

Picture from USGS Scientific Investigations Report 2008-5220

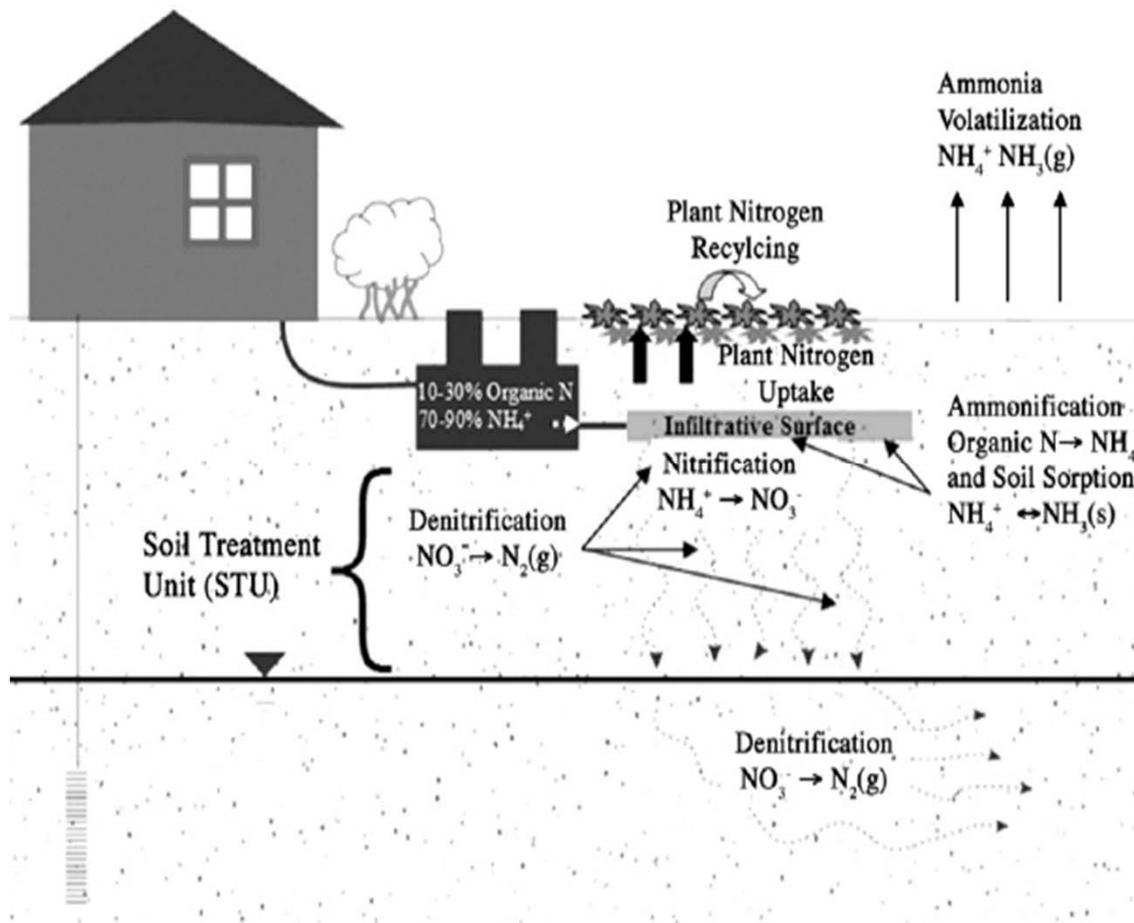
# Estimation of **Nitrate Load** from **Septic Systems** to **Surface Water Bodies** Using **ArcNLET**: an ArcGIS-Based Nitrate Load Estimation Toolkit

Ming Ye ([mye@fsu.edu](mailto:mye@fsu.edu)), Fernando Rios, Liying Wang  
Department of Scientific Computing, [Florida State University](#)

Richard W. Hicks and Paul Z. Lee  
Section of Groundwater and Springs Protection  
Bureau of Watershed Restoration  
[Florida Department of Environmental Protection](#)

Supported by Project WM956 of FDEP

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

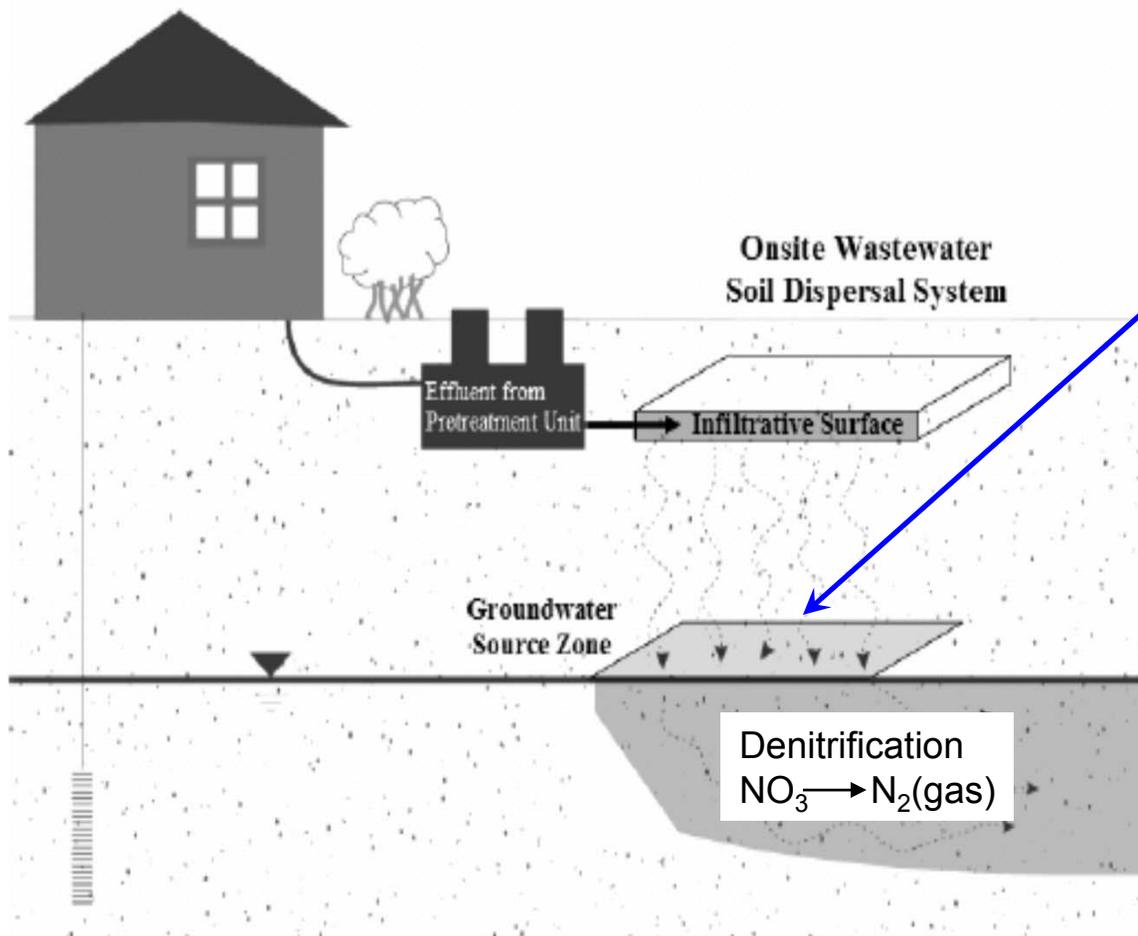


Approximately one-third of the population of Florida utilizes OWTS for wastewater treatment. (Ursin and Roeder, 2008, FDOH)

Ninety percent of the water used for drinking comes from the ground water. (FDEP, 2006)

From Heatwole and McCray (2007)

# Nitrate Fate and Transport in Groundwater



Due to nitrification in the vadose zone, OSTDS can generate  $\text{NO}_3\text{-N}$  concentration at the water table from **25 to 80** mg N/L in most situations (McCray et al., 2005).

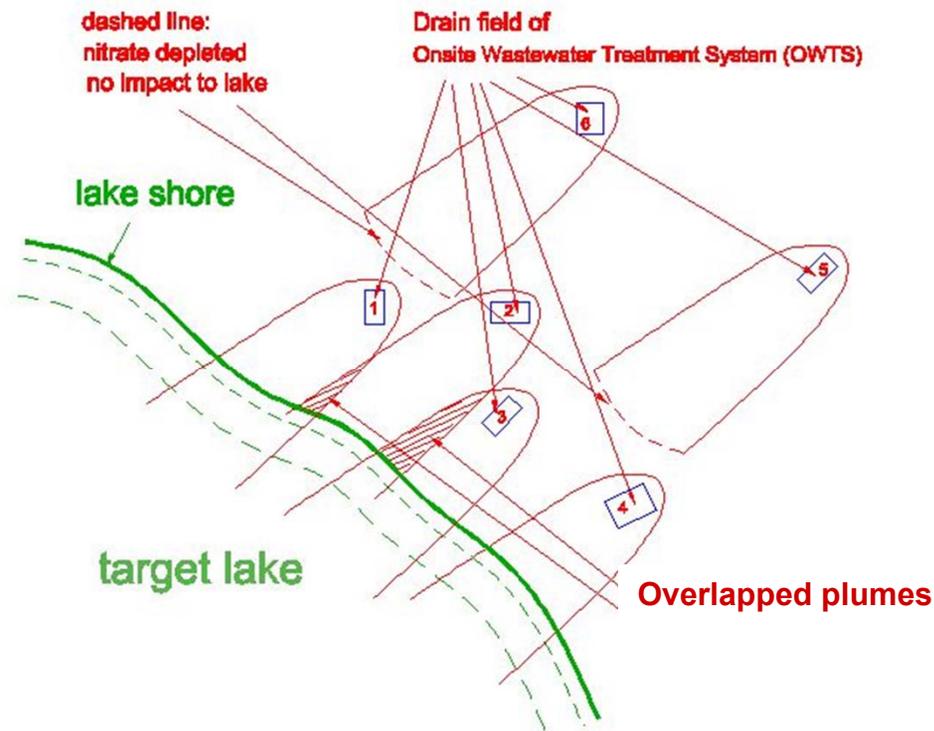
Denitrification ... has been identified as **basic factor** contributing to the generally low levels of nitrate found in the **groundwater of the southeastern United States** (Fedkiw, 1991).

From Heatwole and McCray (2007)

# Motivations

Traditional estimate of nitrate loading (e.g., in TMDL) may **ignore**

- Nitrate from normally working septic systems
- **Denitrification** process in groundwater occurring between drainfield and surface water body
- Effect of spatial locations of septic systems on nitrate load



# Motivations

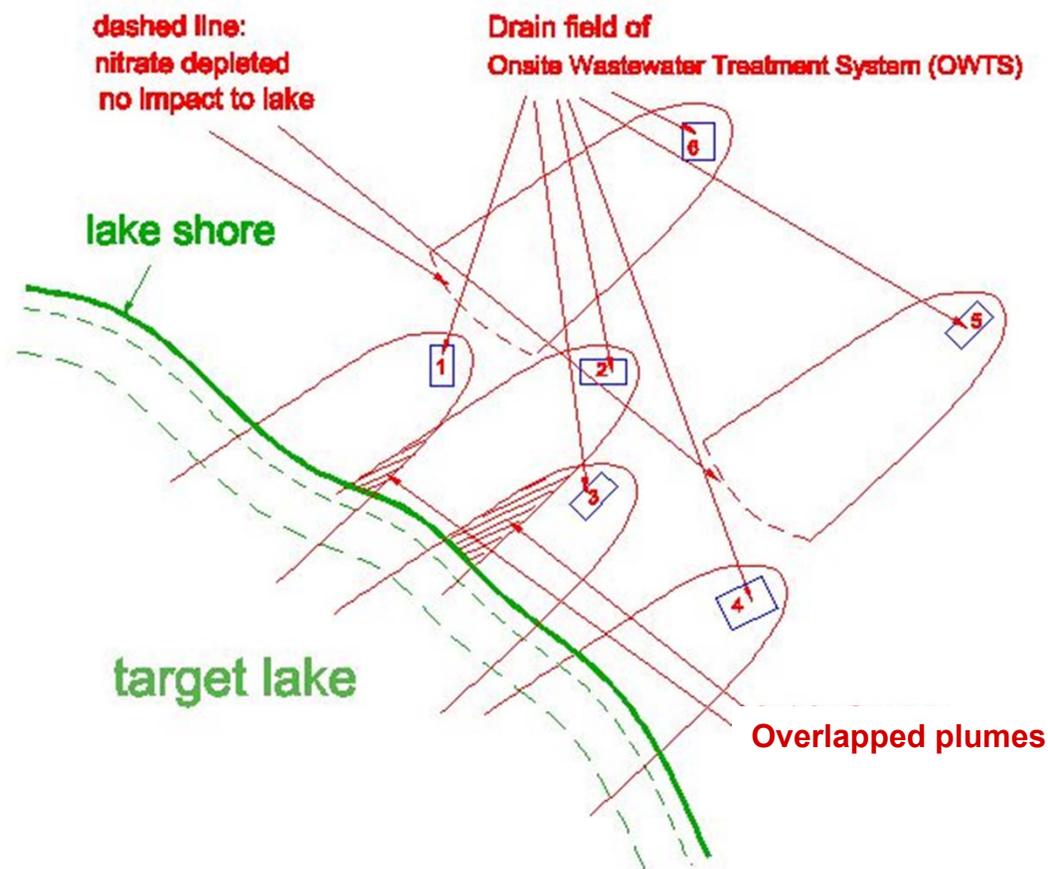
- **Consequence**
  - Under-estimation of nitrate load by ignoring working septic systems
  - Over-estimation of nitrate load by ignoring denitrification
- **Sophisticated numerical models** have been developed to study fate and transport of nitrate from septic system, but they may not be the most suitable tool for certain types of estimation (e.g., in TMDL) for the following reasons:
  - Burden for general users to set up model runs
  - Trained professional to operate the models and interpret modeling results
  - Large input and calibration data and long time of model execution and calibration

# Project Goal

- Goal:** To develop a **simplified model** and software to support the TMDL and other environmental projects.
- It should be **scientifically defensible** under scrutiny.
  - It should be **user-friendly, easy to use, and GIS-based** to incorporate location information for both septic tank cluster and surface water receiving nitrate load.
  - It should be **available in public domain**, to be used by all parties, including the challengers and for comparison reasons

# Conceptual Model

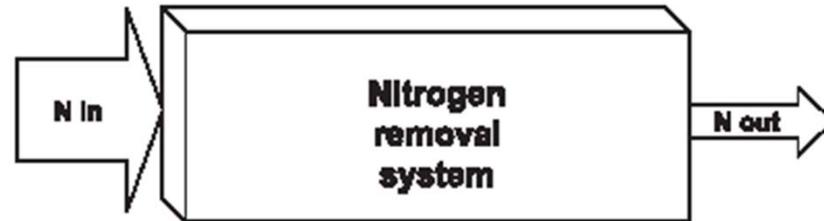
Consider key hydrogeologic processes involved in nitrate transport:



- **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

# Estimation of Nitrate Load

$$M_{in} = M_{out} + M_{dn}$$
$$M_{out} = M_{in} - M_{dn}$$



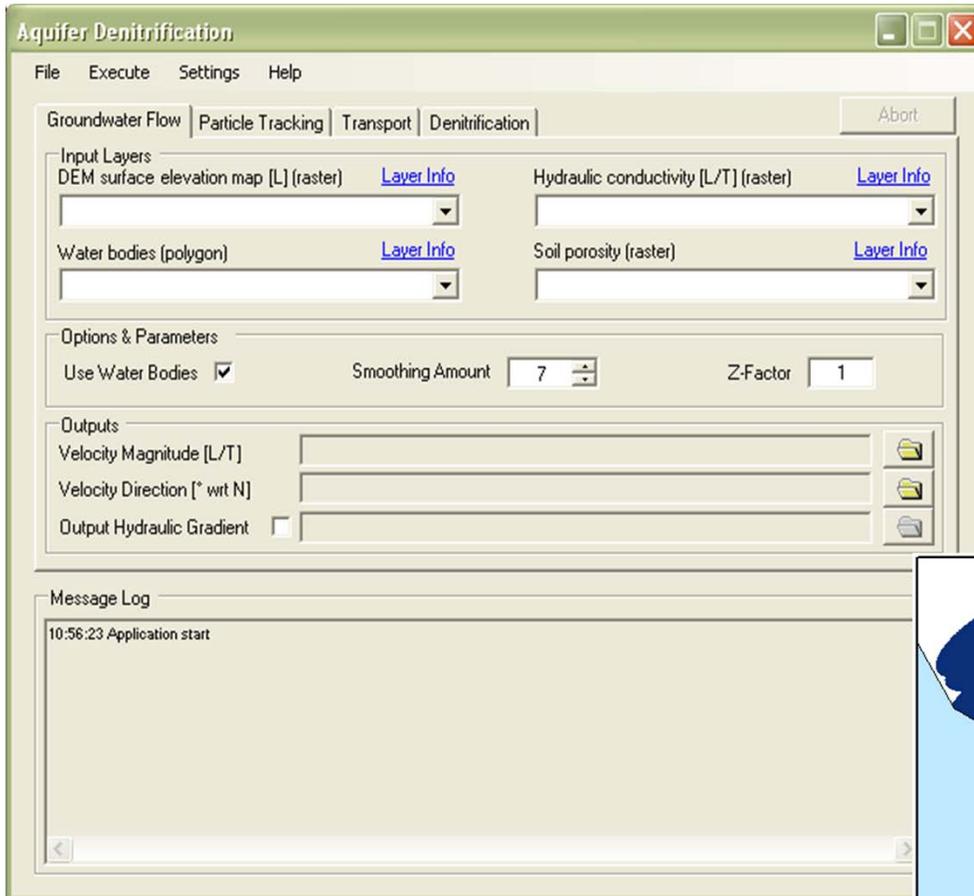
- $M_{out}$  (M/T): nitrate load to rivers
- $M_{in}$  (M/T): nitrate from septic tanks to surficial aquifer
- $M_{dn}$  (M/T): nitrate loss due to **denitrification**

$$M_{dn} = R_{dn} V_g$$

$R_{dn}$  (M/T/L<sup>3</sup>): denitrification rate

$V_g$  (L<sup>3</sup>): volume of groundwater solution, estimated from groundwater flow and reactive transport modeling

# Graphic User Interface (GUI)

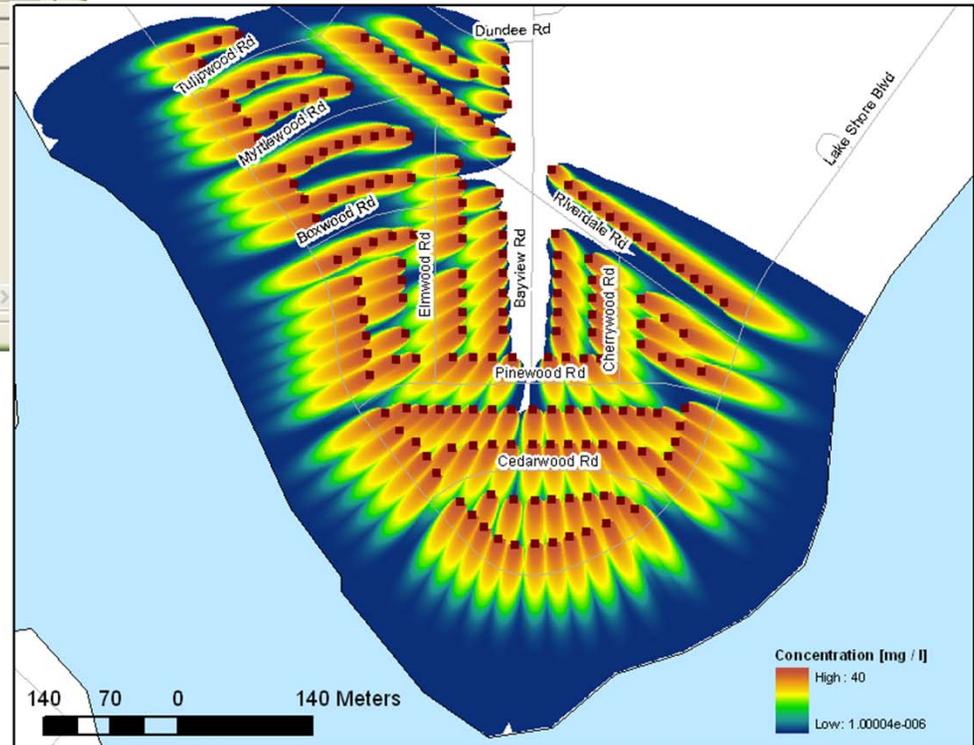


# ArcNLET

The software is developed as an extension of ArcGIS 9.3 and ArcGIS 10

Free download at <http://people.sc.fsu.edu/~mye/ArcNLET/>

Example of simulated nitrate plumes



# Filed Application at Eggleston Heights and Julington Creek Neighborhoods, Jacksonville, FL

Eggleston Heights with 3,500 OSTDS



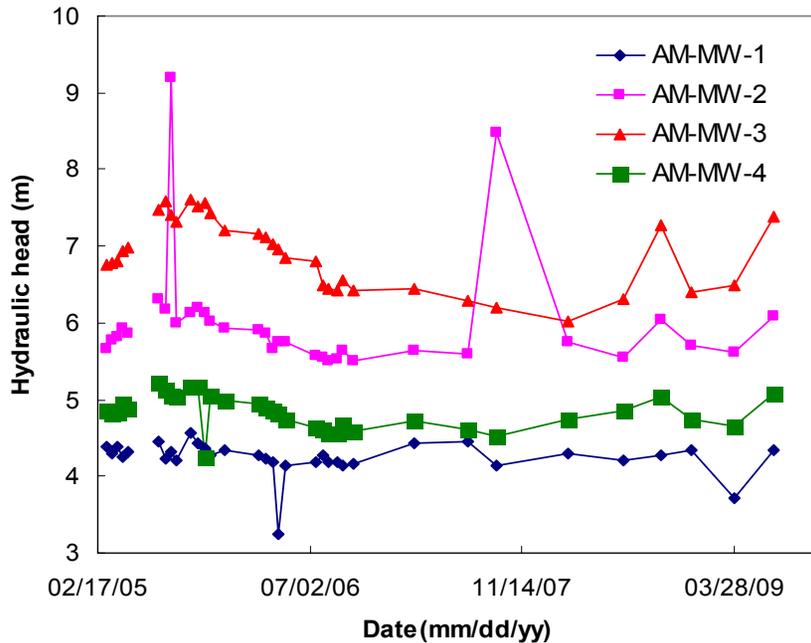
Julington Creek with 2,000 OSTDS



Reasons of selecting the two sites:

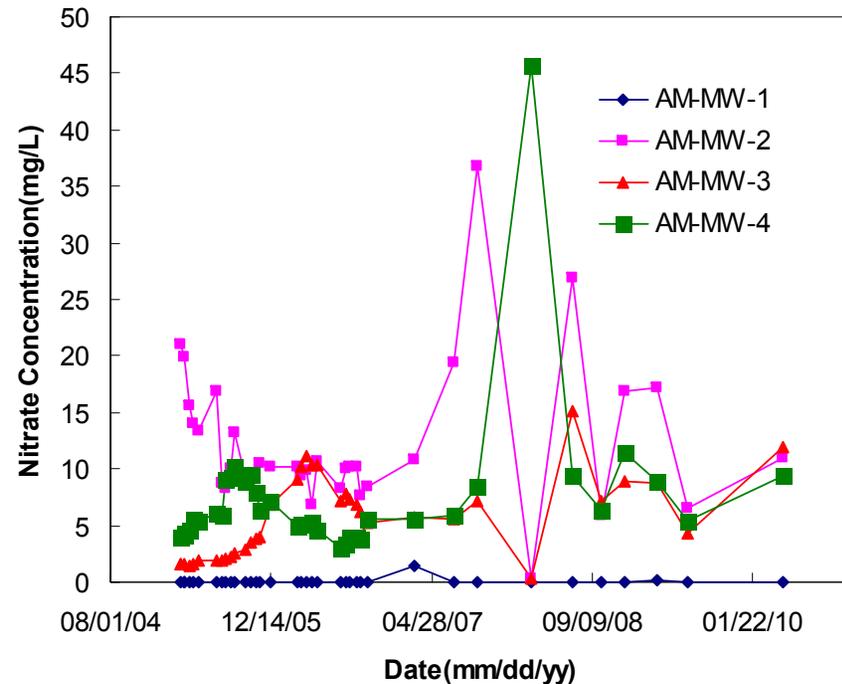
- Nitrate due to septic systems is believed to be one of the reasons of nutrient enrichment in surface water bodies (Leggette et al., 2004)
- Relatively large amount of observations of hydraulic head and nitrate concentrations are available.

# Observations of Hydraulic Head and Nitrate Concentration



- The observed concentrations have large fluctuation due to complicated nitrogen transport and transformation mechanisms.
- No trend is observed.
- The mean value and ranges between upper and lower quartile are used as the calibration targets.

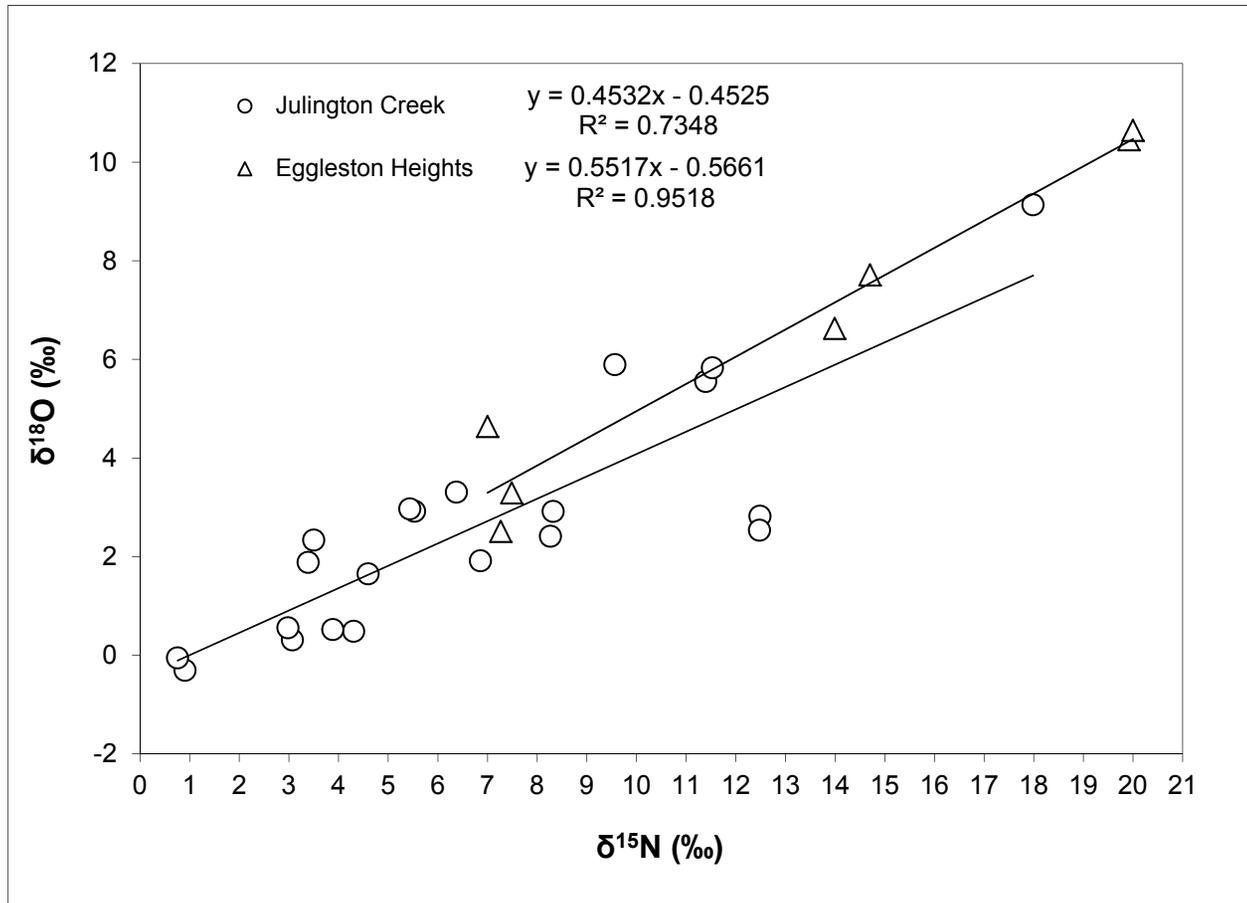
- The observed water tables are relatively stable.
- It is reasonable to assume steady-state flow.
- The mean values are used as calibration targets.



# Isotope Signature of Denitrification

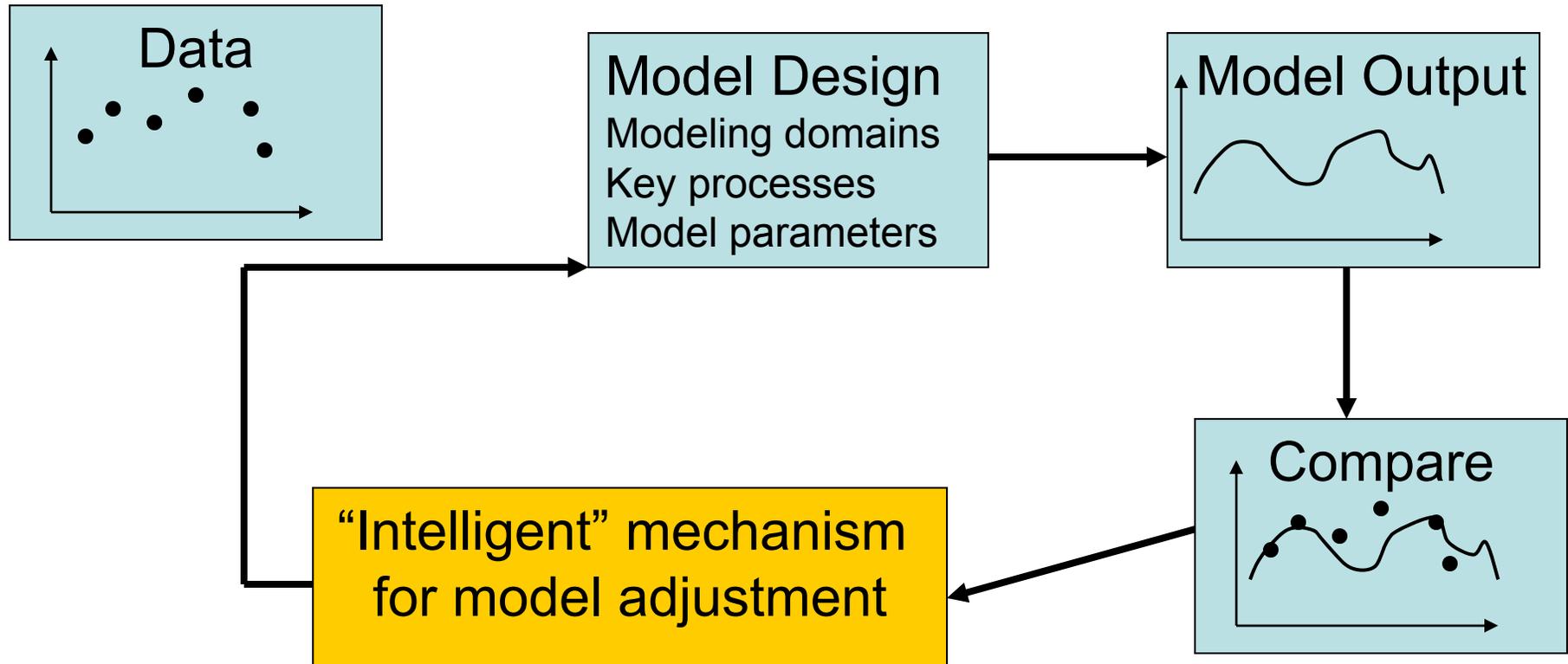
Indication of denitrification occurrence (Chen and Mcquarrie , 2005) :

- Linear relationship
- Slope close to 0.51



$\delta^{18}\text{O}$  vs.  $\delta^{15}\text{N}$  at Julington Creek and Eggleston Heights (Sep & Oct, 2010).

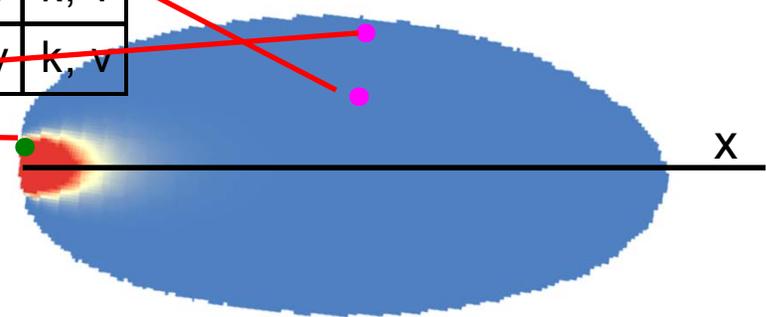
# Model Calibration: Trial and Error



# Global Sensitivity Analysis

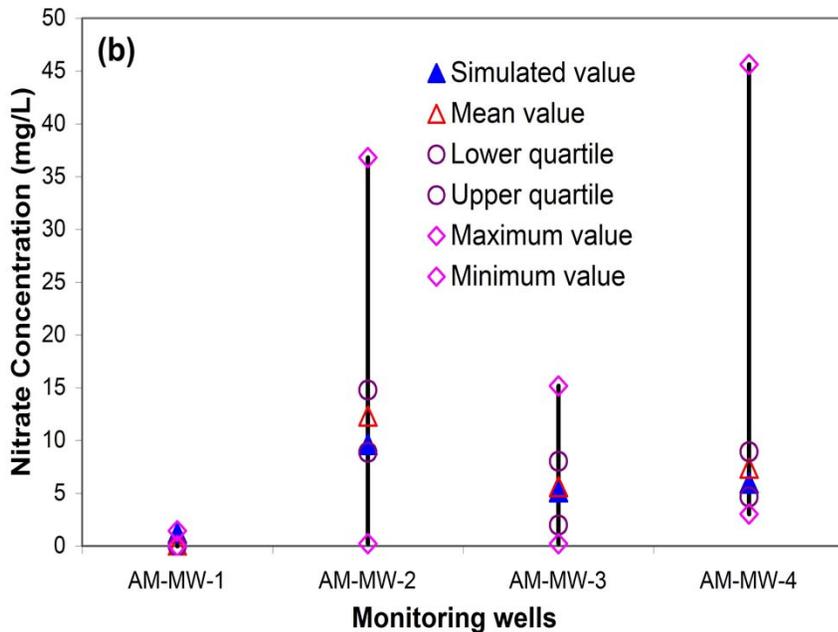
Two parameters most critical to simulated nitrate concentration at selected locations of the plume

x(m) y(m)	0.0001	5	10	15	20	30	40	50
0	$C_0, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$
1	$C_0, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$
2	$C_0, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$
3	$C_0, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$
4	/	$k, v$	$k, v$	$k, v$				
6	/	$\alpha_y, k$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$	$k, v$
8	/	$\alpha_y, k$	$k, \alpha_y$	$k, \alpha_y$	$k, v$	$k, v$	$k, v$	$k, v$
10	/	$\alpha_y, k$	$\alpha_y, k$	$k, \alpha_y$	$k, \alpha_y$	$k, v$	$k, v$	$k, v$
12	/	$\alpha_y, k$	$\alpha_y, k$	$k, \alpha_y$	$k, \alpha_y$	$k, \alpha_y$	$k, v$	$k, v$



# Calibration Results of Nitrate Concentration

## Eggleston Heights



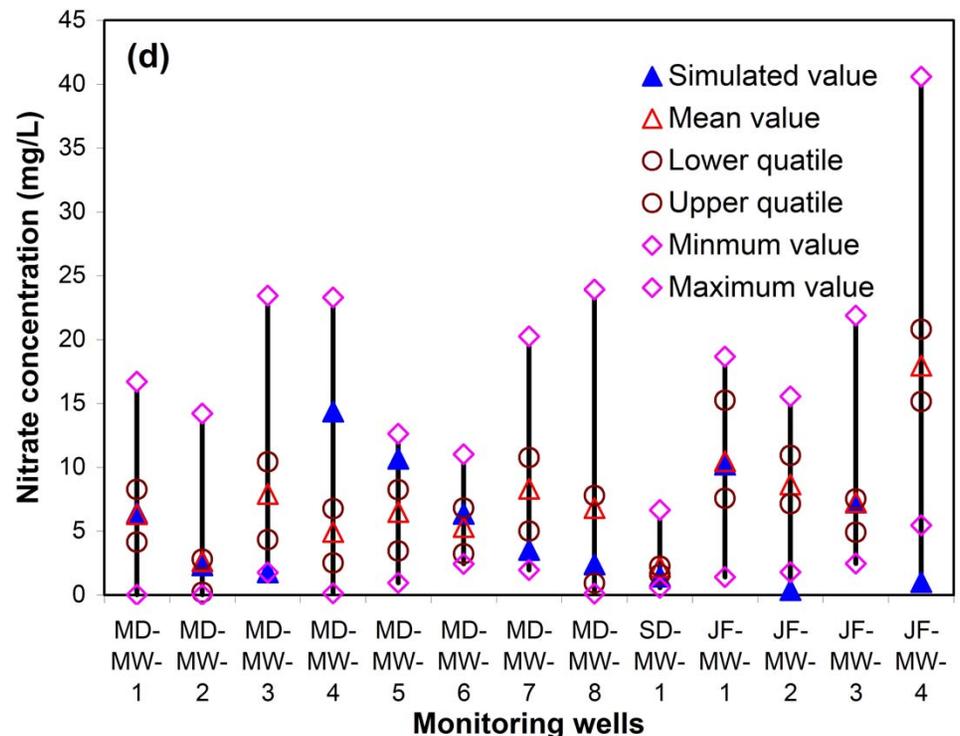
The simulated nitrate concentrations are

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

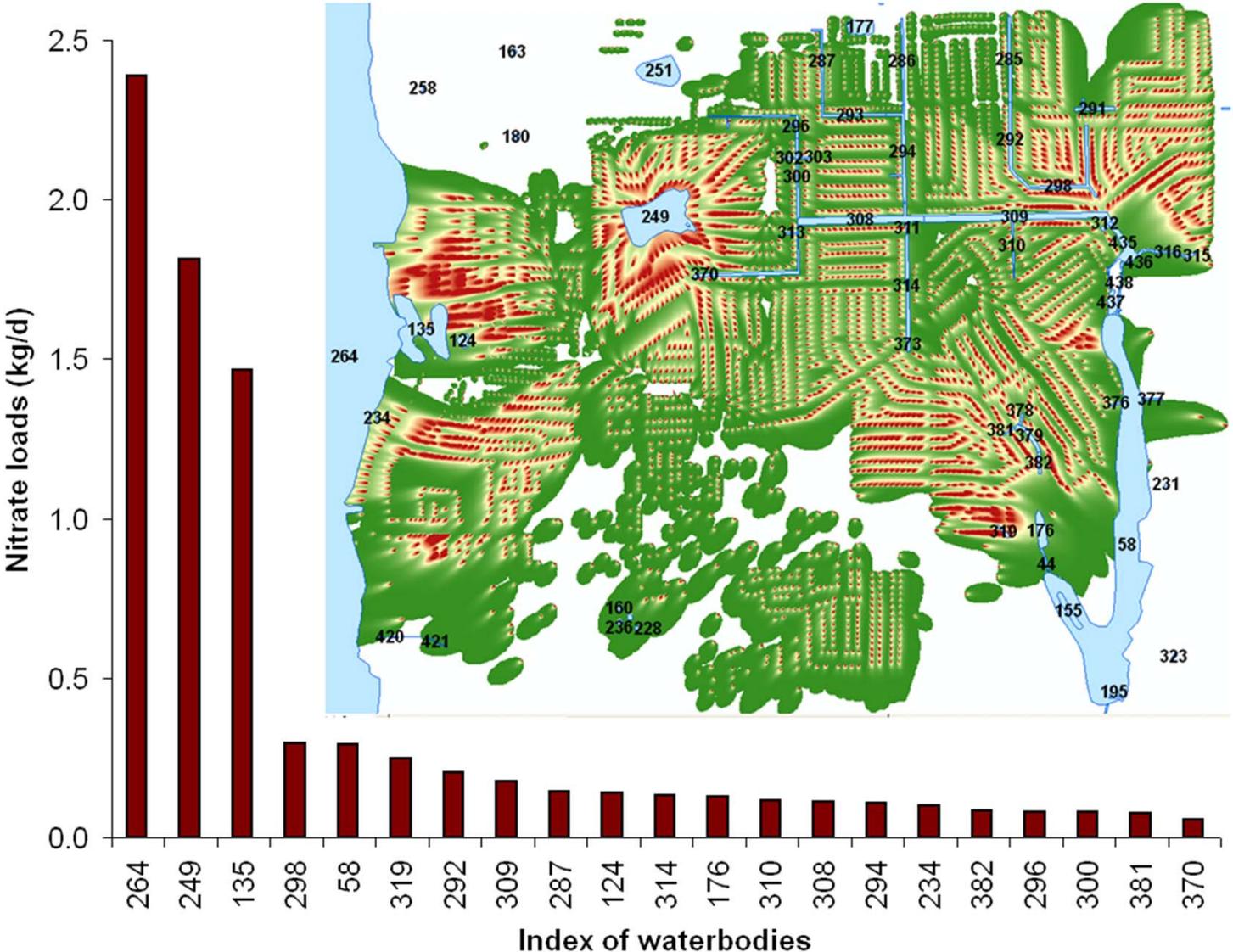
The simulated nitrate concentrations are

- 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 Loads 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*



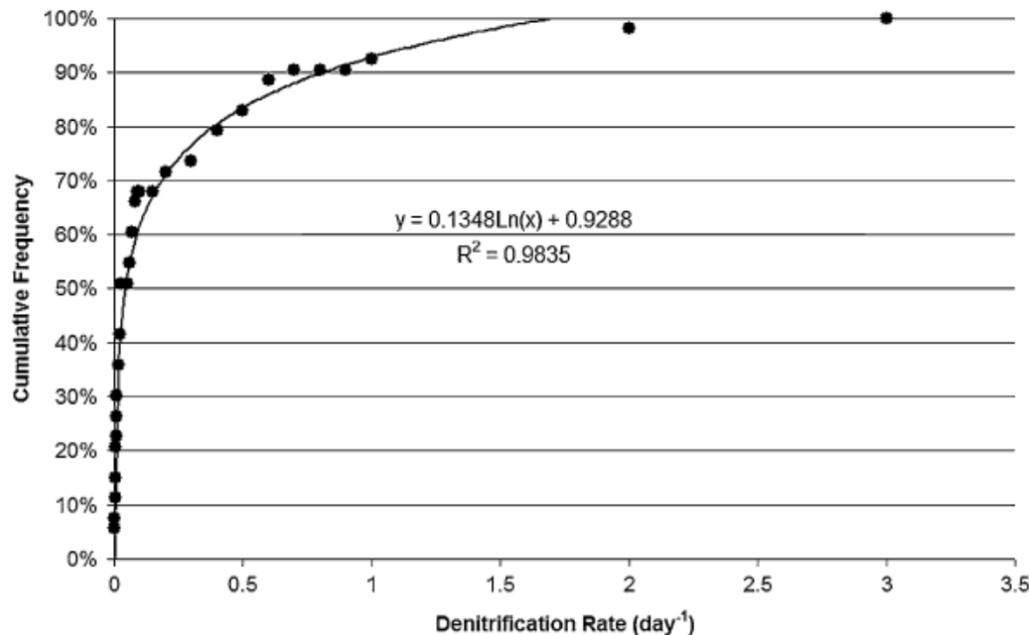
## **The Unknown**

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.

# Challenges: **Uncertainty** in **Input Parameters** and Load Estimates

Computer models are useful tools, but **input parameters** for models are not readily obtained and largely unknown.

Cumulative frequency of denitrification rate  
Statistics based on 53 data from literature



**Median:** 0.025

**Range:** 0.004 – 2.27

Phase I Report: Wekiva River Basin Nitrate Sourcing Study (MACTEC, 2006)

“All inputs used in estimation of inputs and loadings are uncertain to some extent.”

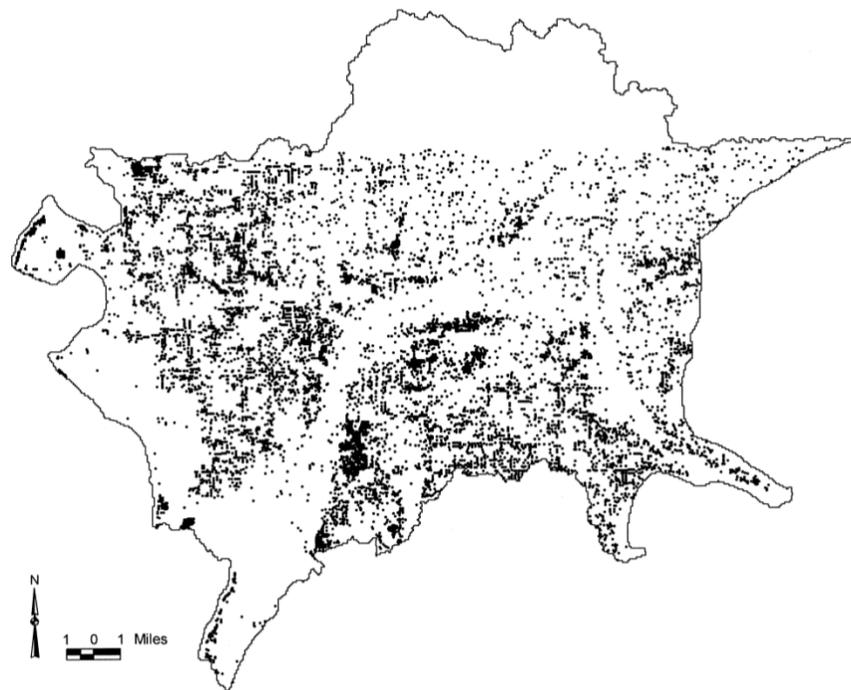
“Significant uncertainties have been identified throughout this report.”

McCray et al. (2005, Ground Water)

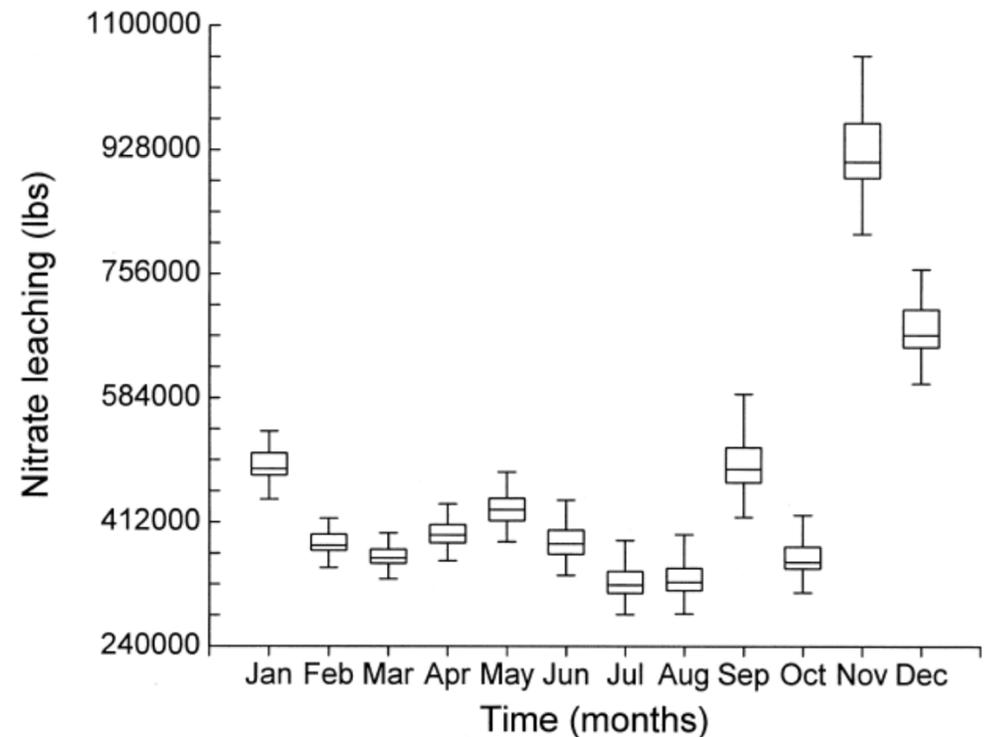
# Challenges: **Uncertainty** in Input Parameters and **Load Estimates**

Estimation of nitrate load for Whatcom County in Washington State

11,619 septic tanks in the study area



Boxplots of the load estimates



Almasri and Kaluarachchi (2004, Journal of American Water Resources Association)

# Lakeshore Example

## Parameter ranges:

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

Longitudinal dispersivity ( $\alpha_L$ ): 0.21 ~ 21.34 m

Horizontal transverse dispersivity ( $\alpha_T$ ): 0.021 ~ 2.134 m

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

## Parameter set 1 (Default)

Load=0.15 lb/day

$\alpha_L=2.113\text{m}$ ,  $\alpha_T=0.234\text{m}$ ,  
 $k=0.008/\text{d}$

## Parameter set 2

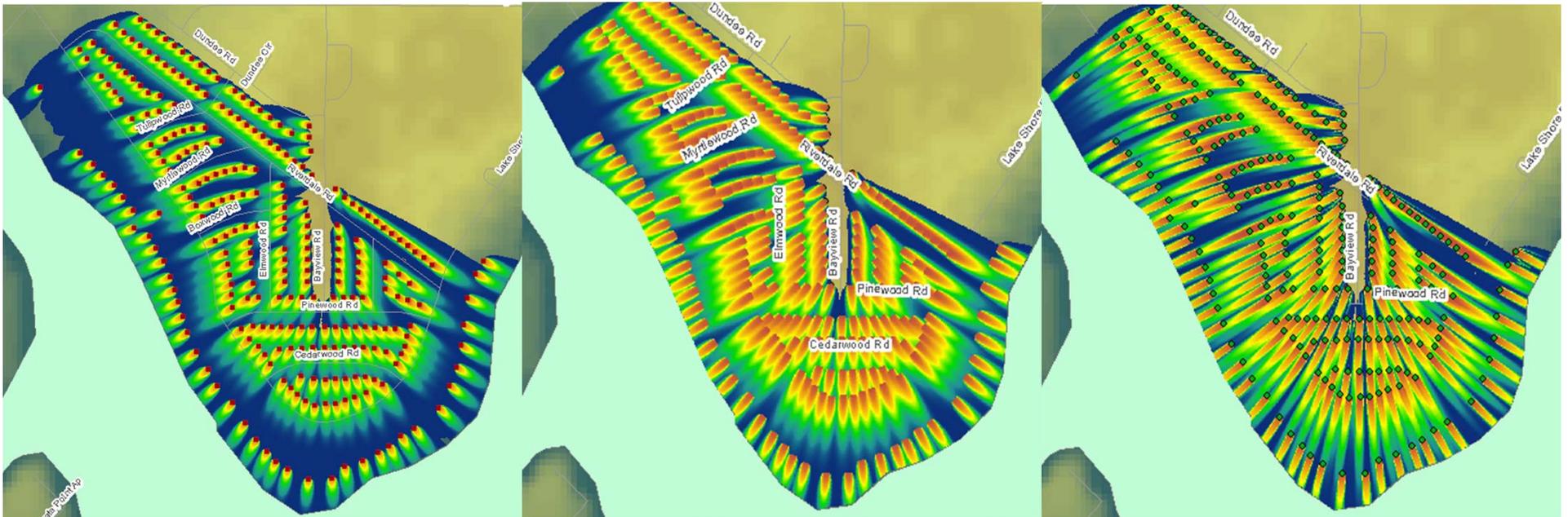
Load=0.25 lb/day

$\alpha_L=2.113\text{m}$ ,  $\alpha_T=0.234\text{m}$ ,  
 $k=0.004/\text{d}$

## Parameter set 3

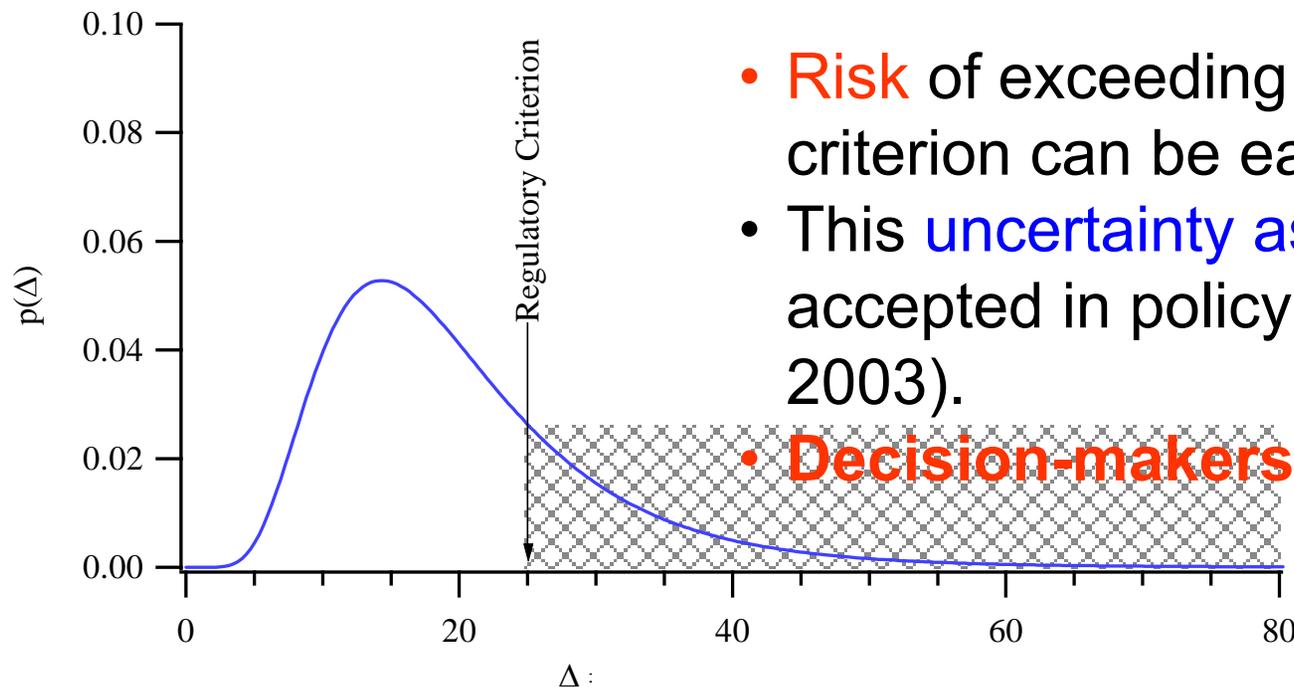
Load=0.60 lb/day

$\alpha_L=21.34\text{m}$ ,  $\alpha_T=0.021\text{m}$ ,  
 $k=0.004/\text{d}$



# Uncertainty Quantification and Reduction

- In management decision making, it is sometime more important to identify and quantify the uncertainty than to attempt to predict a deterministic value of a decision variable.
- **Site-specific** knowledge/information/data is most effective to reduce predictive uncertainty.
- **Probabilistic Predictions:**

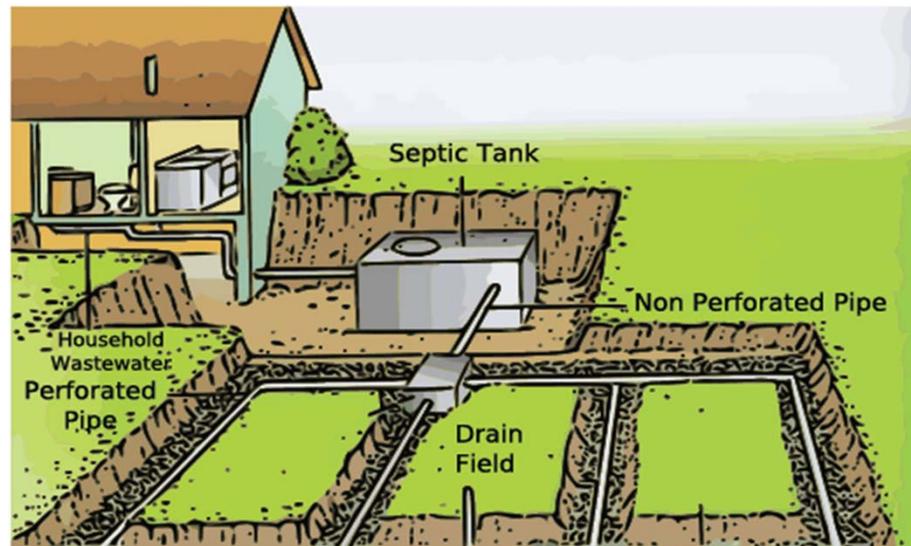


- **Risk** of exceeding the regulatory criterion can be easily calculated.
- This **uncertainty assessment** is accepted in policy (EPA 1997; NRC 2003).
- **Decision-makers make decisions.**

# Conclusions

- ArcNLET, the ArcGIS-based software has been developed for simulation of nitrate transport and estimation of nitrate load from septic systems to surface water bodies.
- The software is user friendly and easy to operate.
- After being calibrated, ArcNLET can yield acceptable simulations of field observations and reasonable load estimates.
- The software is based on a simplified conceptual model of nitrate transport, and should be used as a screening tool for load estimation.
- It is free for download at <http://people.sc.fsu.edu/~mye/ArcNLET/>.
- A software training workshop was given in July to 15 people, and another one is scheduled in fall. Email [mye@fsu.edu](mailto:mye@fsu.edu) if interested.
- On-going work is to quantify and reduce predictive uncertainty of the load estimate.

# Questions?



# Modeling Procedure: Data Preparation

- $N_t = N_0 - R_{dn} V_{aq}$
- Input the **topographic map** of the selected site.
- Input the map of **septic tank locations**. The location can be obtained from the county property appraiser's office. If the actual location of the septic tank on each property lot is unknown, the center of the property polygon will be used as the septic system location.
- Delineate **boundary line of target surface water body** (e.g., a lake and/or a stream) based on the topographic map. The boundary line can be of any shape.
- Delineate **parameter zones** of hydraulic conductivity, percent of soil organic carbon, porosity, and dispersion coefficients to incorporate heterogeneity of the aquifer. These hydraulic properties can be obtained from literature and/or field/laboratory experiments.

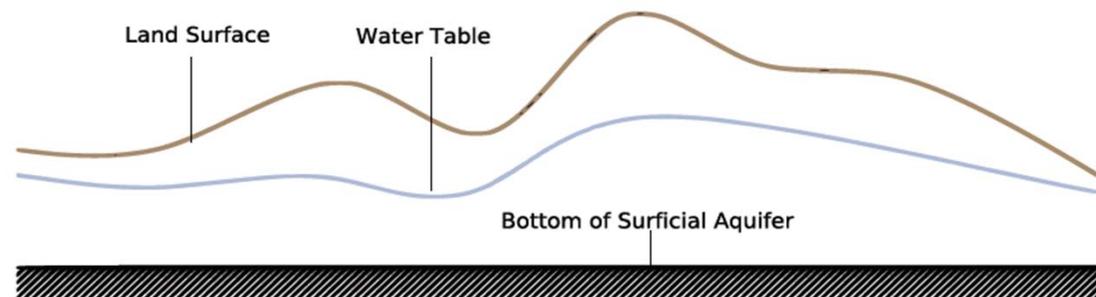
# Modeling Procedure: Estimation

- Determine **hydraulic gradient** along the flowpath from each septic system to the boundary line.
- For each septic system, calculate the **travel time** for each segment based on the Darcy's law. The travel time varies for each segment of each septic system.
- For each septic system, calculate **aquifer volume** within which denitrification would occur using the analytical solution of Domenico and Robbins (1985).
- Calculate **N loss** for each septic tank.
- Calculate **nitrate load** to the target surface water for each septic tank.
- **Sum the load for all the septic tank.**

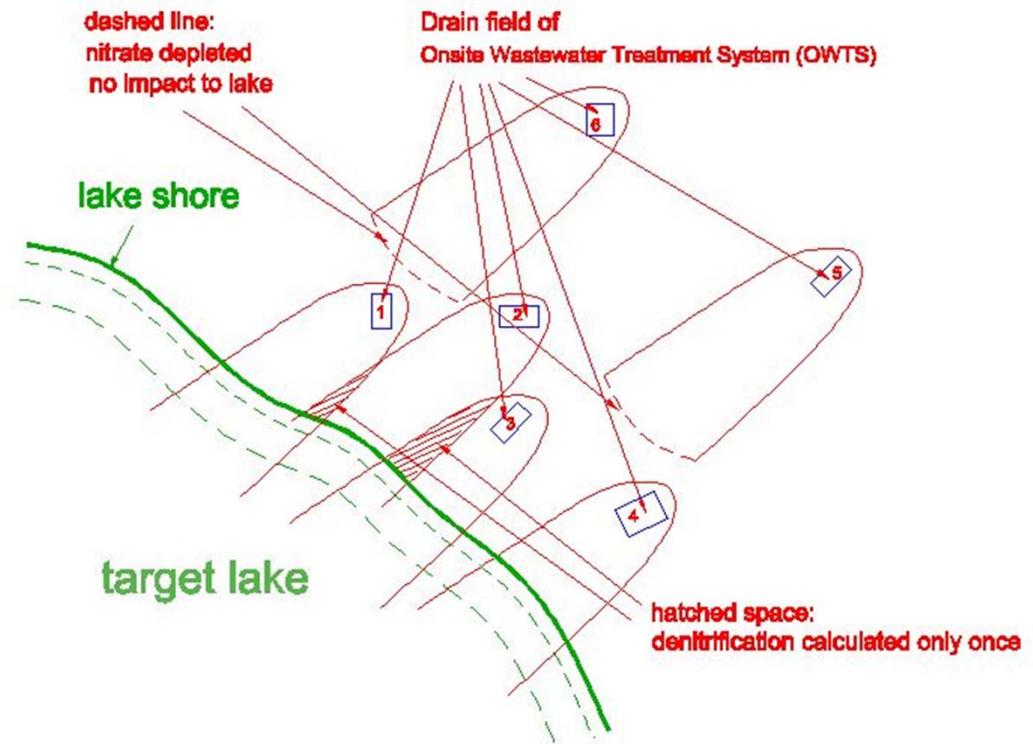
# Groundwater Flow Modeling

## Assumptions and Approximations:

- Steady-state flow
- Ignore mounding on top of water table
- Use Dupuit assumption to simulate 2-D groundwater flow
- Treat water table as subdued replica of the topography
- Process topographic data and approximate hydraulic gradient using the topographic gradient



# Outputs of Groundwater Flow Modeling



- **Flow paths** from each septic tank to surface water bodies
- **Flow velocity** along the flow paths. Heterogeneity of hydraulic conductivity and porosity is considered.
- **Travel time** from septic tanks to surface water bodies

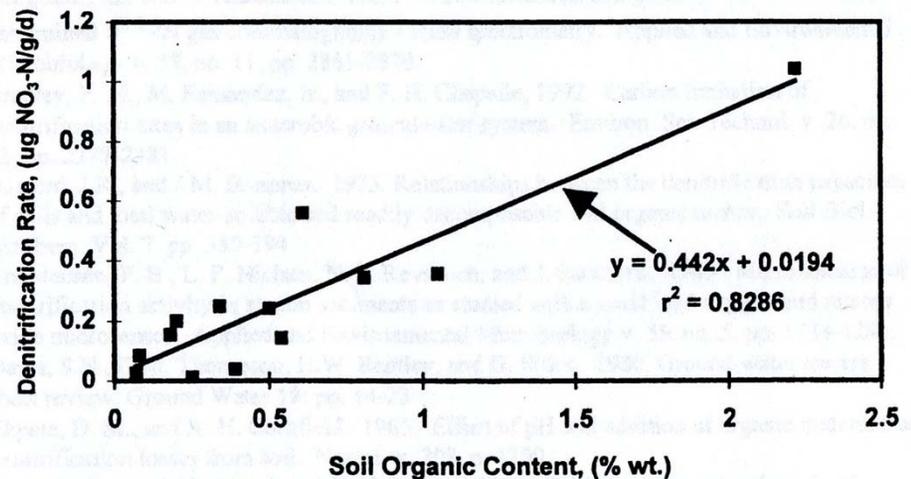
# Denitrification

**Denitrification** refers to the biological reduction of nitrate to nitrogen gas.



Denitrification ... has been identified as **basic factor** contributing to the generally low levels of nitrate found in the **groundwater of the southeastern United States** (Fedkiw, 1991).

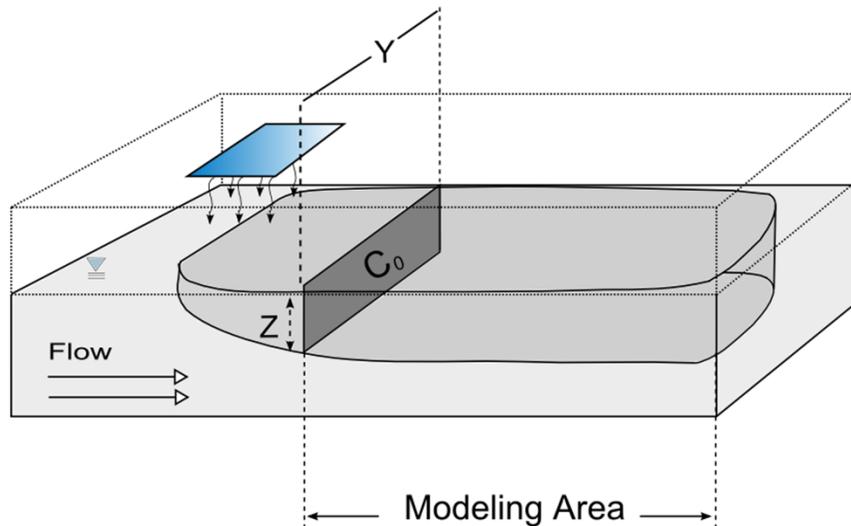
A fairly broad range of heterotrophic **anaerobic bacteria** are involved in the process, requiring an **organic carbon** source for energy as follows



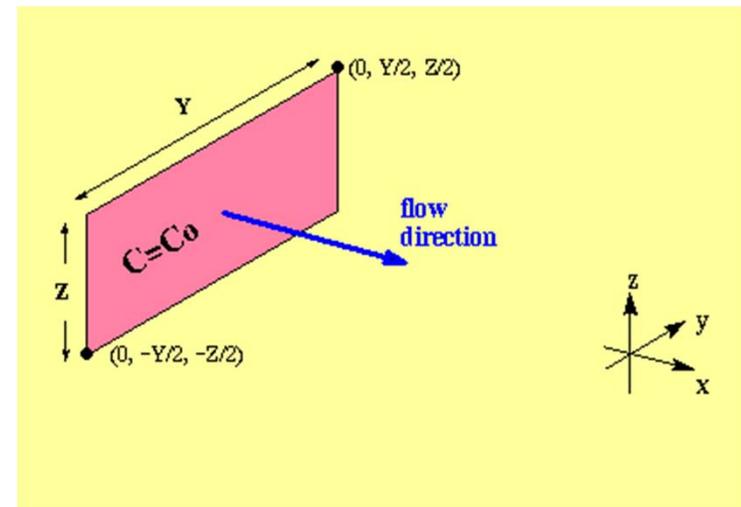
Anderson (1989)

# Nitrate Transport Modeling

EPA BIOCHLOR model



Domenico analytical solution



$$\frac{\partial C}{\partial t} = \underbrace{\alpha_{\ell} v \frac{\partial^2 C}{\partial x^2} + \alpha_{T_h} v \frac{\partial^2 C}{\partial y^2} + \alpha_{T_v} v \frac{\partial^2 C}{\partial z^2}}_{\text{Dispersion}} - \underbrace{v \frac{\partial C}{\partial x}}_{\text{Advection}} - \underbrace{kC}_{\text{Decay}}$$

Dispersion

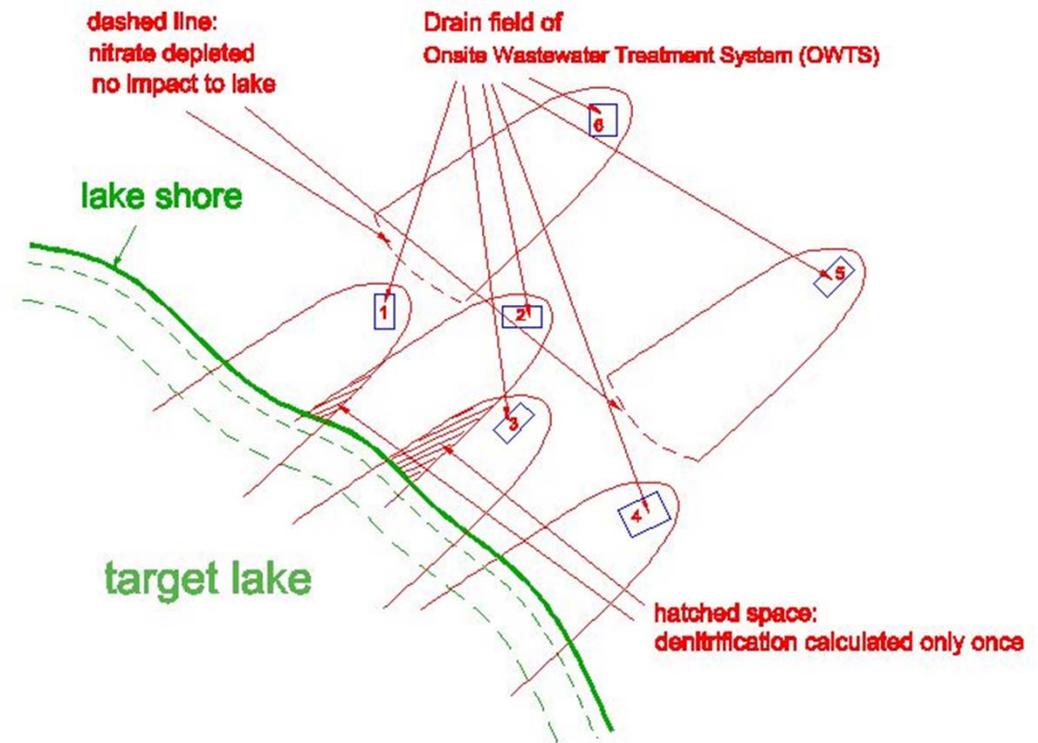
Advection Decay

Denitrification

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

# Outputs of Nitrate Transport Modeling and Calculation of Nitrate Load

- Apply the analytical solution to each septic tank.
- Obtain the nitrate plume of the entire area.
- Calculate mass of inflow and denitrification.
- Calculate load to rivers



$$M_l = M_{in} - M_{dn}$$

$$M_{dn} = R_{dn} V_g$$

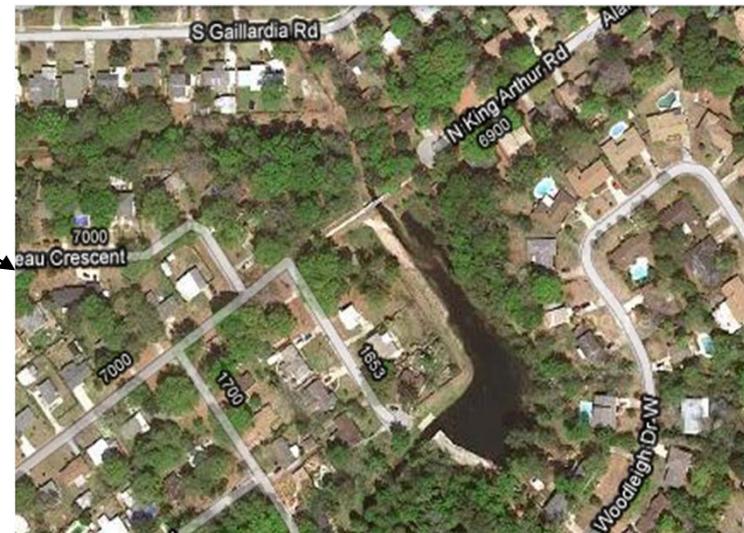
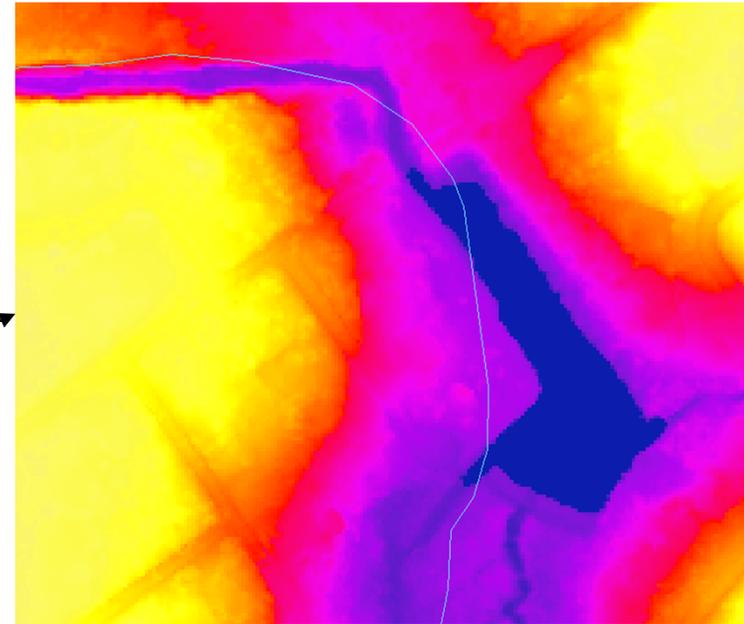
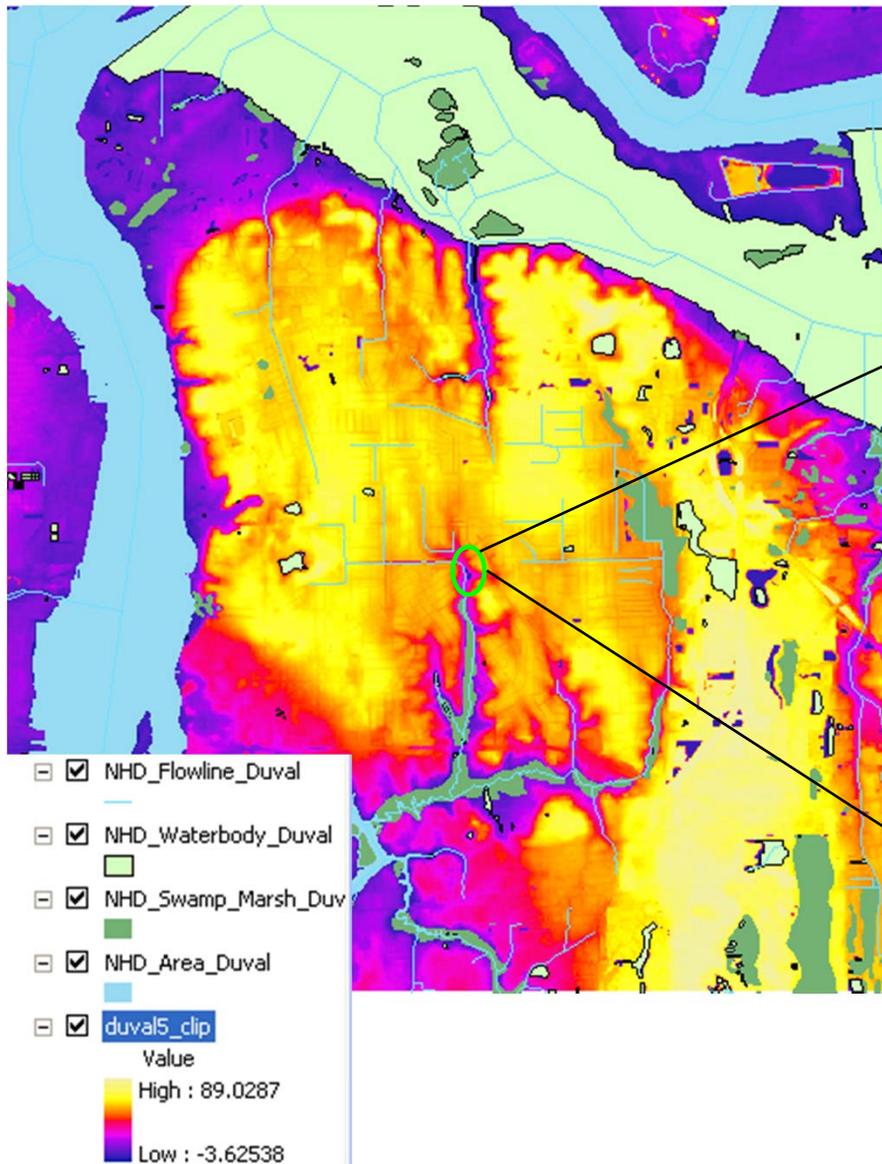
# Development of the ArcGIS Extension

- All the development is within **ArcGIS**, including pre-processing, post-processing, and computation.
- We developed a user-friendly interface using **Visual Basic**.
  - The .NET framework is used to expedite development.
- The software development is for **ArcGIS 9.3**.
  - The software can be updated with newer version of ArcGIS.
- Final product is **an installation file** that installs the ArcGIS extension on PC.

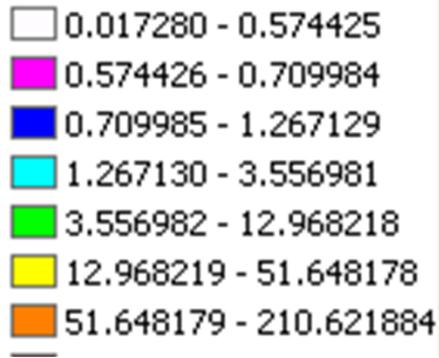
# Summary of Model Inputs and Outputs

- Model Inputs
  - **Flow module**: DEM, Water bodies, Hydraulic conductivity, and Porosity
  - **Transport module**: Source nitrate concentration, Dispersivity, and Decay coefficient
  - **Denitrification module**: none
- Model Outputs
  - **Flow module**: Flow velocity and path
  - **Transport module**: Nitrate plume
  - **Denitrification module**: Amount of nitrate load

# Use LiDAR Data to Update NHD Data



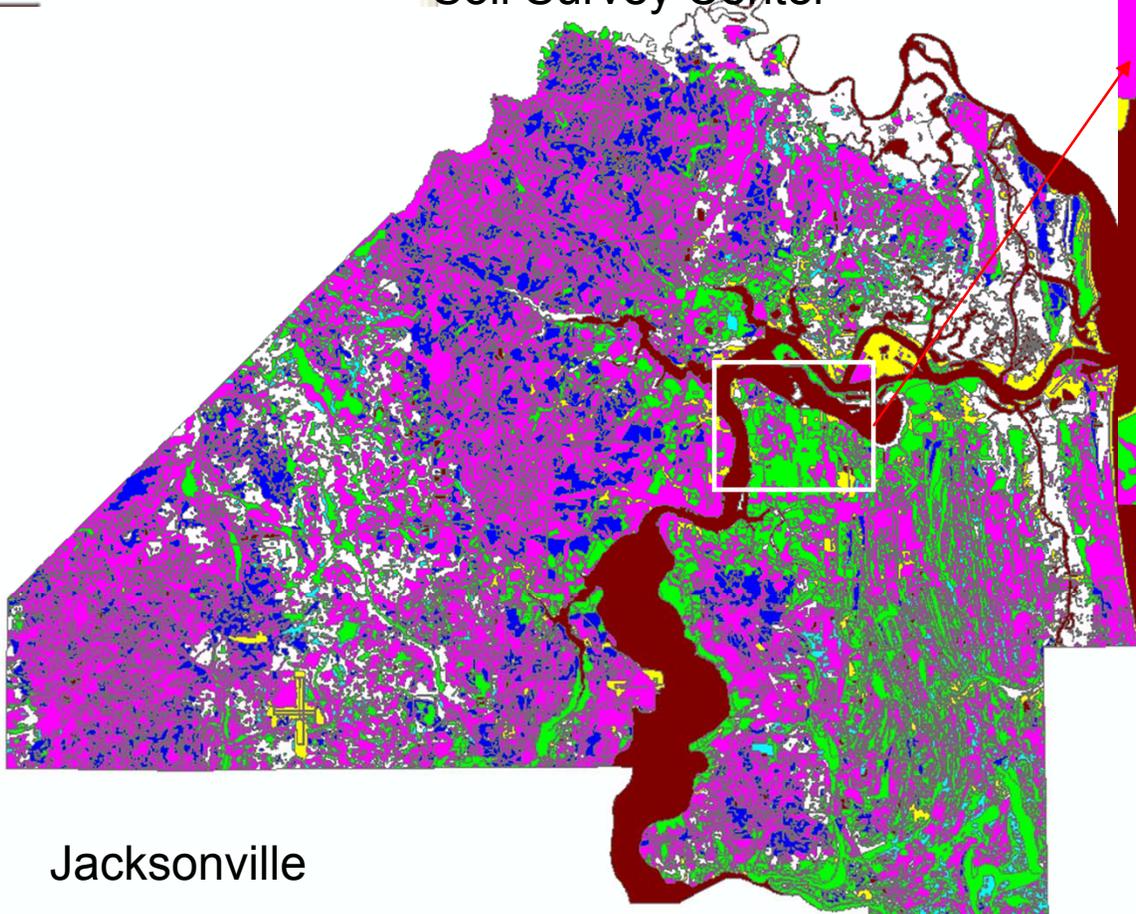
# Heterogeneous Hydraulic Conductivity



The hydraulic conductivity data is derived from the vertical permeability data download from Soil Data Mart, USDA NRCS National Soil Survey Center

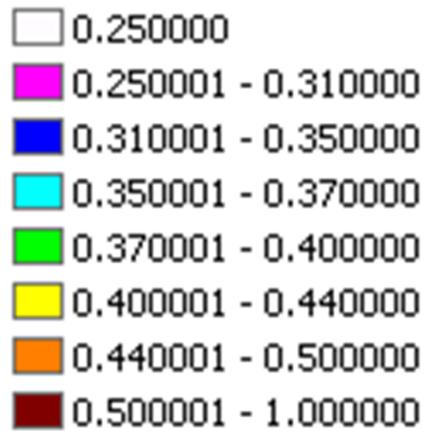


Eggleston Heights

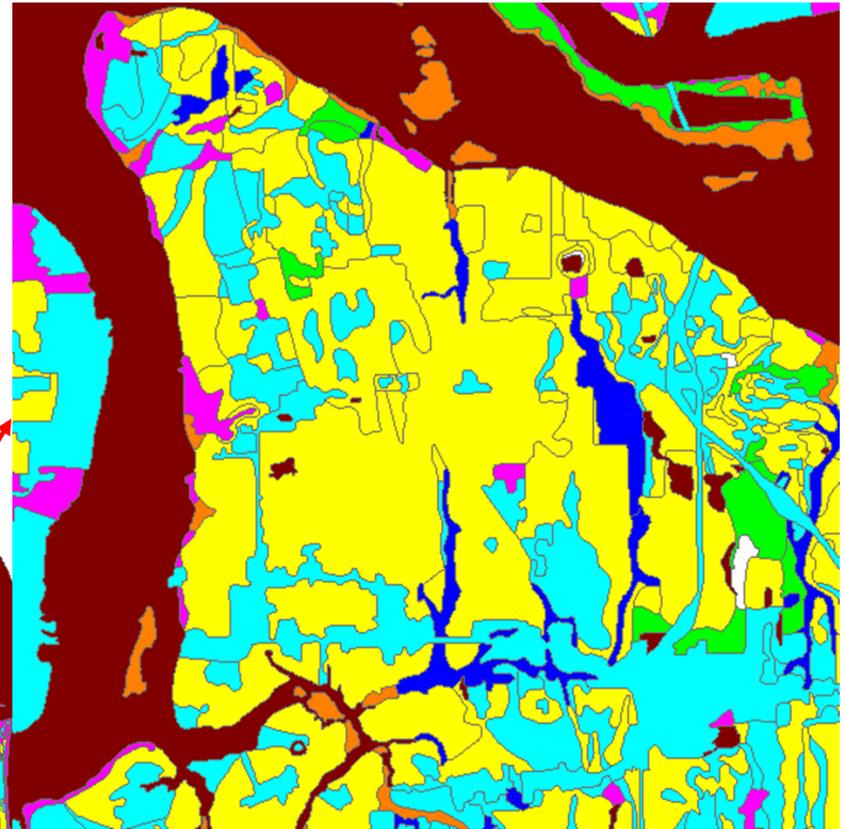
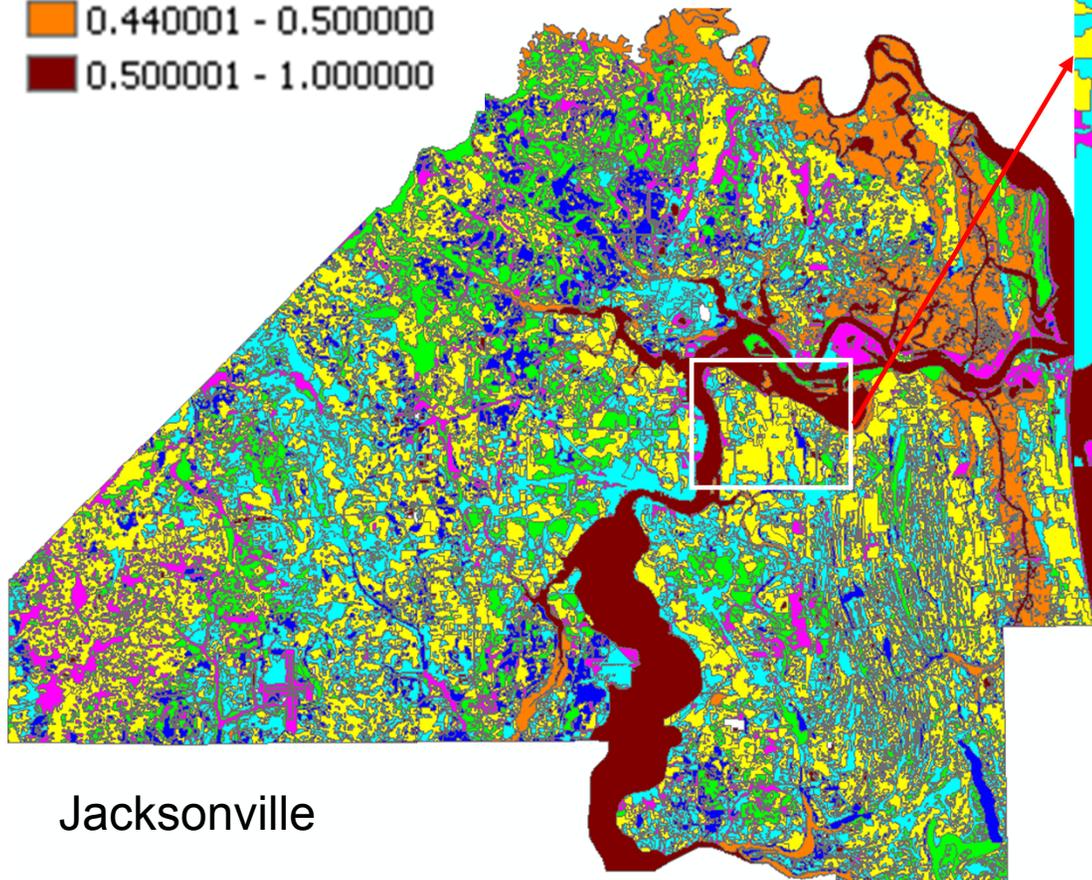


Jacksonville

# Heterogeneous Porosity



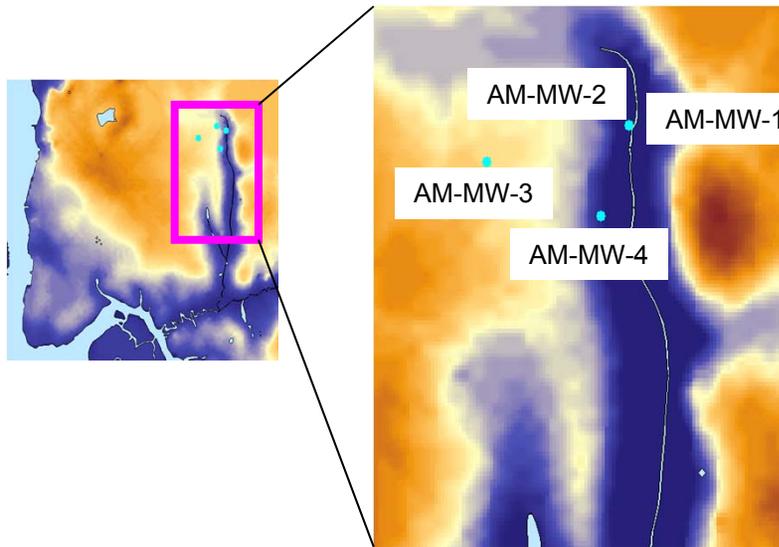
The porosity data is derived from “the estimated volumetric soil water content at or near zero bar tension” data download from Soil Data Mart, USDA NRCS National Soil Survey Center



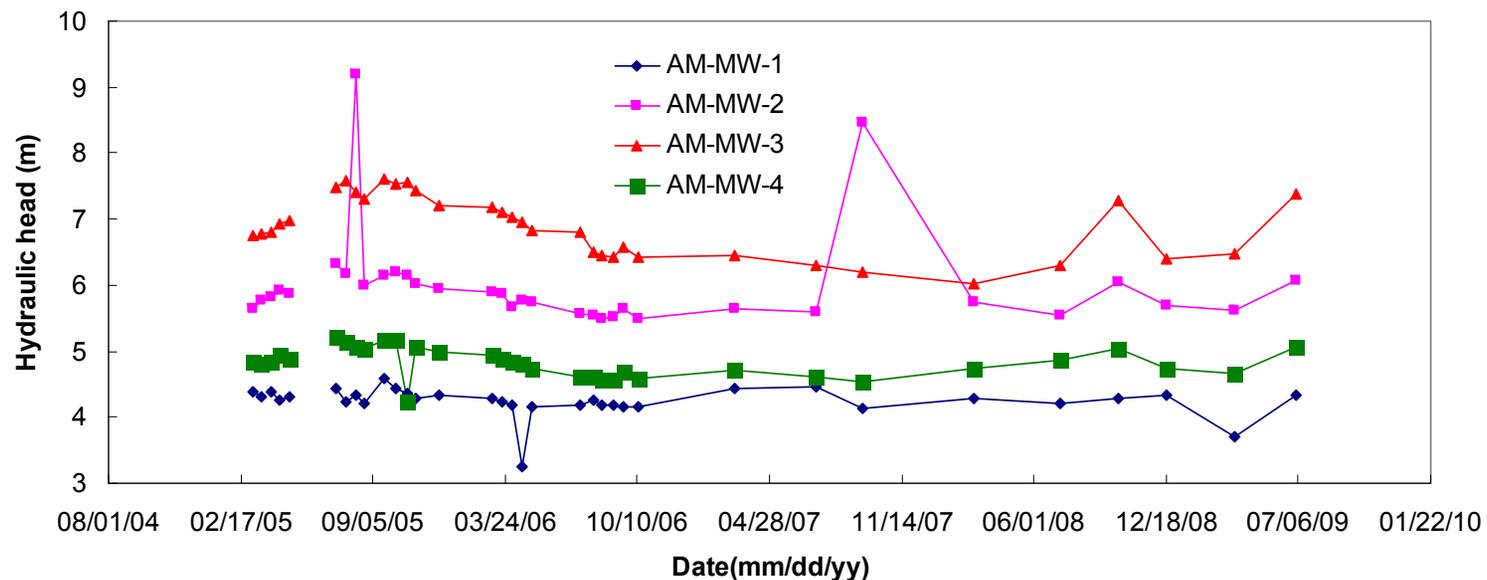
Eggleston Heights

Jacksonville

# Observations of Hydraulic Head

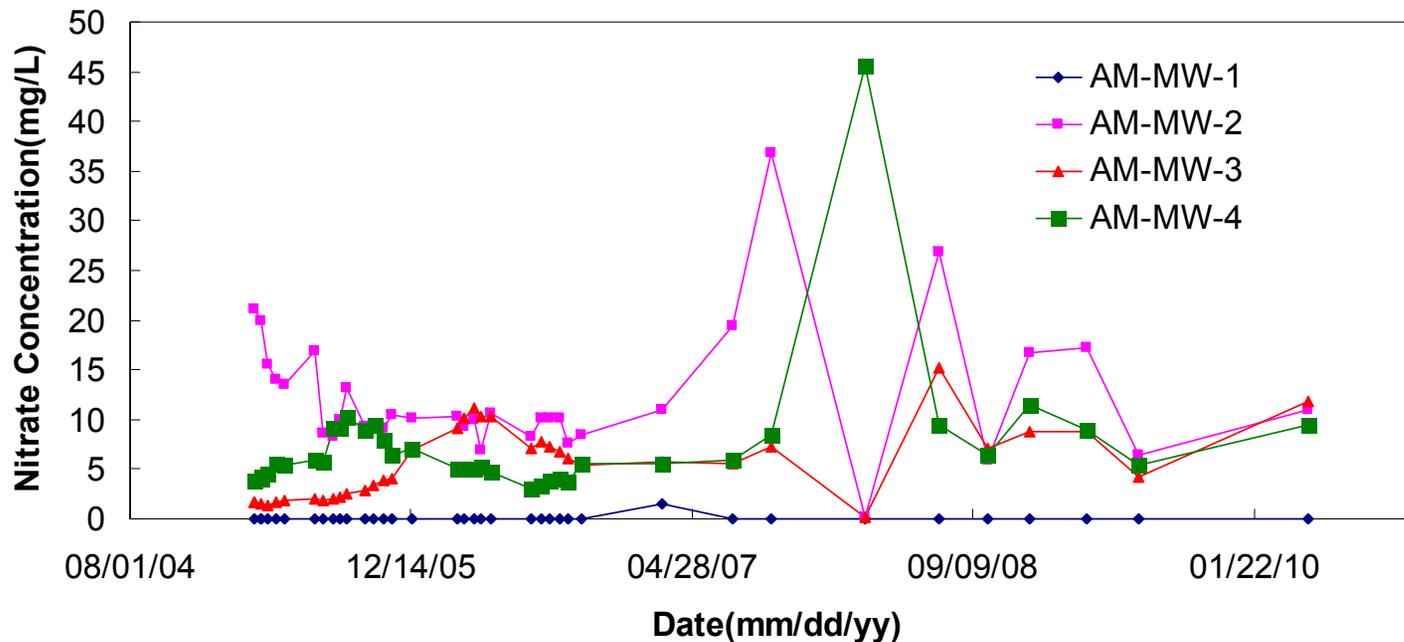
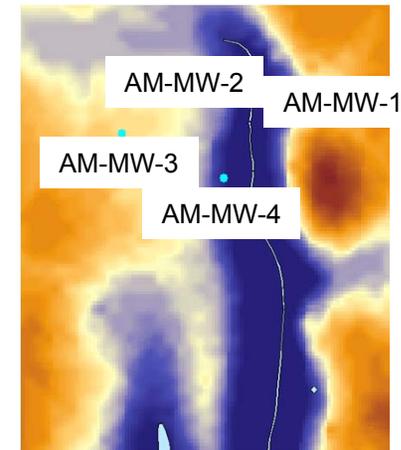


- Four monitoring wells
- Monitoring data from 2005 to 2009
- Water table is relatively stable



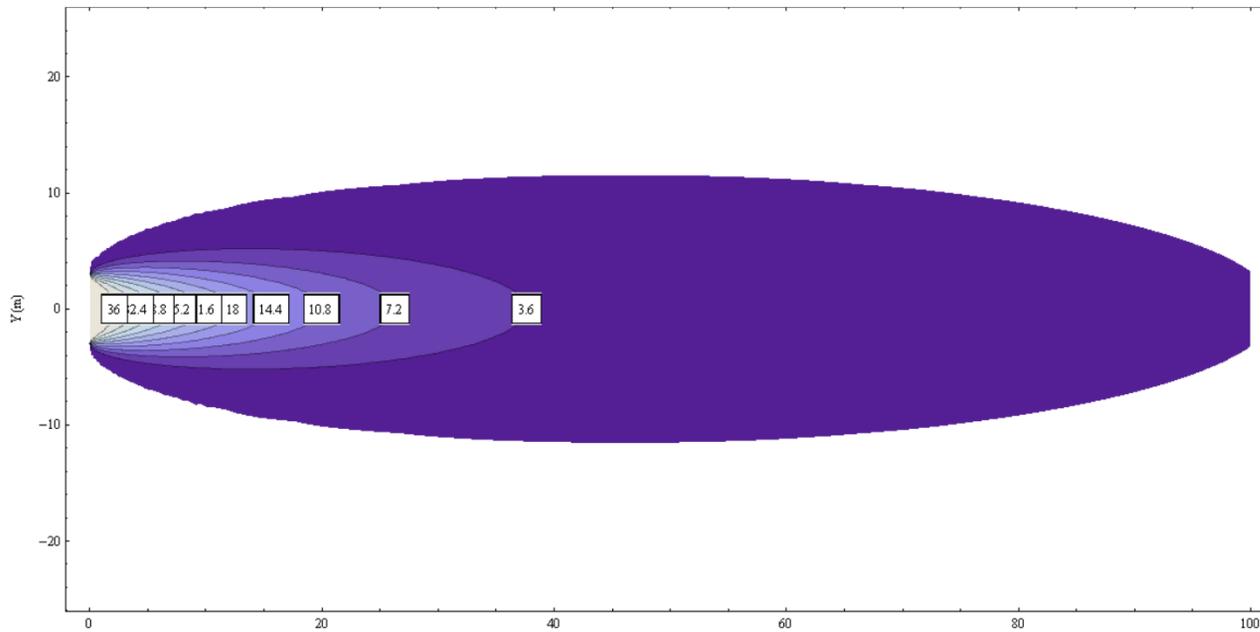
# Observations of Nitrate Concentration

- Monitoring data from 2005 to 2010
- Observations vary but without apparent increasing or decreasing trends
- Isotope data indicate that effect of lawn fertilizer on concentration is negligible.



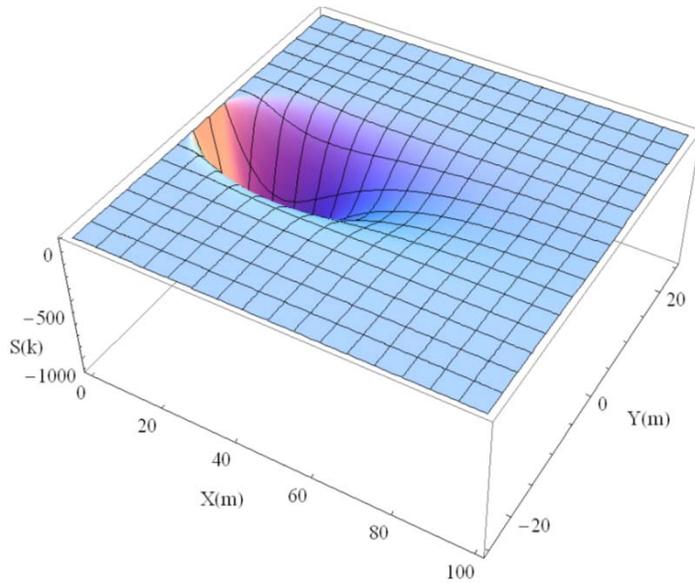
# Sensitivity Analysis

- What control plume size and nitrate concentration?
- **Nominal parameters:**  
 $C_0=40\text{mg/L}$ ,  $v=0.15\text{m}$ ,  $\alpha_x=2\text{m}$ ,  $\alpha_y=0.2\text{m}$ , and  $k=0.008/\text{d}$
- Corresponding concentration



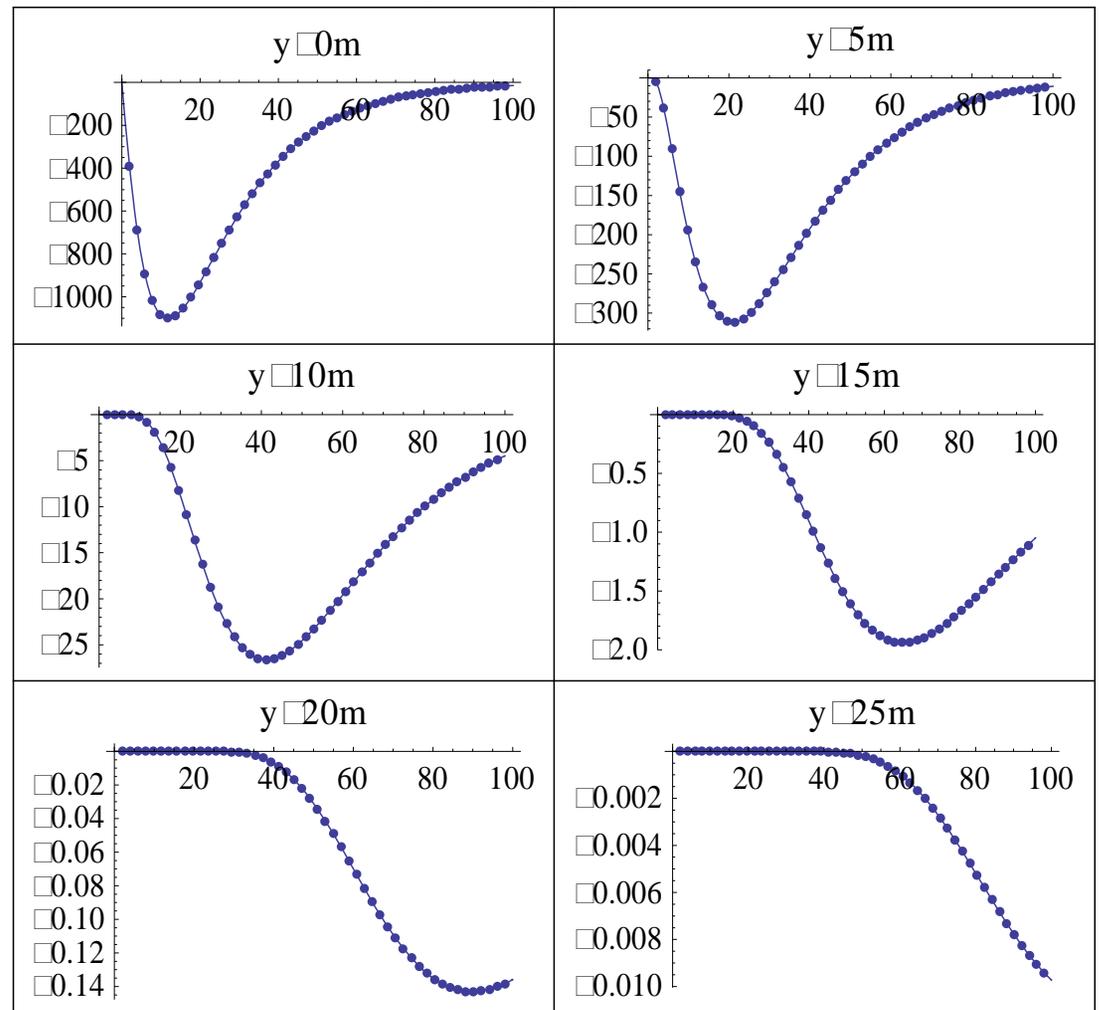
The outer contour line is for  $C=0.1 \text{ mg/L}$

# Sensitivity to $k$ at Different Horizontal Cross-Sections

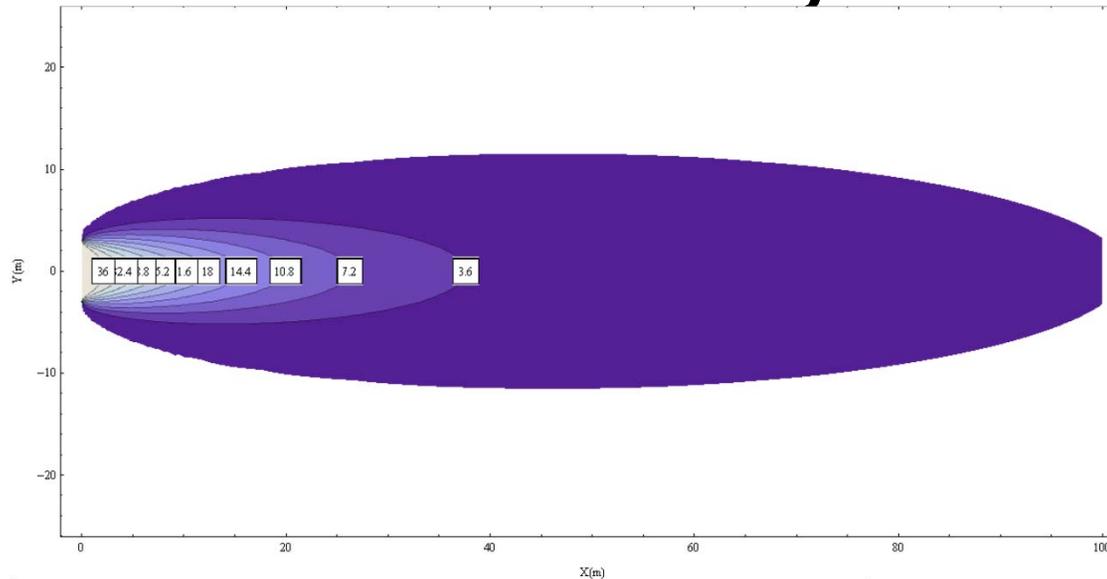


- $k$  is important to concentration simulation.
- The sensitivity varies dramatically in space.

Sensitivity along  $y$  cross-sections



# Global Sensitivity Analysis



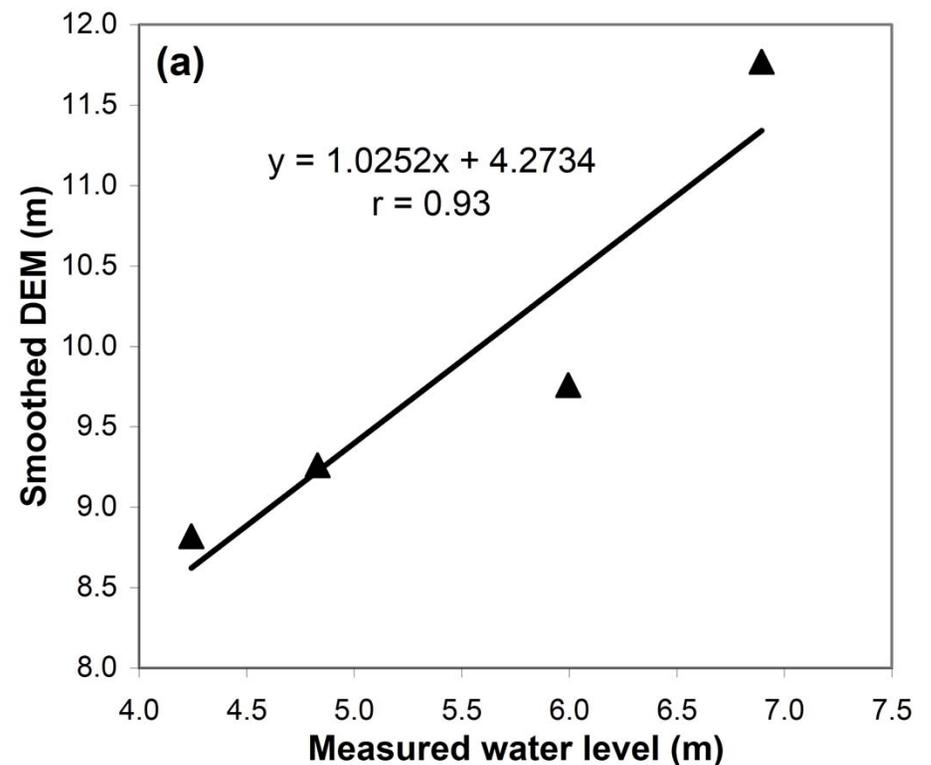
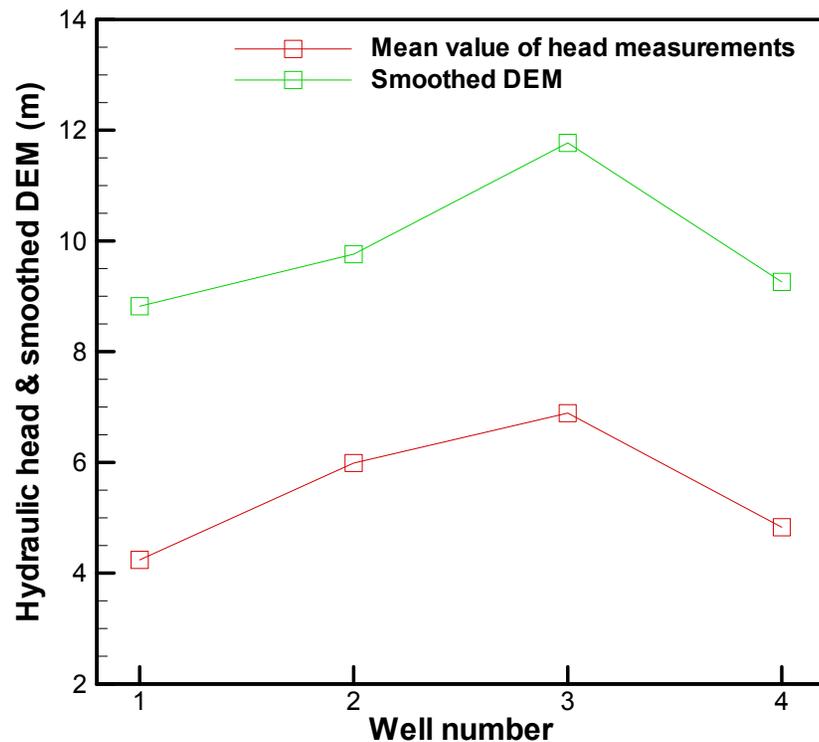
x(m) y(m)	0.0001	5	10	15	20	30	40	50
0	$C_0, v$	k, v	k, v	k, v				
1	$C_0, v$	k, v	k, v	k, v				
2	$C_0, v$	k, v	k, v	k, v				
3	$C_0, v$	k, v	k, v	k, v				
4	/	k, v	k, v	k, v				
6	/	$a_y, k$	k, v	k, v	k, v	k, v	k, v	k, v
8	/	$a_y, k$	k, $a_y$	k, $a_y$	k, v	k, v	k, v	k, v
10	/	$a_y, k$	$a_y, k$	k, $a_y$	k, $a_y$	k, v	k, v	k, v
12	/	$a_y, k$	$a_y, k$	k, $a_y$	k, $a_y$	k, $a_y$	k, v	k, v

Two most critical parameters to simulated nitrate concentration at every location.

# Calibration Results: Heads

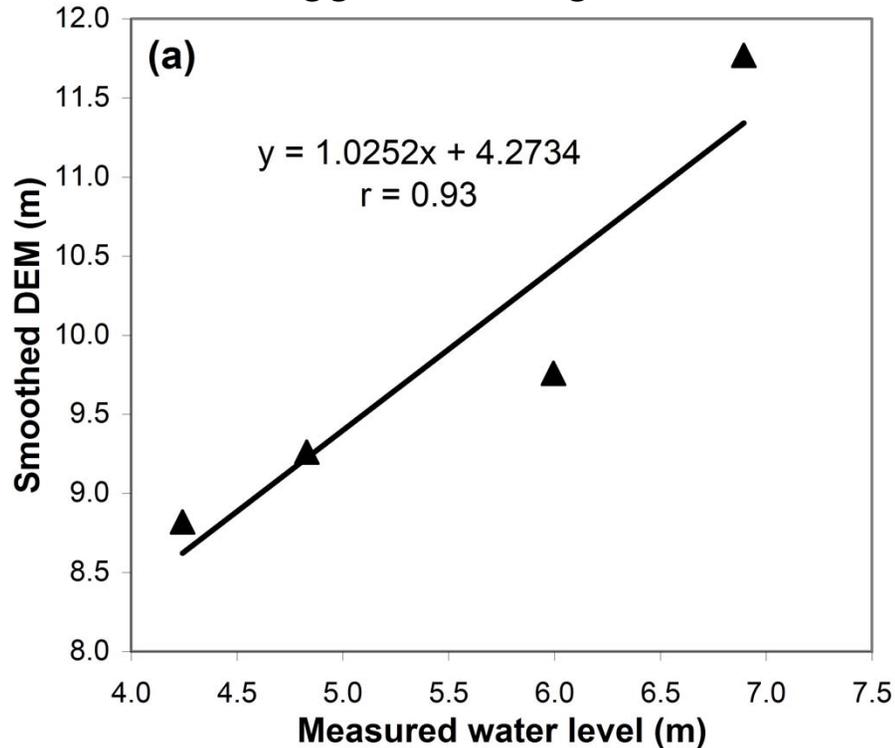
Smoothed DEM agree well with mean observed hydraulic head

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

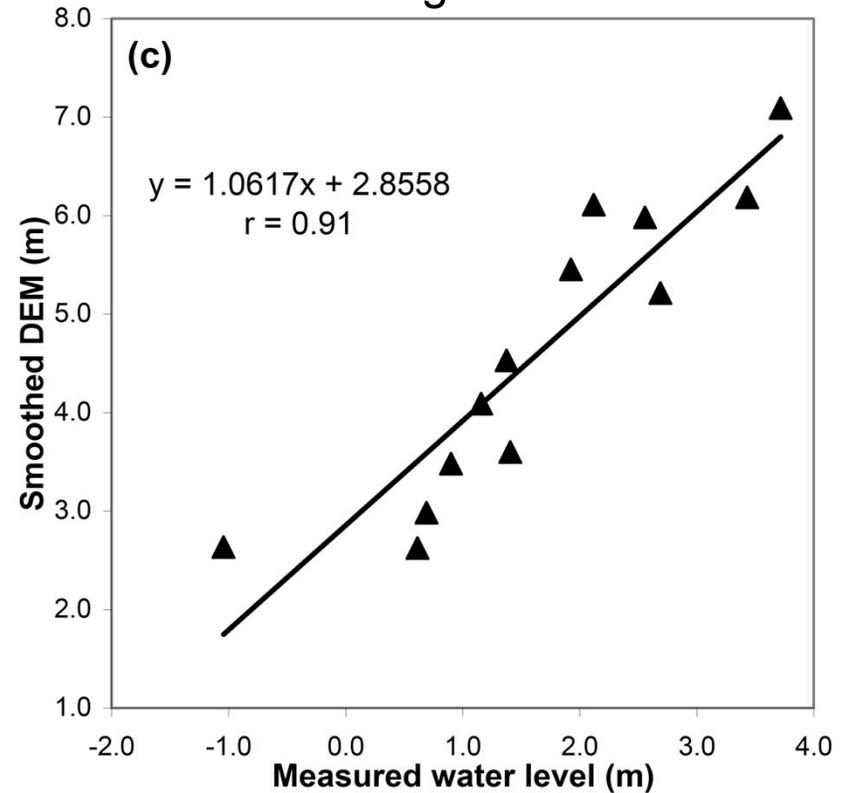


# Calibration Results of Hydraulic Gradient

## Eggleston Heights



## Julington Creek

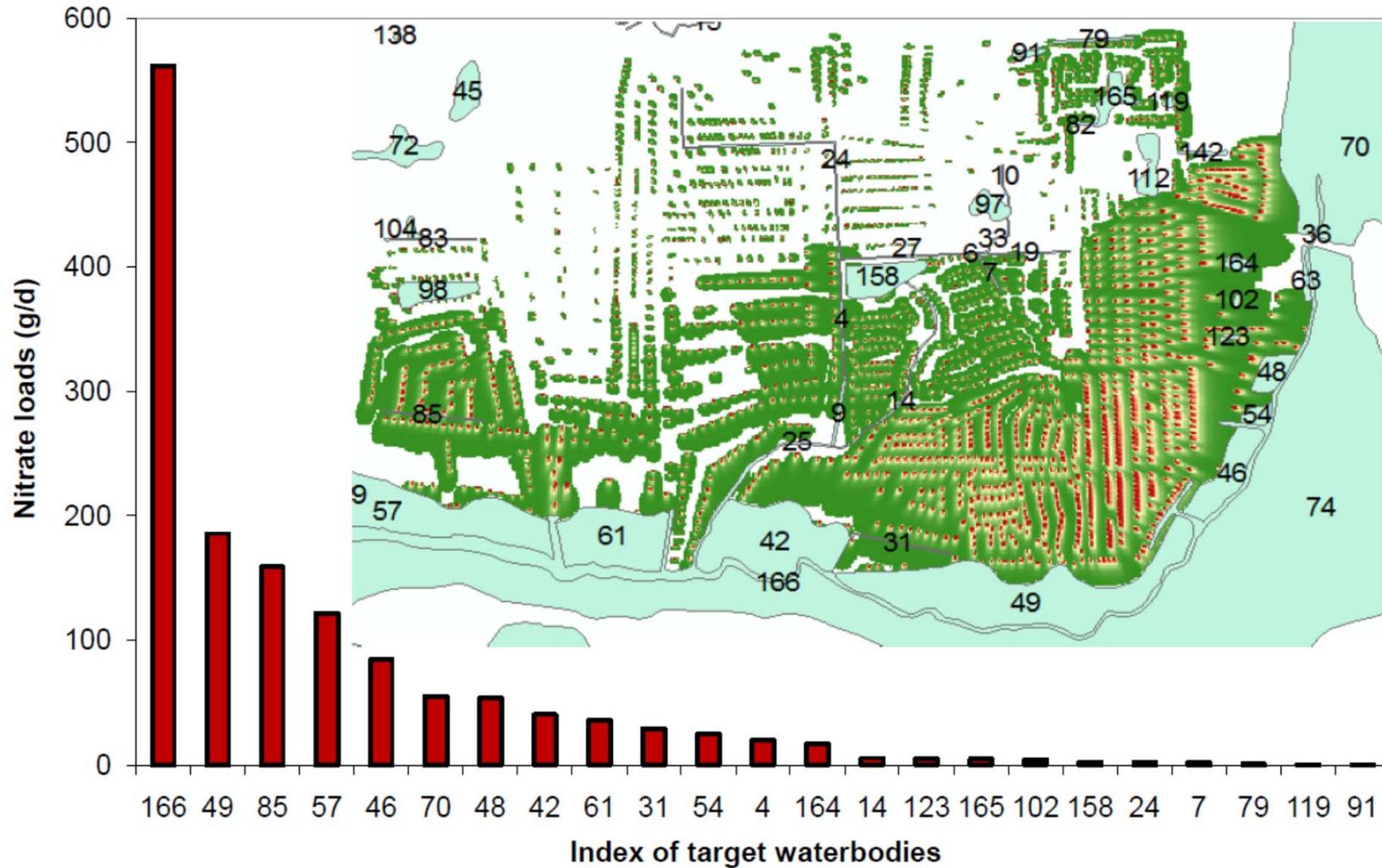


The smoothed DEM agree well with the observed water table shape with a linear correlation coefficient of more than 0.9 and slope of the linear regression close to 1.0

## Estimated Source Input Mass Flux and Loads

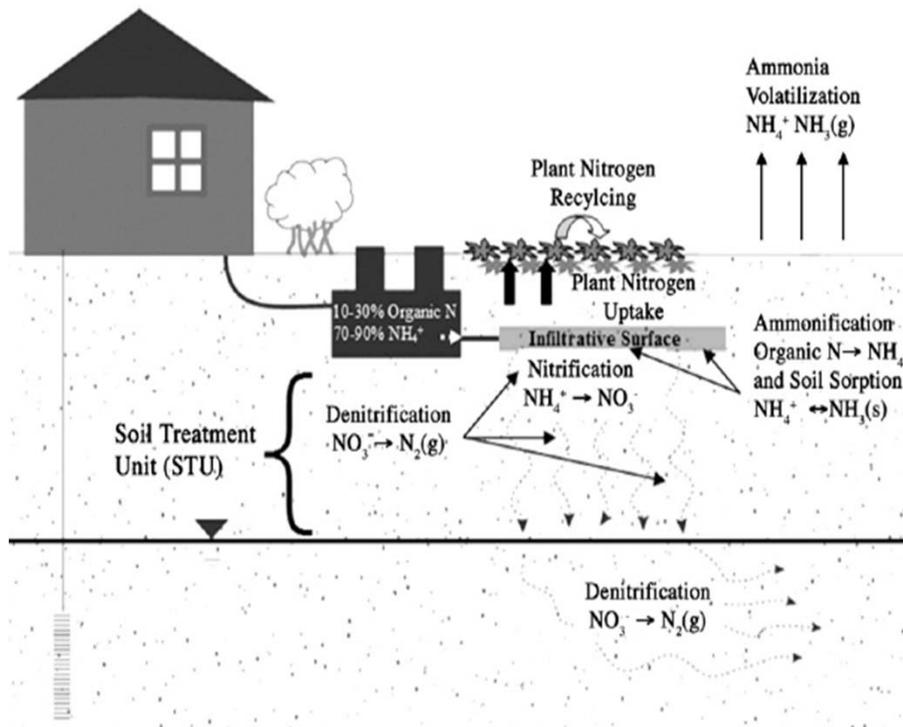
- Based on the summary report of Anderson (2006) for Florida, average source input mass flux is estimated as **20 g/sep/day**.
- For Eggleston Heights, the estimated source input mass flux from **3495** septic systems is **115.4kg** per day (**33g/sep/day**), about **92.5%** of which is lost due to denitrification and **7.5%** contributes to the loads to surface waterbodies.
- For Julington Creek, the estimated source input mass flux from **1924** septic systems is **59.4kg** per day (**31g/sep/day**), about **97.6%** of which is lost due to denitrification and **2.4%** contributes to the loads to surface waterbodies.

# Estimated Nitrate Load at Julington Creek



# Prospective Research

- Continue developing the software to meet other needs of DEP environmental management and regulation.
- Consider nitrification process (e.g., nitrification and plant up-take) in the vadose zone.
- Apply this software to different sites to provide guidelines for environmental management and regulation.



Due to nitrification in the vadose zone, OSW can generate  $\text{NO}_3\text{-N}$  concentration at the water table from **25 to 80** mg N/L in most situations. (McCray et al., 2005)

