Picture from USGS Scientific Investigations Report 2008–5220

An Overview of ArcNLET and Associated Tools for Estimation of Nitrate Load from Septic Systems to Surface Water Bodies

March 7th, 2013

Presentation to the SJRWMD

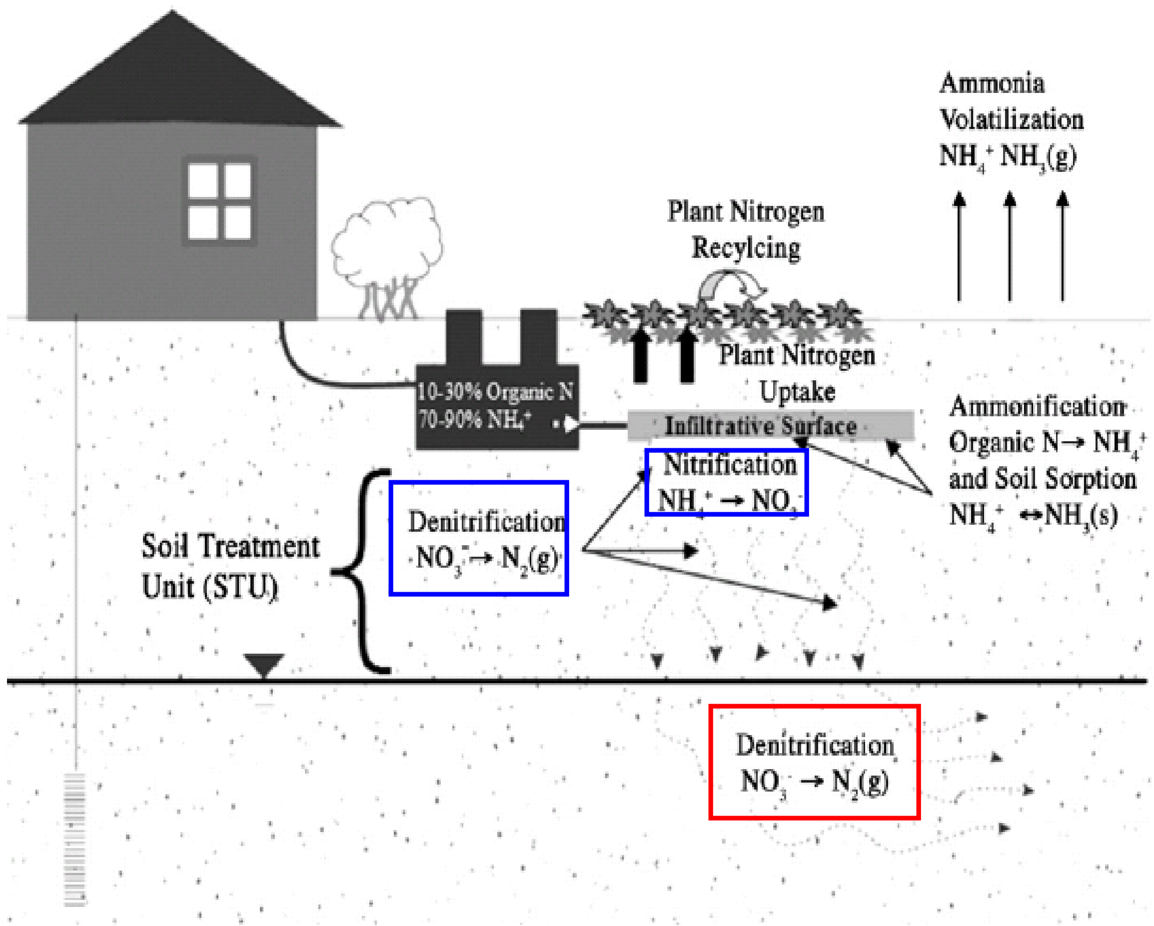
Project Team Members

- 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:
  - Fernando Rios (Graduated in 2010)
  - Raoul Fernendes (Graduated in 2011)
  - Nathan Potratz (Since 2012)
- Post-docs:
  - Liying Wang (2010-2012)
  - Huaiwei Sun (Since 2012)

Outlines

- Development rational
- Functions of ArcNLET and associated software
- Requirements of using ArcNLET
- Simplification and limitations of ArcNLET
- Applications ArcNLET at Julington Creek and Eggleston Height neighborhoods
- On-going and future research
- Suggestion and comments

Schematic of an Onsite Sewage Treatment and Disposal System (OSTDS) 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

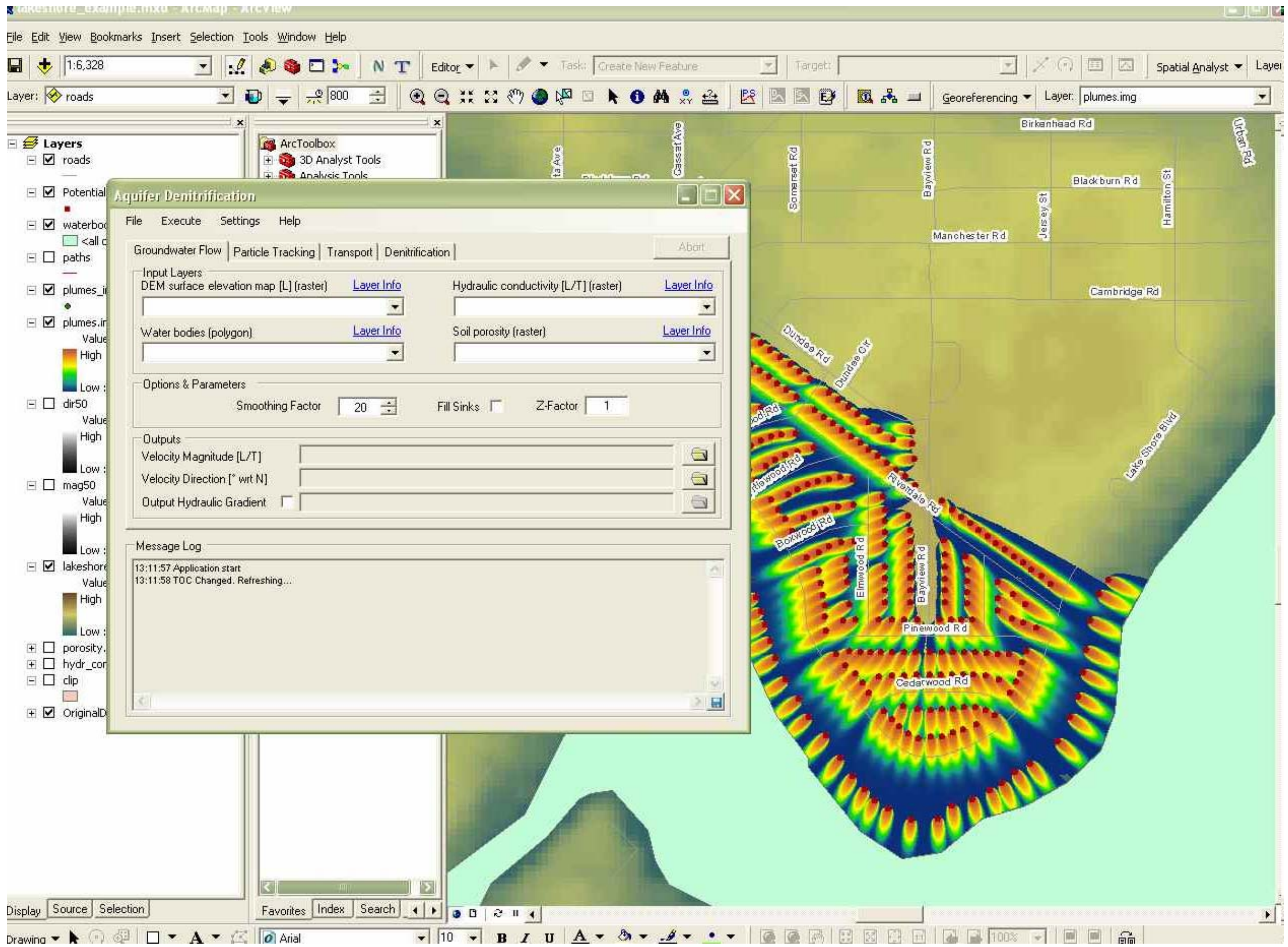
- Groundwater flow
- Solute transport
- Denitrification

ArcNLET-MC: Quantify uncertainty of ArcNLET simulations

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

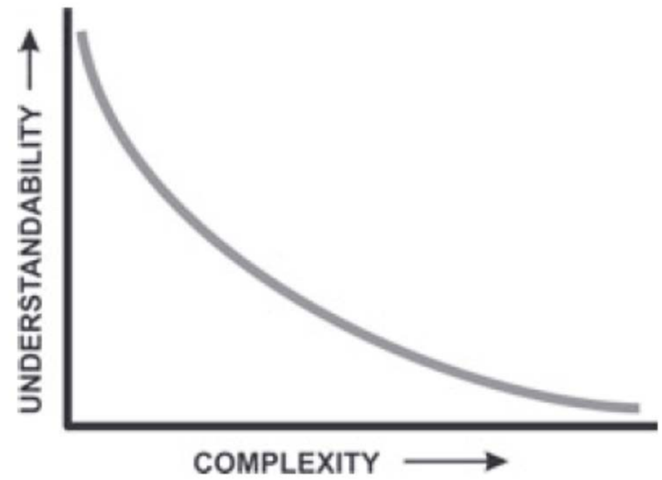


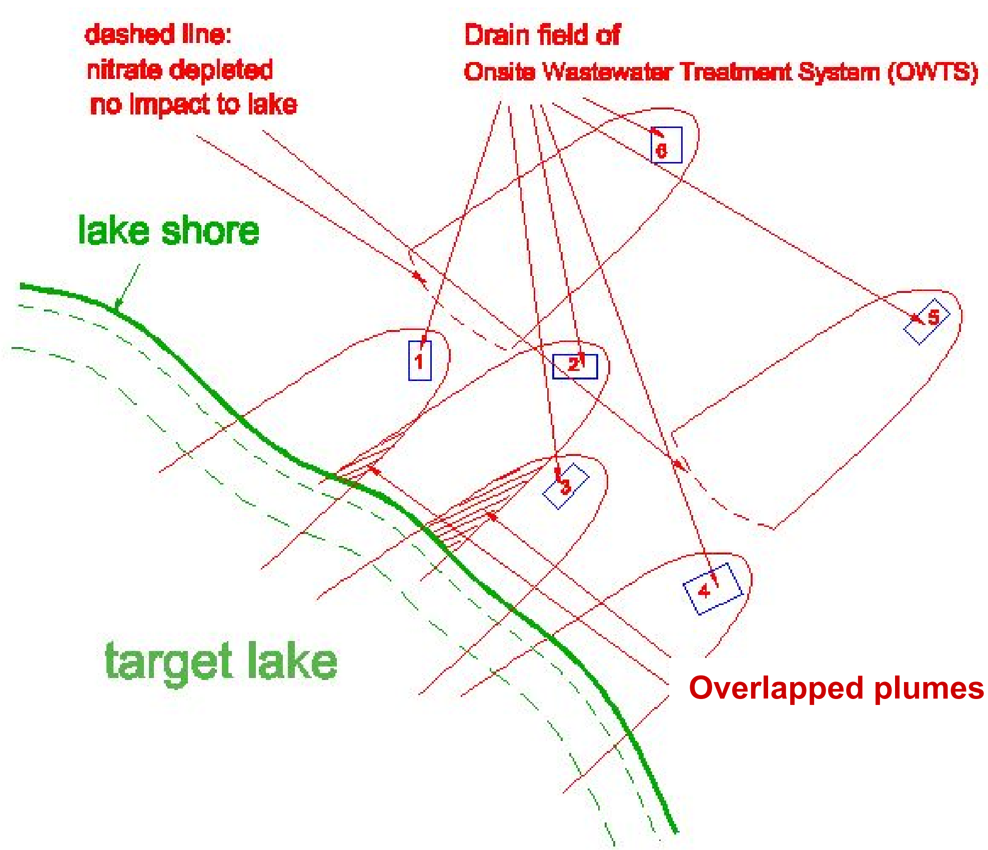
Compatible with ArcGIS 9.3 and 10

Why Developing ArcNLET?

- There is no suitable tool for estimating nitrate load to meet TMDL requirements and perform LSJR Nitrogen BMAP. 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 either individual or clustered 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

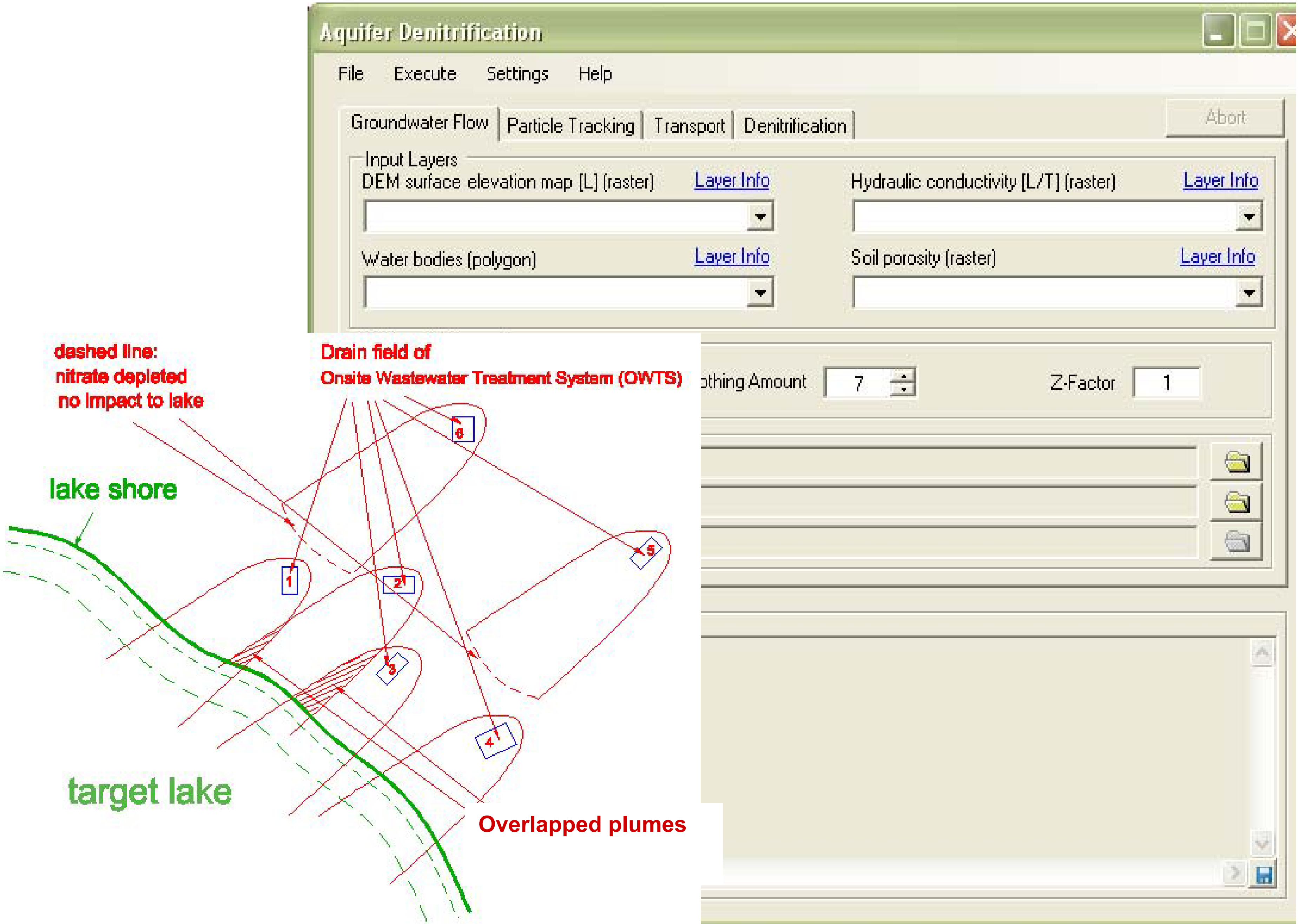
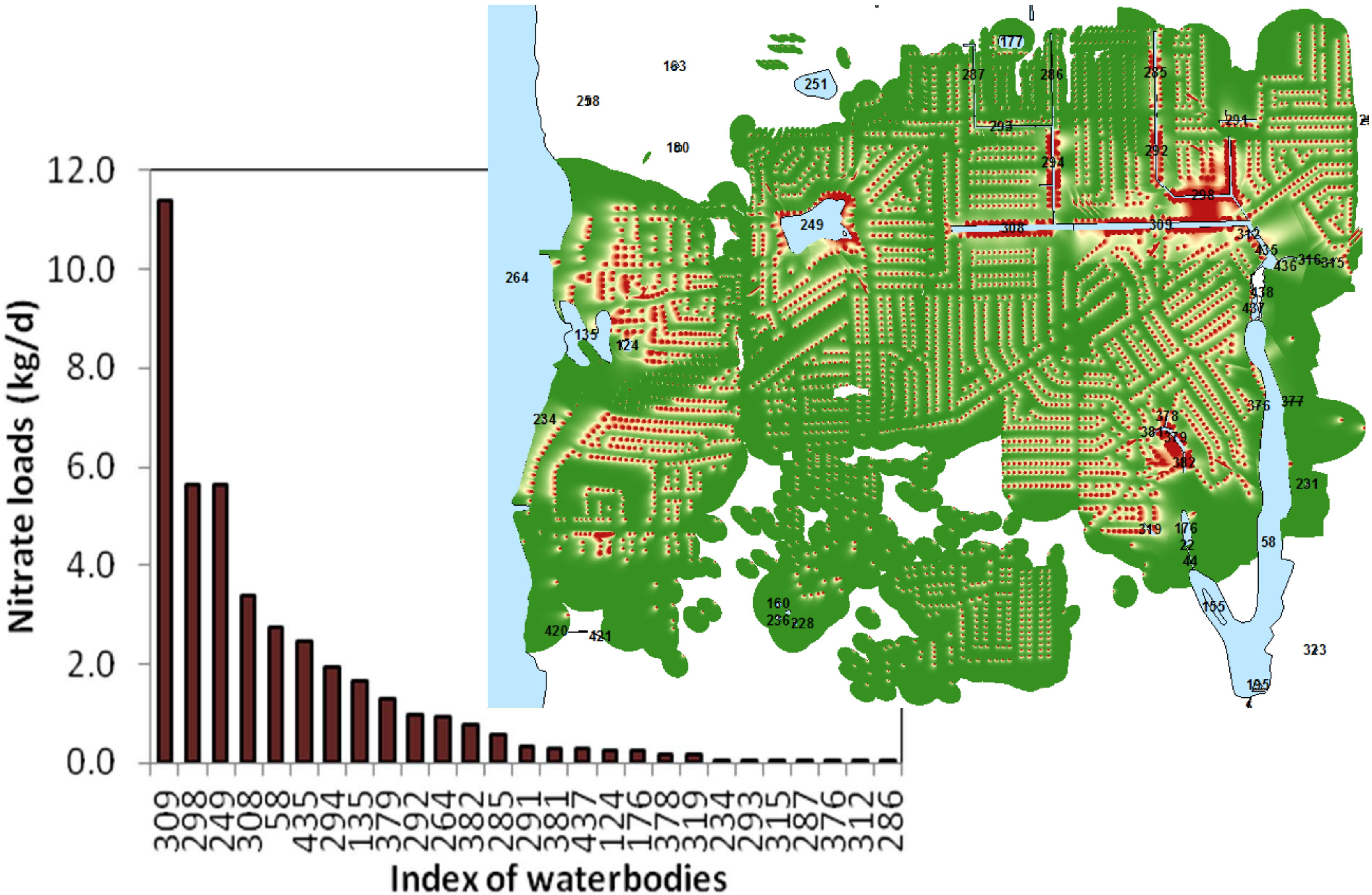


Illustration of simulated nitrate plumes and nitrate load



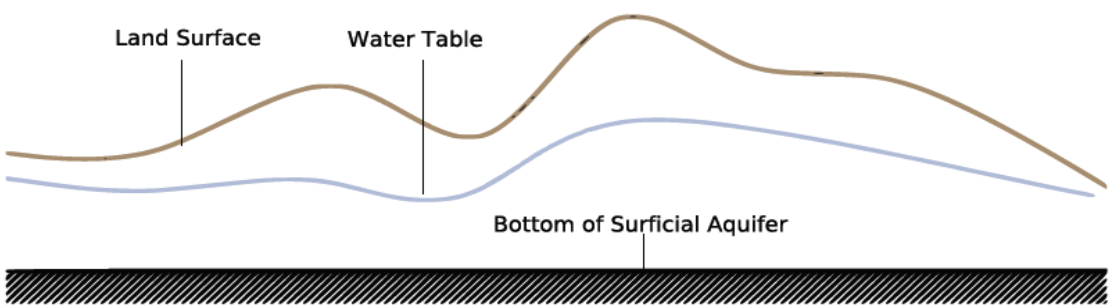
Simplifications and Limitations in Groundwater Flow Modeling

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

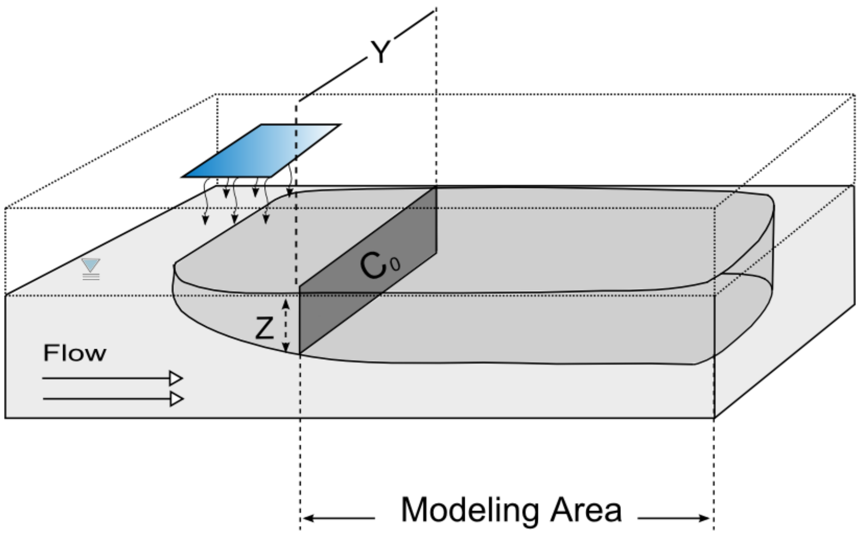
Limitations:

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

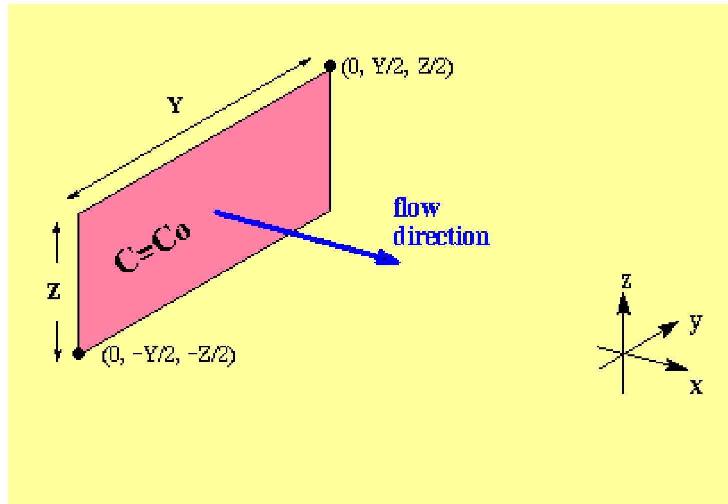


Simplifications and Limitations in Nitrate Transport Modeling

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
  - 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
  - Difficult to determine the size of source plane
  - Difficult to obtain the decay coefficient

Inputs Data of ArcNLET

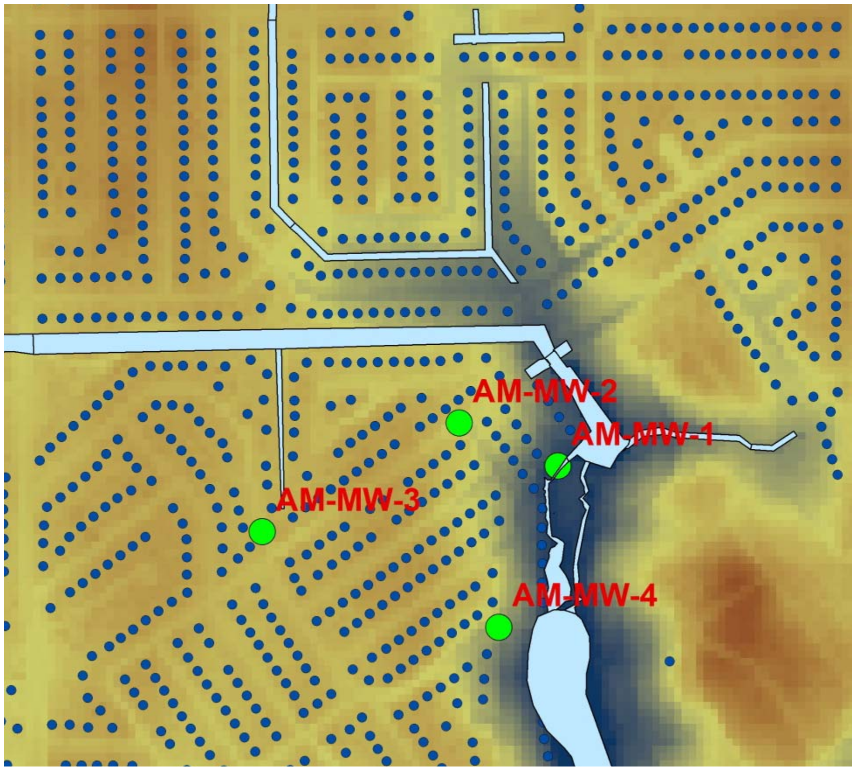
- All input data files are in ArcGIS format.
- Topography (DEM: Digital Elevation Model): Process it to obtain water table
- Locations of septic tanks
- Locations of water bodies
- Hydrogeological and transport parameters
  - Smoothing factor (used to process topograph)
  - Hydraulic conductivity
  - Porosity
  - Dispersivity
  - Decay coefficient of denitrification
  - Source plane dimension and concentration

Requirements on Potential Users

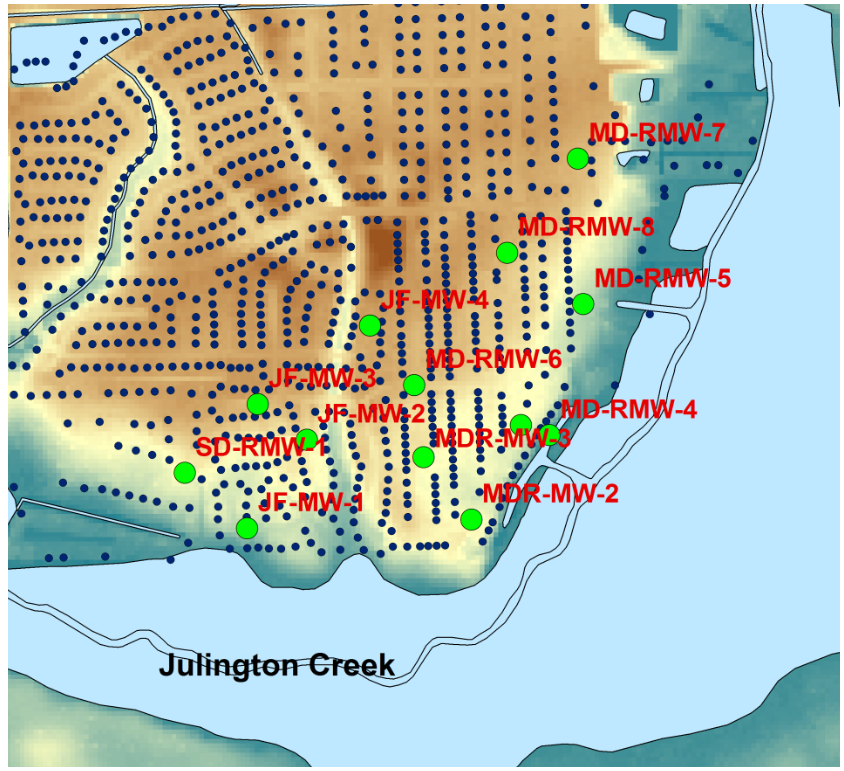
- The GUI make it easier for some with little experience in analyzing groundwater transport problems to apply a solute-transport model to a field problem.
- **Users of ArcNLET need to have**
  - Basic knowledge of hydrogeology such as concepts of groundwater flow and solute transport
  - Intermediate level of ArcGIS skills for preparing input files and visualizing software output files
- The model (simple or complex) is not an end in itself, but a tool by which 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 before using the model for general purposes.

Application at Eggleston Heights and Julington Creek Neighborhoods, Jacksonville

Eggleston Heights with 3,500 OSTDS



Julington Creek with 2,000 OSTDS



Reasons of selecting the two sites:

- Nitrate due to septic systems is believed to be one of the reasons of nutrient enrichment in surface water bodies (Leggette et al., 2004)
- Relatively large amount of observations of hydraulic head and nitrate concentrations are available.

Food for Thought

Victor Baker, the former President of the Geological Society of America, Member of Academy of Sciences, once said:

"Allowing the public to believe that a problem can be resolved … through elegantly formulated … models is the moral equivalent of a lie."

Pilkey, O.H. and L.P. Javis, 2007. Useless Arithmetic – Why Environmental Scientists Can't Predict the Future, New York, Columbia University Press.

Leonard Konikow (2011, Ground Water): "the secret to successful solute-transport modeling may simply be to lower your expectations."

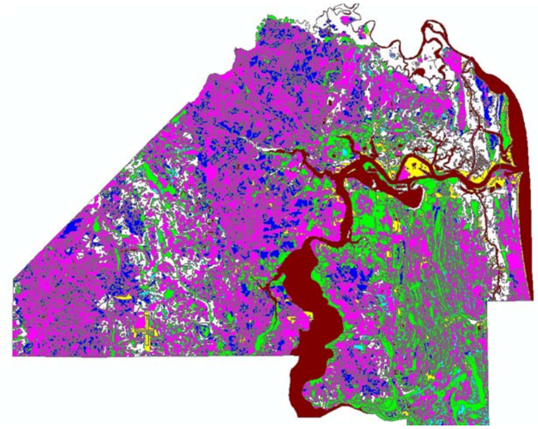
Challenges of Applications

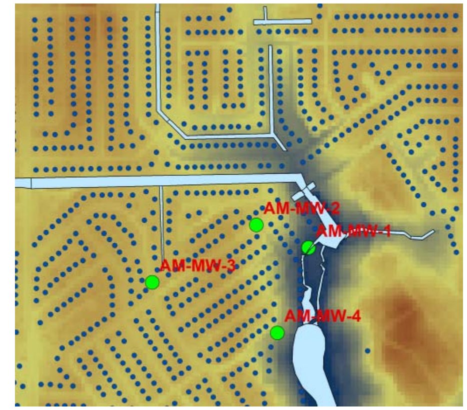
- Keith Beven (2001): The Dalton Lecture
  How far can we go in distributed hydrological modeling?

  "The principles are general and we have at least a qualitative understanding of their implications, but the difficulty comes in the fact that we are required to apply hydrological models in particular catchments, all with their own unique characteristics."
- For a fixed model structure, model outputs are determined by model parameters. However, in most applications, there is no site-specific measurements of model parameters.

What do we have?

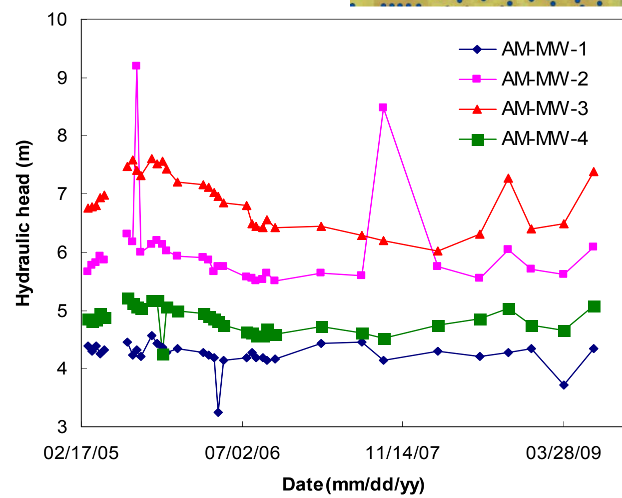
- SSURGO database for Duval County that contains hydraulic conductivity and porosity
- Observations of hydraulic head and nitrate concentration
- Evidence of denitrification

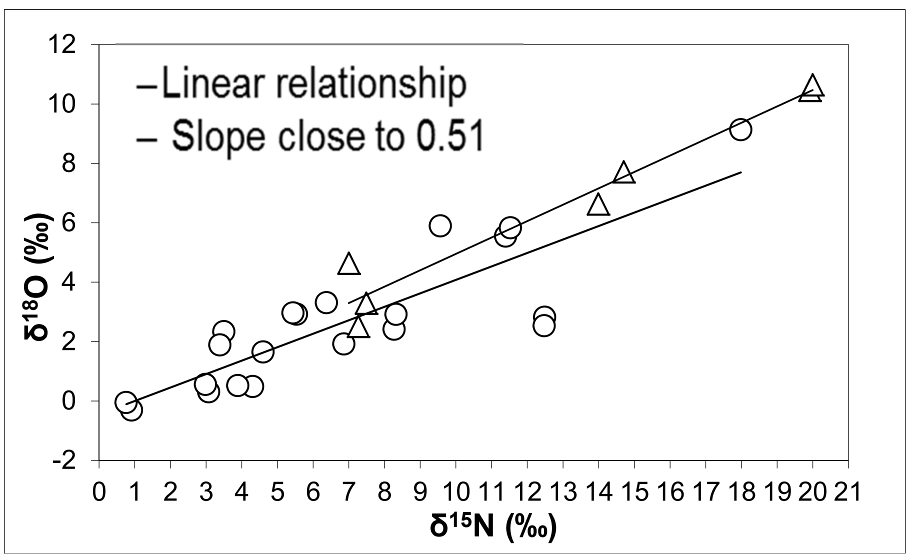


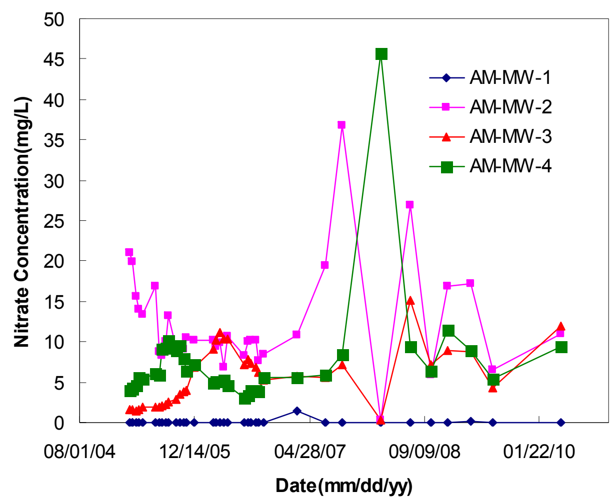


What do we need?

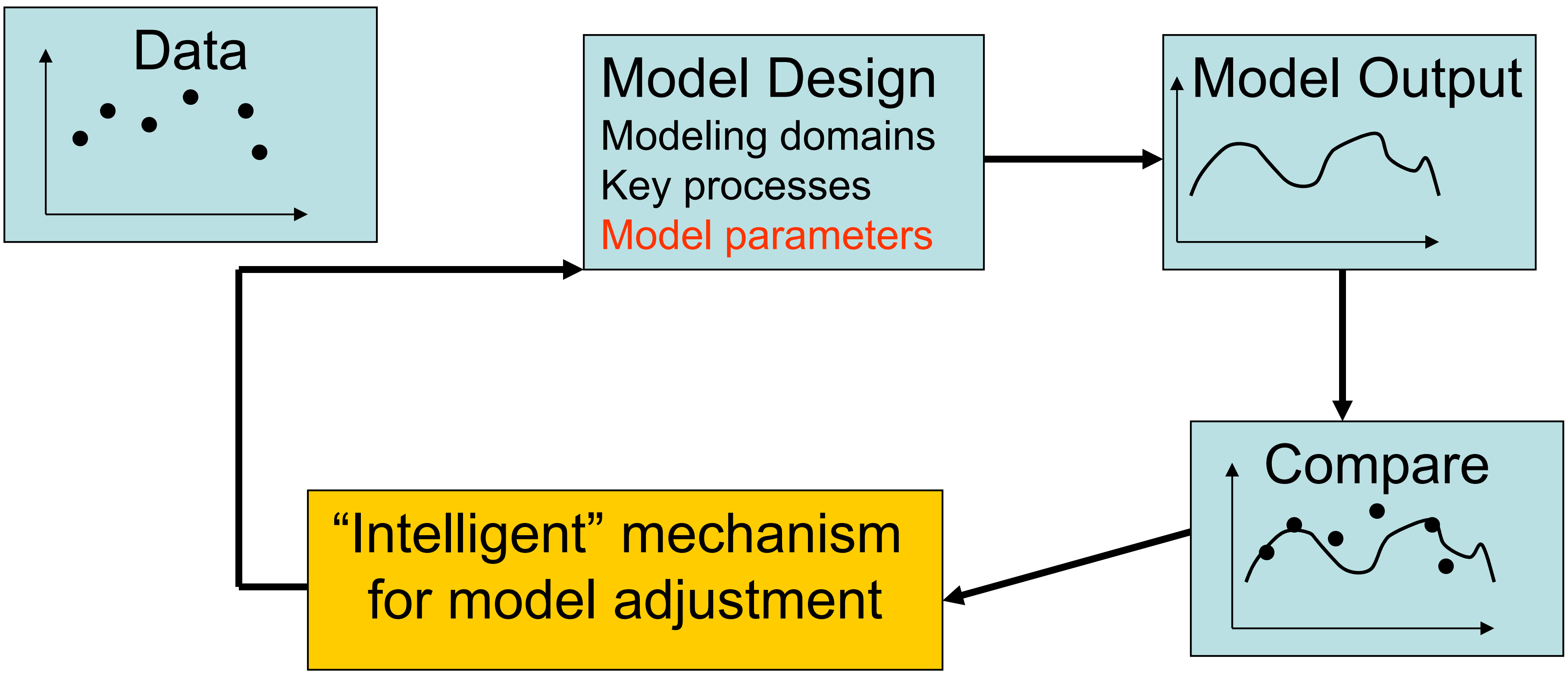
- Smoothing factor
- Dispersivity
- Decay coefficient of denitrification
- Source plane size and concentration







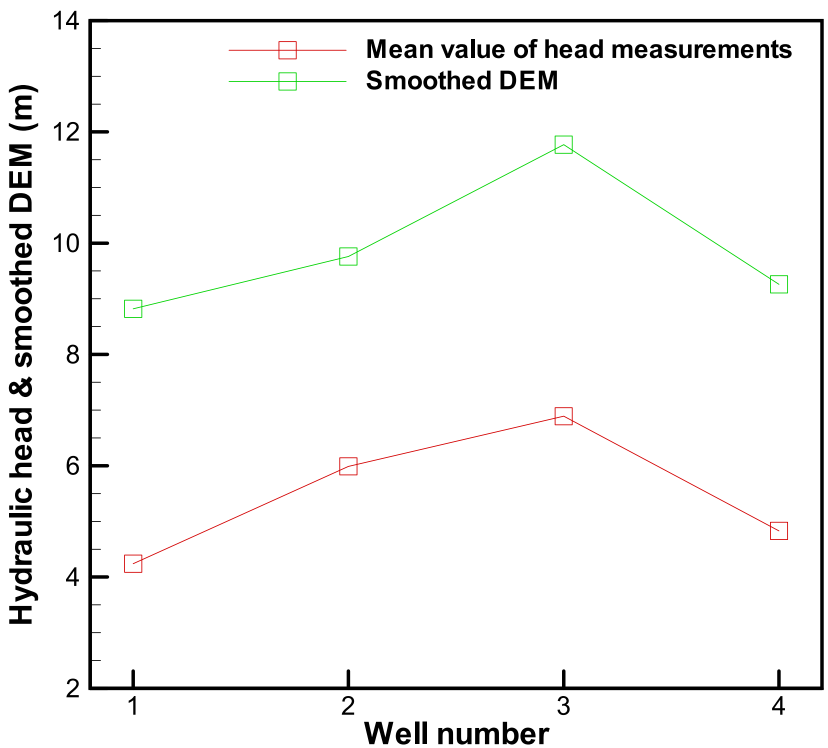
Manual Model Calibration: Trial and Error

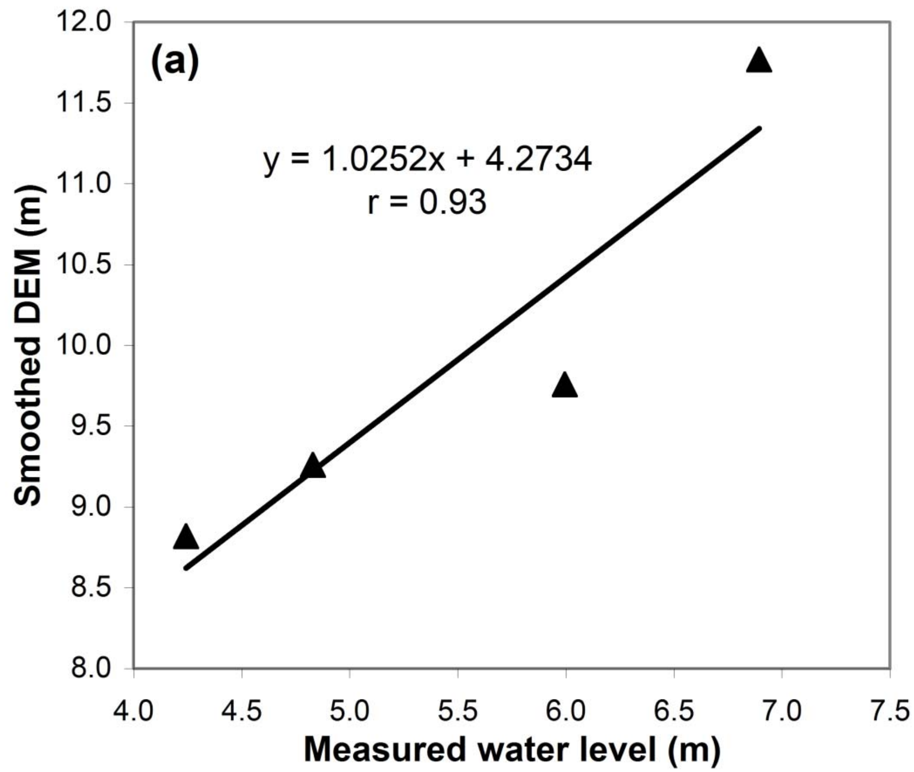


Calibration Results: Heads

Smoothed DEM agree well with mean observed hydraulic head

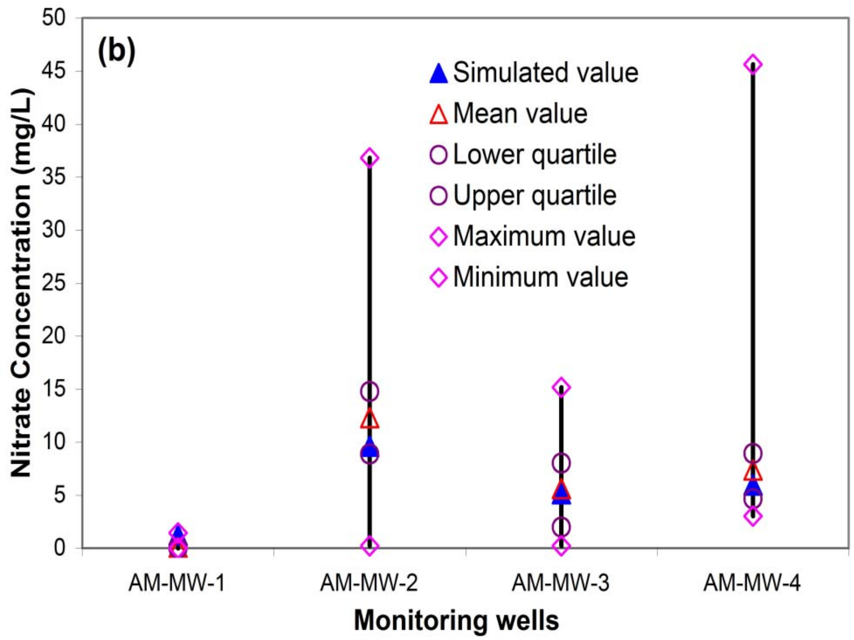
- correlation coefficient of 0.93 and
- the slope of linear regression close to 1.





Calibration Results: Nitrate Concentrations

Eggleston Heights



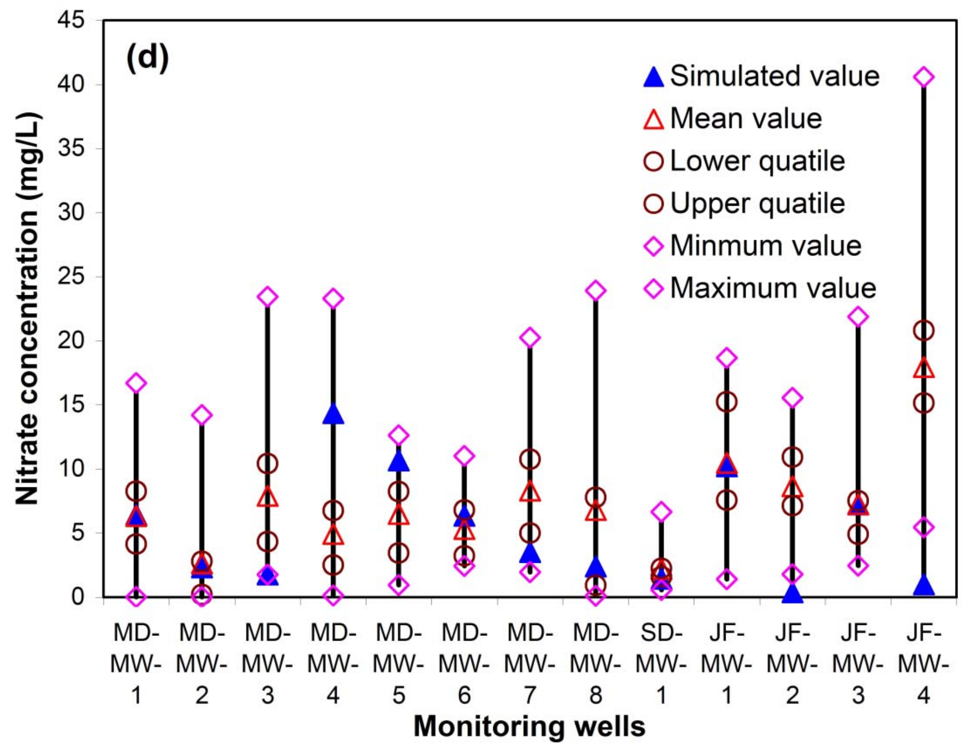
The simulated nitrate concentrations are

- Close to the mean observations, and
- Fall within the inter-quartile of the observed concentrations.

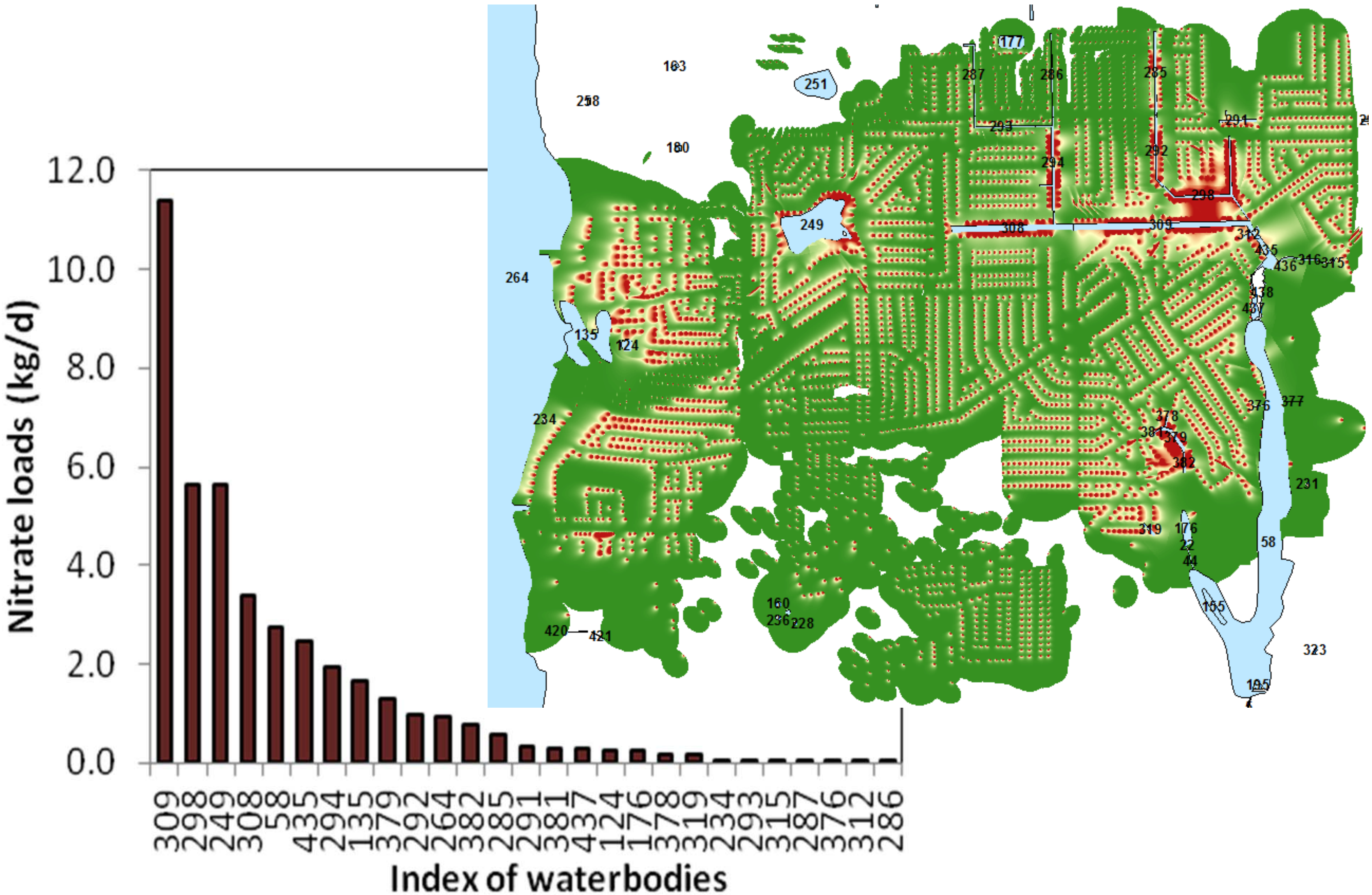
The simulated nitrate concentrations are

- Close to the mean observations at seven out of 13 wells, and
- Fall within the minimum and maximum ranges of the observed concentrations at 11 out of 13 wells.

Julington Creek



Nitrate Load Estimation for Eggleston Heights Neighborhood



Challenges: Uncertainty in Input Parameters and Load Estimates

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

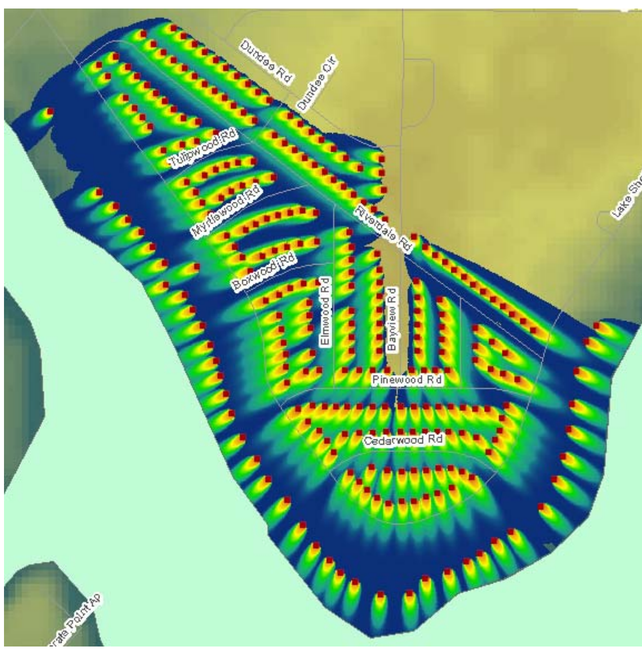
The Unknown
As we know,
There are *known knowns*.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also *unknown unknowns*,
The ones we don't know
We don't know.

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

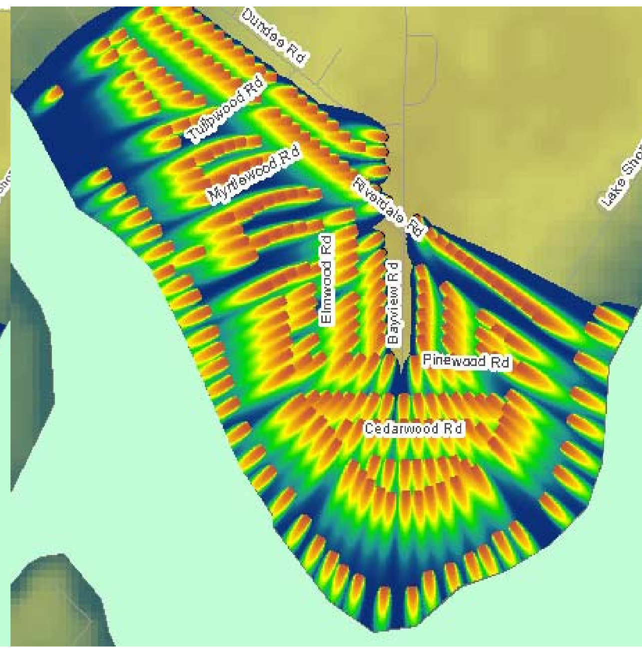
An Illustrative Example

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

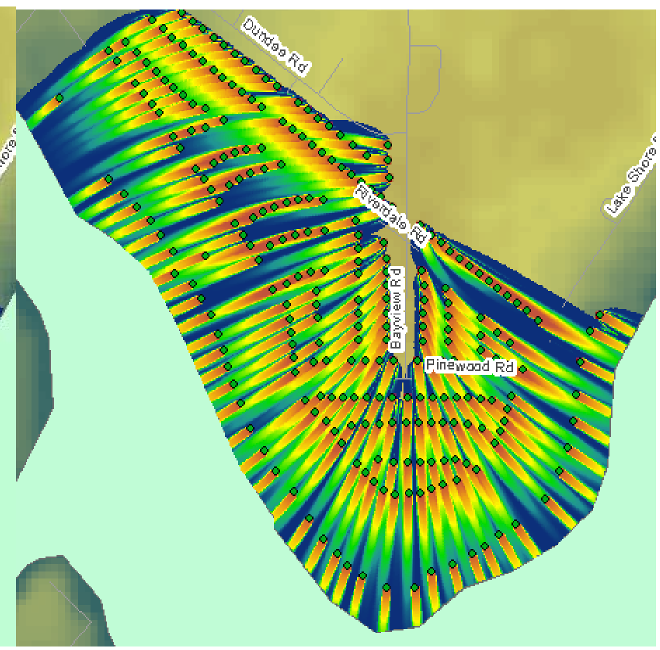
Parameter set 1
Load=0.15 lb/day
α_L=2.113m, α_T=0.234m,
k=0.008/d



Parameter set 2
Load=0.25 lb/day
α_L=2.113m, α_T=0.234m,
k=0.004/d

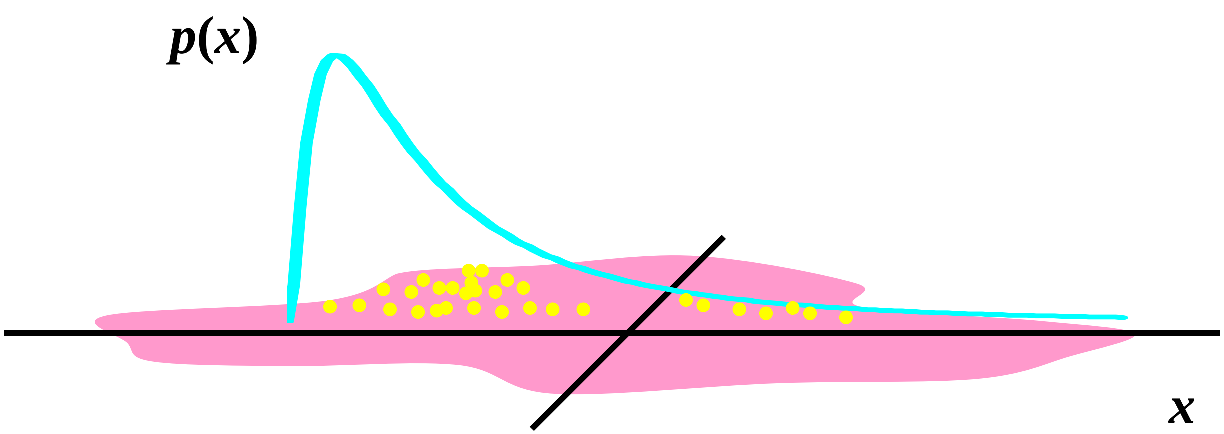


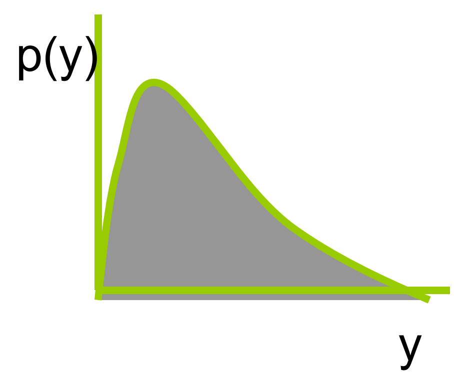
Parameter set 3
Load=0.60 lb/day
α_L=21.34m,α_T=0.021m
k=0.004/d



Monte Carlo Method to Address Parametric Uncertainty

- Identify random parameters X and their distributions *p*(x) (uncertainty characterization)
- Draw samples (x) from the distributions
- Run the model, y=f(x), for each sample
- Obtain probability density function, p(y) of desired predictions





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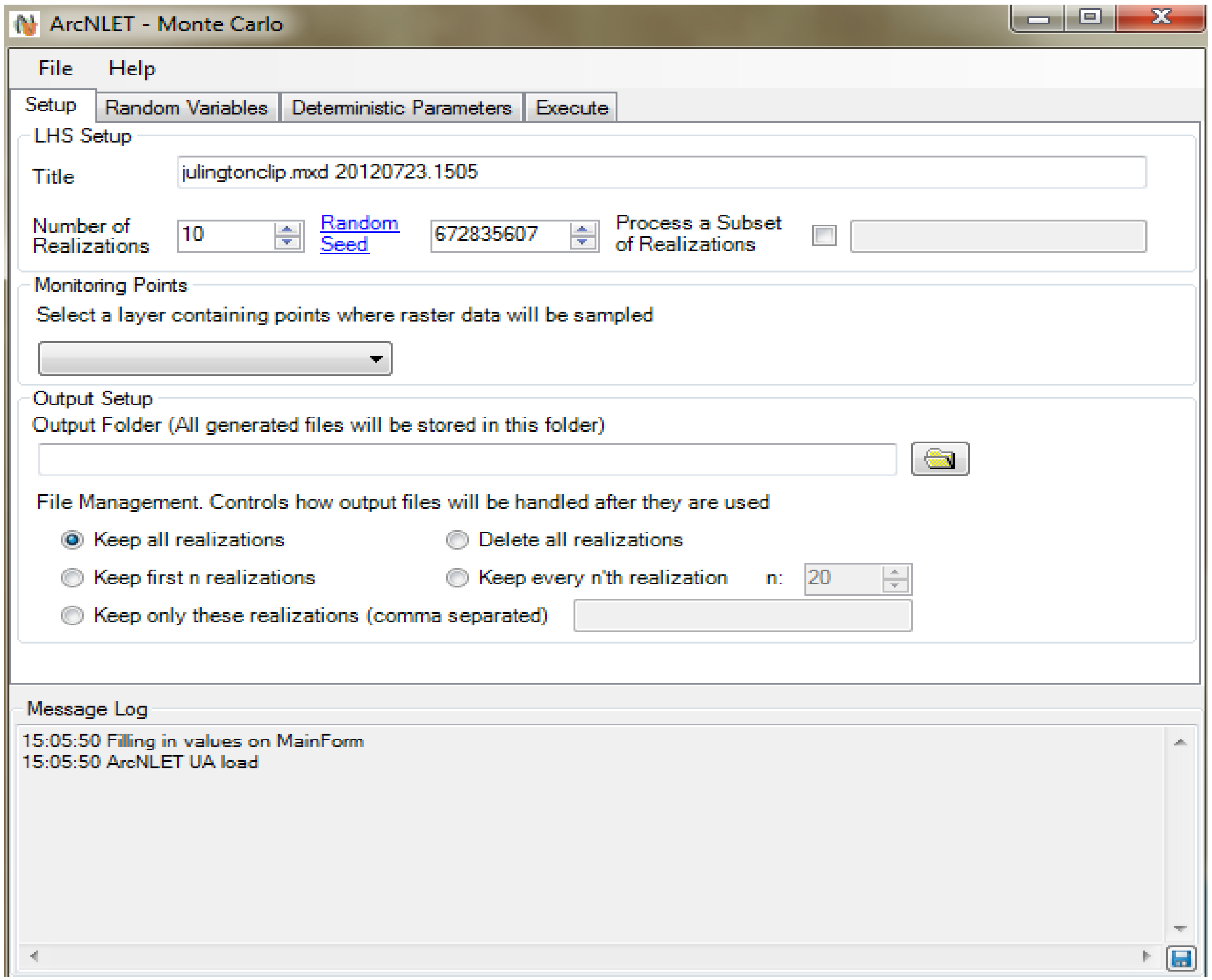
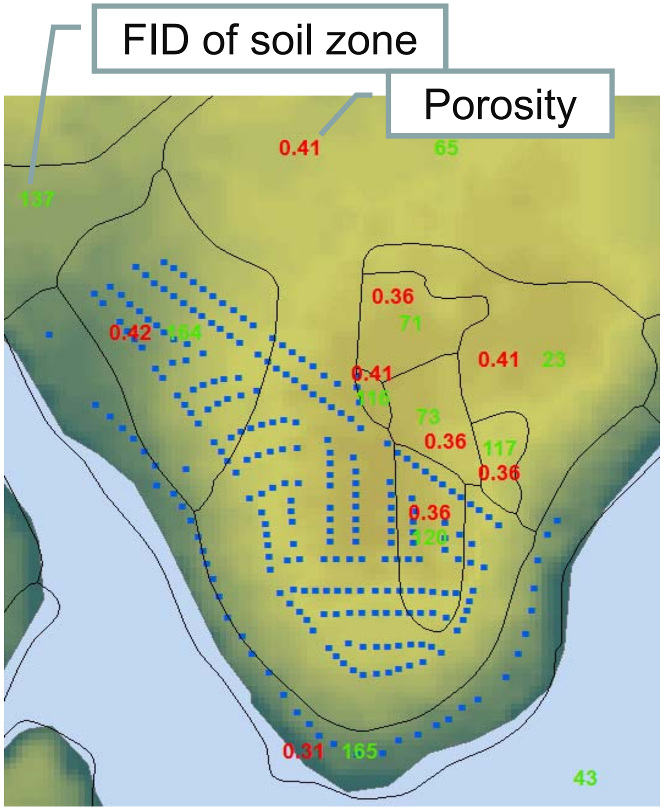
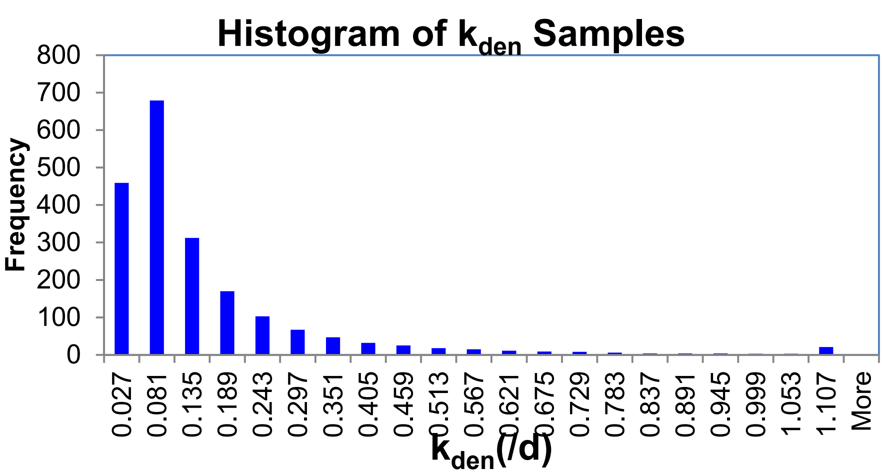
ArcNLET-MC for Uncertainty Quantification

Recently developed. Have not been released.



Random Parameter and Their Distributions



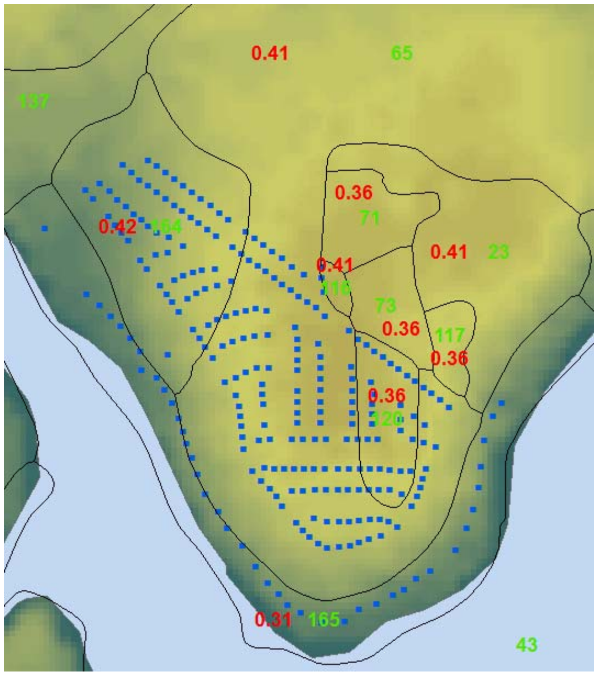


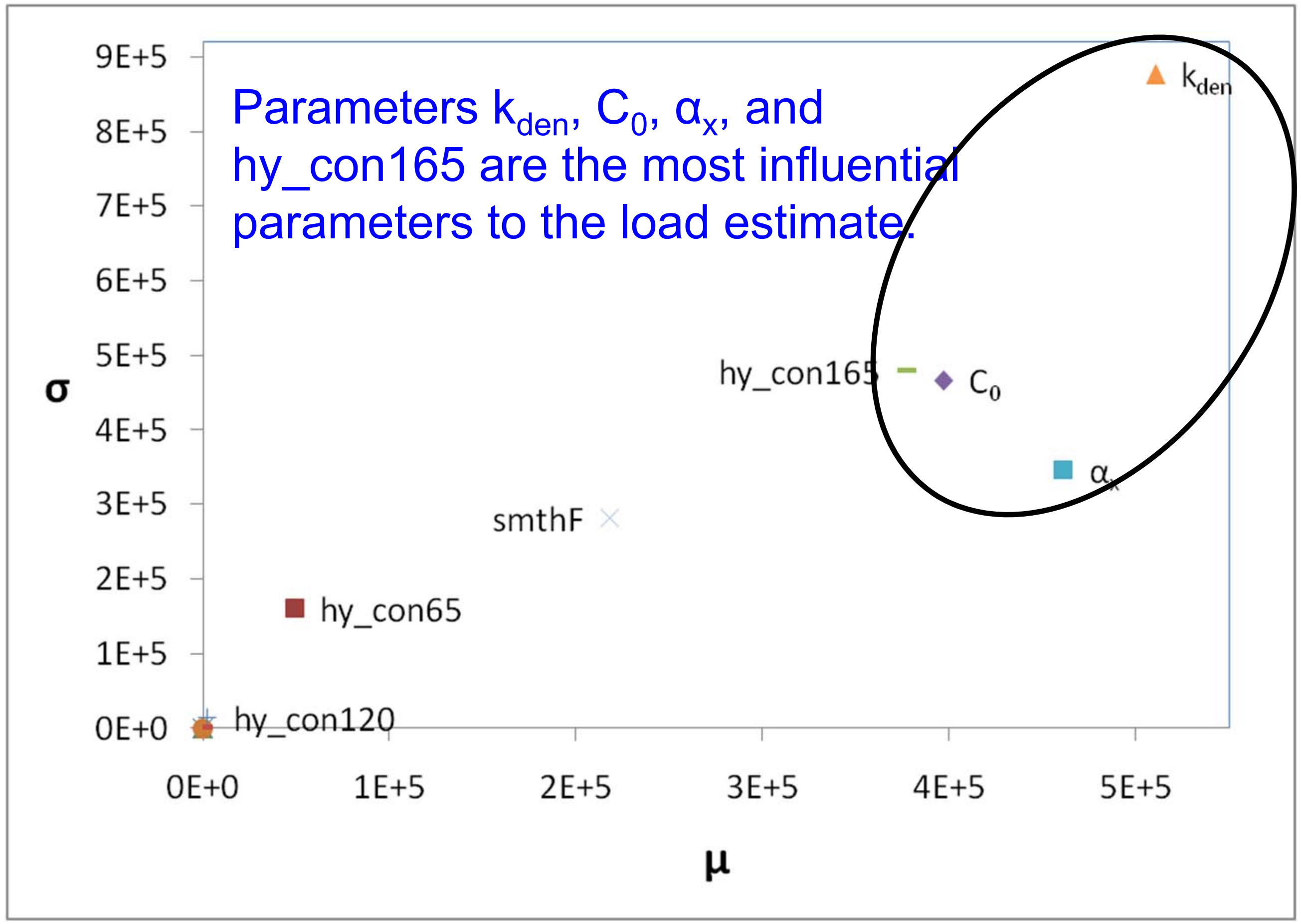
Maximum, minimum and representative values of hydraulic conductivity is derived from soil data

Parameter	Distribution	Max	Representative	Min
hy_con23	TRIANGULAR	3.6593	7.9488	12.1976
hy_con65	TRIANGULAR	3.6593	7.9488	12.1976
hy_con71	TRIANGULAR	0.122	0.6705	1.2198
hy_con73	TRIANGULAR	0.122	0.6705	1.2198
hy_con116	TRIANGULAR	3.6593	7.9488	12.1976
hy_con117	TRIANGULAR	0.122	0.6705	1.2198
hy_con120	TRIANGULAR	1.2198	6.696	12.1976
hy_con164	TRIANGULAR	0.122	0.6912	1.2198
hy_con165	TRIANGULAR	12.1824	21.3408	30.4992
C_0	NORMAL	25		80
α_x	NORMAL	0.21		21.34
k_{den}	LOGNORMAL	0.004		1.08
smthF	UNIFORM	20		80

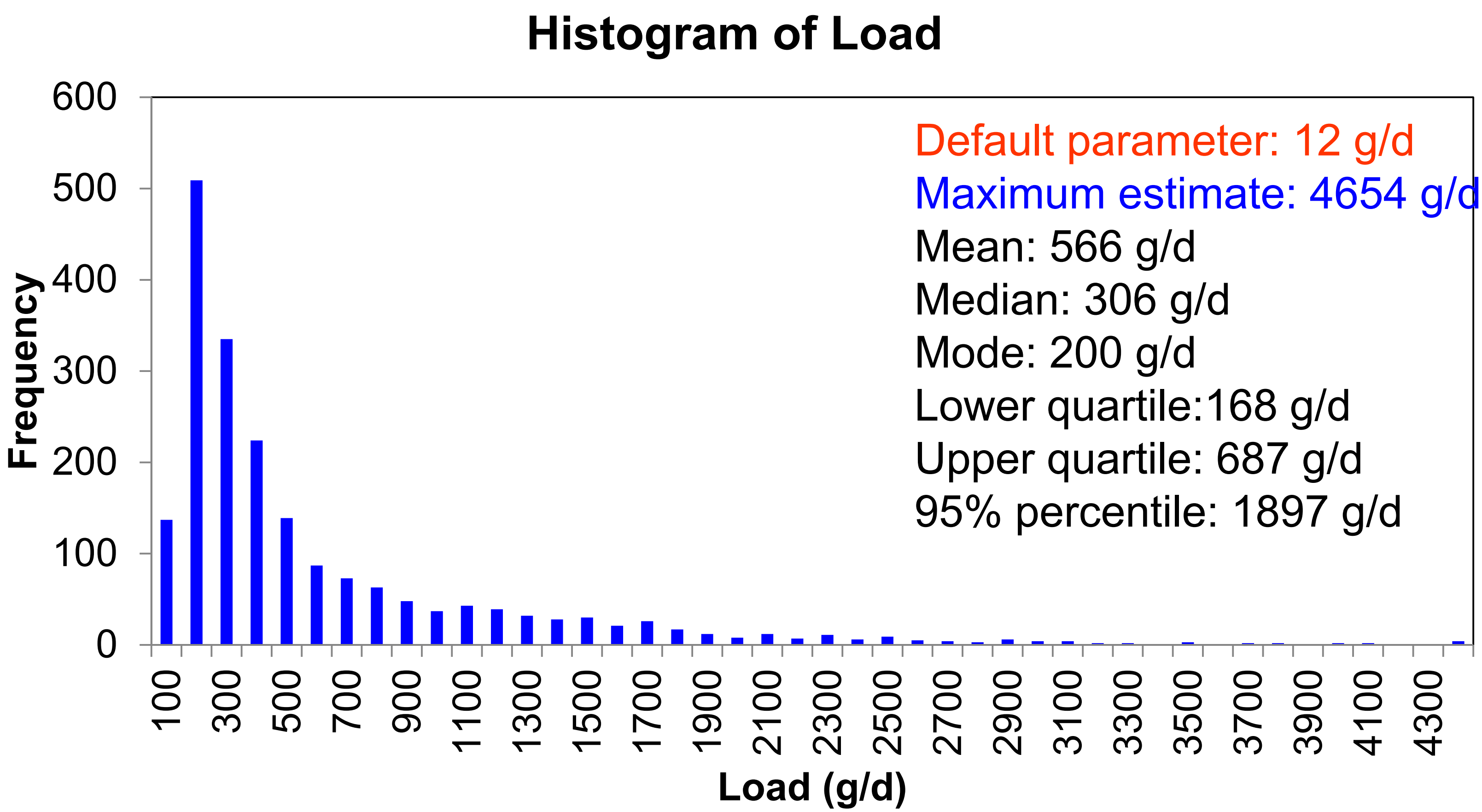
Distributions of LHS Samples

Identify Influential Model Parameters





Uncertainty Analysis

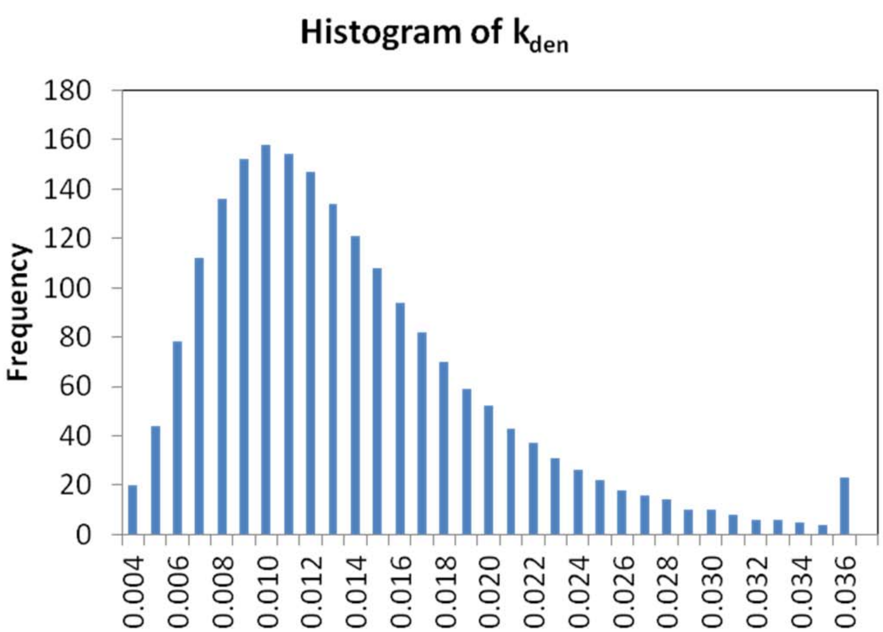


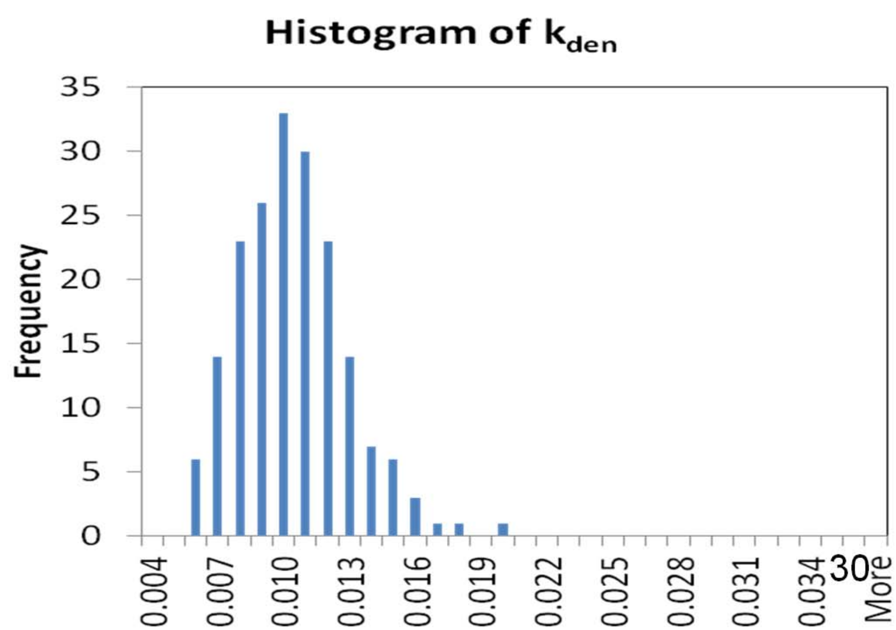
- The load estimation has large uncertainty.
- The uncertainty is inherent but can be reduced if more data and information becomes available.

Uncertainty Reduction by Field Observations

- The parametric uncertainty can be reduced dramatically by incorporating the field observations into model calibration.
- Take the first-order decay coefficient as an example.

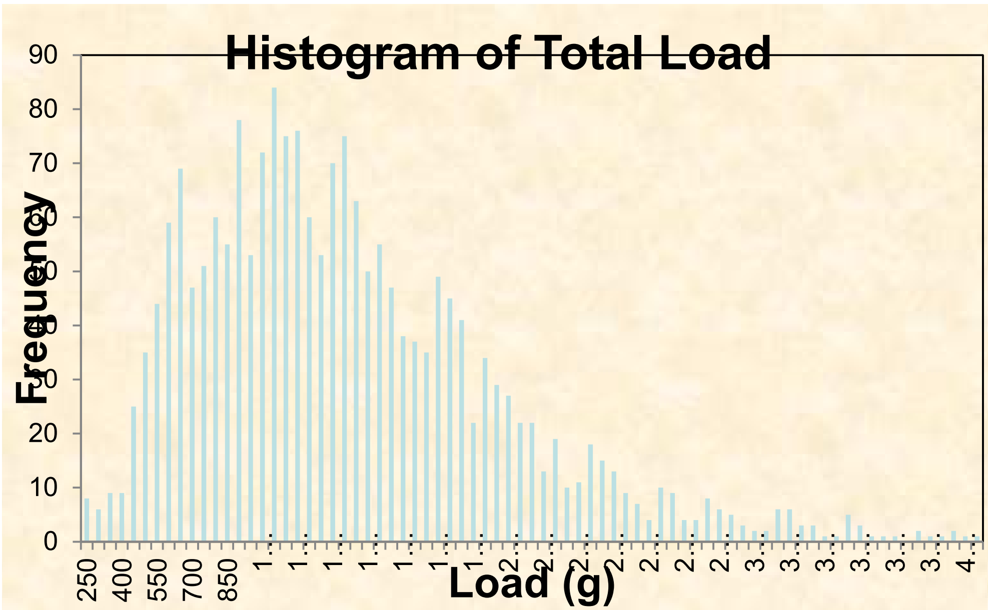
Minimum	0.004	Minimum	0.005
Maximum	0.036	Maximum	0.019



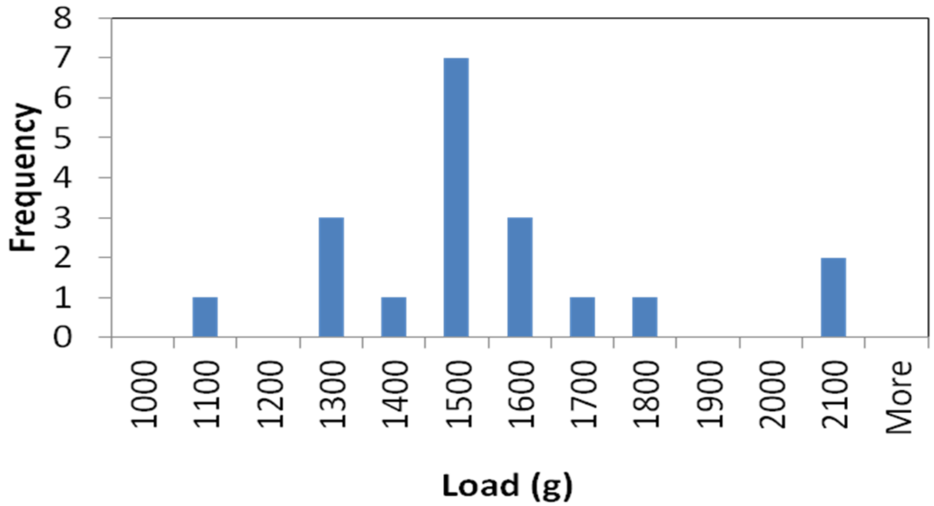


Uncertainty Reduction of Load Estimation

Load estimates before incorporating field observations.

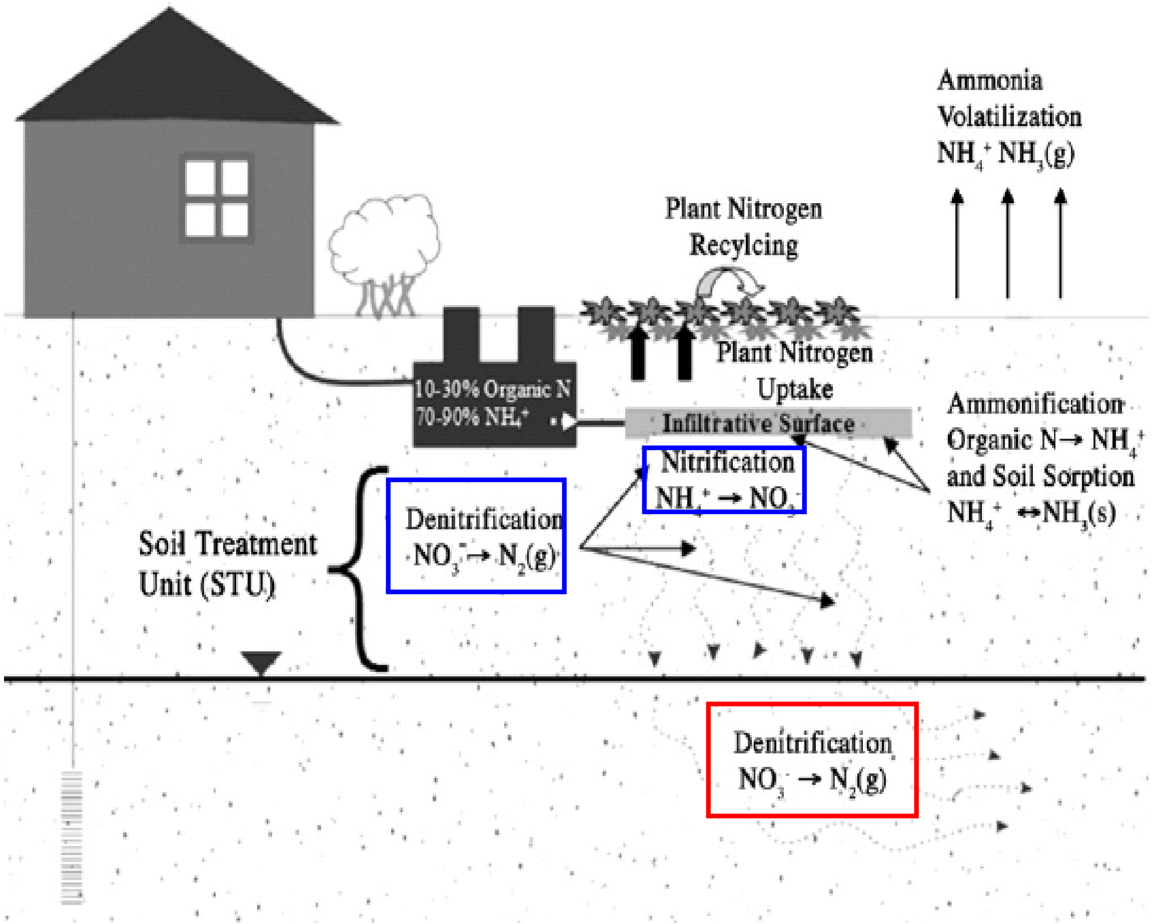


Mean	1334.48
Median	1225.43
Standard Deviation	652.61
Minimum	177.62
Maximum	5655.87
Realizations	2000
95th percentile	2581.89
5th percentile	513.28



Mean	1504.24
Median	1466.39
Standard Deviation	257.08
Minimum	1048.57
Maximum	2078.18
Realizations	19

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



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Soil Processes: Simulated using VZMOD

- Unsaturated flow
- Solute transport
- Nitrification and denitrification

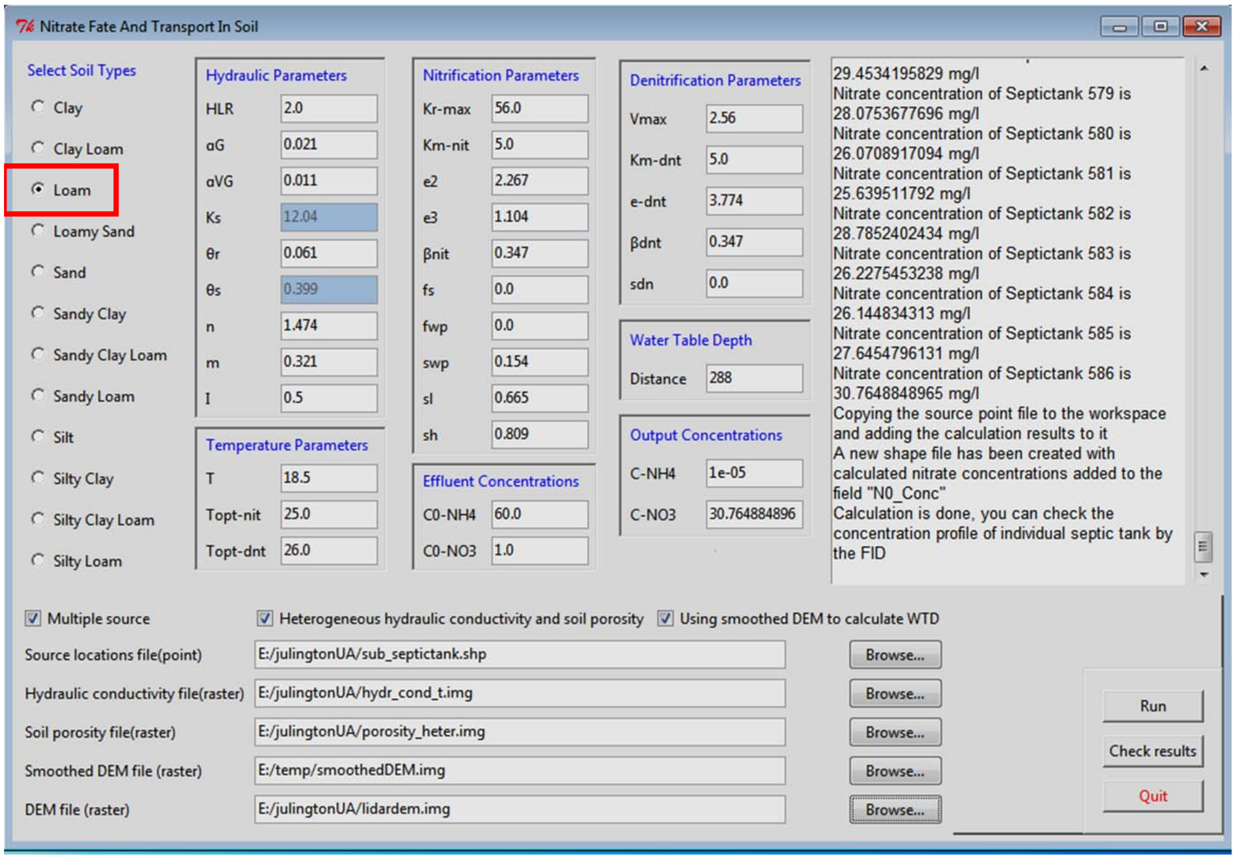
Groundwater Process: Simulated using ArcNLET

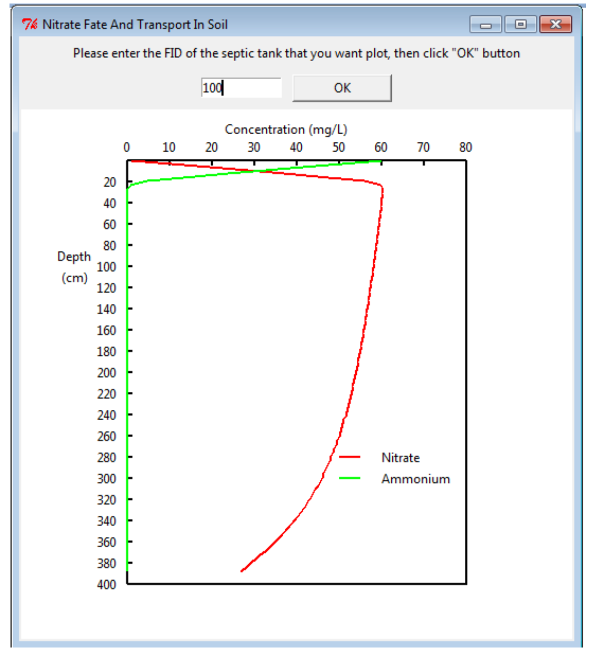
- Groundwater flow
- Solute transport
- Denitrification

ArcNLET-MC: Quantify uncertainty of ArcNLET simulations

Illustration for loamy soil

- Share data files of ArcNLET such as raster files of DEM, hydraulic conductivity and porosity.
- Model parameters for various soil types.
- Estimate nitrate load to groundwater for multiple septic tanks.





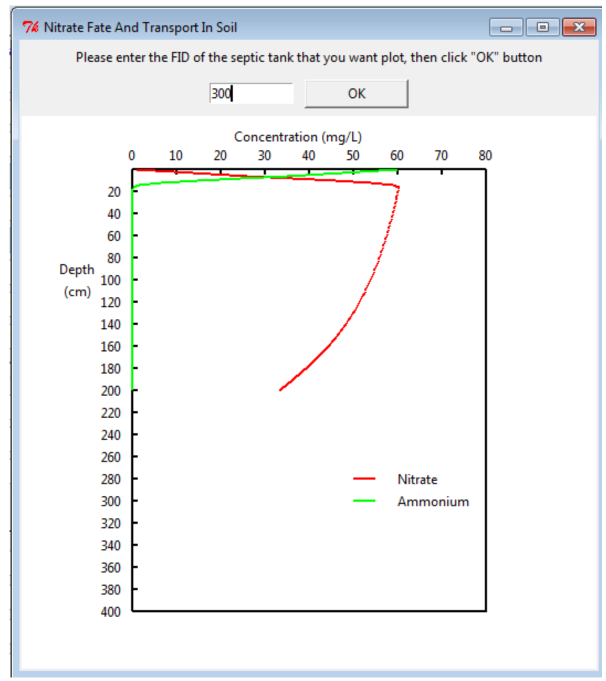
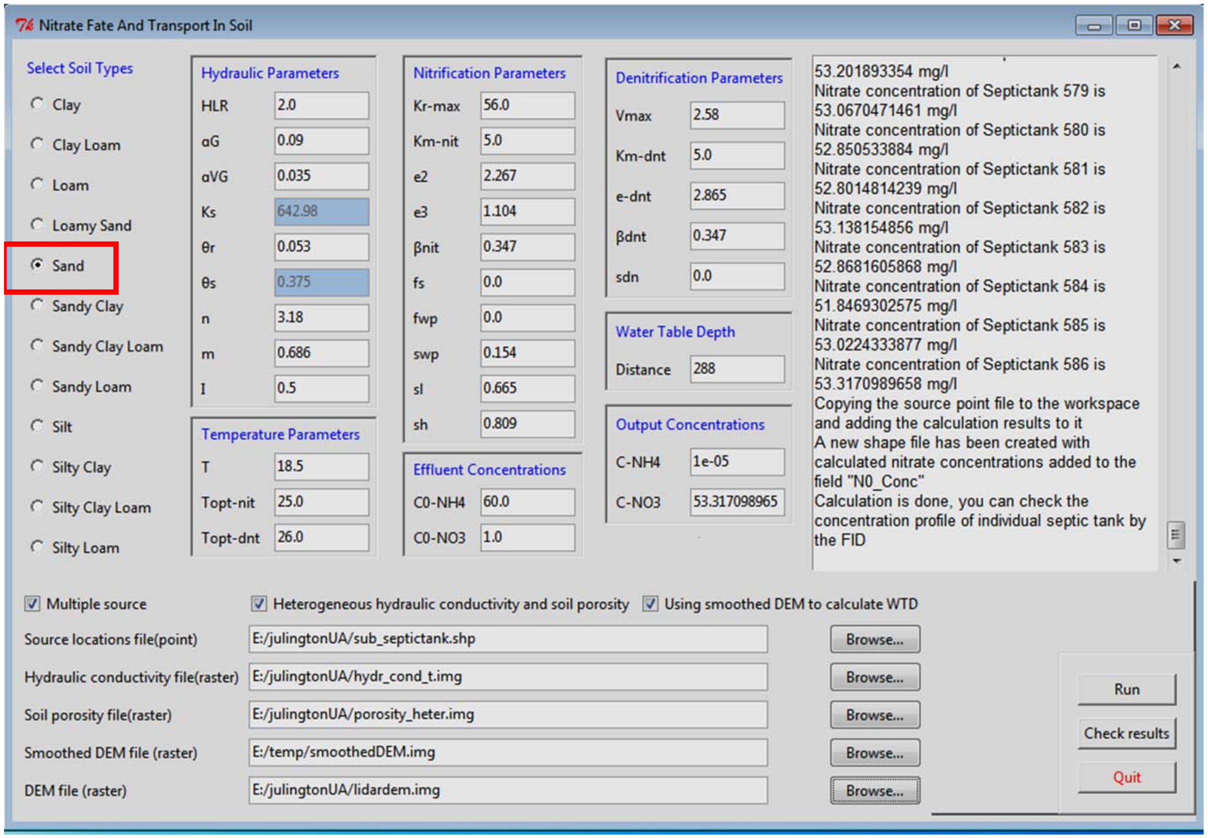
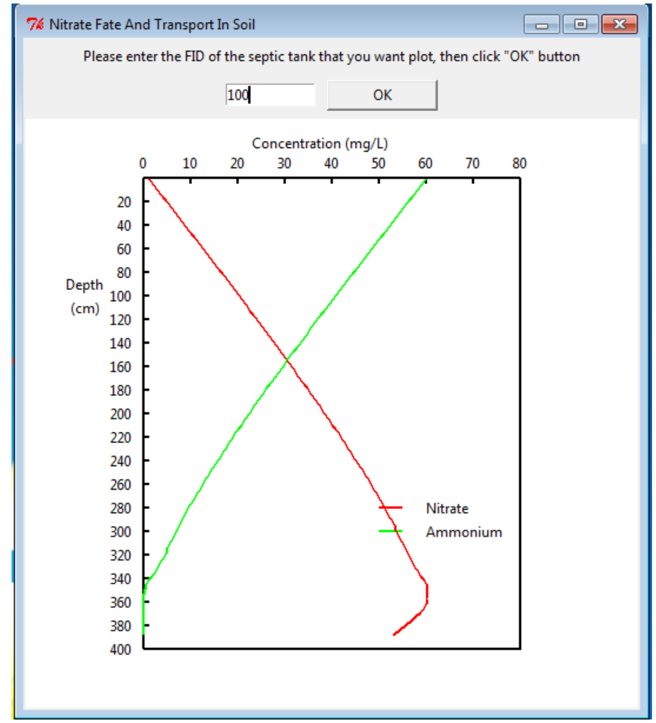
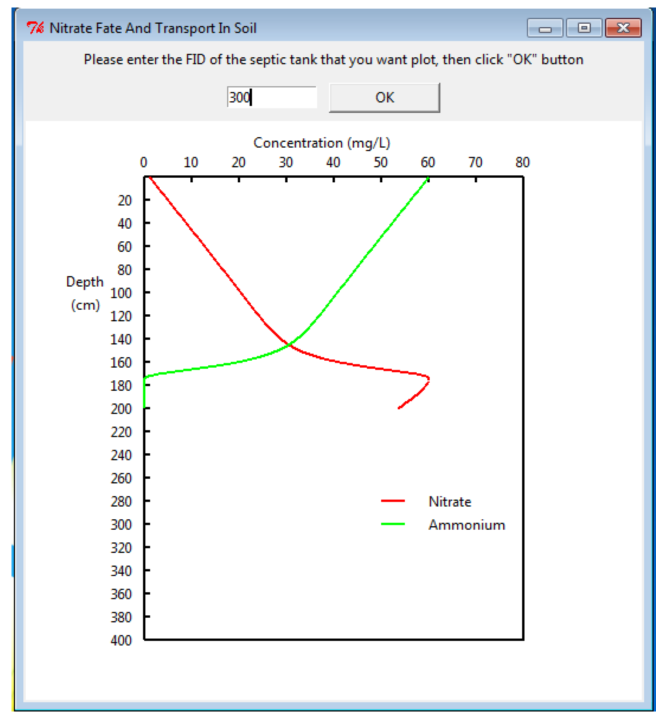


Illustration for sandy soil







On-going and Future Research

- Analyzing monitoring data collected with SJRWMD support to better understand hydrogeology and nitrogen dynamics in neighborhoods of Jacksonville (e.g., controlling factors of nitrogen concentrations)
- Validating ArcNLET using existing and new data such as groundwater baseflow collected by the City
- Supporting FDEP on an effort of selecting representative sites to better characterizing model parameters
- Developing new functions of ArcNLET, e.g., simulating ammonium concentrations
- Applying ArcNLET to other sites in Florida

References

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

  - Rios, J.F. (student), M. Ye, L. Wang, P.Z. Lee, H. Davis, and R.W. Hicks, 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, 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.

Questions, Suggestions, and Comments?