ArcGIS-Based Nitrate Load Estimation Toolkit (ArcNLET) for Estimation of Nitrogen Load from Septic Systems to Surface Water Bodies: Models, Softwares, Applications, and Perspectives

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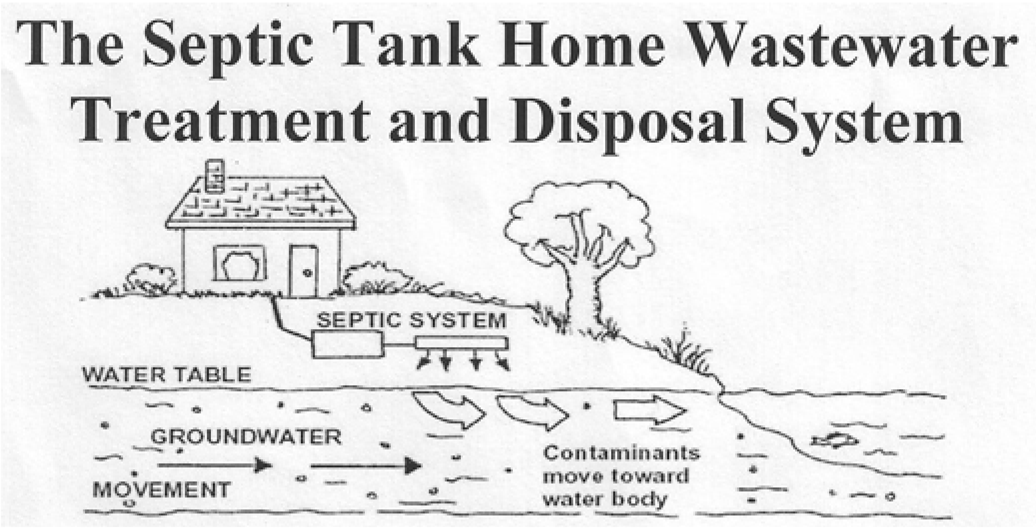
Outlines

- Introduction of ArcNLET
  - Rational of developing ArcNLET
  - Functions of ArcNLET and associated software
  - Data requirements of using ArcNLET
- ArcNLET modeling for the City of Port St. Lucie, the City of Stuart, and Martin County
- On-going ArcNLET modeling for IRC
- Suggestions and comments

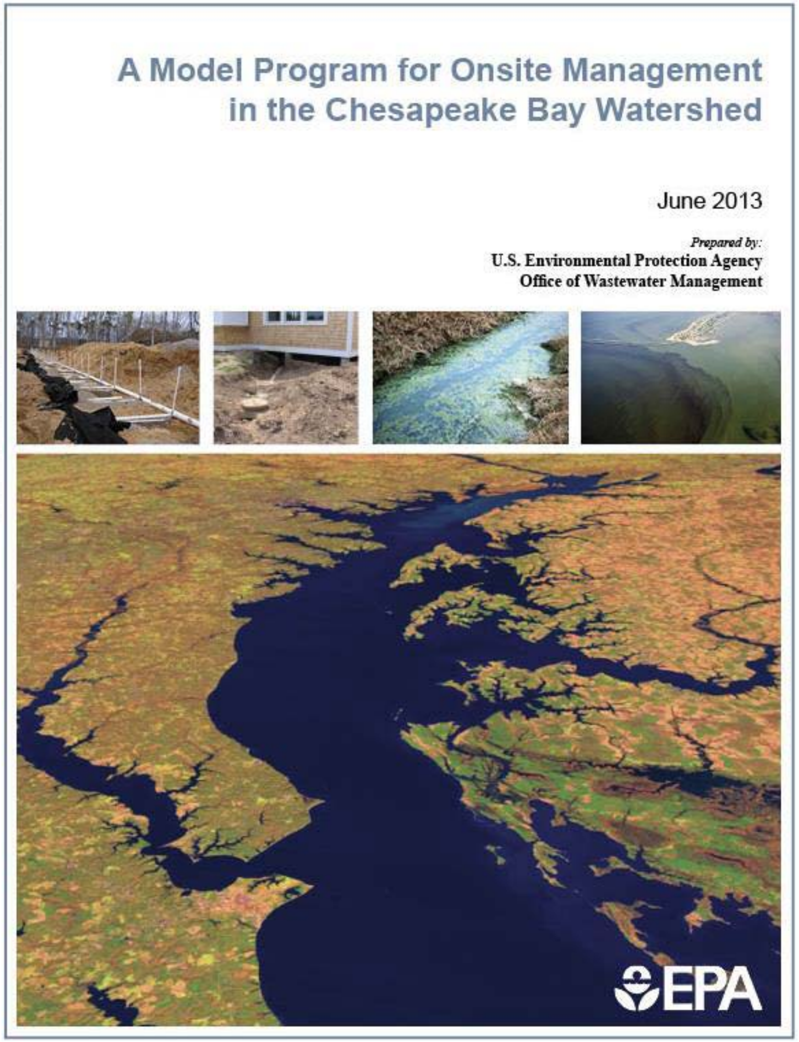
ArcNLET Project Team

- 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:
  - Yan Zhu (2014-present)
  - Huaiwei Sun (2012-2013)
  - Liying Wang (2010-2012)

Septic Systems and Nitrogen Loads

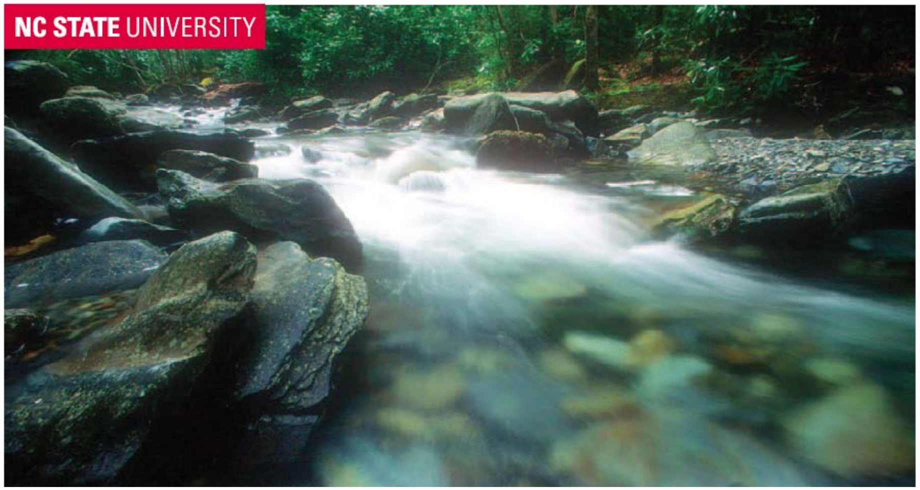


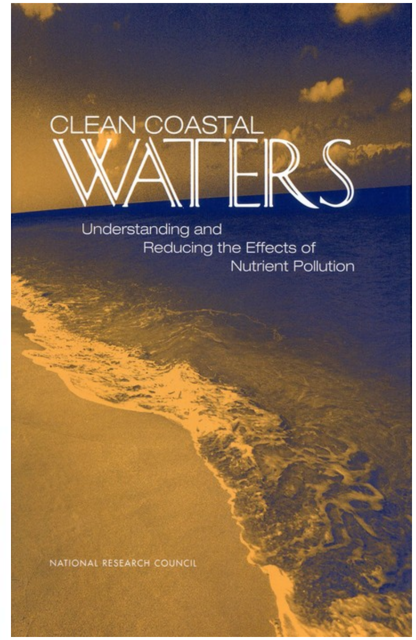
- Septic systems contribute approximated 8.3 million pounds to the Bay, about 5% of the total nitrogen load (USEPA, 2013).
- While this is not the largest source of nitrogen pollution to the Bay, it is important to reduce the load from septic systems in the effort to improve water quality.
- Given the trends in population growth, nitrogen loads from septic systems are expected to increase.
- Sustainable decision-making and management of nitrogen pollution due to septic systems are urgently needed.



Potential Nitrogen Contributions
from On-site Wastewater Treatment Systems
to North Carolina's River Basins and Sub-basins

North Carolina Agricultural Research Service (2007)

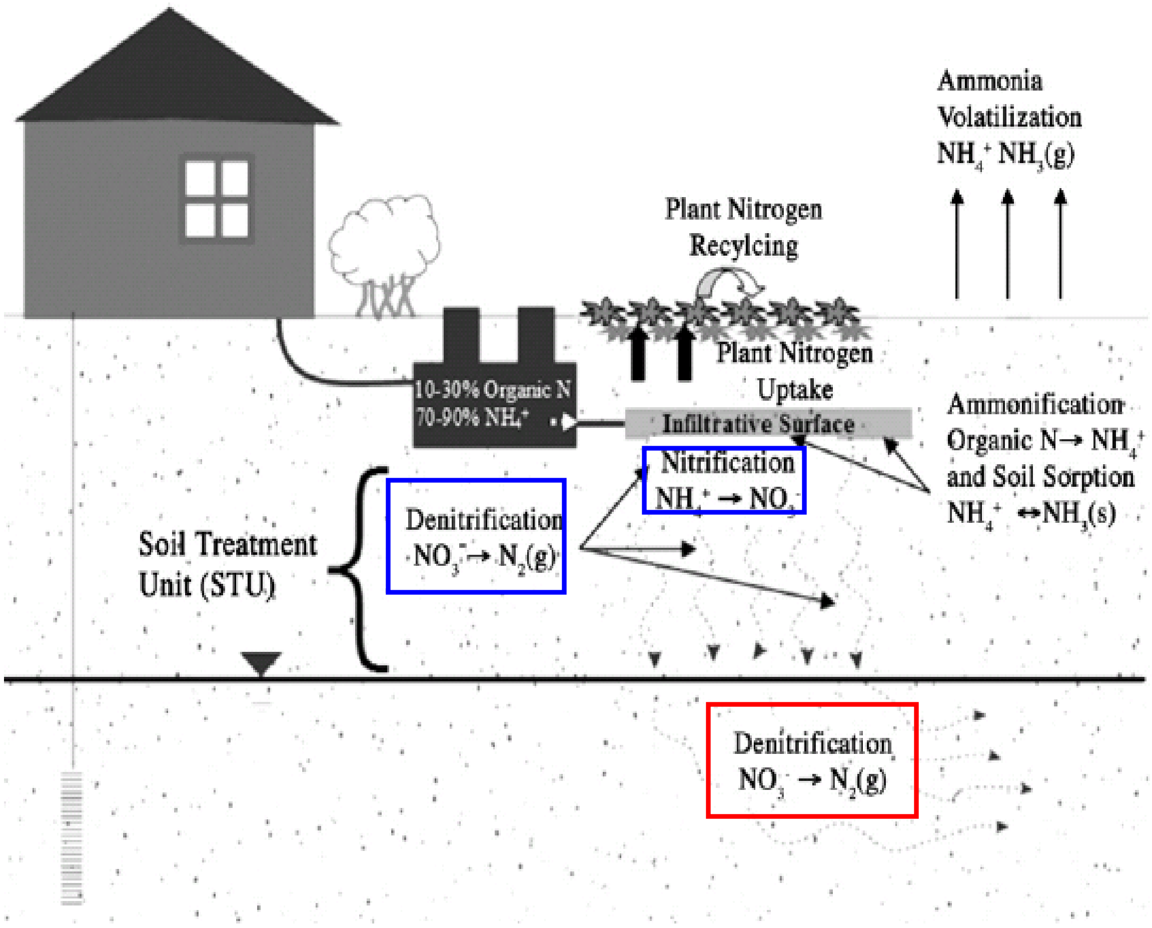




Recommendation: Improve models so they are more useful to coastal managers (National Research Council, 2000).

- "Little is known, however, about the extent of nitrogen (N) loadings to soils from on-site wastewater treatment systems in North Carolina."
- "As a result, existing models and nutrient management plans for the state's watersheds, such as the Neuse River basin wide nutrient reduction plan developed by the N.C. Department of Environment and Natural Resources (N.C. DENR, 1997), have typically ignored these potential inputs."

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

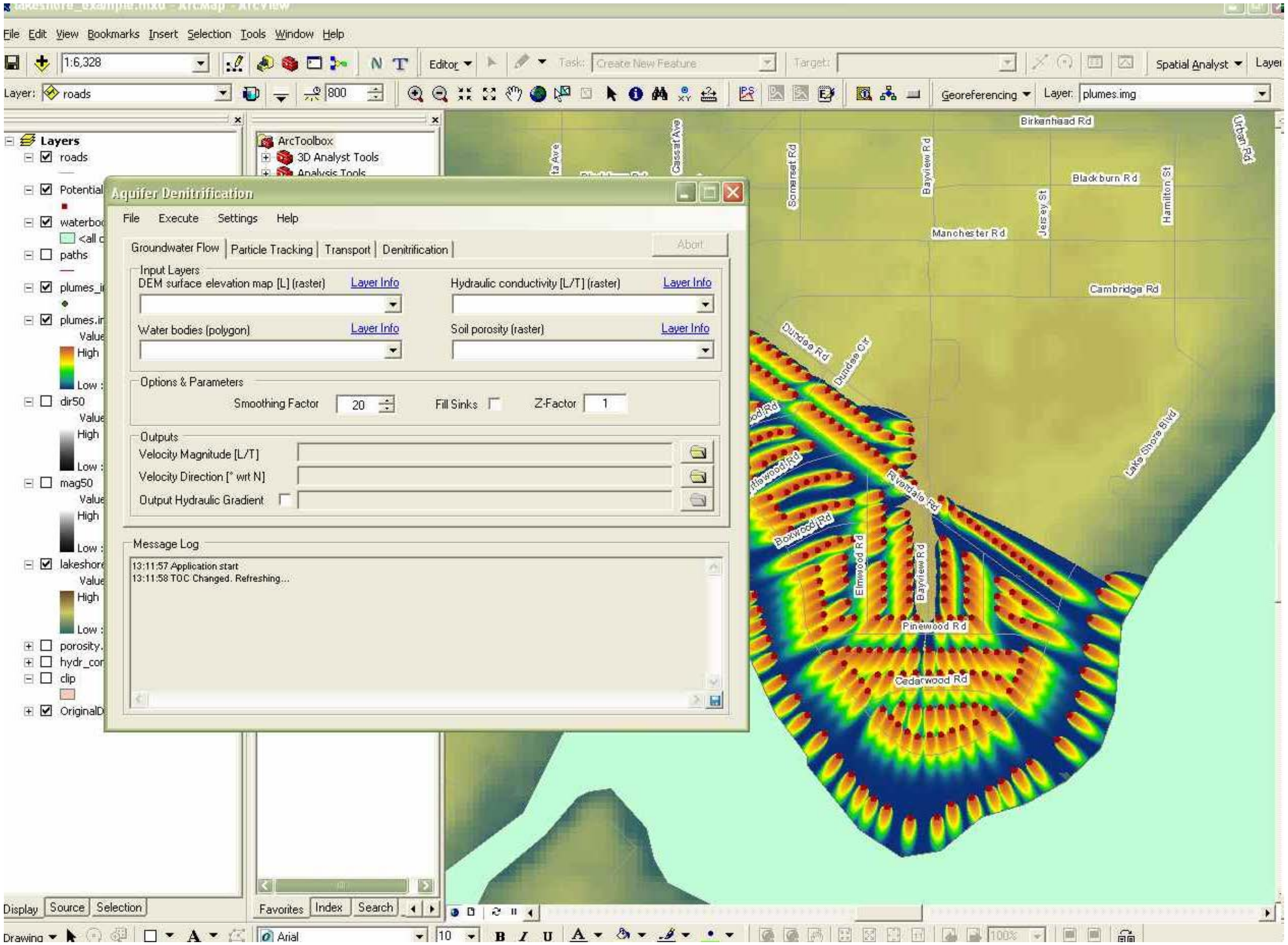
Why Developing ArcNLET?

- 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.

What is ArcNLET?

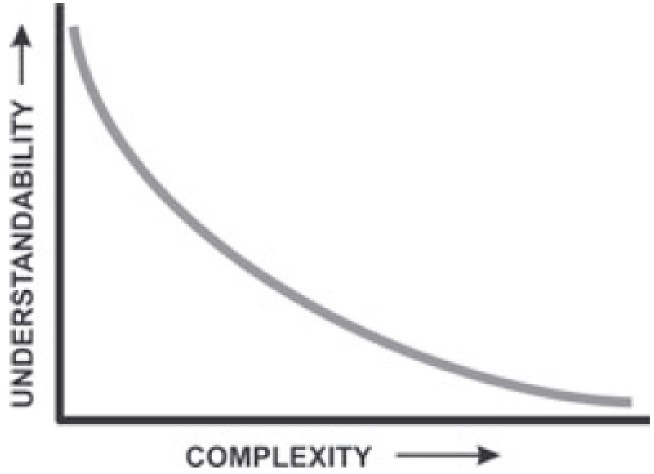
ArcGIS-based Nitrate Load Estimation Toolkit

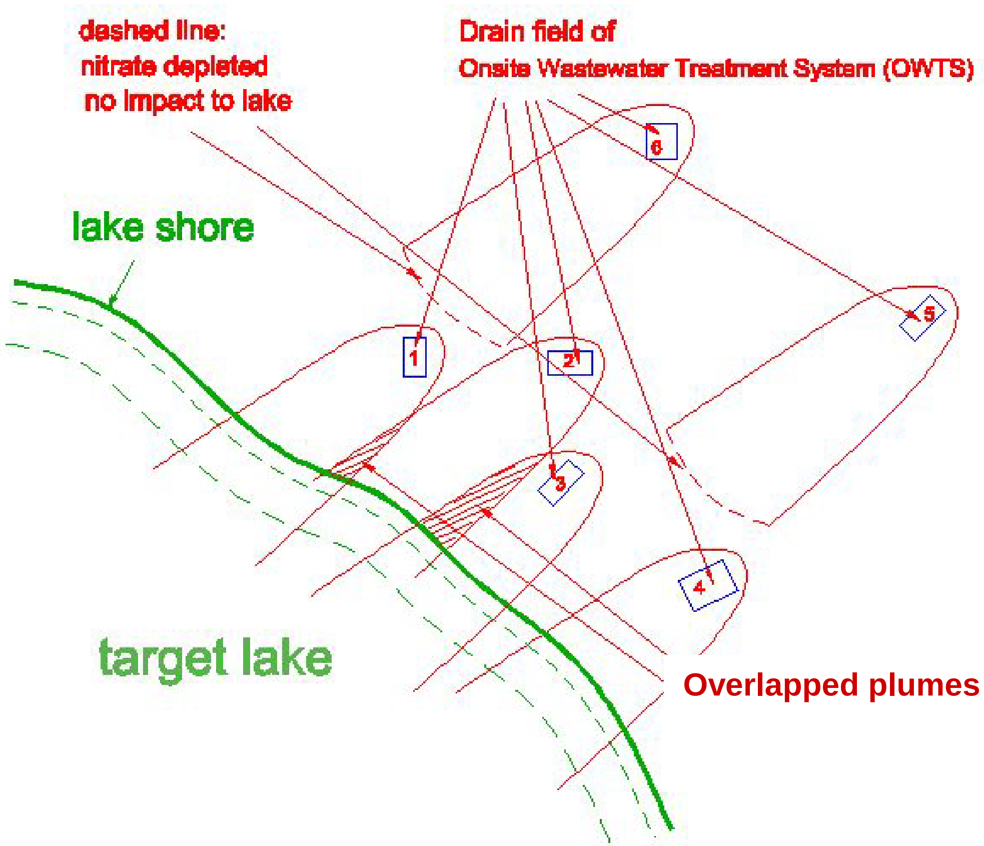
- A simplified conceptual model of groundwater flow and solute transport
- Implementation as an ArcGIS extension
- Calculation of nitrate plume and nitrate load



Compatible with ArcGIS 9.3, 10.0, and 10.1

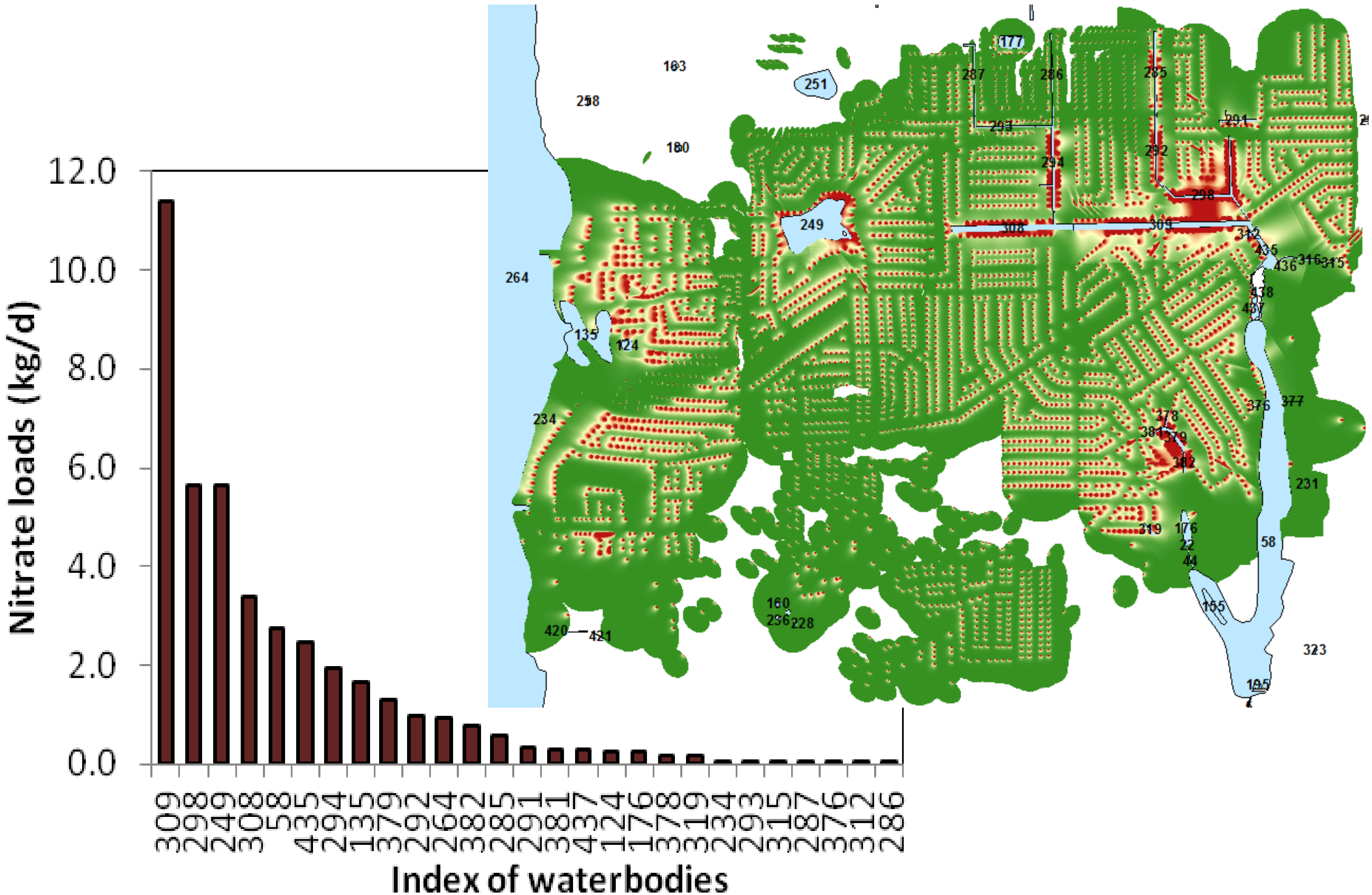
Simplified Conceptual Model to consider key hydrogeologic processes involved in nitrate transport:





- ***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

Illustration of simulated nitrate plumes and nitrate load

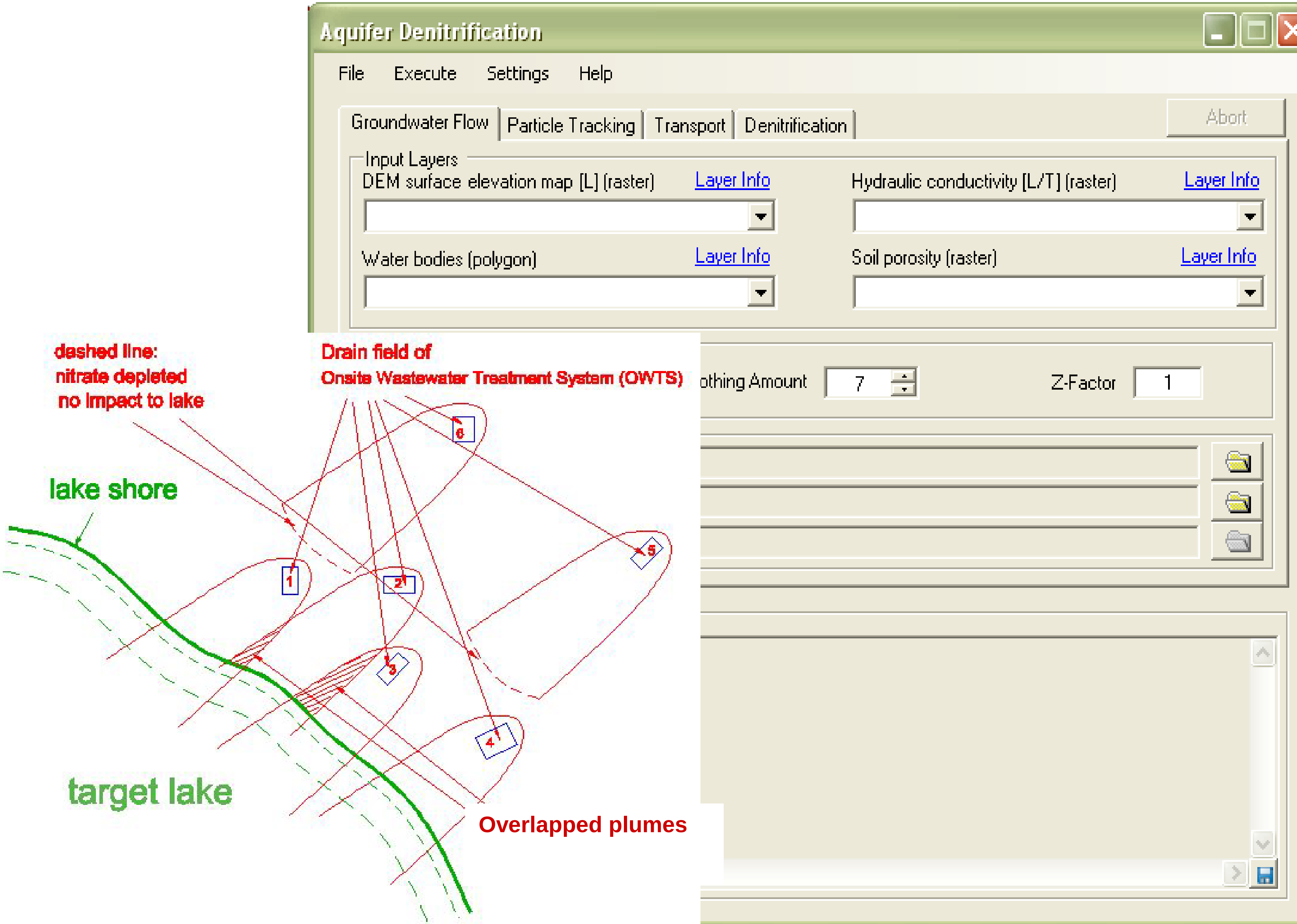


Software Download and References

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

  - Ye, M., J.F. Rios, and L. Shi (2014), A new ArcGIS-based software of uncertainty analysis for nitrate load estimation, *Ground Water*, Software Spotlight, Accepted.
  - 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.

ArcNLET Functions: Graphic User Interface



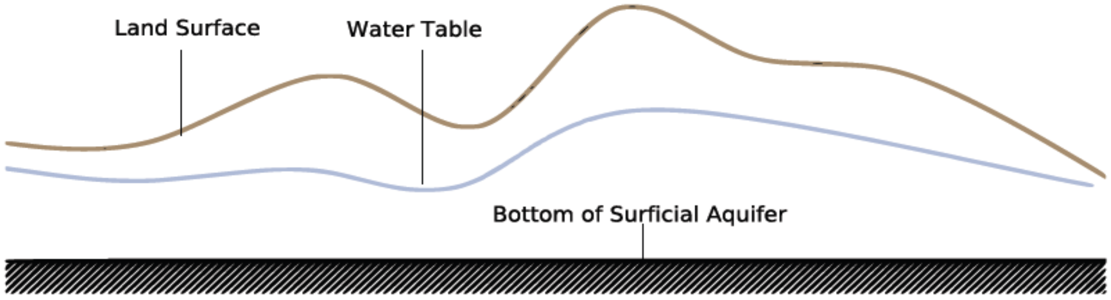
Simplifications and Limitations in Groundwater Flow Modeling

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

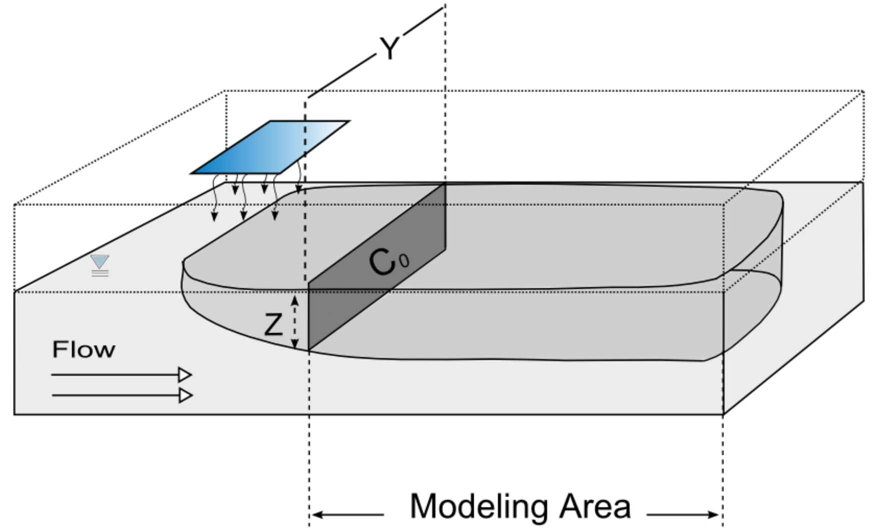
Limitations:

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

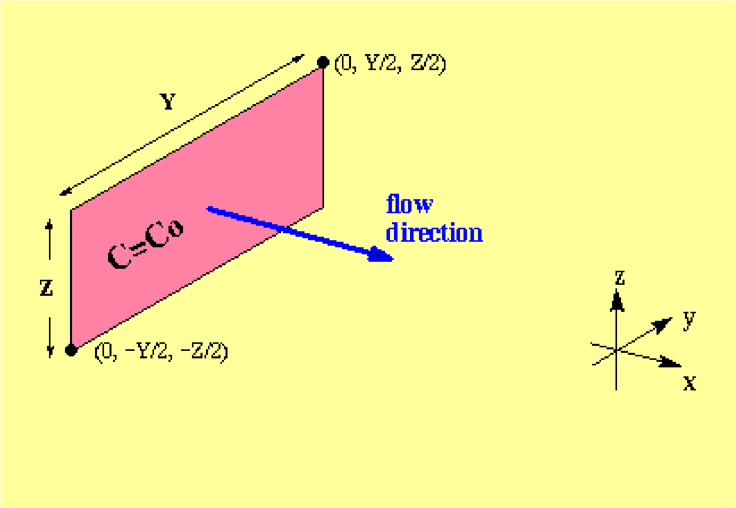


Simplifications and Limitations in Nitrate Transport Modeling

EPA BIOCHLOR model



Domenico analytical solution



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

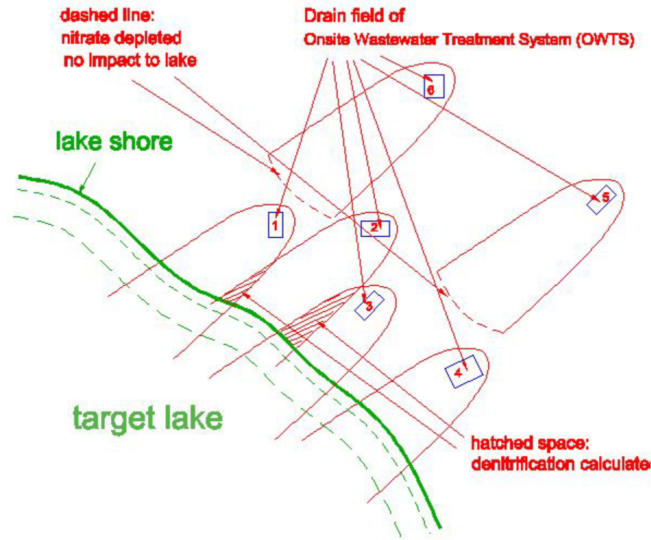
Dispersion Advection Decay Denitrification

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

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

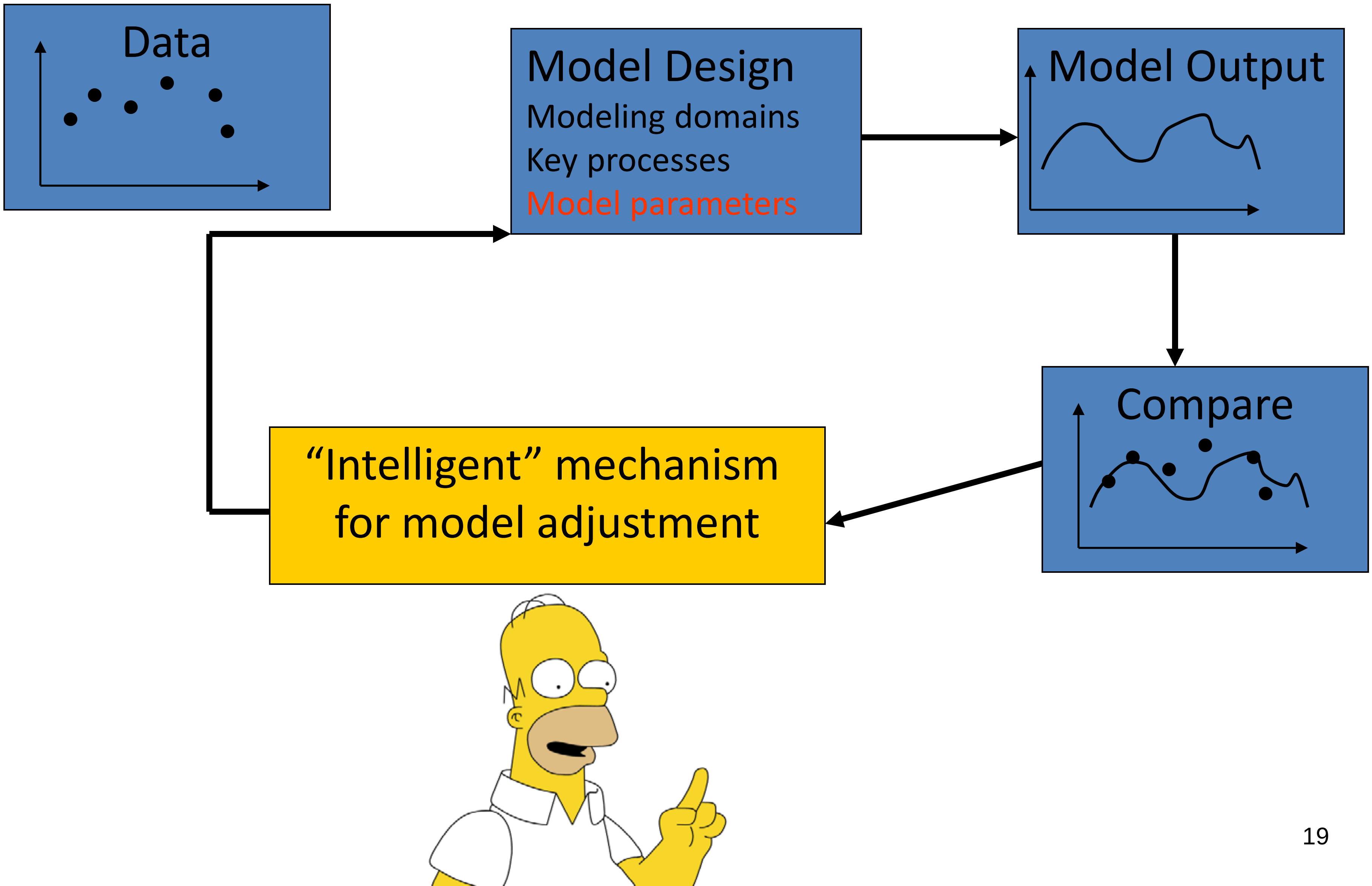
Requirements on Potential Users

- The GUI make it easier for some with little experience in analyzing groundwater transport problems to apply a solute-transport model to a field problem.
- **Users of ArcNLET need to have**
  - Basic knowledge of hydrogeology such as concepts of groundwater flow and solute transport
  - Intermediate level of ArcGIS skills for preparing input files and visualizing software output files
- A model (simple or complex) is not an end in itself, but a tool to organize one's thinking and engineering judgment.
- **Interpretation and improvement of ArcNLET results require**
  - Fundamental understanding of groundwater flow and solute transport
  - Familiarity with site-specific information such as geology and hydrogeology
- It may be useful to test and tune the model for several representative sites to find representative parameter values and use them for prediction.

Model Calibration

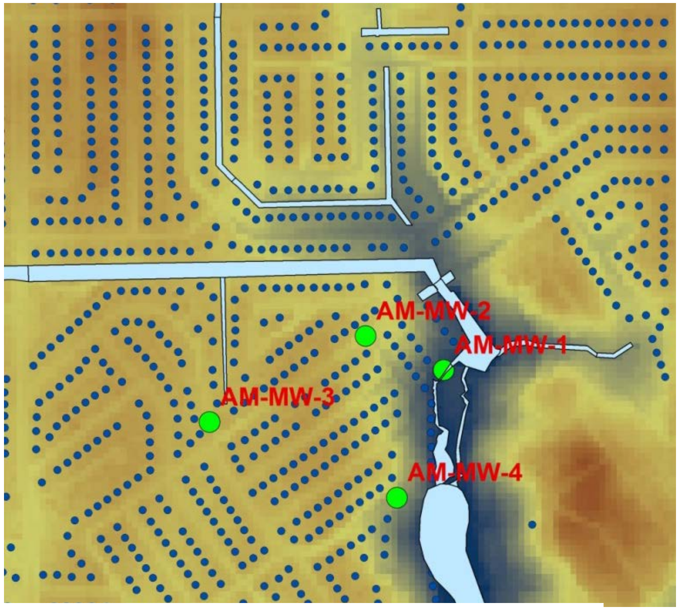
- The ArcNLET model requires several model parameters that are largely unknown, which is common in groundwater modeling.
- The parameter values may be obtained from literature review, but the values are not site-specific.
- A better way to determine site-specific parameter values is model calibration to adjust the parameter values to match model simulations to site observations of system state variables such as hydraulic head and nitrate concentration.

Manual Model Calibration: Trial and Error

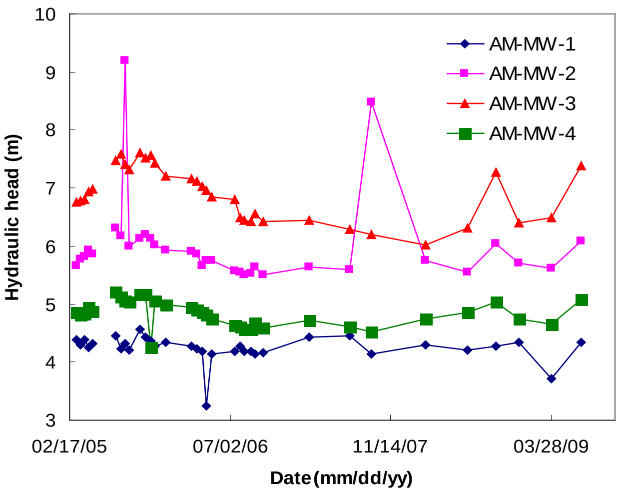


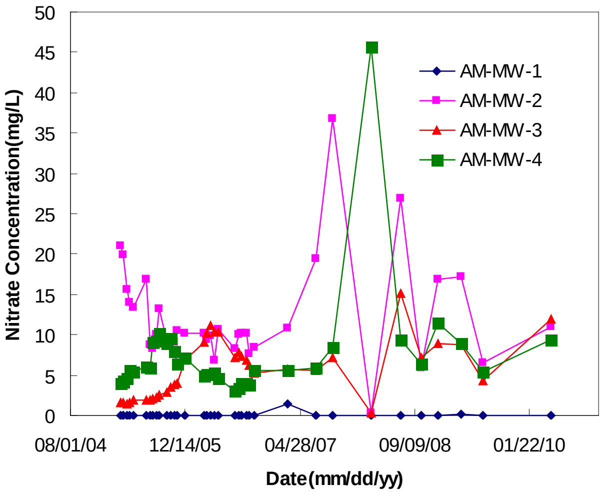
Example Model Calibration

Eggleston Heights with 3,500 OSTDS



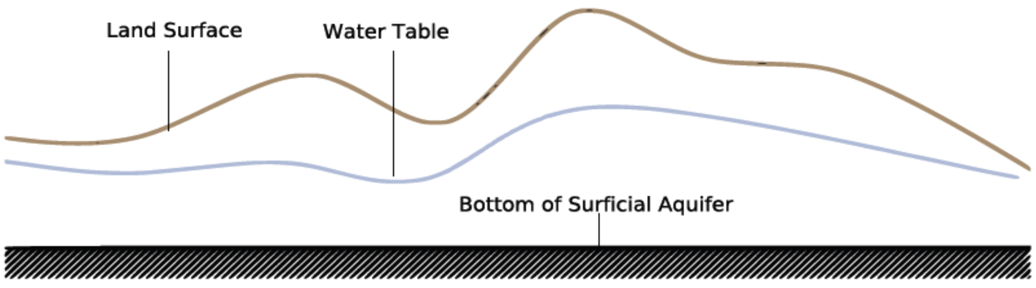
- Two neighborhoods in the City of Jacksonville:
  - Eggleston Height
  - Julington Creek
- Relatively large amount of observations of hydraulic head and nitrate concentrations are available.



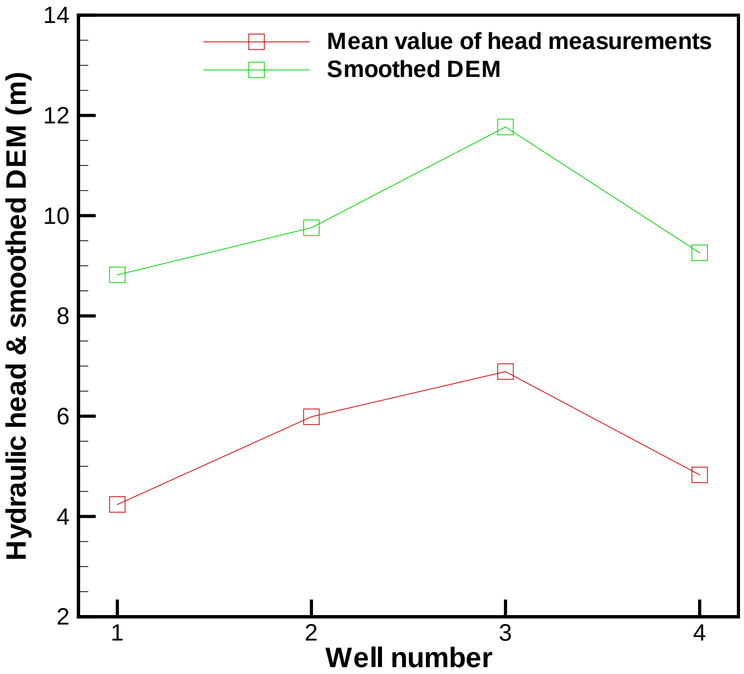


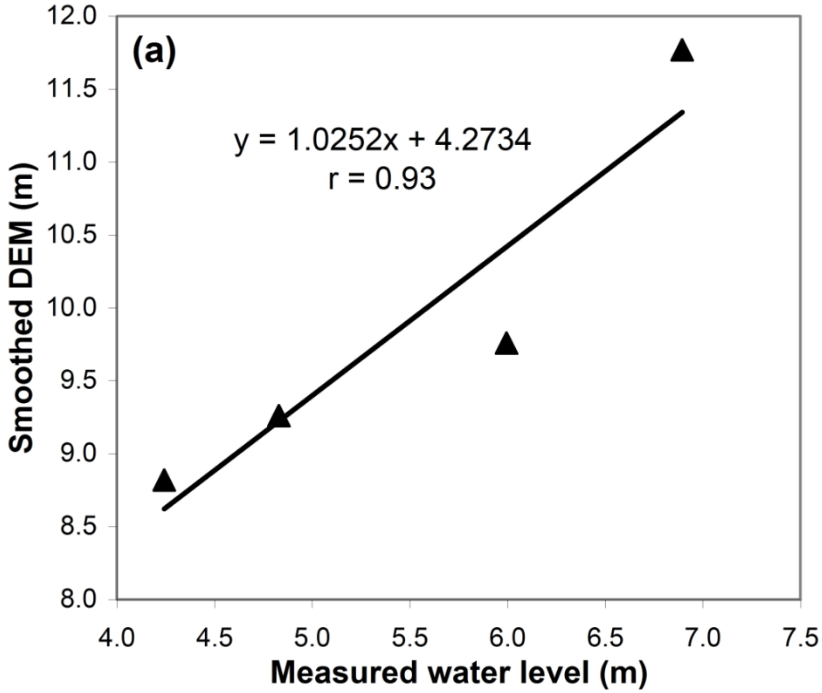
Average values are used as the calibration targets.

Model Calibration Results: Heads



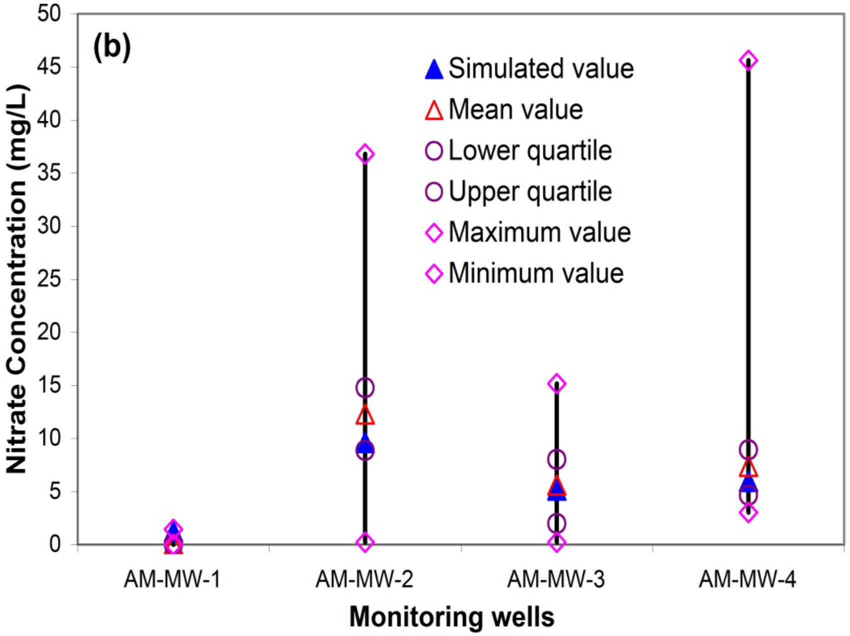
The smoothed DEM agrees well with the mean observed hydraulic head, because the correlation coefficient (0.93) and the slope of linear regression (1.03) are close to one.

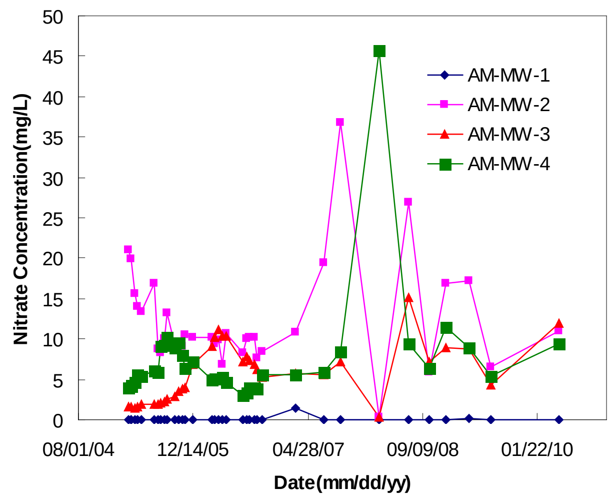




Model Calibration Results: Nitrate Concentrations

- The simulated nitrate concentrations are close to the mean observations.
- Because of the large variability of concentration observations, it happens often that simulated nitrate concentrations deviate from mean observations.
- We consider that the calibration is reasonable if the simulations fall within the inter-quartile of the observed concentrations, which covers 50% of the data.





Challenges: Uncertainty in Input Parameters and Load Estimates

Poetry of Donald H. Rumsfeld:
Feb. 12, 2002
Department of Defense news briefing

The Unknown
As we know,
There are *known knowns*.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also *unknown unknowns*,
The ones we don't know
We don't know.

The calibrated parameters are just one possible combination, and there may be other parameter combinations that give similar model fit but different load estimates.

An Illustrative Example

Parameter ranges:

Hydraulic conductivity (*K*): 0.0864 ~ 30.4992 m/d

Longitudinal dispersivity (α_L): 0.21 ~ 21.34 m

Horizontal transverse dispersivity (α_T): 0.021 ~ 2.134 m

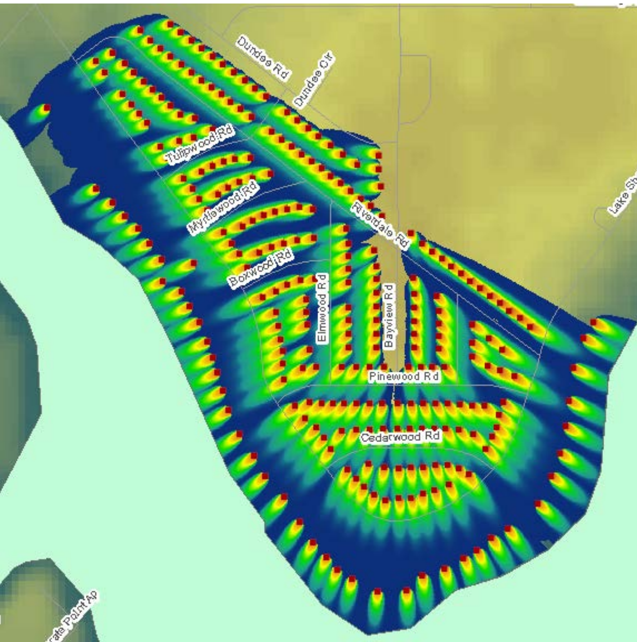
First-order decay coefficient (*k*): 0.004 ~ 2.27 /d

Parameter set 1

Load=0.15 lb/day

α_L=2.113m, α_T=0.234m

k=0.008/d

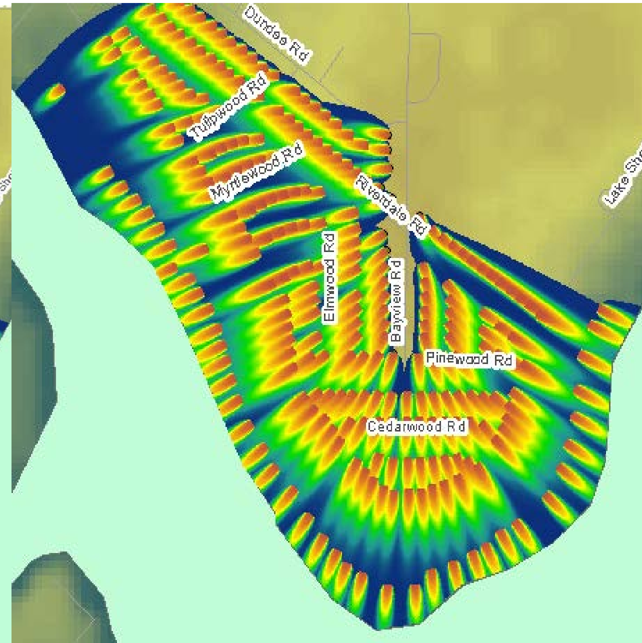


Parameter set 2

Load=0.25 lb/day

α_L=2.113m, α_T=0.234m

k=0.004/d

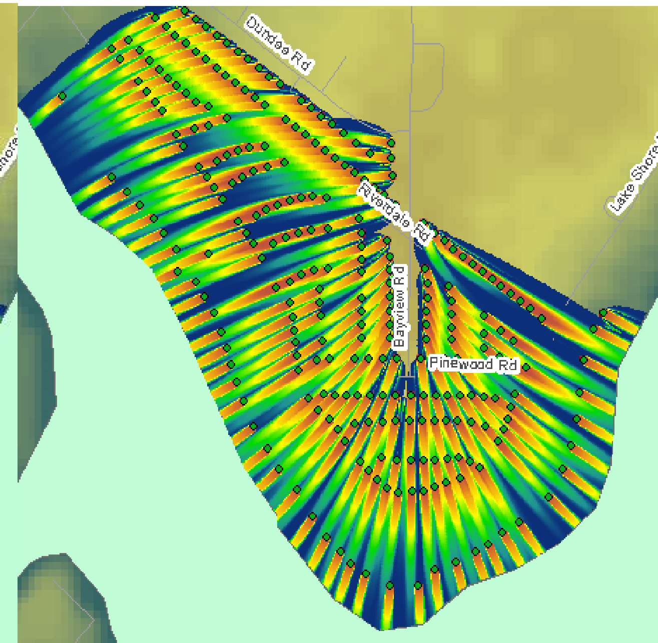


Parameter set 3

Load=0.60 lb/day

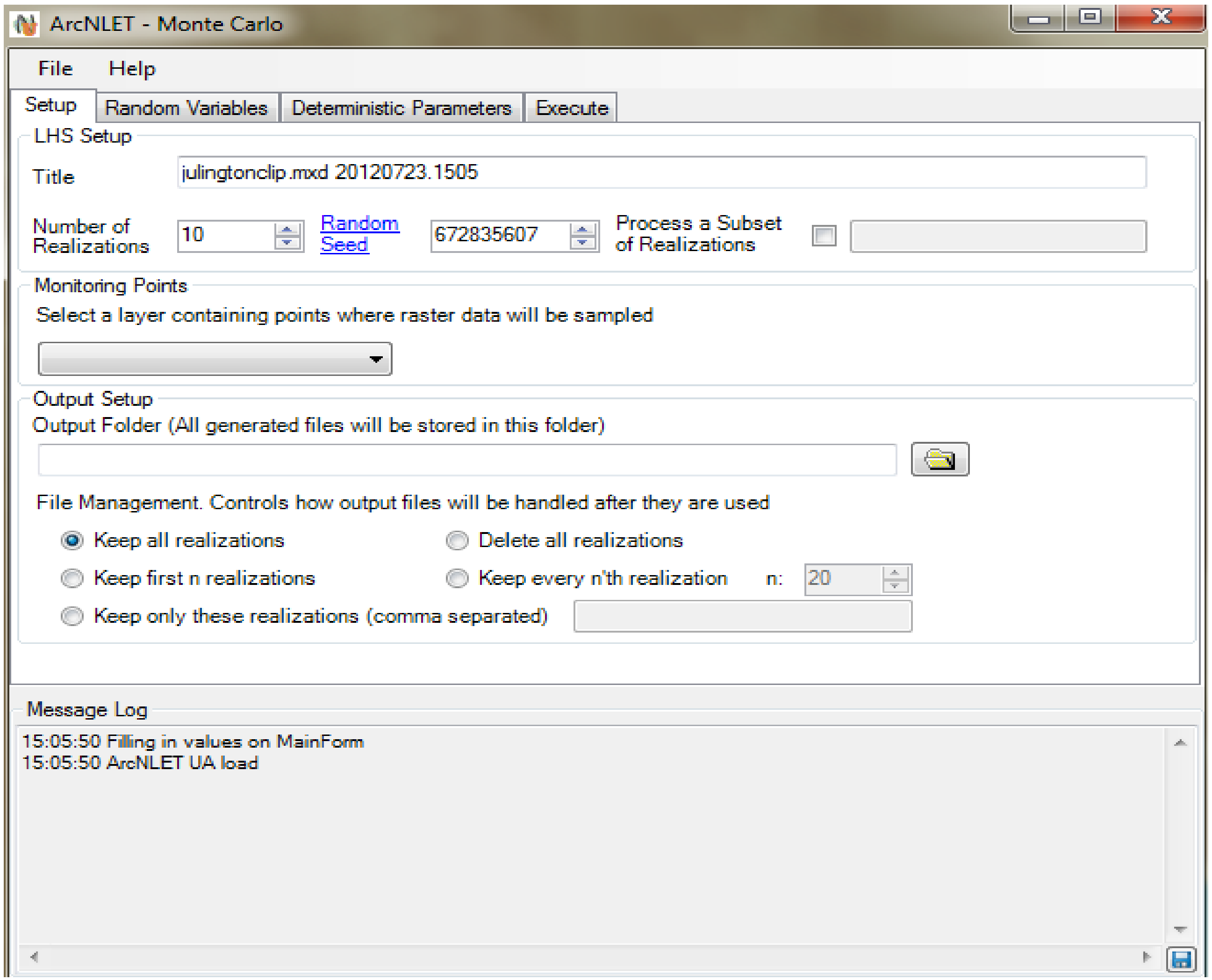
α_L=21.34m,α_T=0.021m

k=0.004/d

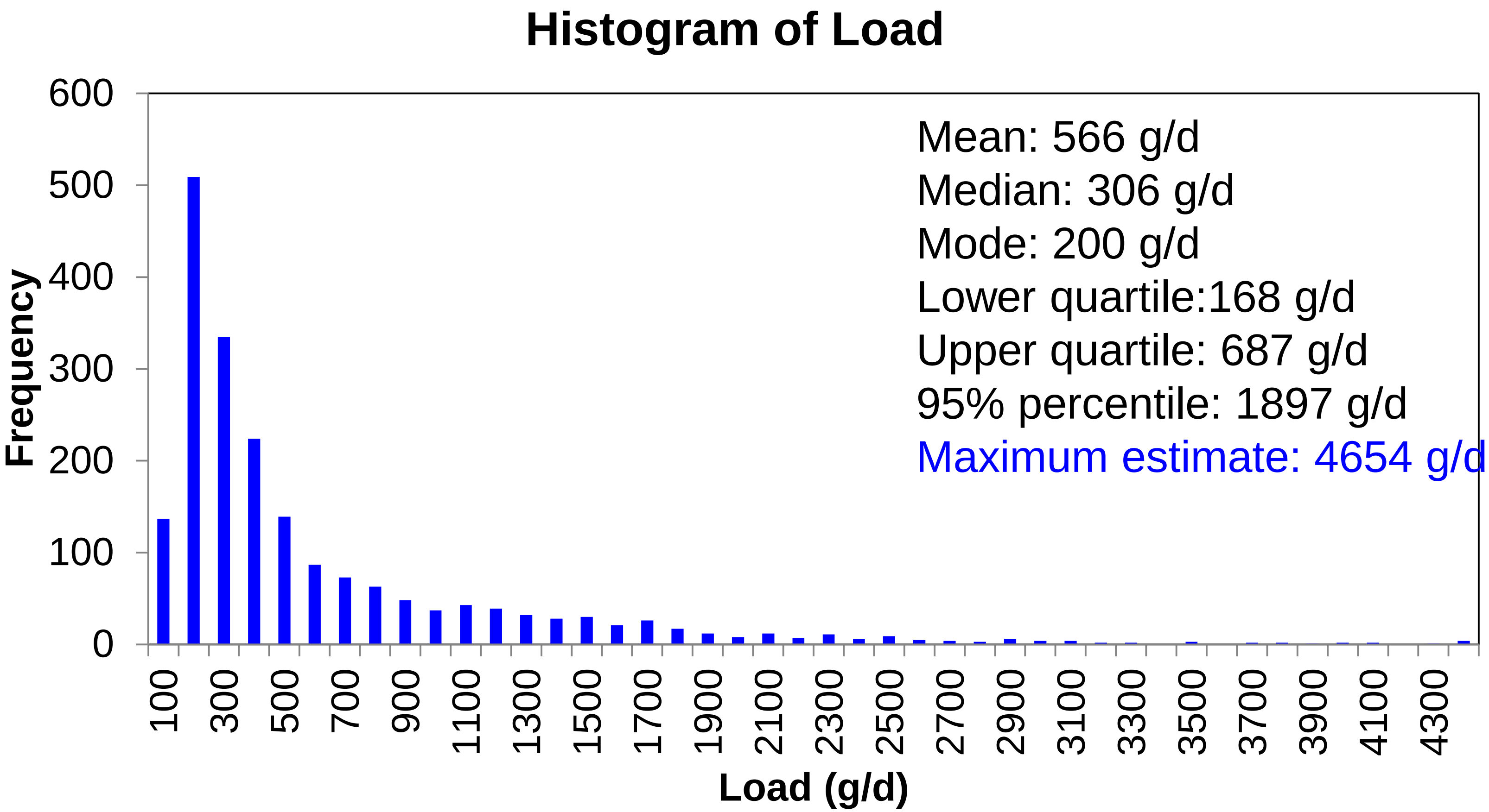


ArcNLET-MC for Uncertainty Quantification

Recently released in ArcNLET 2.0.



Uncertainty Analysis



- The load estimation has large uncertainty.
- Uncertainty reduction can be achieved if more data and information becomes available.

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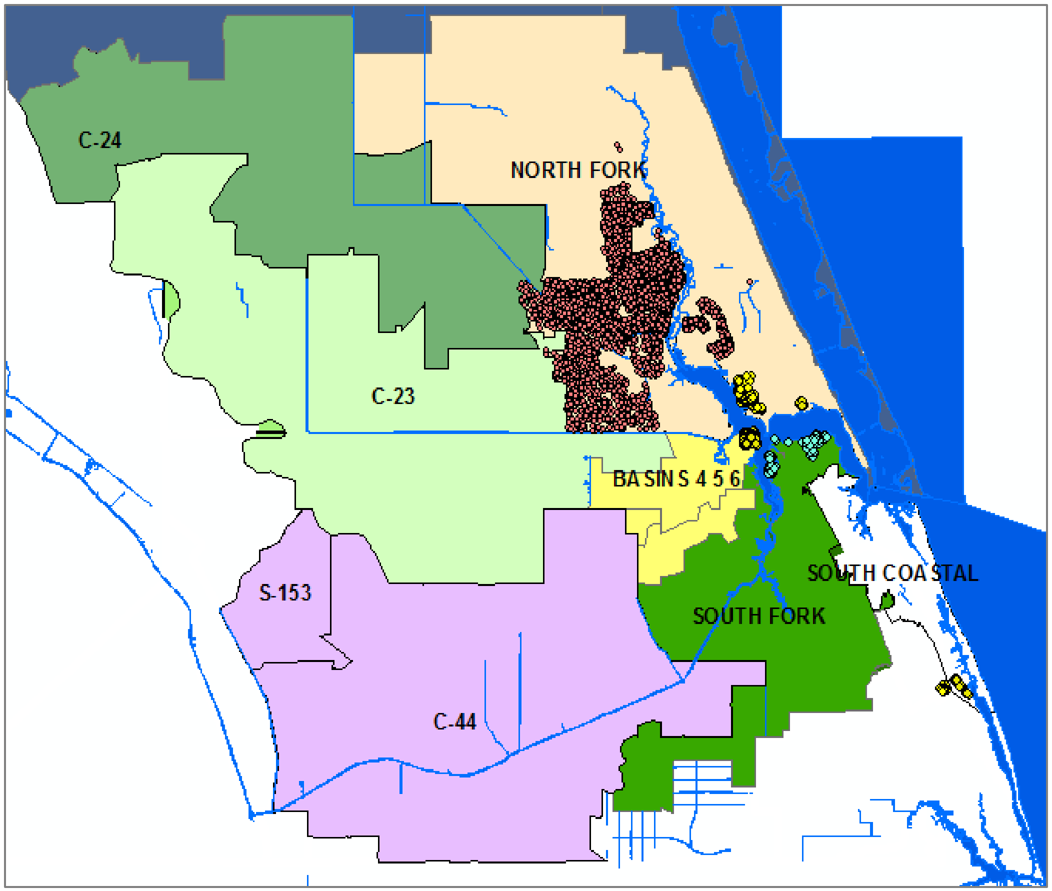
ArcNLET modeling for the City of Port St. Lucie, the City of Stuart, and Martin County



A technical report has been submitted to FDEP. It can be requested from me or Katie directly.

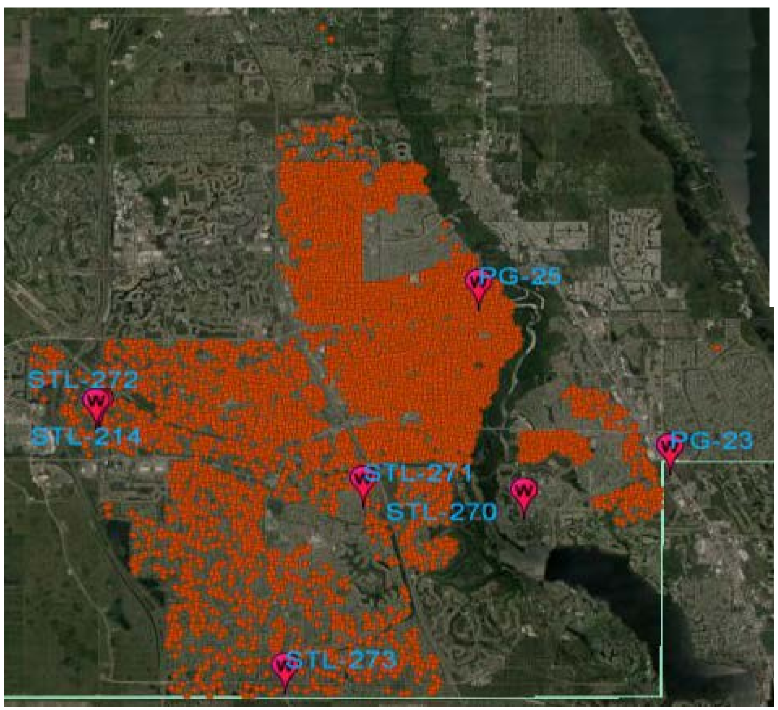
Modeling Procedure

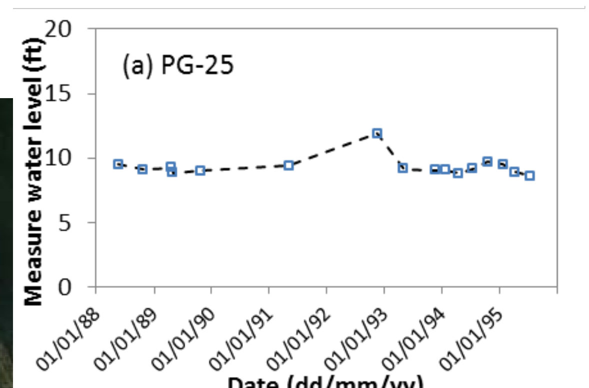
For each site, whenever site-specific data are available,

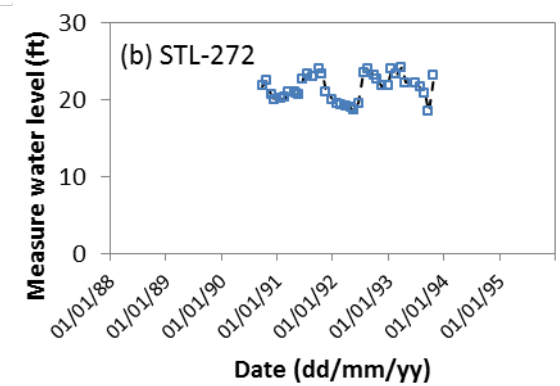
- Compile historical data to understand groundwater flow and nitrogen transport at the modeling sites. (Chapter 3)
- Select calibration data of hydraulic head and nitrogen concentration to estimate ArcNLET flow and transport model parameters. (Chapter 3)
- Calibrate the ArcNLET model. (Chapter 4)
- Simulate nitrogen transport at the modeling site, using the calibrated model. (Chapter 4)
- Estimate the nitrogen load. (Chapter 4)
- Conduct Monte Carlo simulation to address uncertainty in model parameters. (Chapter 5)

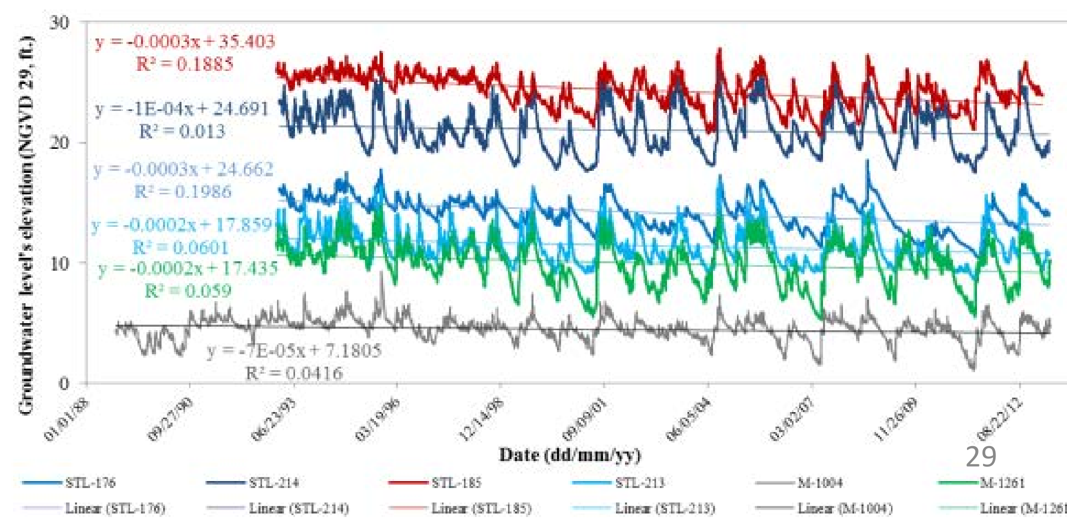
Compiled Data: Water Level

The data in the modeling sites are old (measured in the period of 1988-1995), but their average values are still representative of the groundwater conditions of the modeling sites.



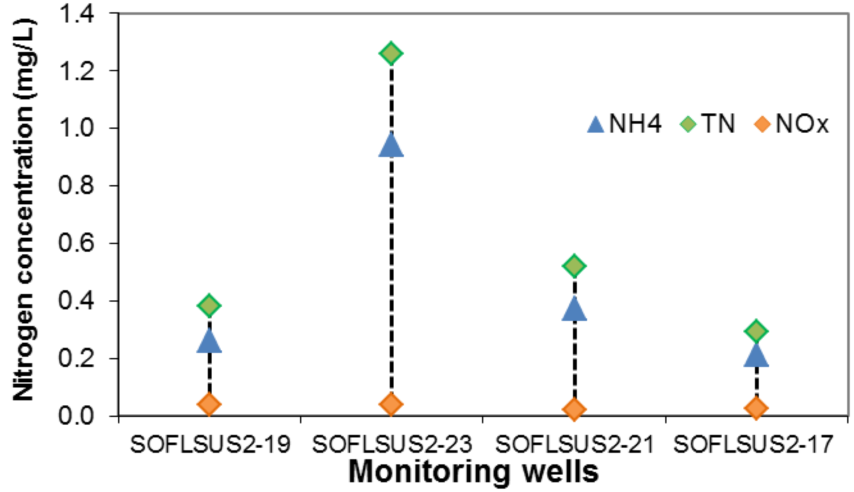






Compiled Data:
Nitrogen Concentration

- Observations of nitrogen concentrations are extremely scarce.
- Four data are available in the City of Port St. Lucie and one data in Martin County.
- The data at well PG-25 was measured in 1976-1977. The other four data were measured in 2008.



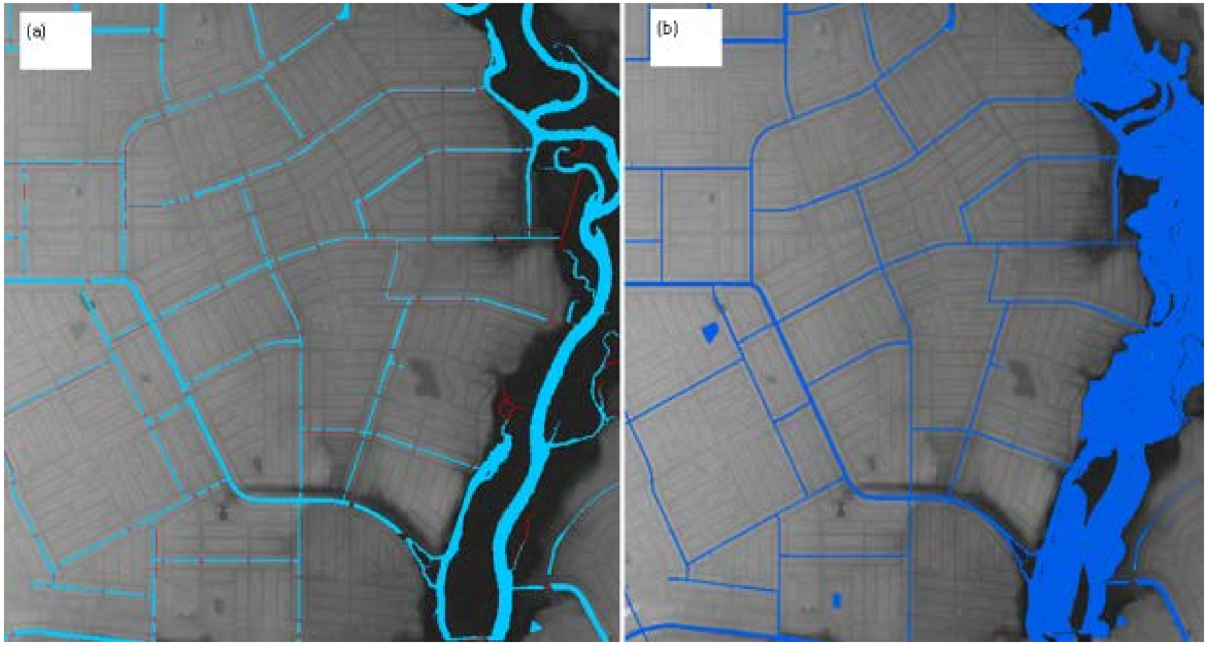
Area	Wells	Data source	NO_x	NH4	TN/DIN
City of Port St. Lucie	SOFLSUS2-19	USGS	0.040	0.220	0.380
	SOFLSUS2-21	USGS	0.021	0.349	0.520
	SOFLSUS2-23	USGS	0.040	0.900	1.260
	PG-25	USGS	0.005	0.283	0.288
Martin County	SOFLSUS2-17	USGS	0.002	0.210	0.290

More data are necessary to validate the modeling results, improve nitrogen transport modeling, and reduce estimation uncertainty.

Data for ArcNLET Modeling

- All the GIS data needed for ArcNLET modeling are available in the public domain or from local environmental agencies.
- Local data are important, e.g., the canals in the City of Port St. Lucie.

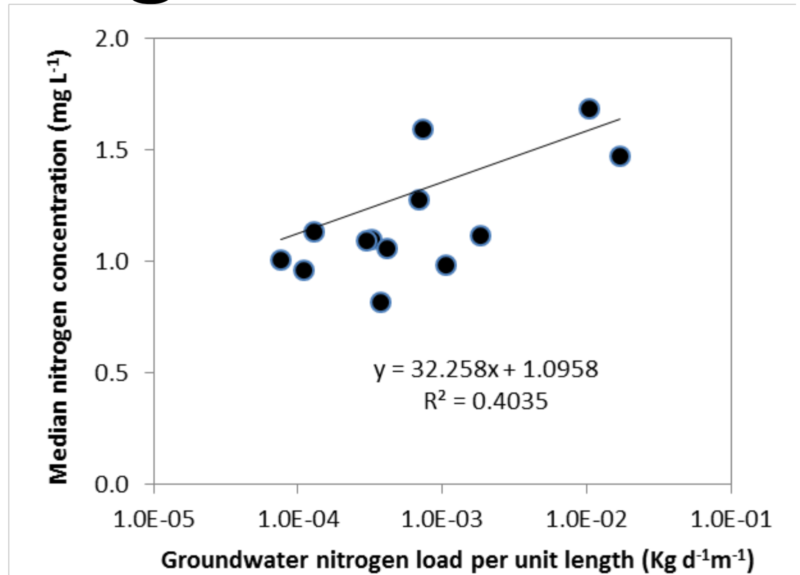
Local
canal data

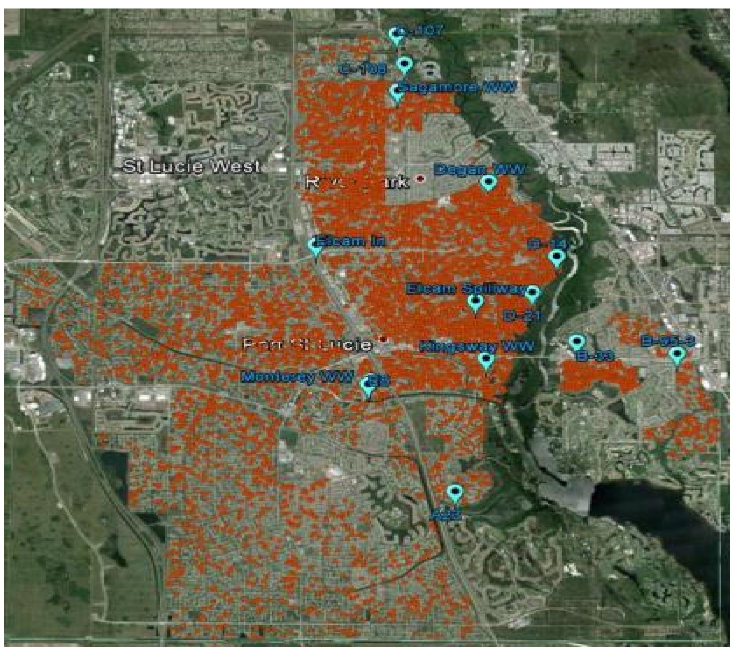


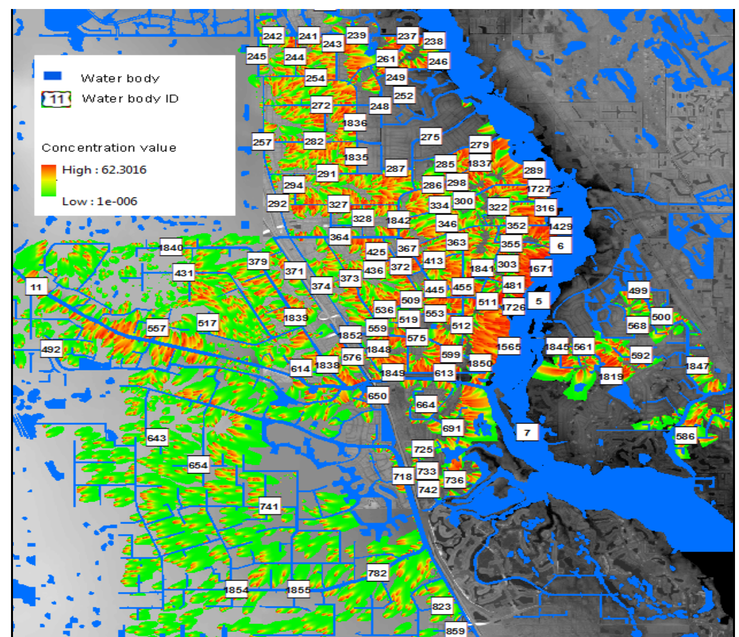
Local
canal data
+
National
NHD data

Simulated Nitrogen Plumes

A strong correlation is observed between the median values of surface water nitrogen concentration and the nitrogen loads to the corresponding surface water bodies.

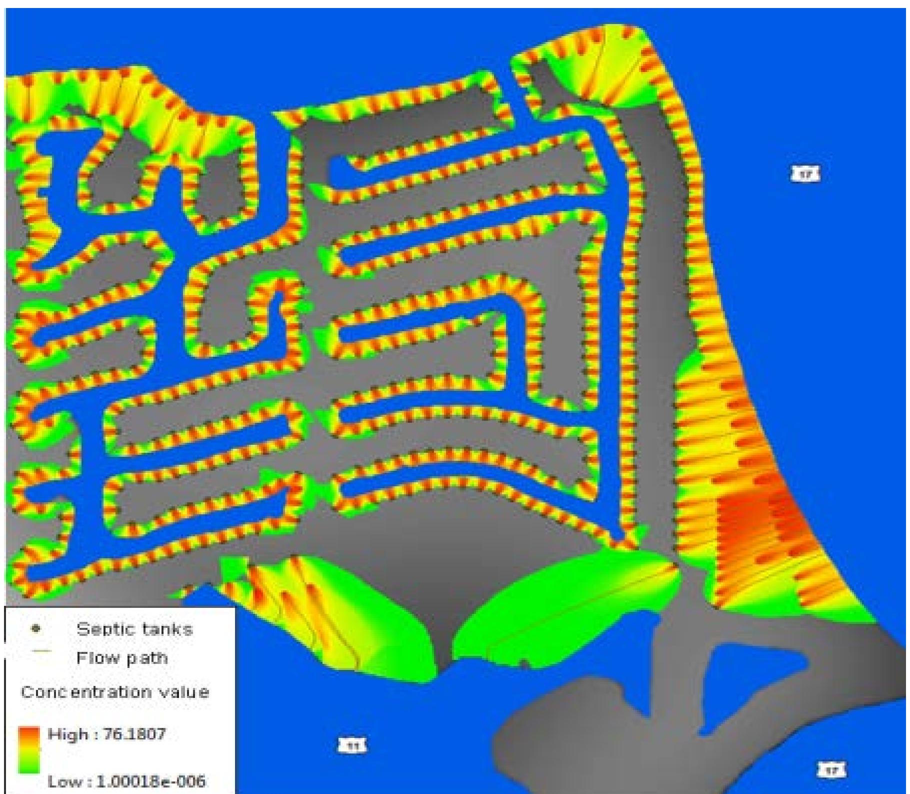


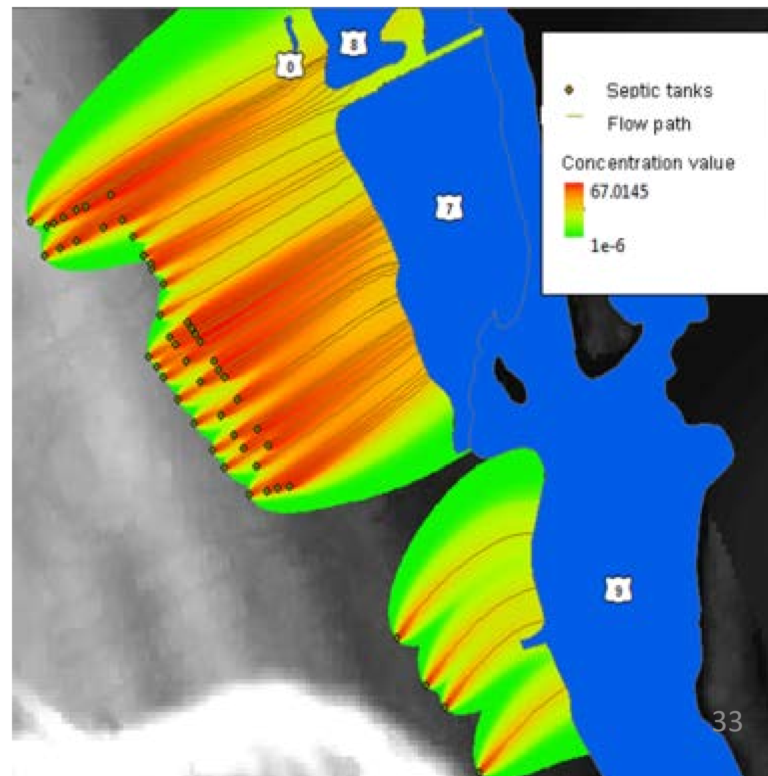




Spatial Variability of Nitrogen Plumes

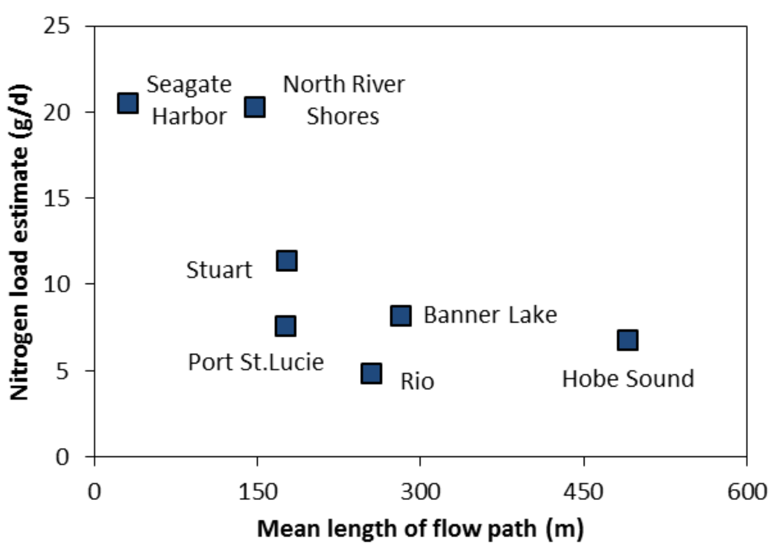
Spatial variability is obvious at different modeling sites, e.g., Seagate Harbor (left) (reduction ratio of 10.8%) and Hobe sound (right) (reduction ration of 70.5%) in the Martin County.

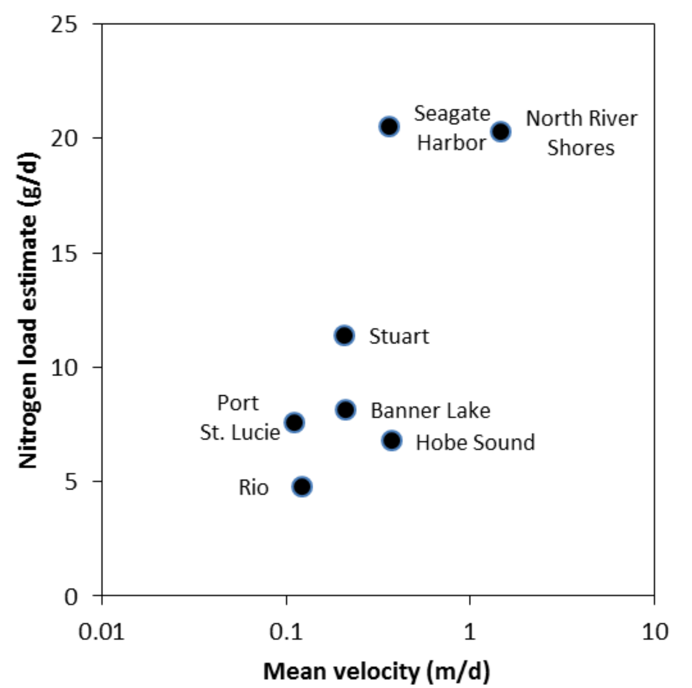




Factors Controlling Load Estimate

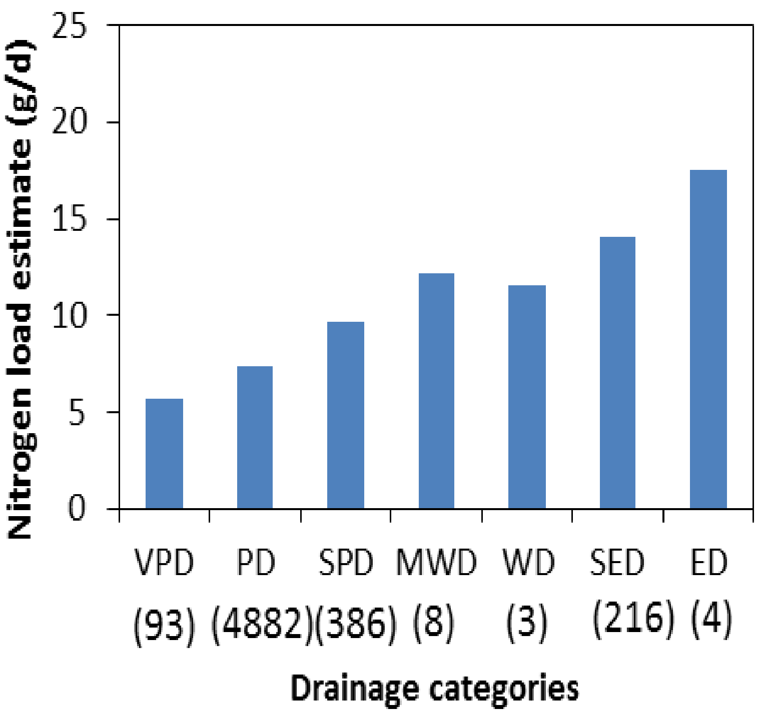
- Mean length of flow path (left): long mean length of flow path corresponds to more denitrification and thus less load estimate.
- Mean velocity (right): larger mean velocity results in shorter travel time, less denitrification, and thus more load estimate.





Factors Controlling Load Estimate

In the City of Port St. Lucie, the load estimate increases when the drainage condition changes from very poorly drained to excessively drained, because nitrogen transport is faster in well-drained soil is faster than in poorly drained soil.



VPD: very poorly drained
PD: poorly drained
SPD: somewhat poorly drained
MWD: moderately well drained
WD: well drained
SED: somewhat excessively drained
ED: excessively drained

The number of septic systems corresponding to each drainage condition is given in the parentheses

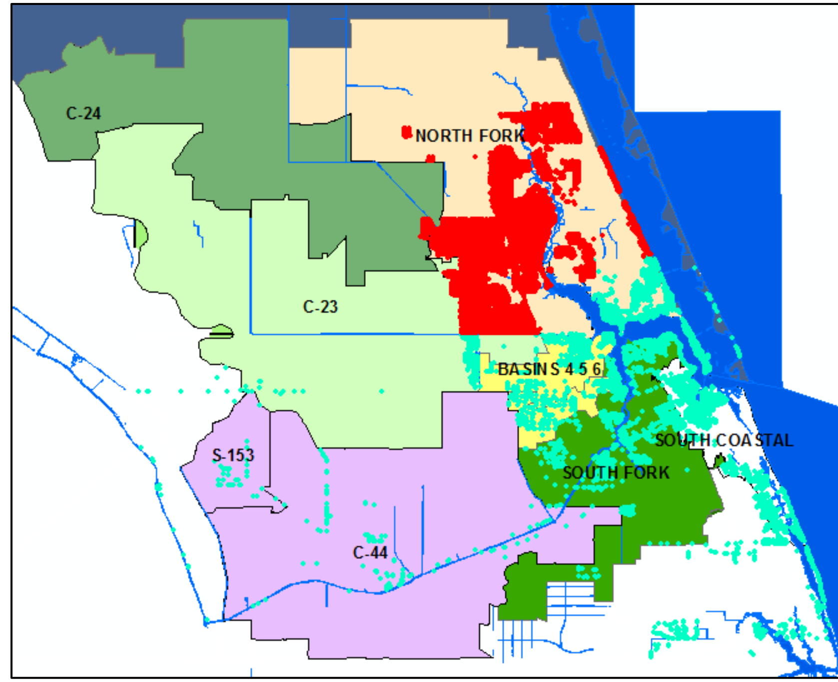
Comparison with Literature Data

The nitrogen reduction ratios in this study have a large range but are comparable with the literature data, especially with that of Roeder (2008) obtained in the Wekiva Study.

Reference	Site Location	Daily nitrogen loads per septic system (g/d)	Daily nitrogen loadings to surface water per septic system (g/d)	Nitrogen reduction ratio
Roeder (2008)	Wekiva Study Area, FL	21.7		**70.0%** [a]
Valiela et al. (1997)	Waquoit Bay, MA	23	9.87 [b]	**57.1%**
Meile et al. (2010)	McIntosh County, GA			**65-85 %** [c]
This study	Port St. Lucie, FL	23	7.60	67.0%
	Stuart, FL	23	11.4	50.4%
	North River Shores, FL	23	20.3	11.7%
	Seagate Harbor, FL	23	20.5	10.8%
	Banner Lake, FL	23	8.15	64.6%
	Rio, FL	23	4.80	79.1%
	Hobe Sound, FL	23	6.78	70.5%

The septic system removal (actual and hypothetical) is

- absolutely worthy for the North Fork and Basin 4-5-6 sub-basins,
- (somewhat) worthy for the South Fork sub-basins,
- unworthy for C-24, C-23 and C-44/S-135 sub-basins.



	Basin 4-5-6	C-23	C-24	C-44/ S-153	North Fork	South Fork
Percentage of nitrogen load from septic systems to BMAP estimated load	22.87%	0.03%	1.66%	0.00%	31.20%	10.33%
Percentage of load reduction of removed septic systems to BMAP required reduction	33.67%	0.05%	1.71%	0.00%	17.02%	1.35%
Percentage of load reduction to BMAP required reduction	81.02%	0.06%	3.25%	0.00%	85.75%	25.76%

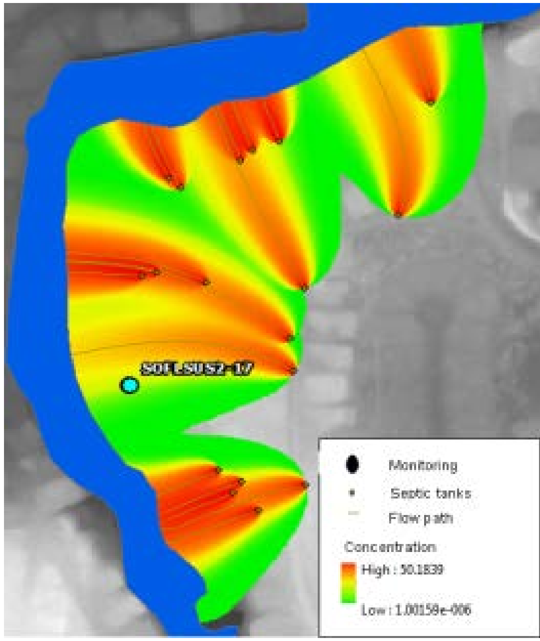
Uncertainty Analysis: Compare with Field Observations

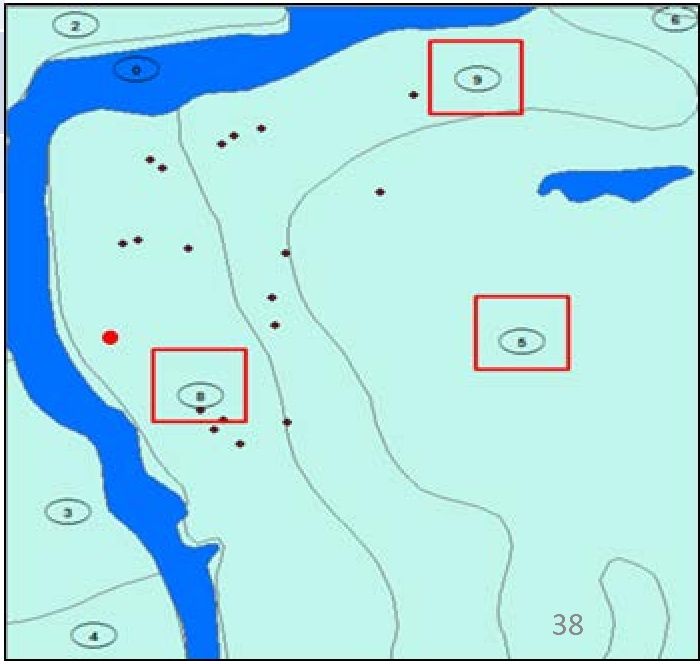
- A monitoring well is available at the site.
- Random parameters based on literature data

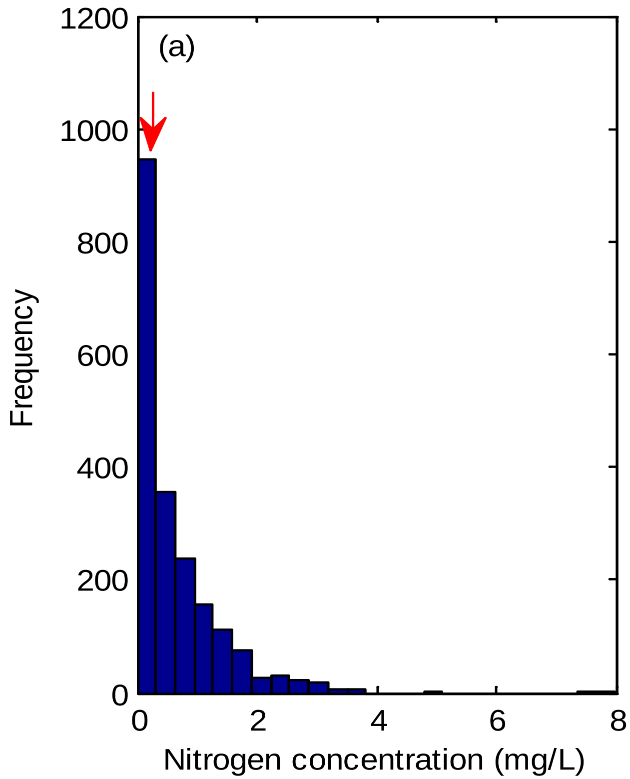
Parameter	Distribution	Minimum	Mode	Maximum
Smoothing Factor	Uniform	20	N/A	80
Longitudinal Dispersivity	Normal	1	N/A	100
Source Plane Concentration	Normal	25	N/A	80
Decay Coefficient	Lognormal	5.4E-5	N/A	0.015

- Random parameters (hydraulic conductivity) based on site-specific data.

Soil Zone FID	Minimum	Mode	Maximum
5	3.629	7.949	12.18
8	12.18	18.14	24.36
9	12.18	18.14	24.36



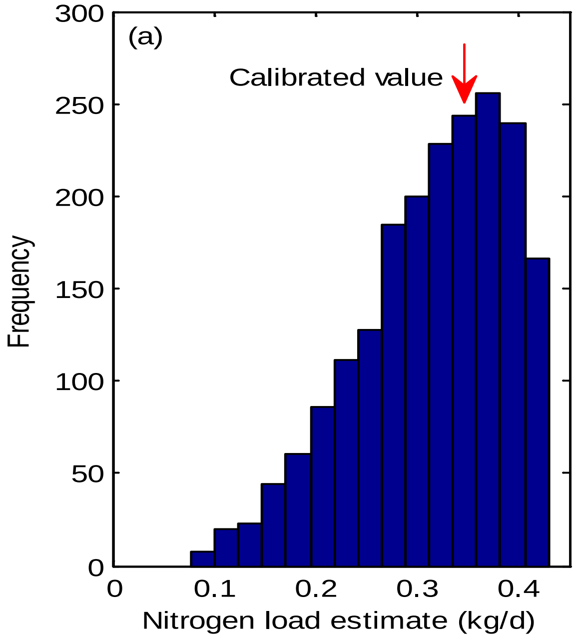


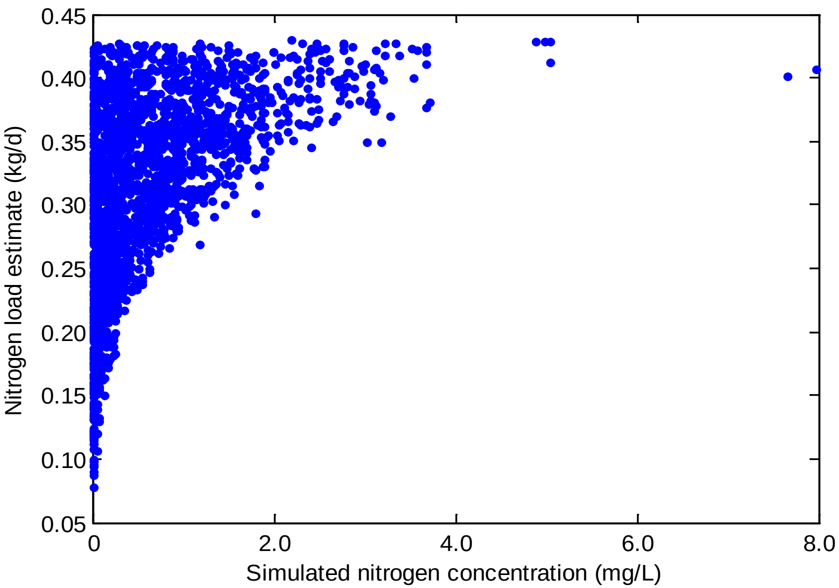


The simulated concentration at the monitoring location follows a lognormal distribution, which is attributed to the lognormal distribution of the first-order decay coefficient of denitrification, the most influential parameter to nitrogen concentration.

- The histogram indicates that, with the parameter distributions considered in this study, it is significantly more likely for the model to simulate low concentration values than to high values.
- This is consistent with the low nitrogen concentration of 0.29 mg/L observed at the monitoring well, suggesting that the calibrated model is likely to reflect nitrogen transport at the calibration site.

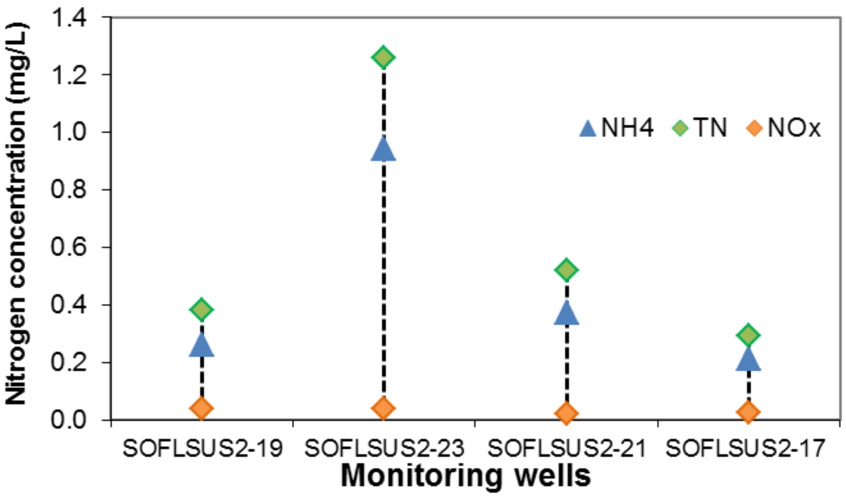
Relation between Concentration and Load Estimate

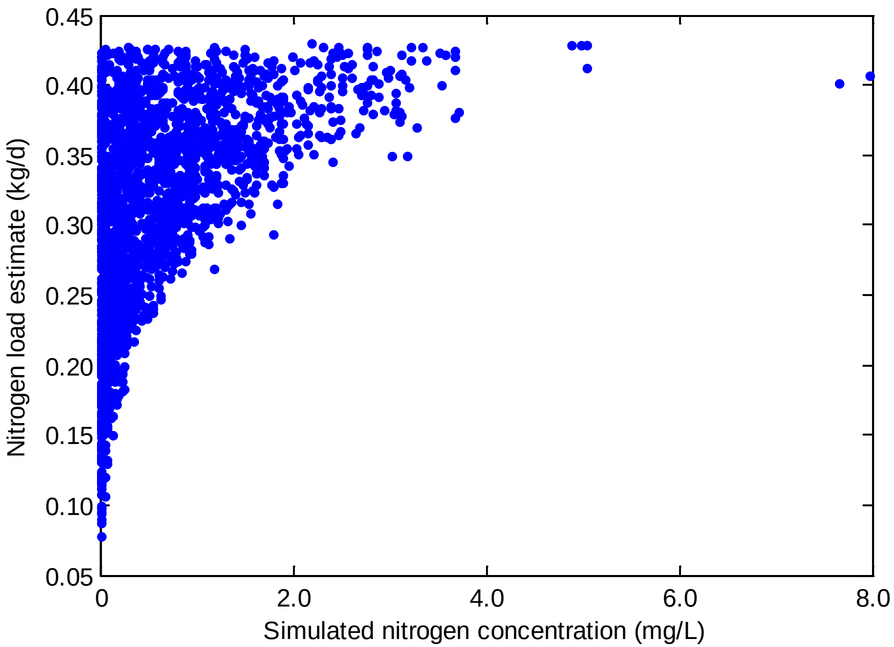




- The estimated loads corresponding to the calibration data is relatively large.
- The overall positive correlation indicates that larger nitrogen concentration corresponds to larger load.
- However, larger load estimate may be still possible for low concentration, because uncertainty in the load estimate increases when the simulated concentration decreases.
- The uncertainty can be reduced by collecting more field observations (e.g., continuous monitoring at the well), as more monitoring data can remove the realizations that cannot simulate the monitoring data.

Use of Monitoring Data





For Calibration:

- Are the one-time measurements of nitrogen concentration representative of nitrogen concentration in time?
- Are the measurements at the several locations representative in space?
- The model calibration can be updated by assimilating the new data.

For Uncertainty Reduction:

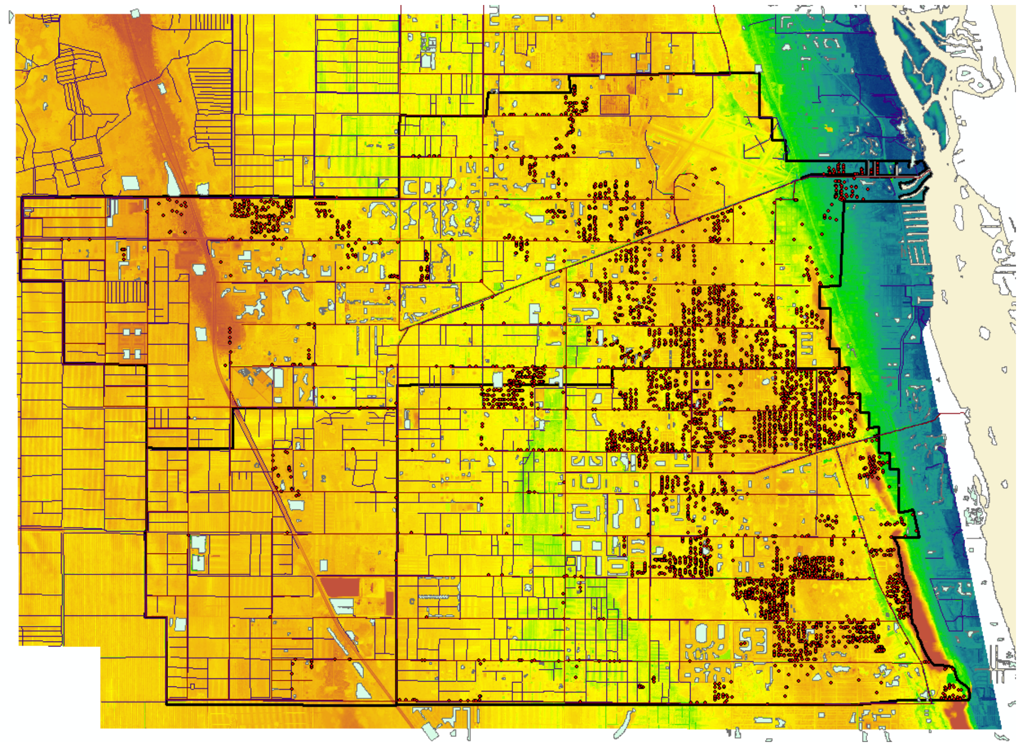
- If observed nitrogen concentrations are continuously higher than the simulated value, the bottom figure indicates that the load estimate will be higher with smaller uncertainty.
- If the opposite, we can update the modeling results by removing the realizations that give higher concentration , which will also reduce the uncertainty and give more certain load estimate.

On-Going ArcNLET Modeling for IRL

Data collected and compiled:

- LiDAR DEM (15ft and 5ft)
- Septic tank locations (parcels with no sewer service)
- Water bodies (canals, waterbodies, shorelines, …)
- Hydraulic conductivity and porosity (SSURGO)

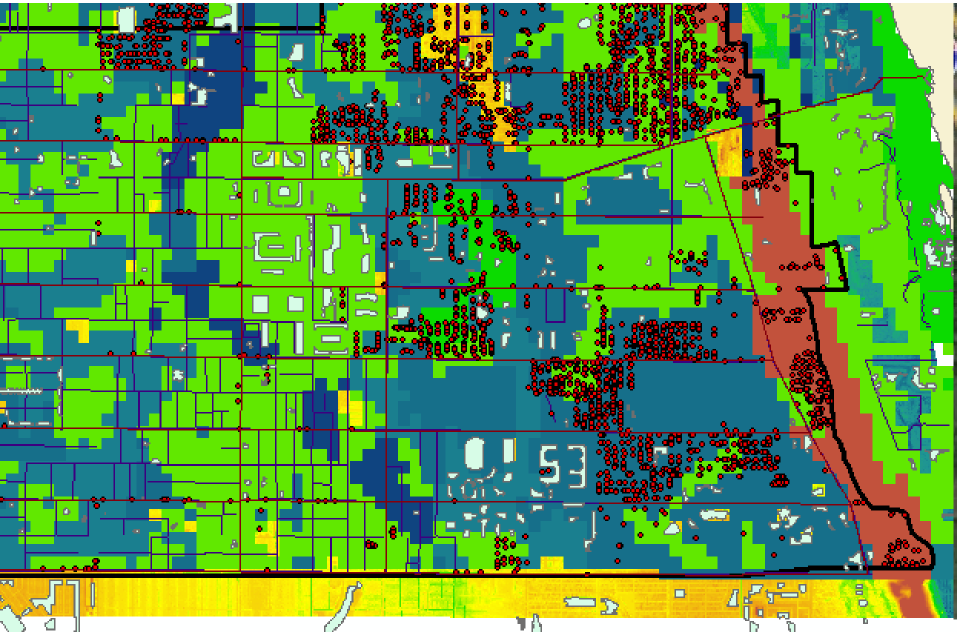
Help from Vincent Burke, Arjuna Weragoda, and Will Rice for data collection is greatly appreciated.



Main Canal and South Canal

Devils in Details

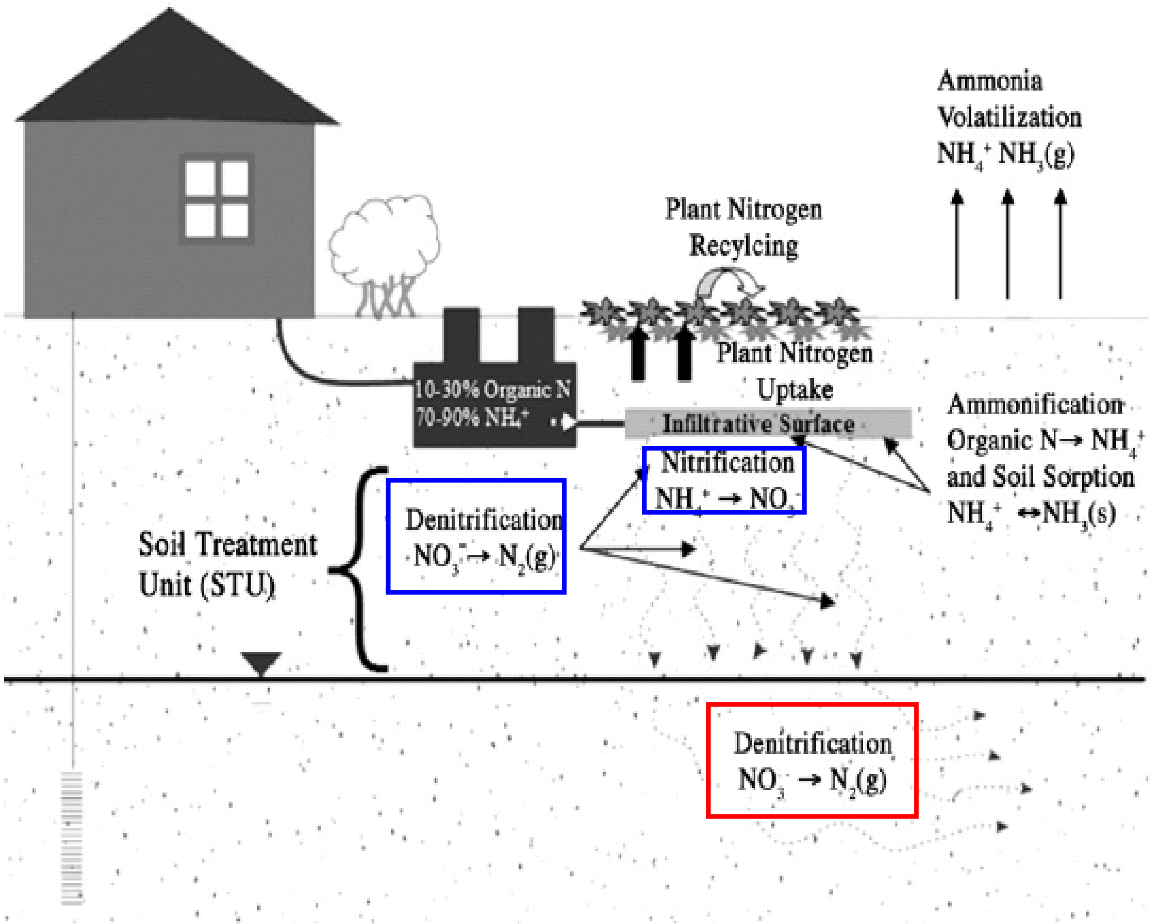
- ~1% error in septic tank locations
- Inconsistent between the datasets (e.g., DEM and SSURGO)
- Site-specific handling (e.g., landfill with elevation of 111 ft)



Future Work

- Clean the data needed for setting up ArcNLET flow and transport modeling.
- Collect monitoring data of hydraulic head and nitrogen concentration.
- Conduct model calibration and estimate nitrogen load in an iterative manner when new data (e.g., seepage measurements) arrive.
- Evaluate the load estimates and make management suggestions.

Model Integration



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

Conclusions

- ArcNLET has been developed as a numerical model and software for nitrogen load estimation.
- The software has been used for several different sites in Florida.
- Preliminary modeling for IRL has started, and modeling results should be available in next couple of months.
- Modeling results (including uncertainty quantification) may be useful to management of nutrient pollution in IRL.
- Model results can be used to provide insights and guidelines of data collection.

Questions, Suggestions, and Comments?