ArcGIS-Based Nitrate Load Estimation Toolkit (ArcNLET) for Estimation of Nitrogen Load from Septic Systems to Lake Roberts: Forward and Inverse Modeling

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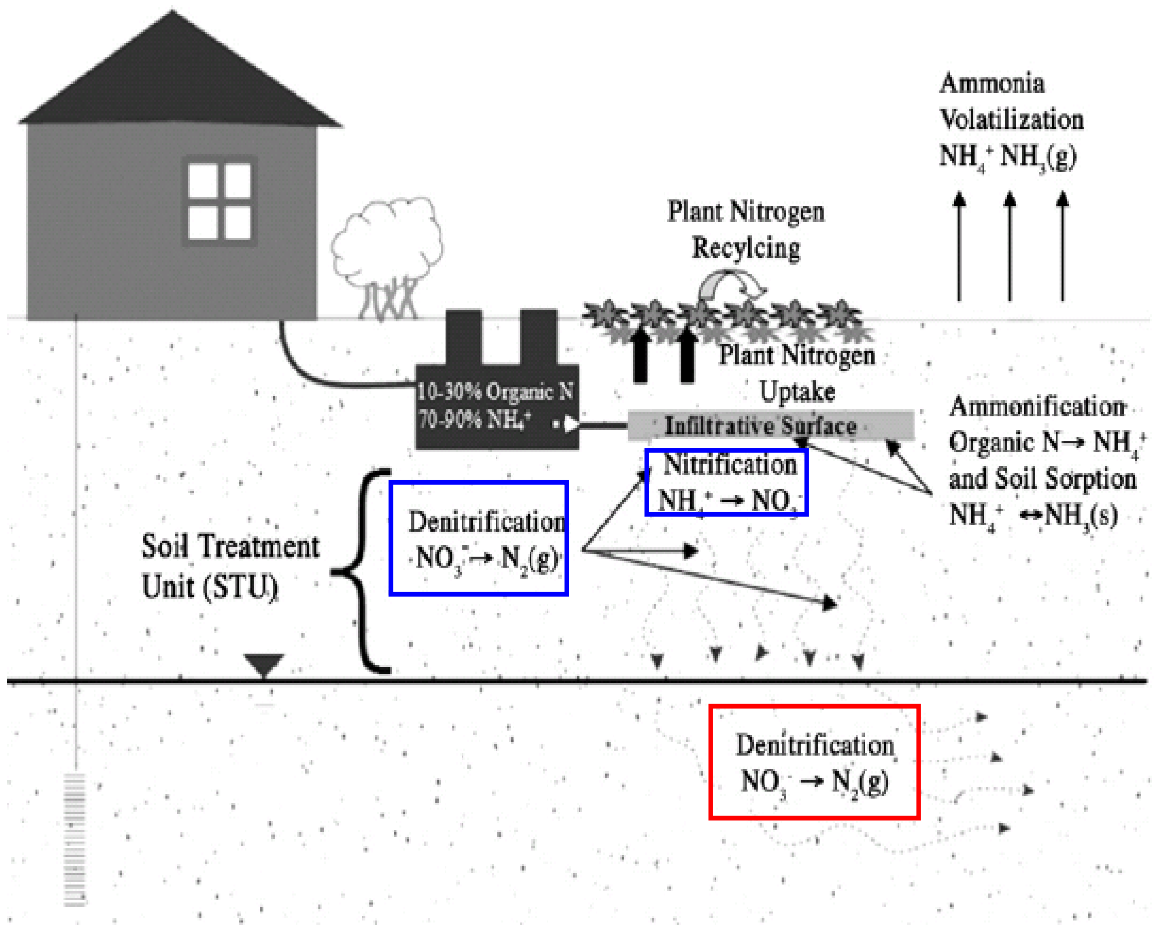
Outlines

- Introduction of ArcNLET
  - Rational of developing ArcNLET
  - Functions of ArcNLET and associated software
  - Data requirements of using ArcNLET
- Estimation of nitrogen load to Lake Roberts
- Model calibration against seepage data
- Suggestions and comments

ArcNLET Project Team

- Contract Manager:
  - Rick Hicks (FDEP) (Richard.W.Hicks@dep.state.fl.us)
- Principal Investigators:
  - Ming Ye (FSU) (mye@fsu.edu)
  - Paul Lee (FDEP) (retired in 2012)
- Graduate Students:
  - Raoul Fernendes (Graduated in 2011)
  - Fernando Rios (Graduated in 2010)
- Post-docs:
  - Mohammad Sayemuzzaman (2014 – present)
  - Yan Zhu (2014-present)
  - Huaiwei Sun (2012-2013)
  - Liying Wang (2010-2012)

Schematic of an Onsite Sewage Treatment and Disposal System and Subsurface Nitrogen Transformation and Removal Processes



From Heatwole and McCray (2007)

Soil Processes: Simulated using VZMOD
- Unsaturated flow
- Solute transport
- Nitrification and denitrification

Groundwater Process: Simulated using ArcNLET
- Groundwater flow
- Solute transport
- Denitrification

ArcNLET-MC: Quantify uncertainty of ArcNLET simulations

Software Download and References

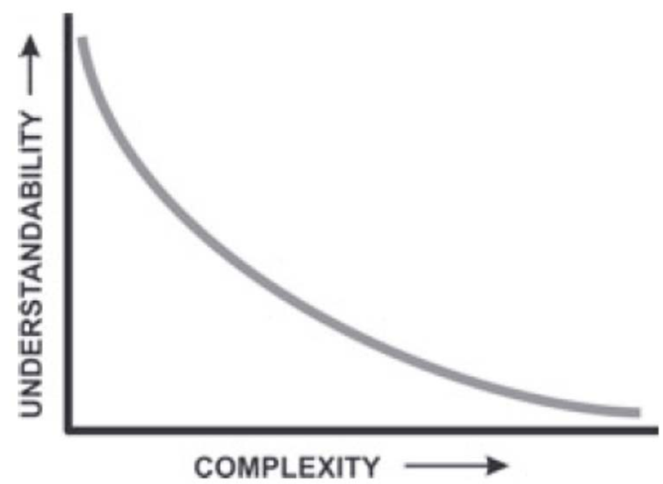
- ArcNLET: http://people.sc.fsu.edu/~mye/ArcNLET
- VZMOD: http://people.sc.fsu.edu/~mye/VZMOD
- Peer-reviewed publications:

  - **Ye, M.**, H. Sun, and K. Hallas, Numerical Estimation of Nitrogen Load from Septic Systems to Surface Water Bodies for Nutrient Pollution Management in the St. Lucie River and Estuary Basin, Florida, *Environmental Earth Sciences*, Under Review.
  - Ye, M., J.F. Rios, and L. Shi (2014), A new ArcGIS-based software of uncertainty analysis for nitrate load estimation, *Ground Water*, Software Spotlight, doi: 10.1111/gwat.12228.
  - Rios, J.F. (*student*), M. Ye, L. Wang, P.Z. Lee, H. Davis, and R.W. Hicks (2013), ArcNLET: A GIS-based software to simulate groundwater nitrate load from septic systems to surface water bodies, *Computers and Geosciences*, 52, 108-116, 10.1016/j.cageo.2012.10.003.
  - Wang, L. (*post-doc*), M. Ye, J.F. Rios, R. Fernandes, P.Z. Lee, and R.W. Hicks (2013), Estimation of nitrate load from septic systems to surface water bodies using an ArcGIS-based software, *Environmental Earth Sciences*, DOI 10.1007/s12665-013-2283-5.
  - Wang, L. (*post-doc*), M. Ye, P.Z. Lee, and R.W. Hicks (2013), Support of sustainable management of nitrogen contamination due to septic systems using numerical modeling methods, *Environment Systems and Decisions*, 33, 237-250, doi:10.1007/s10669-013-9445-6.

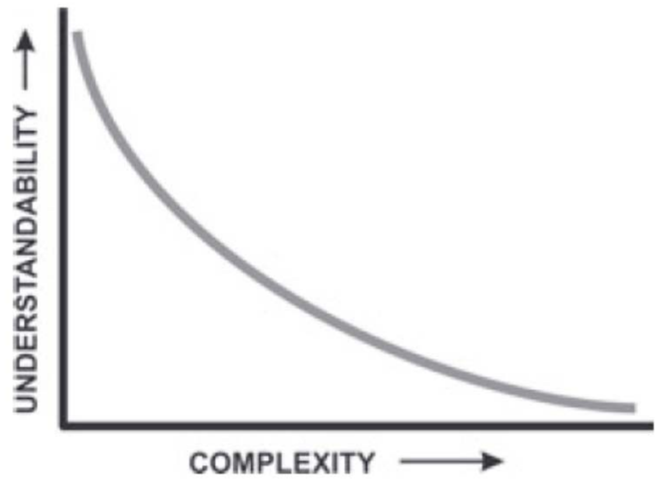
Why Developing ArcNLET?

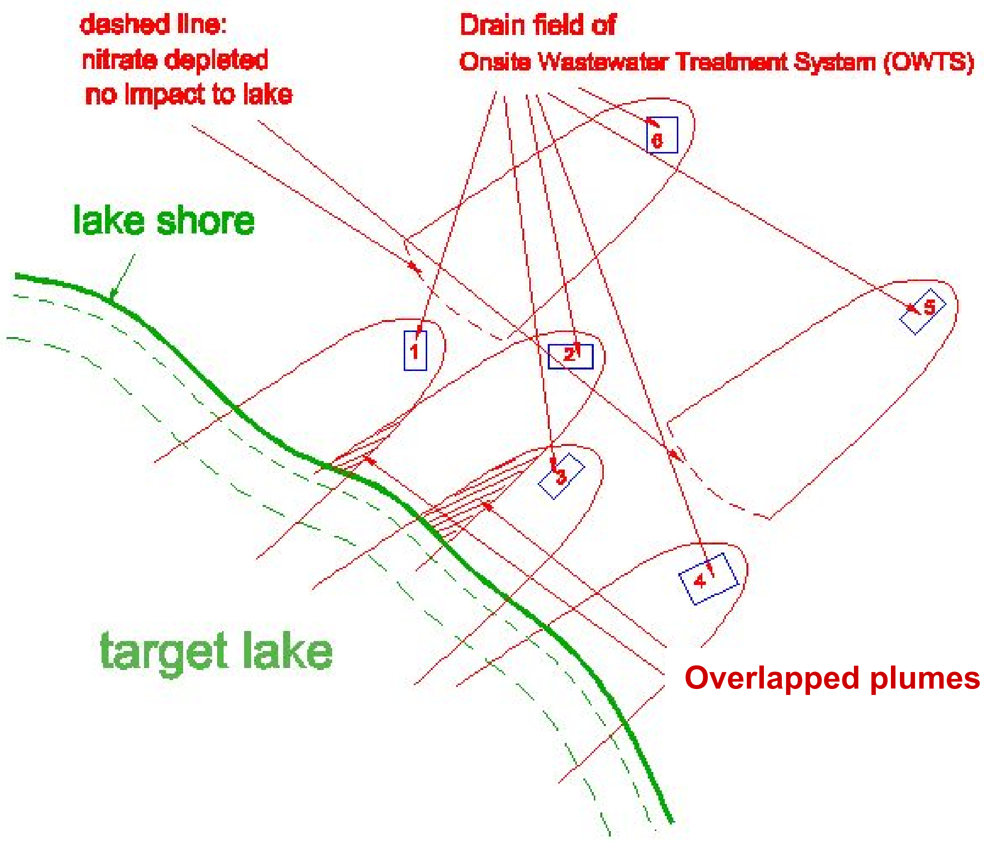
- There is no suitable tool for estimating nitrate load to meet TMDL requirements and perform nitrogen BMAPs. Existing tools are either too simple or too complex.
- Develop a simplified model that consider key hydrogeologic processes of groundwater flow and nitrate fate and transport.
- Implement the model by developing a user-friendly ArcGIS extension to
  - Simulate nitrate fate and transport including the denitrification process
  - Consider multiple septic tanks
  - Provide a management and planning tool for environmental management and regulation

- Disseminate the software and conduct technical transfer to FDEP staff and other interested parties.



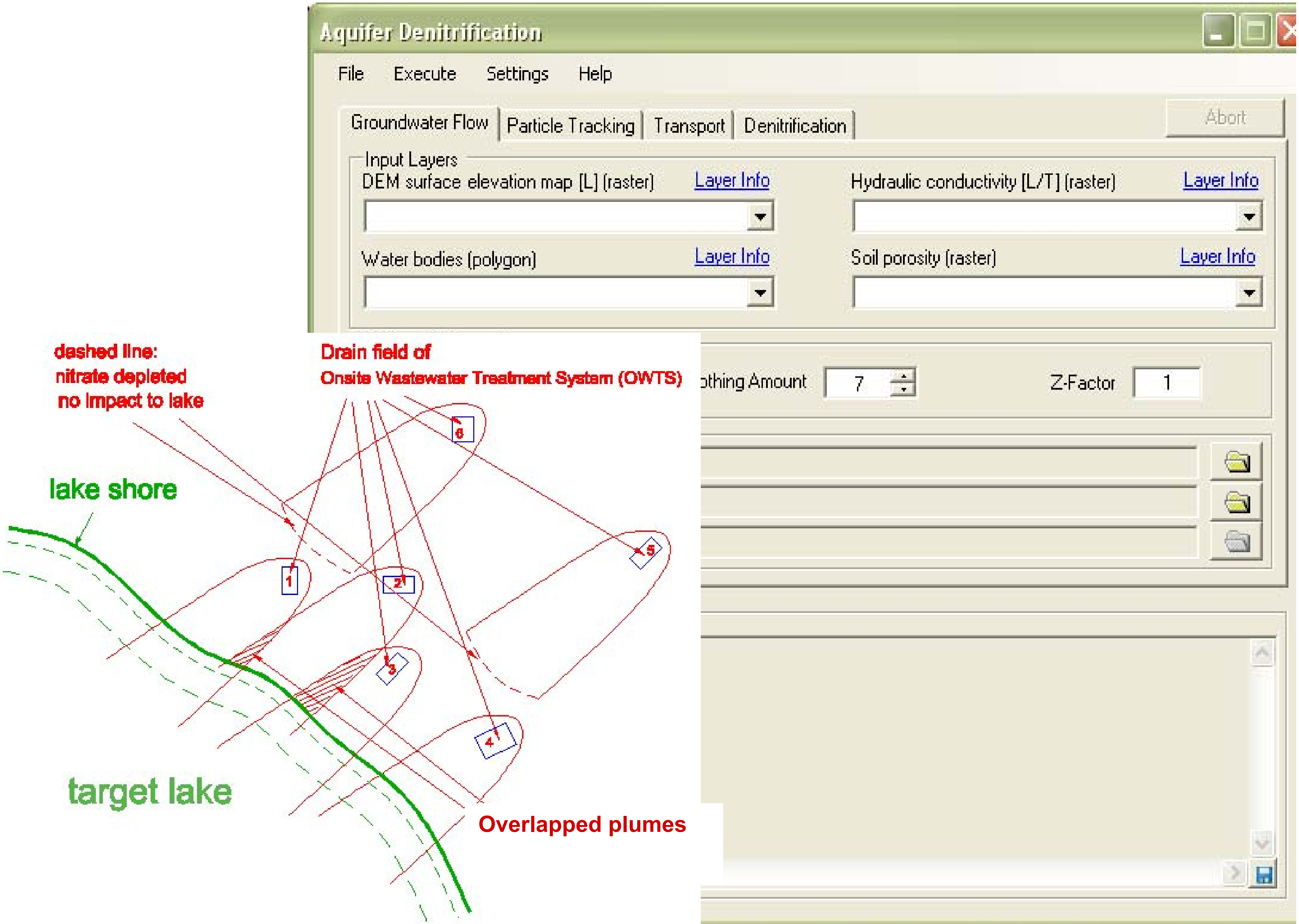
Simplified Conceptual Model to consider key hydrogeologic processes involved in nitrate transport:





- ***Groundwater flow model*** to estimate
  - flow path
  - flow velocity
  - travel time
- ***Nitrate transport model*** to consider
  - Advection
  - Dispersion
  - Denitrification
- ***Load estimation model*** to estimate nitrate load

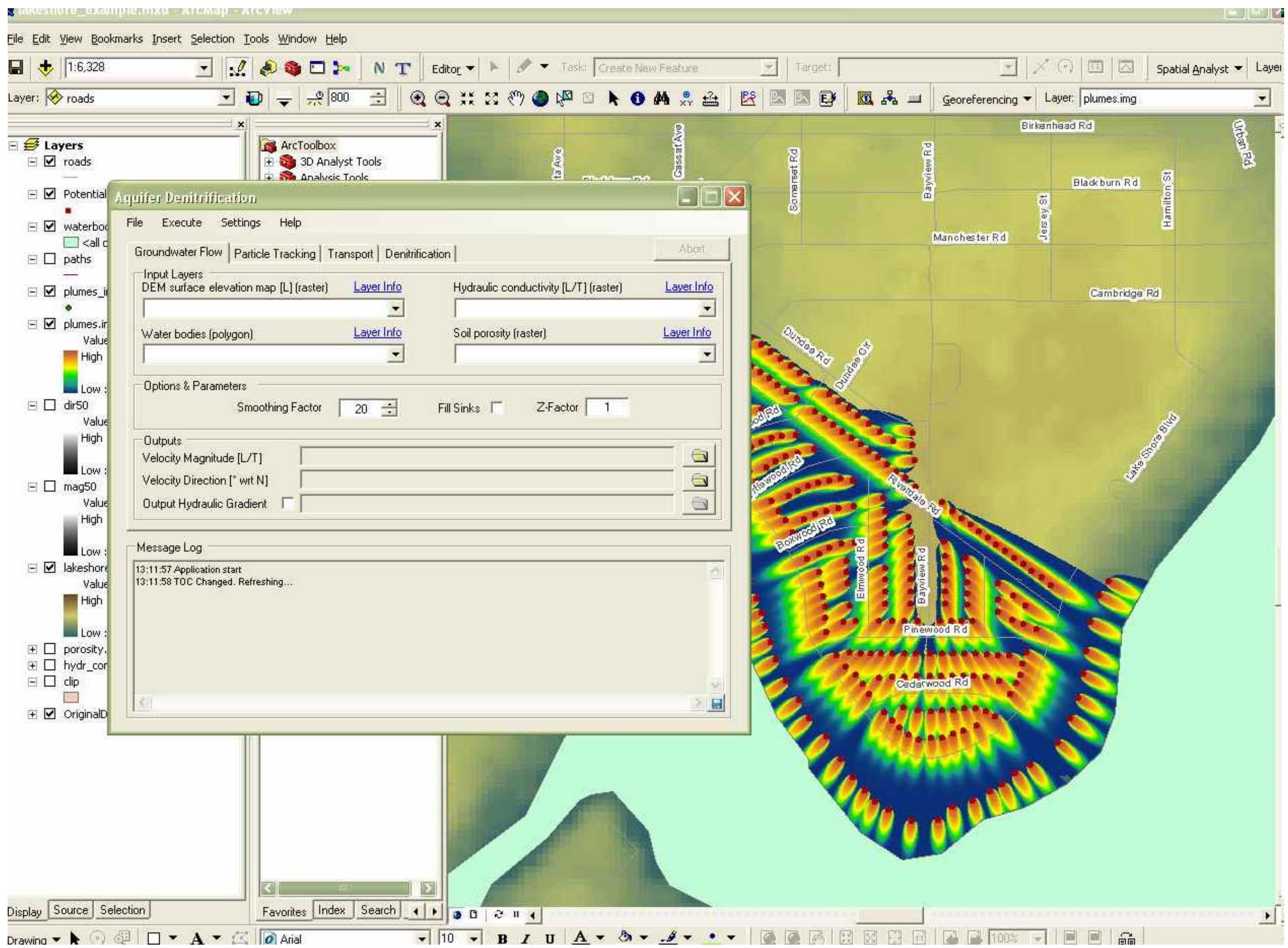
ArcNLET Functions: Graphic User Interface



What is ArcNLET?

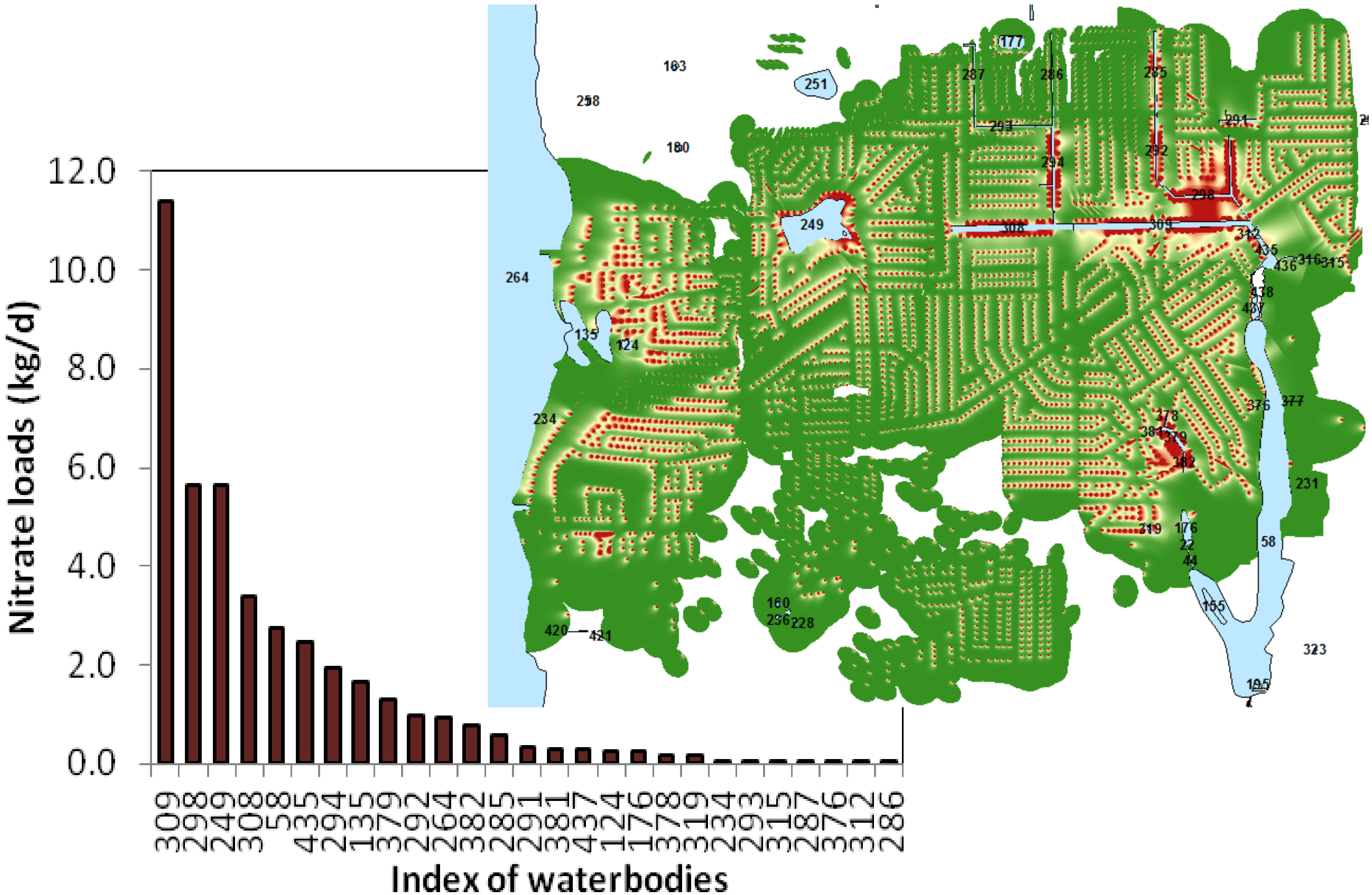
ArcGIS-based Nitrate Load Estimation Toolkit

- A simplified conceptual model of groundwater flow and solute transport
- Implementation as an ArcGIS extension
- Calculation of nitrate plume and nitrate load



Compatible with ArcGIS 9.3, 10.0, and 10.1

Illustration of simulated nitrate plumes and nitrate load



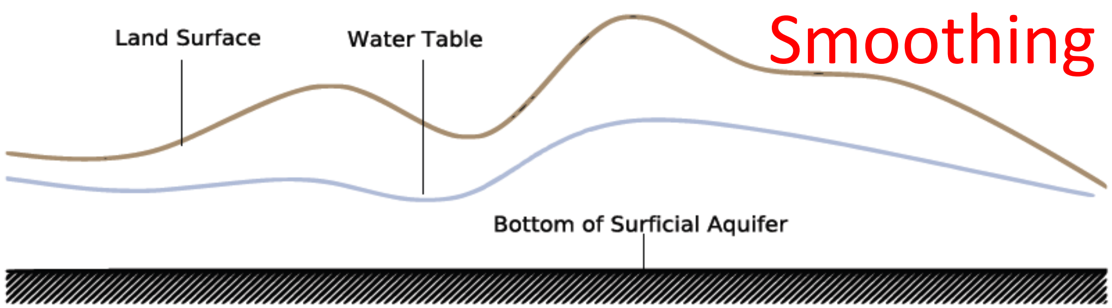
Simplifications and Limitations in Groundwater Flow Modeling

Simplifications:

- Treat water table as subdued replica of topography (Process topographic to approximate shape of water table)
- Use Dupuit assumption to simulate 2-D, horizontal groundwater flow

Limitations:

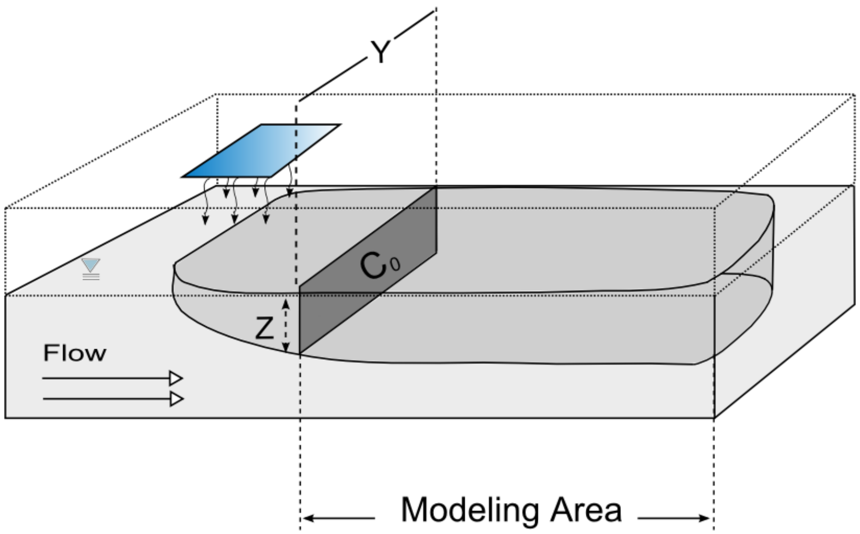
- Steady-state flow
- 2-D flow instead of fully 3-D flow



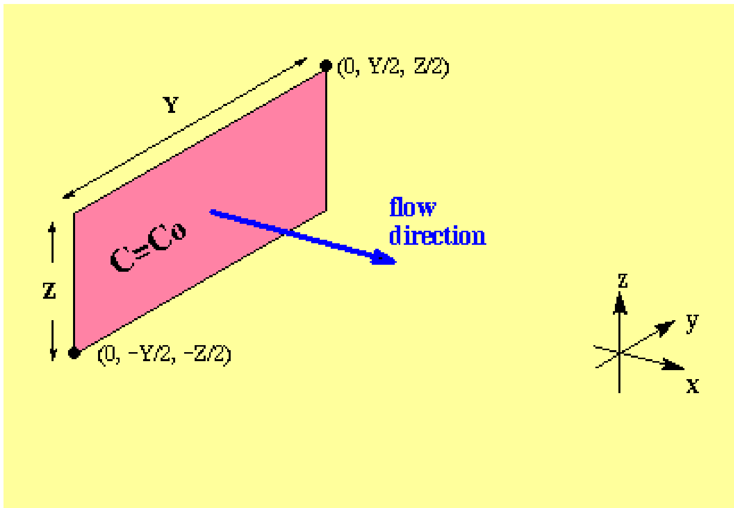
Smoothing Factor

Simplifications and Limitations in Nitrate Transport Modeling

EPA BIOCHLOR model



Domenico analytical solution



$$\frac{\partial C}{\partial t} = \alpha_\ell v \frac{\partial^2 C}{\partial x^2} + \alpha_{T_h} v \frac{\partial^2 C}{\partial y^2} + \alpha_{T_v} v \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial x} - kC$$

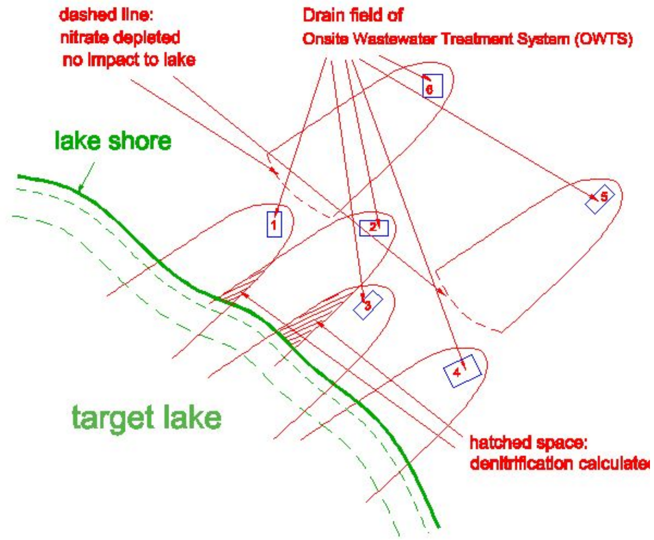
Dispersion | Advection | Decay | **Denitrification**

$$C(x,y,z,t) = \frac{C_0}{8} F_1(x,t) F_2(y,x) F_3(z,x)$$

Simplifications and Limitations in Nitrate Transport Modeling

- Simplifications:
  - Analytical solution of transport model with uniform flow
  - Linear kinetic reaction for denitrification process
- Limitations:
  - Only consider nitrate (a new module is being developed to simulate ammonium)
  - Pseudo-3D model
  - Steady state model
  - Use of empirical or calibrated value of decay coefficient

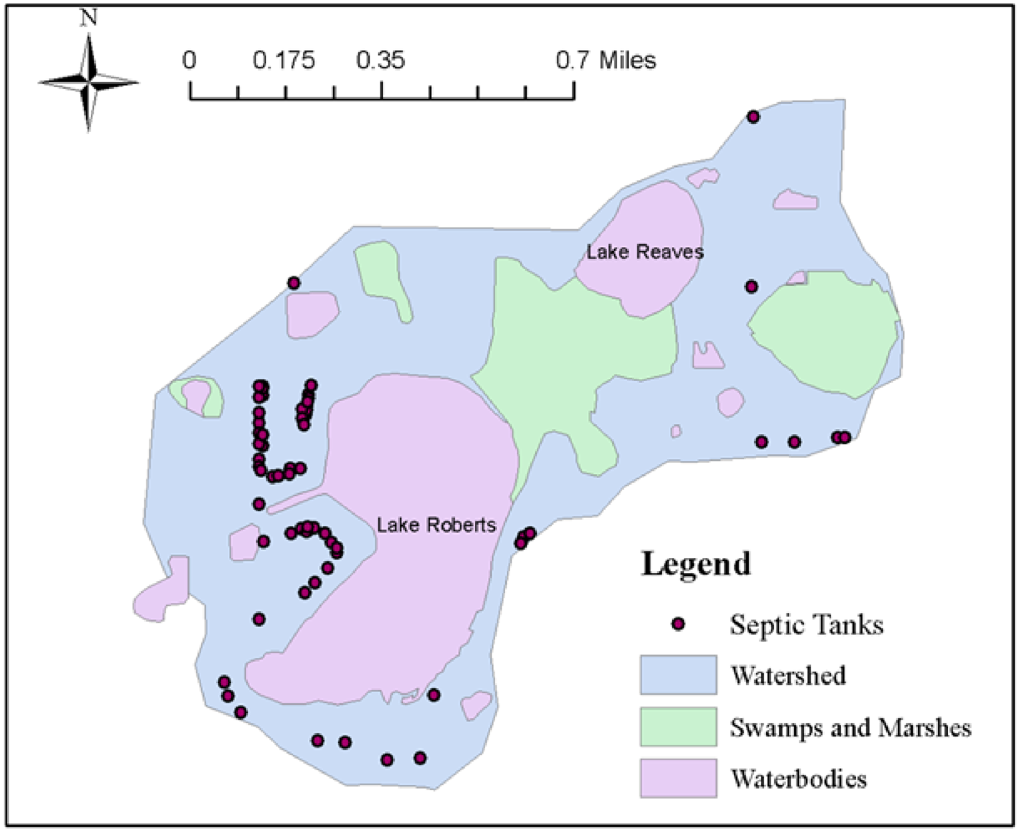
Input Data of ArcNLET



All input data files are in ArcGIS format.

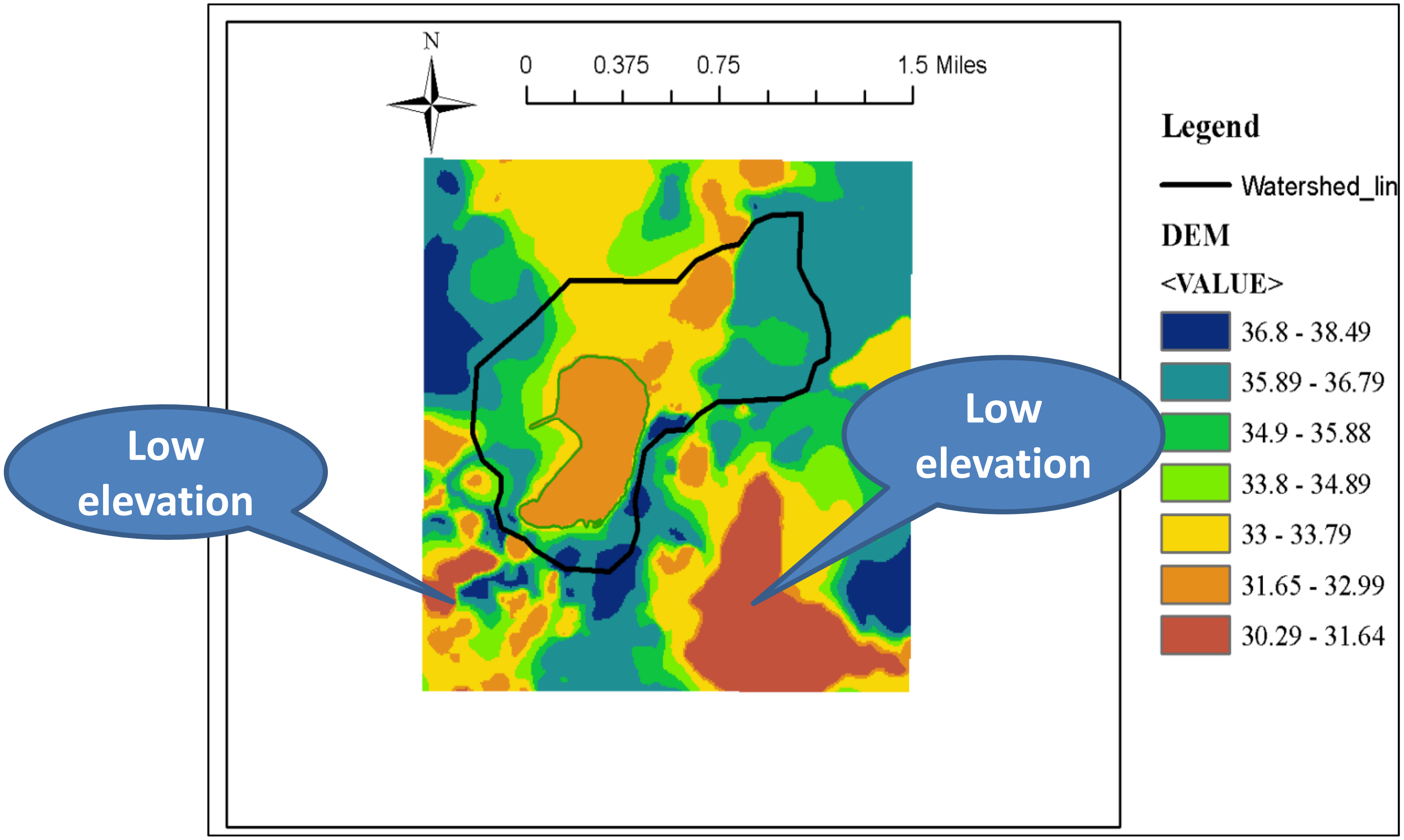
- Locations of septic tanks
- Locations of water bodies
- Topography (DEM: Digital Elevation Model): Process it to obtain water table
- Hydrogeological and transport parameters
  - Smoothing factor (used to process topography)
  - Hydraulic conductivity (from SSURGO)
  - Porosity (from SSURGO)
  - Dispersivity
  - Decay coefficient of denitrification
  - Source load and concentration

Modeling Domain and Model Setup



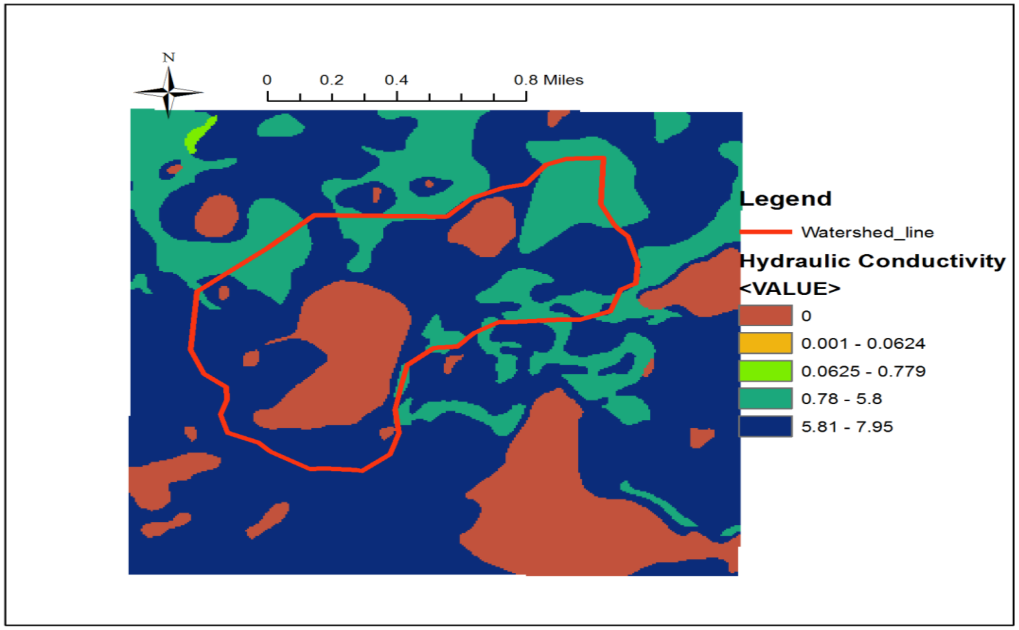
- Boundary of the watershed
- Locations of septic tanks (83 septic systems), water bodies, and swamps and marshes
- The swamps and marshes are merged into water bodies later on for calculation of nitrogen load.

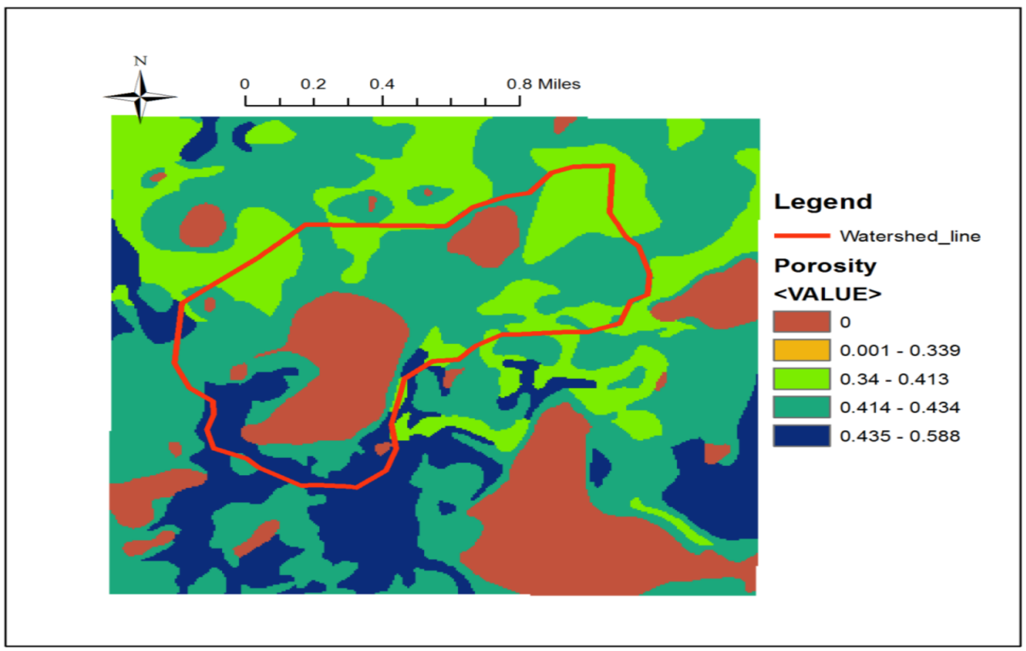
Digital Elevation Model (DEM)



- DEM of the Lake Roberts watershed and its vicinity.
- The low elevations may affect groundwater flow paths as discussed later on.

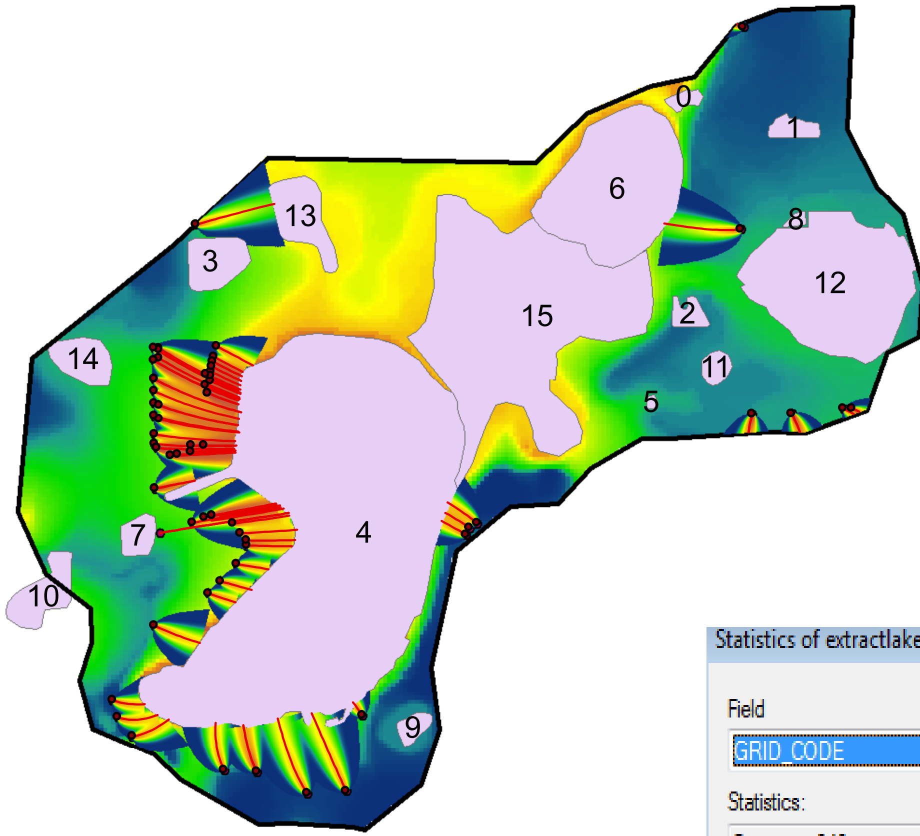
Hydraulic Conductivity and Porosity





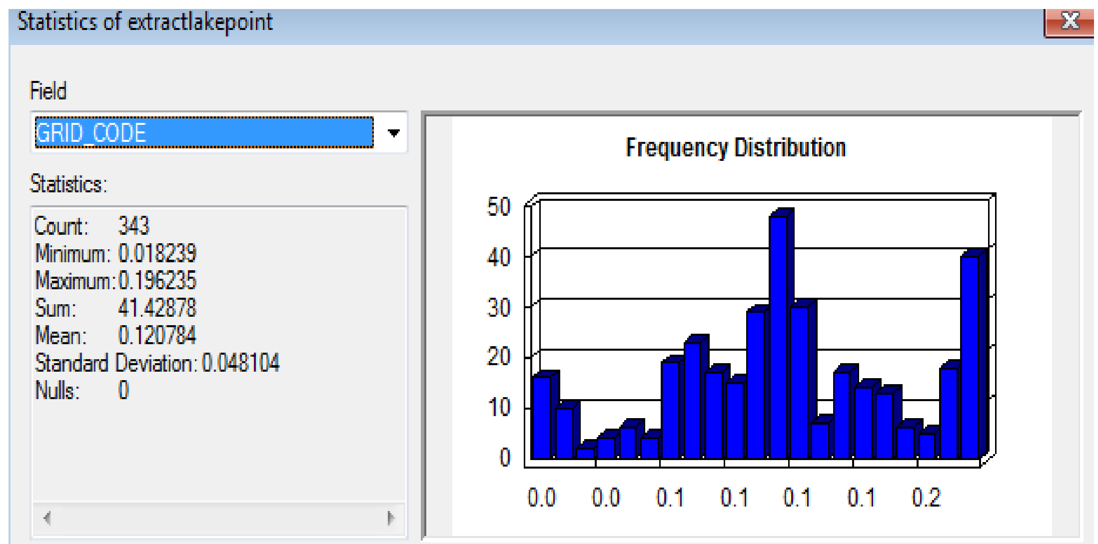
- Hydraulic conductivity and porosity data are processed from the Soil Survey Geographic (SSURGO) database.
- There is a soil zone around the Lake Robert, and its value of hydraulic conductivity is 7.95 m/d.
- This value however will be decreased to match simulated groundwater flow with seepage meter measurments.

Simulation without Model Calibration



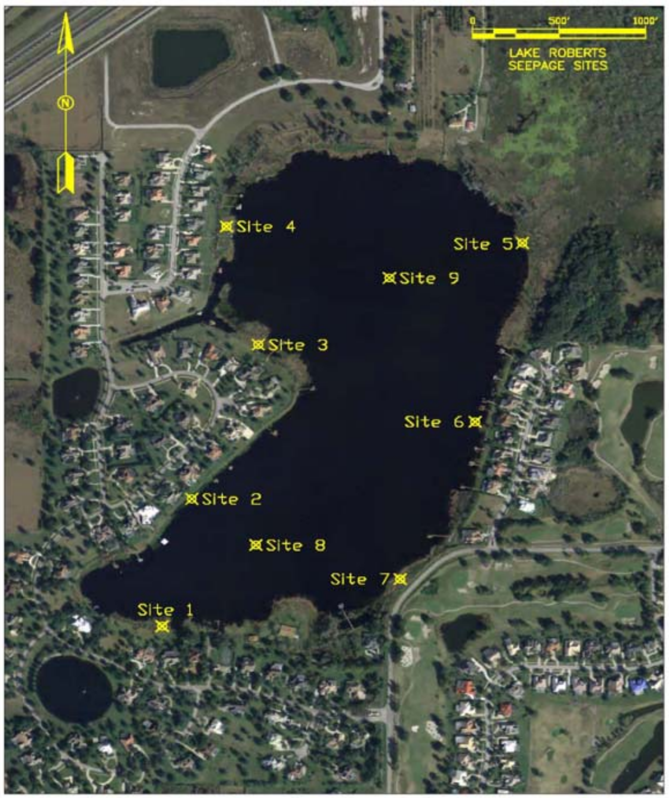
Simulated flow paths and nitrogen plumes

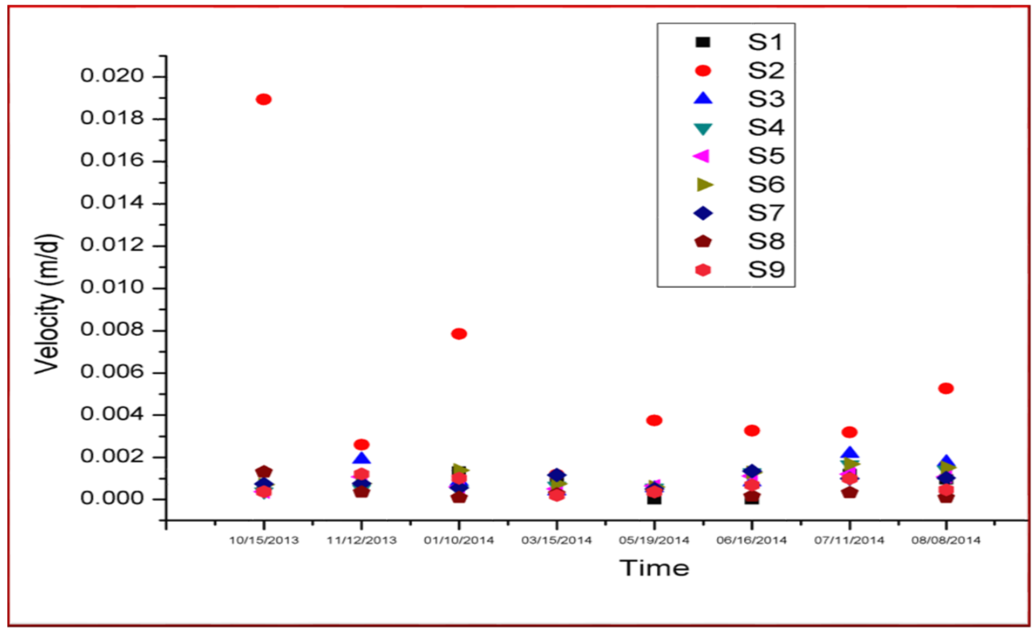
Statistics of simulated groundwater flow (m/d) to the lake



Seepage Measurements

Calibration is needed!

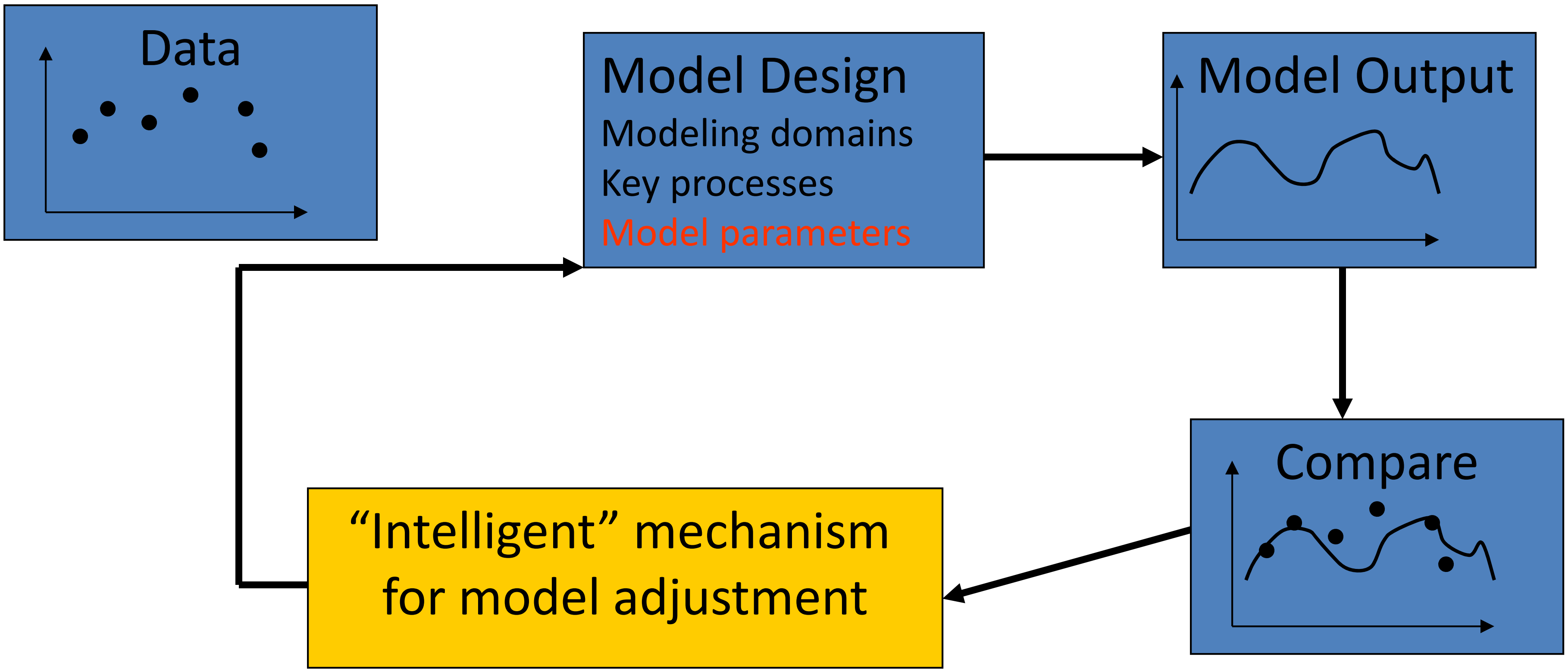




Measured seepage rate: 0.00~0.019 m/d. Most are in the order of magnitude of 0.001 m/d.

Seepage velocities at the 9 measurement sites

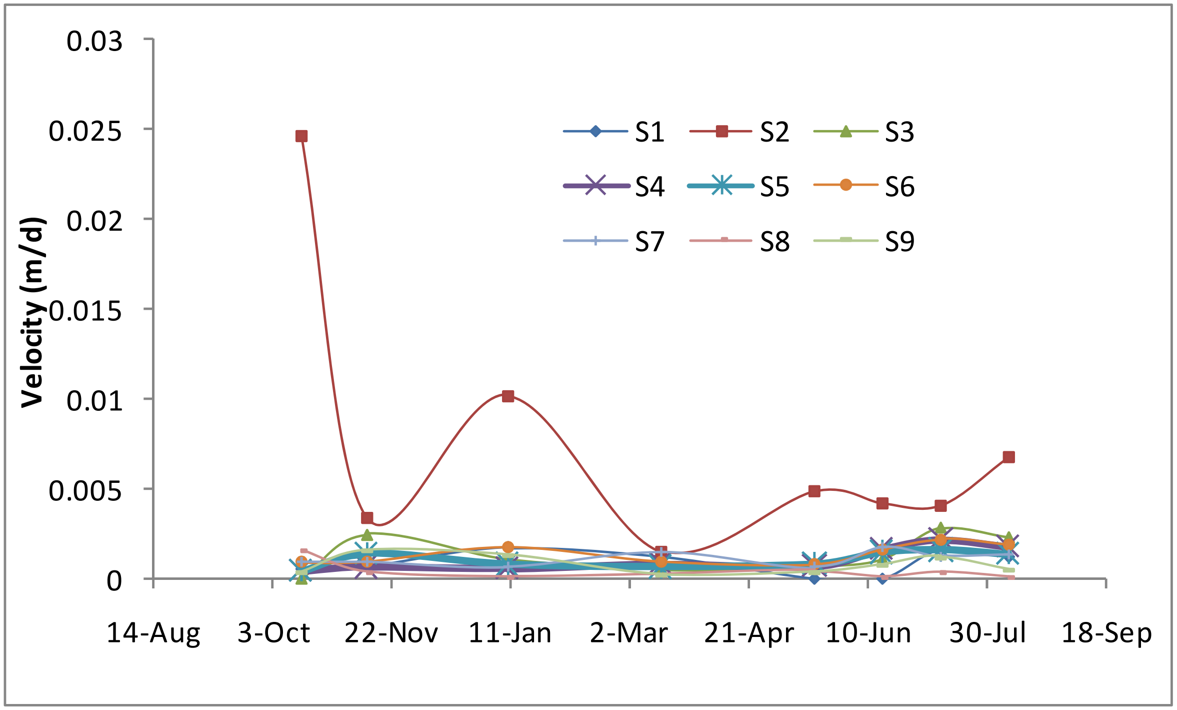
Manual Model Calibration: Trial and Error



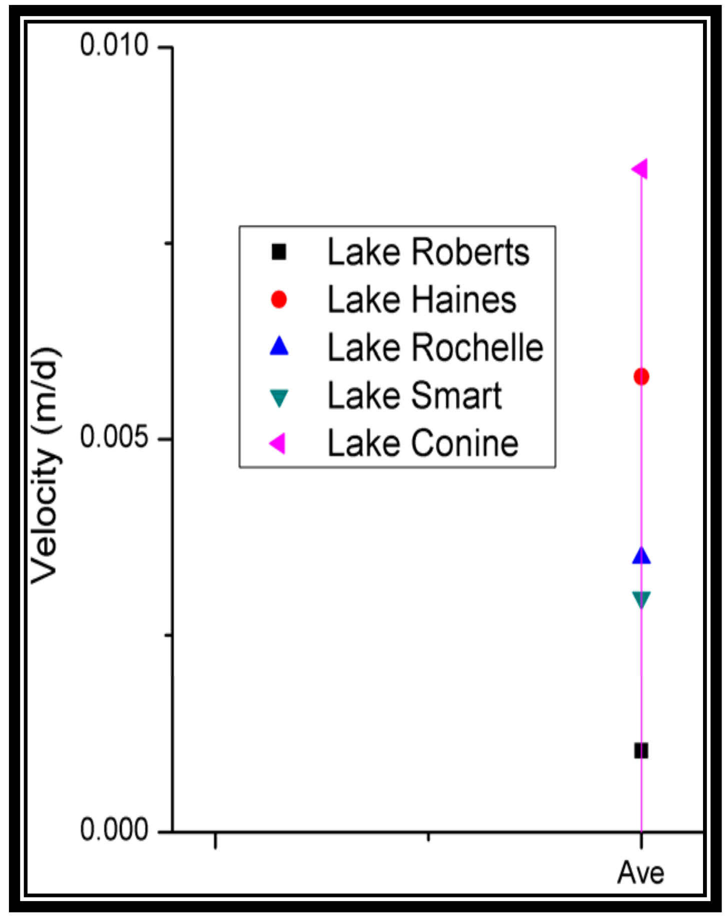
- Hydraulic head
- Nitrogen concentration

Process and Analyze Seepage Measurements

At the Lake Roberts watershed, since the seepage velocity is far less than 0.48 m/d, the measured velocity is corrected by multiplying with the correction factor of 1.3 suggested by Belanger and Montgomery (1992) .



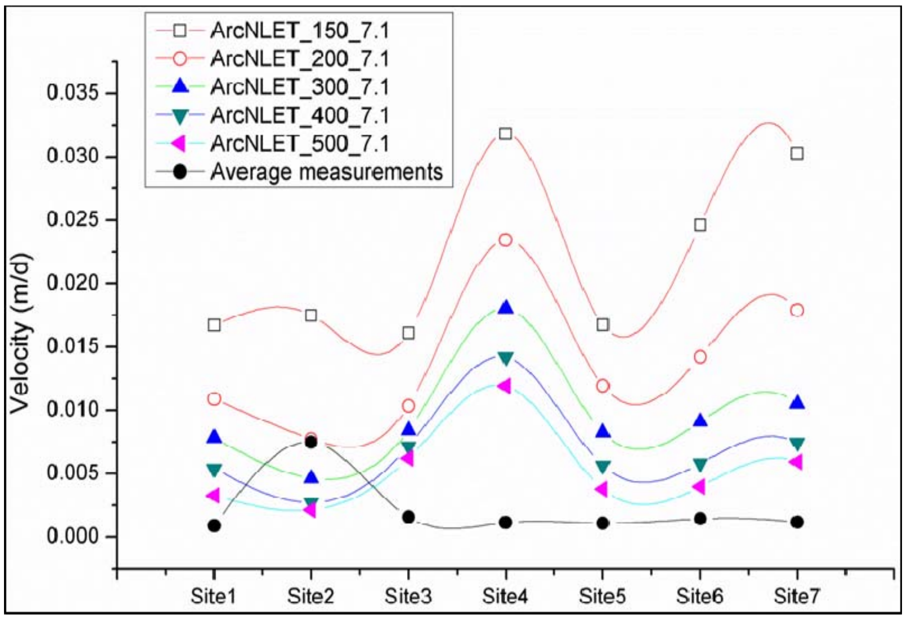
However, the measurements are significantly smaller than those measured in the other four lakes also located in the Orange County.



Model Calibration: Hydraulic Gradient

Model calibration to decrease

- **Hydraulic gradient and**
- **Hydraulic conductivity**



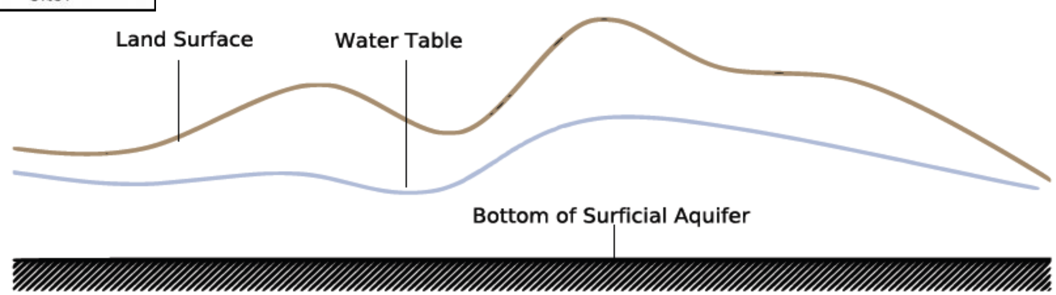
Darcy's law

$$q_x = -K\frac{\partial h}{\partial x} \approx -K\frac{\partial z}{\partial x}$$

$$q_y = -K\frac{\partial h}{\partial y} \approx -K\frac{\partial z}{\partial y}$$

Larger smoothing factor leads to flatter shape of water table and thus smaller hydraulic gradient.

Smoothing Factor



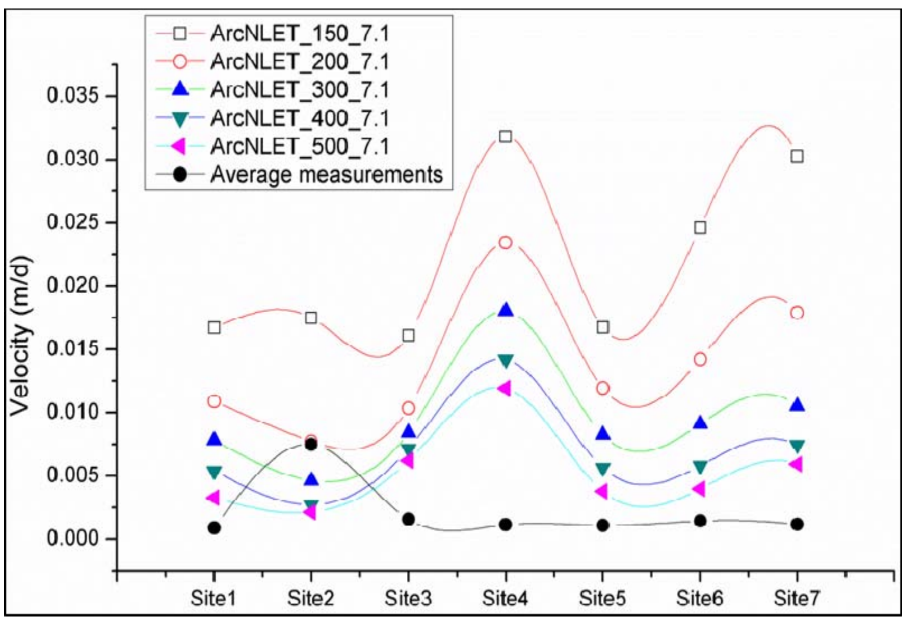
Model Calibration: Hydraulic Conductivity

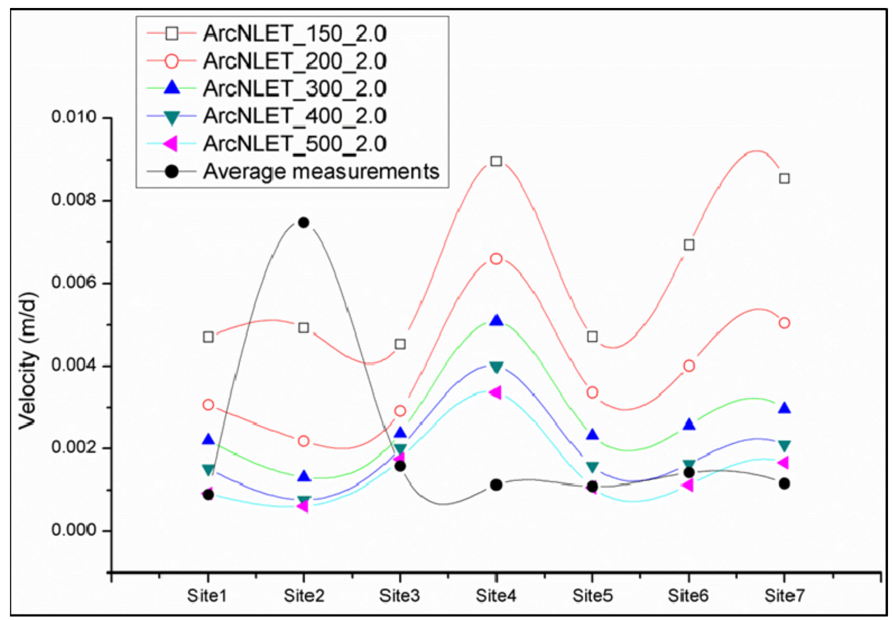
Model calibration to decrease
- **Hydraulic gradient and**
- **Hydraulic conductivity**

Darcy's law

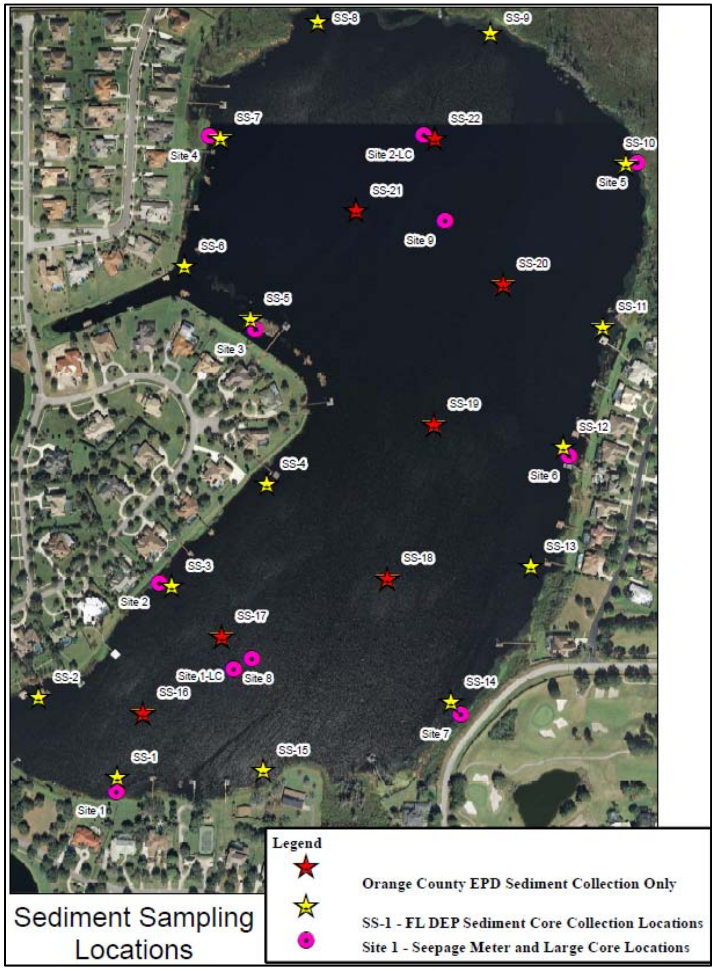
$$q_x = -K \frac{\partial h}{\partial x} \approx -K \frac{\partial z}{\partial x}$$

$$q_y = -K \frac{\partial h}{\partial y} \approx -K \frac{\partial z}{\partial y}$$





Hydraulic Conductivity Based on Soil Samples

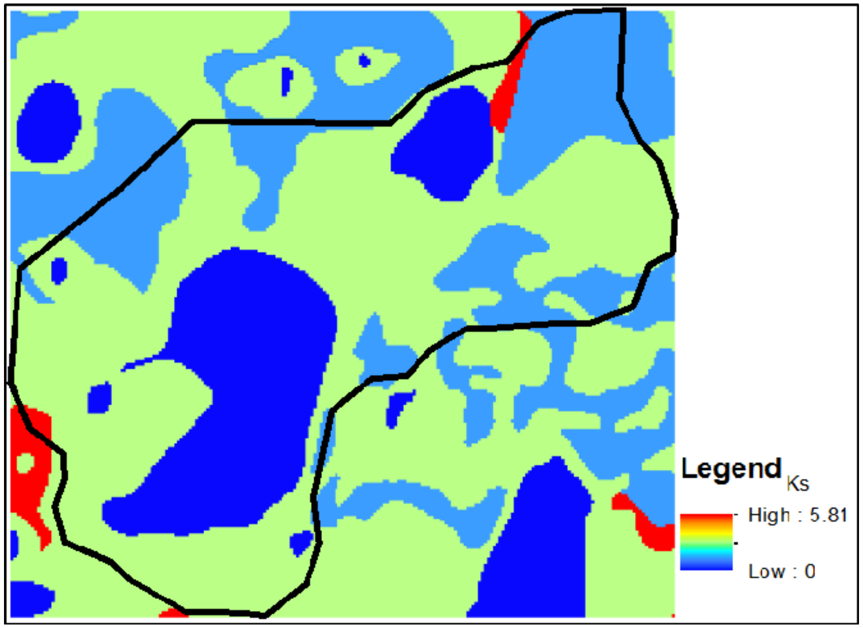


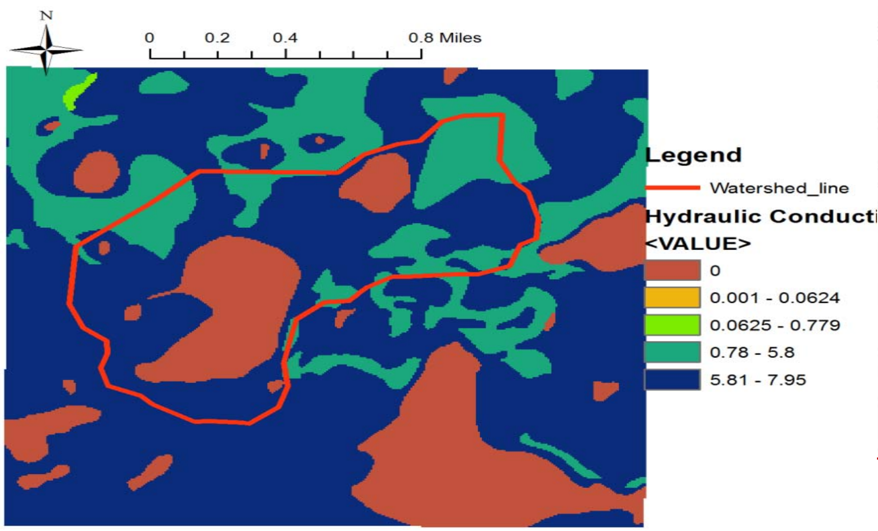
Sediment Sampling Locations

- Fifteen samples (SS-1 – SS-15), four of which (SS-2, SS-7, SS-10, and SS-12) are loamy sand. The rest of samples are sand.
- Literature values

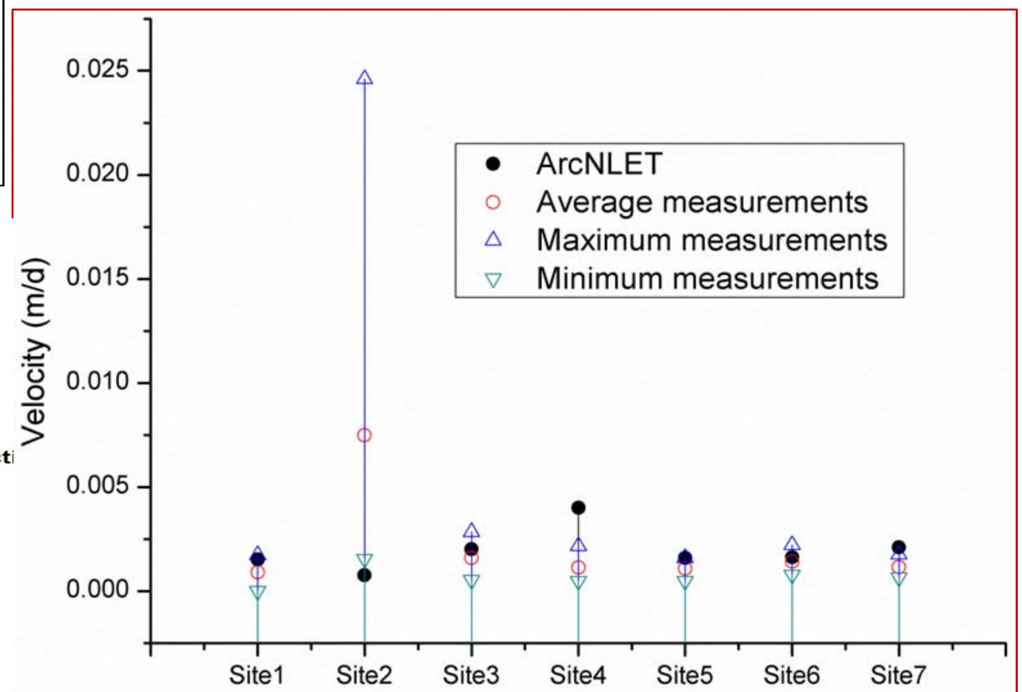
	Loamy Sand		Sand	
	cm/h	m/d	cm/h	m/d
Average	14.59	3.50	29.70	7.13
Min	6.08	1.46	8.34	2.00
Max	44.92	10.78	61.66	14.80

Calibration Results

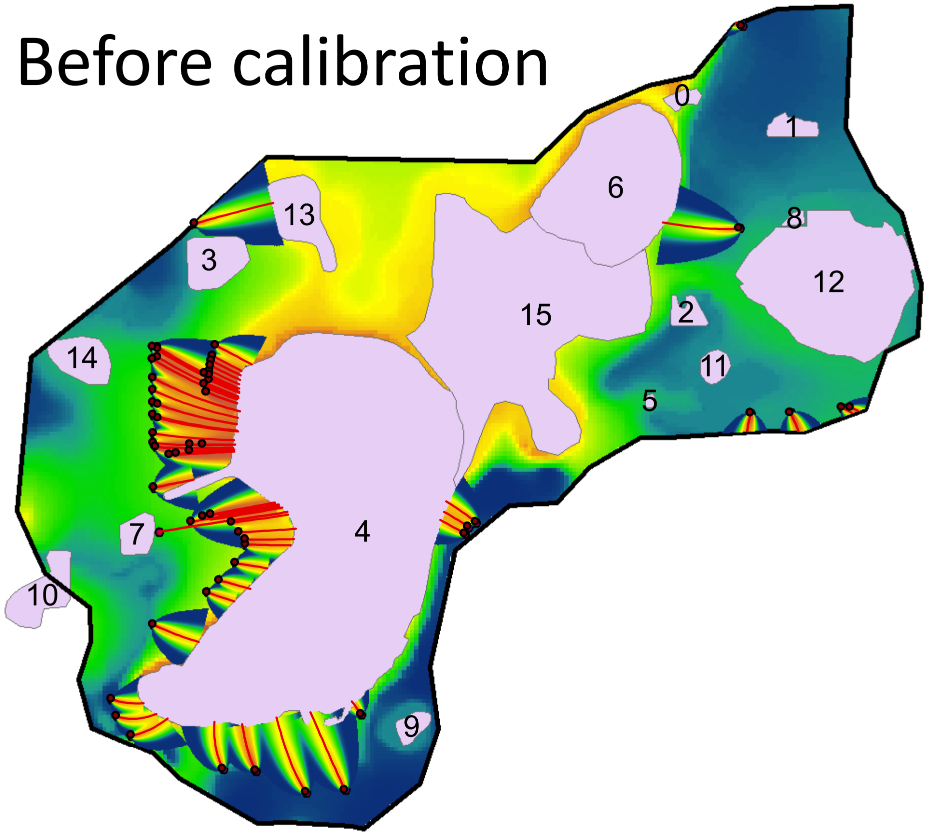


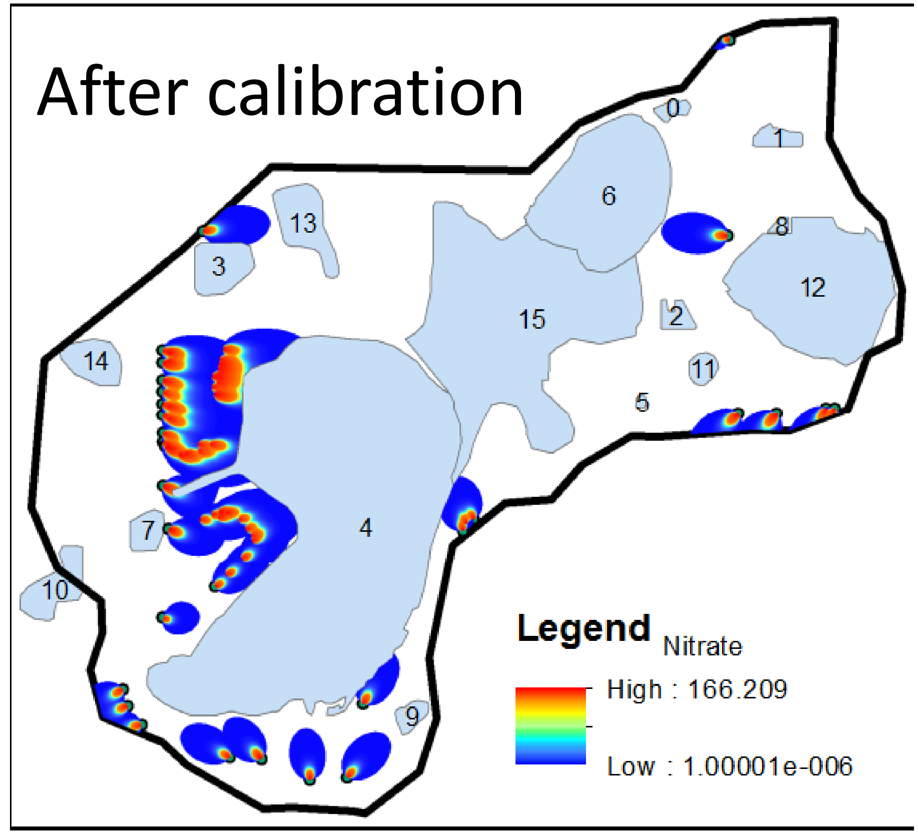


- Smoothing factor = 400
- For the sand zone, use K=2.0 m/d.
- Simulations can reasonably match the observations.



Simulated Plumes



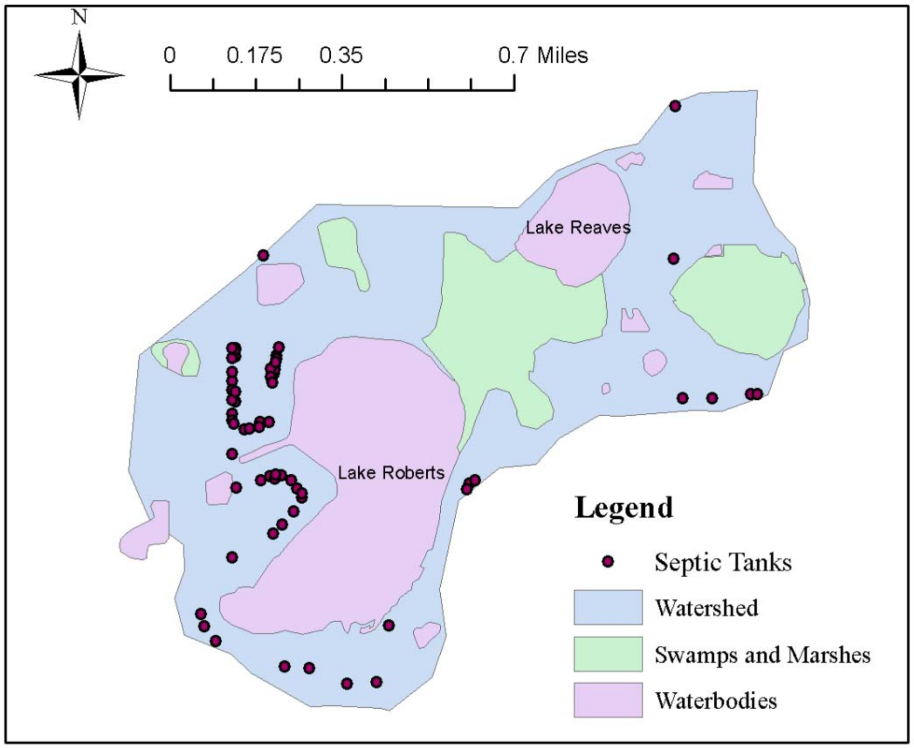


Waterbody FID	Load (lb/yr)	Reduction Ratio (%)
4	1122.84	15.28
6	7.39	62.08
13	7.23	62.92
Sum	1137.458	16.62

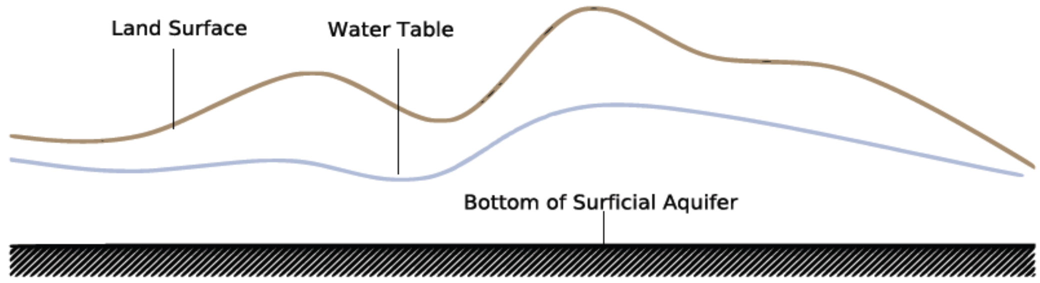
Waterbody FID	Load (lb/yr)	Reduction Ratio (%)
4	711.80	45.49
15	17.65	9.42
sum	729.46	47.28

Discussion: Septic Tank Locations

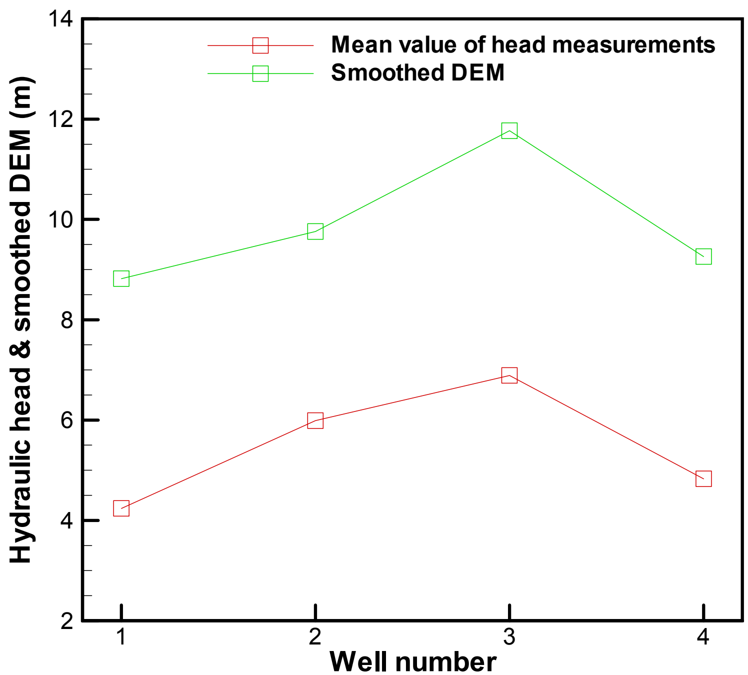
Is the septic tank layer from FDOH current?

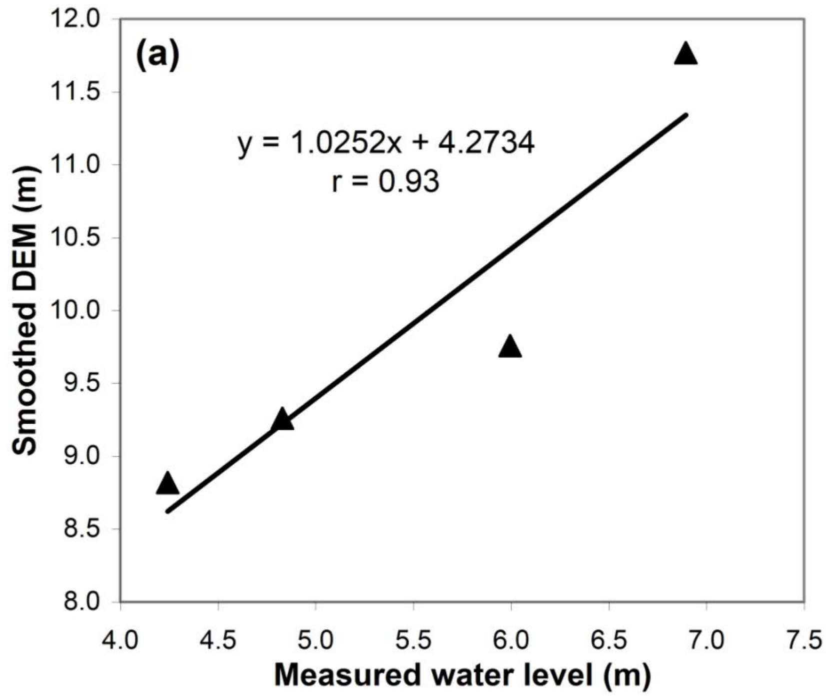


Discussion: Head data are needed



The smoothed DEM agrees well with the mean observed hydraulic head, because the correlation coefficient (0.93) and the slope of linear regression (1.03) are close to one.





Discussion: Why is seepage low?

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
Average	0.00069	0.00576	0.00122	0.00086	0.00083	0.00109	0.00089	0.00037	0.00066
Average/ Min	---	5	3	2	2	2	2	4	4
Max/Min	---	16	5	4	3	3	3	14	7

- Average values and the ratios of average/min and max/min for Lake Roberts (top table) and four other lakes (right table)
- The variability is significantly smaller for Lake Roberts.

Lake	Site	Average	Max/Min	Average/Min
Haines	LH-ES	0.00368	77	37
	LH-NS	0.00235	21	6
	LH-WS	0.00735	4	2
	LH-WD	0.00254	74	12
Rochelle	LR-WS	0.00234	74	23
	LR-SS	0.00403	113	29
	LR-NS	0.00168	26	13
	LR-ND	0.00257	146	37
Smart	LS-NS	0.00191	482	191
	LS-WS	0.00161	119	54
	LS-SS	0.00335	9	3
	LS-SD	0.00126	27	10
Conine	LC-SS	0.01666	56	29
	LC-NS	0.00131	55	19
	LC-ES	0.00153	119	38
	LC-ED	0.00233	44	15

Discussion: Nitrogen concentration in groundwater

High total nitrogen concentration in the lake water.

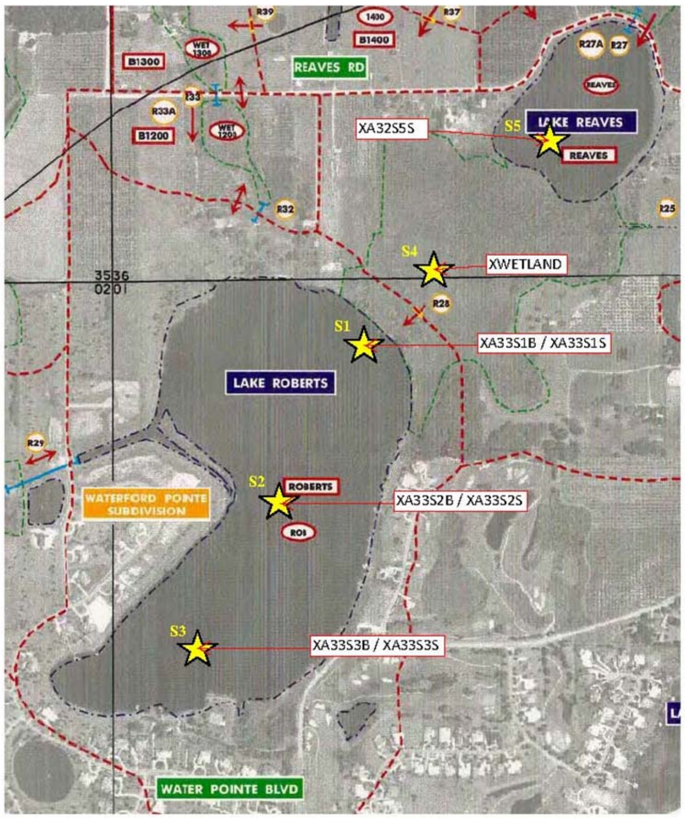
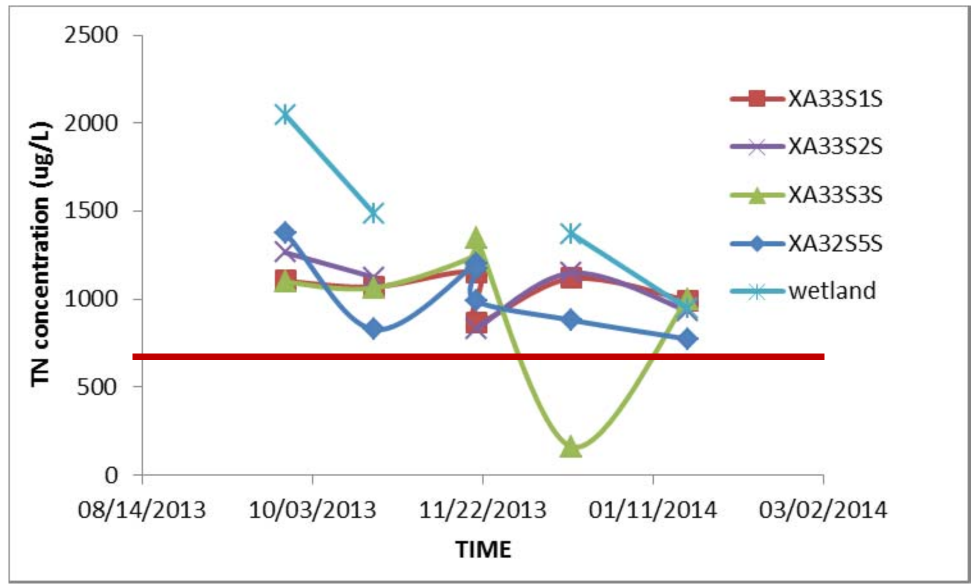


Figure 1: Surface Water Sampling Points

★ Surface Water Sampling Site, S2 is the Site that Orange County EPD also samples
S4 = Marsh Sample Site
S5 = Lake Reaves Sample Site

Lake Roberts and the locations of the 5 surface water samples



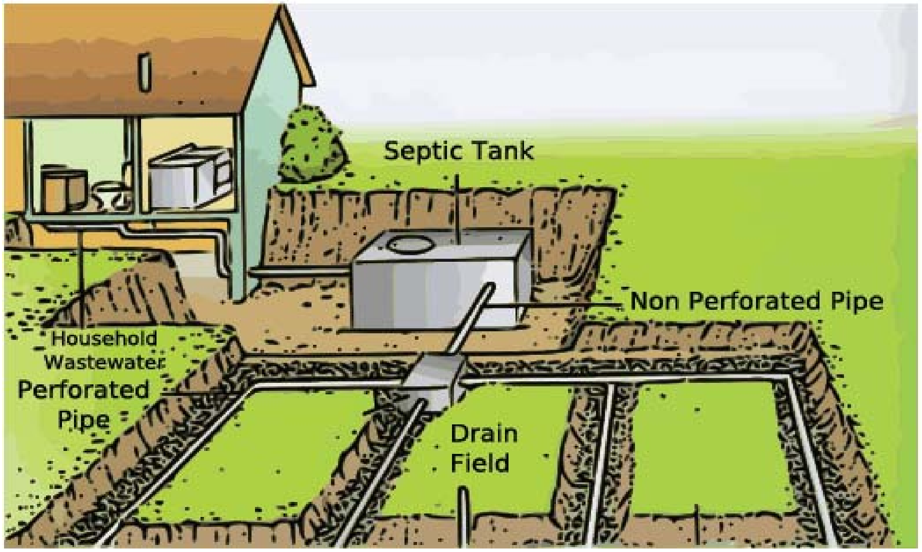
TN concentration of surface water.

Most exceed the EPA Ecoregion recommended criteria of 0.661 mg/L.

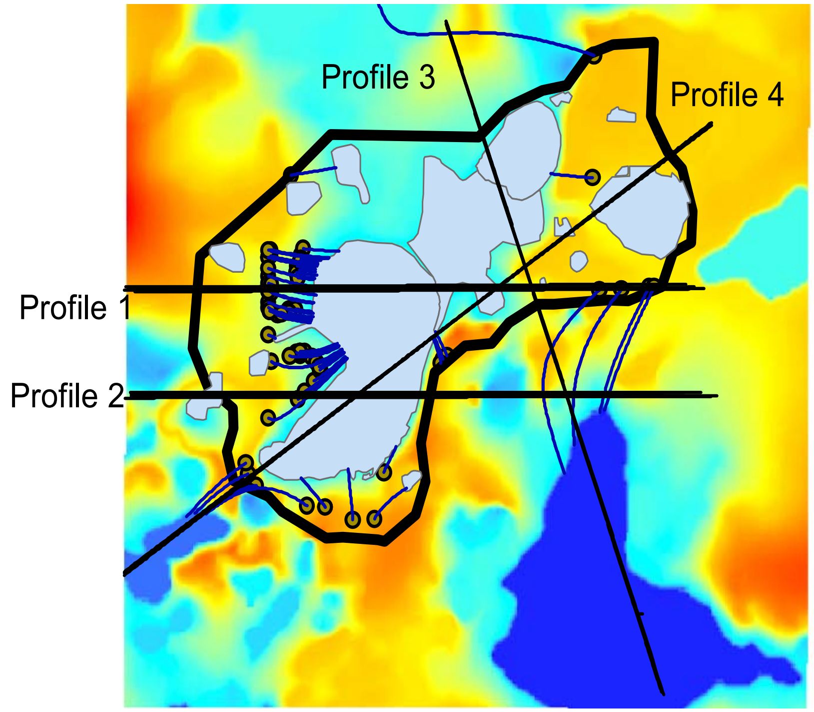
Conclusions

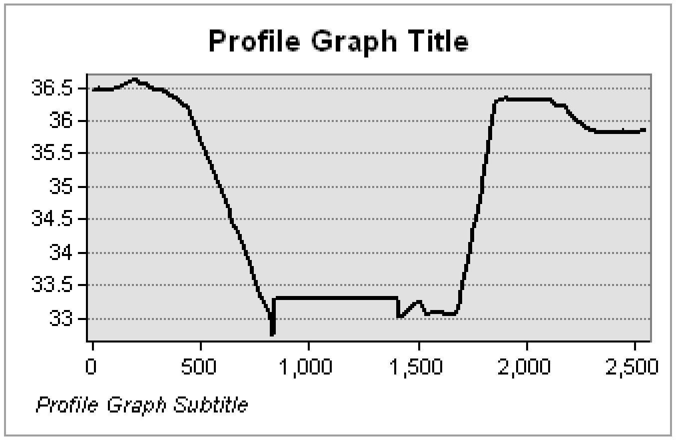
- ArcNLET has been developed as a numerical model and software for nitrogen load estimation.
- The software has been used for Lake Roberts.
- After model calibration, model simulations can reasonably match field observations of seepage rate.
- More data may be needed to improve understanding of nitrogen transport in surficial aquifers.

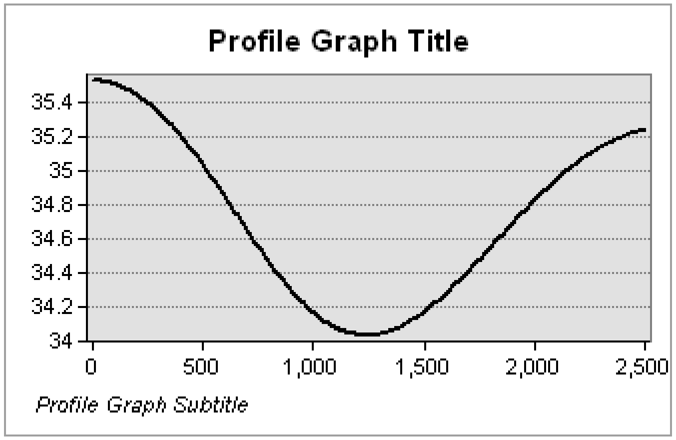
Questions, Suggestions, and Comments?



Profile 1







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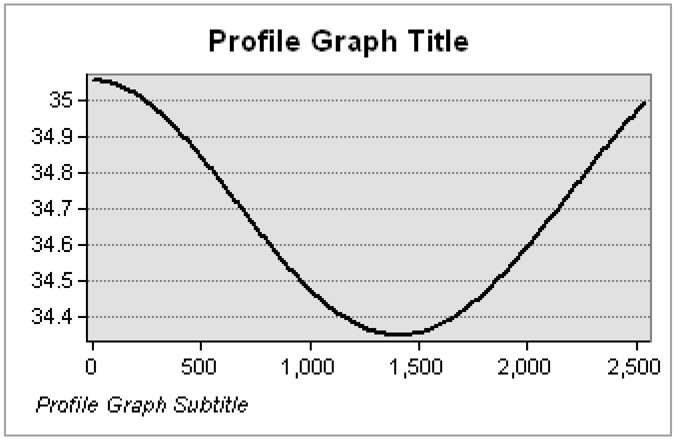

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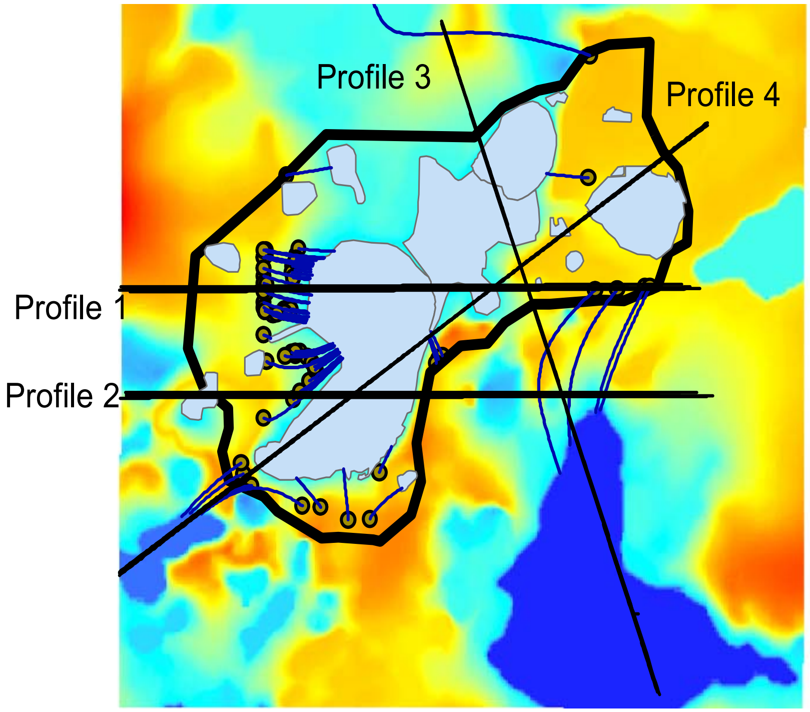
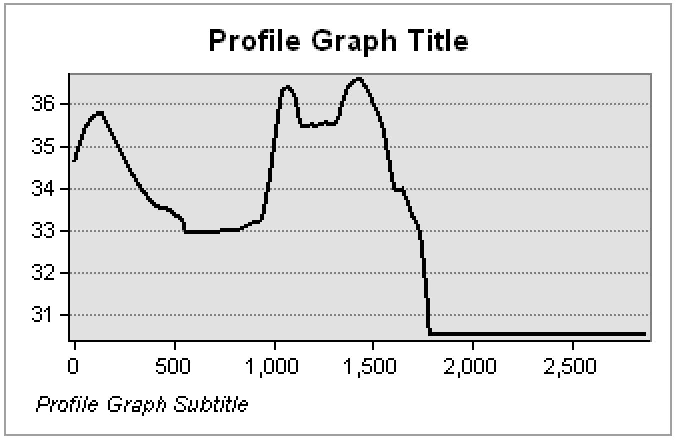
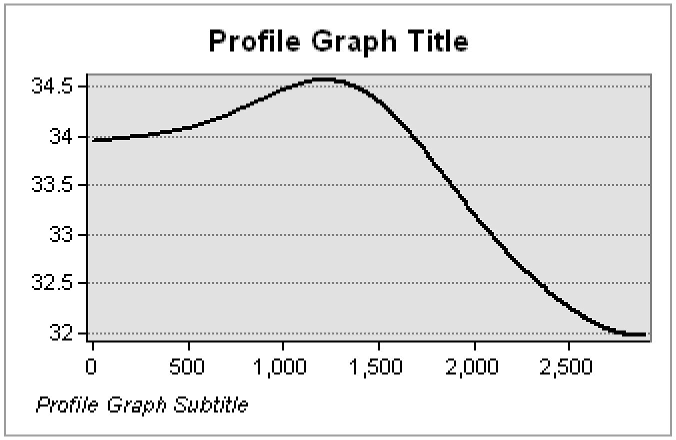
Profile 3







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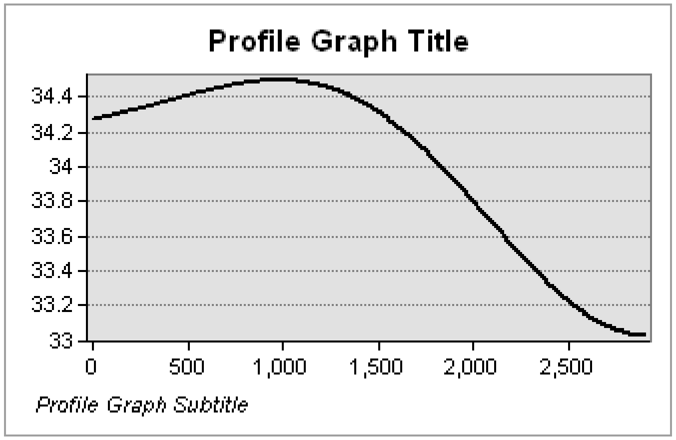

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