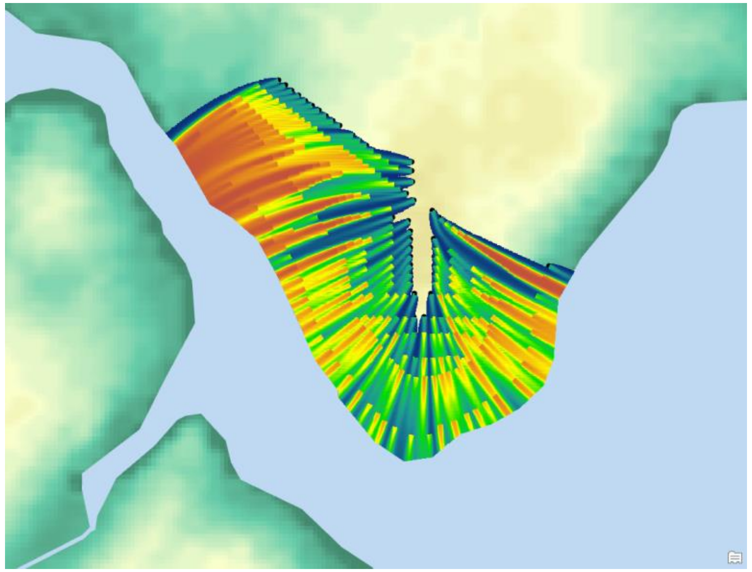
Objective: simulate nitrate, ammonium, and phosphate plumes in groundwater.

- Inputs
  - Septic tank location and concentration values entering groundwater
  - Particle paths and waterbodies
  - Reactive transport parameters
- Outputs
  - Nitrate, ammonium, and phosphate plumes



3.7 Procedure 5, transport module

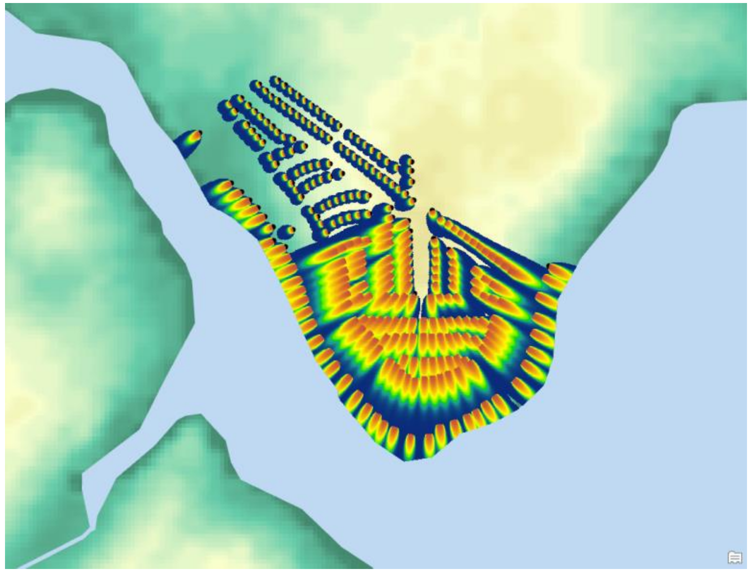
- NH_4-N plumes



Low High

1e-6 0.0007 mg/L

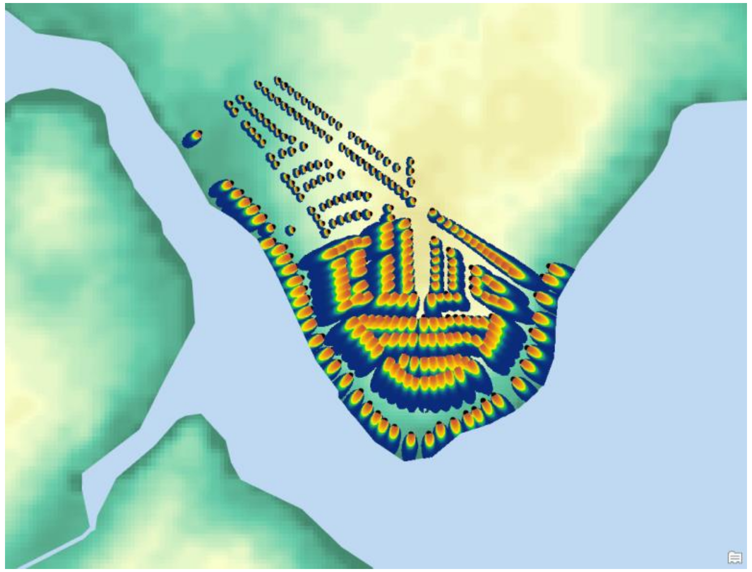
- NO_3-N plumes



Low High

1e-6 57.0 mg/L

- PO_4-P plumes



Low High

1e-6 2.6 mg/L

3.8 Procedure 6, load estimation module

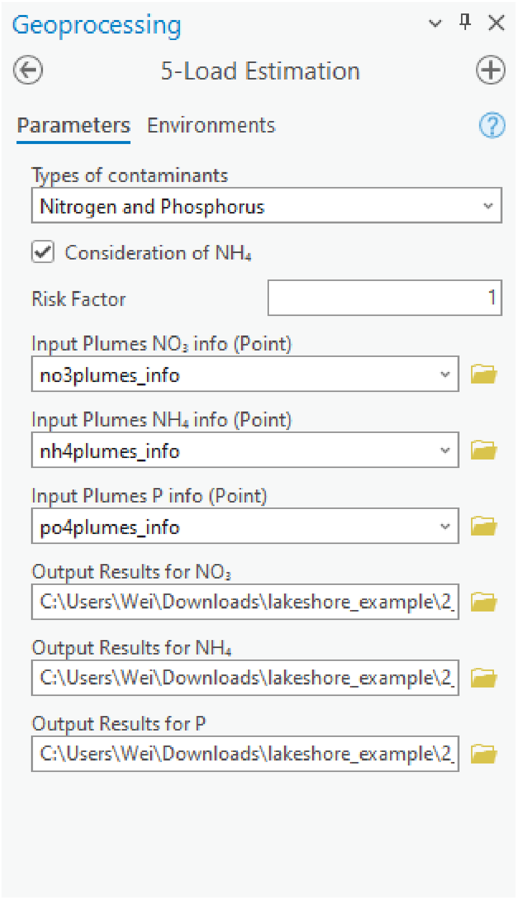
Objective: estimate nitrate, ammonium, and phosphate loading to surface waterbodies.

➢Inputs

- Plume information shapefile of NH_4-N
- Plume information shapefile of NO_3-N
- Plume information shapefile of PO_4-P

➢Outputs

- Loading results, CSV files



3.8 Procedure 6, load estimation module

Loading estimation results

	NH_4-N	NO_3-N	PO_4-P
Loading to groundwater (g/d)	0.059	19,409.1	450.5
Removed in groundwater (g/d)	0	18,632.7	422.6
Loading to surface waterbodies (g/d)	0.059	776.4	27.9

Reference

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Thank you!