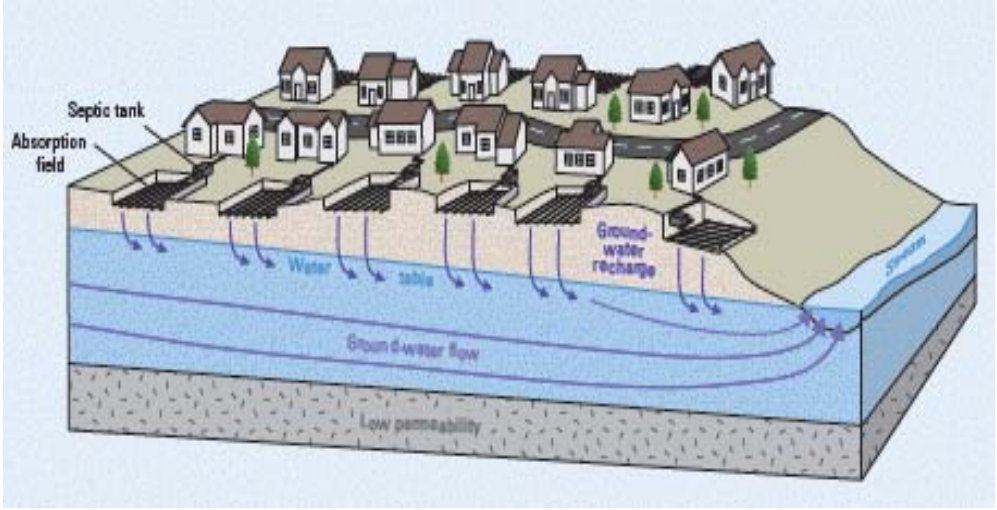


Picture from USGS Scientific Investigations Report 2008–5220

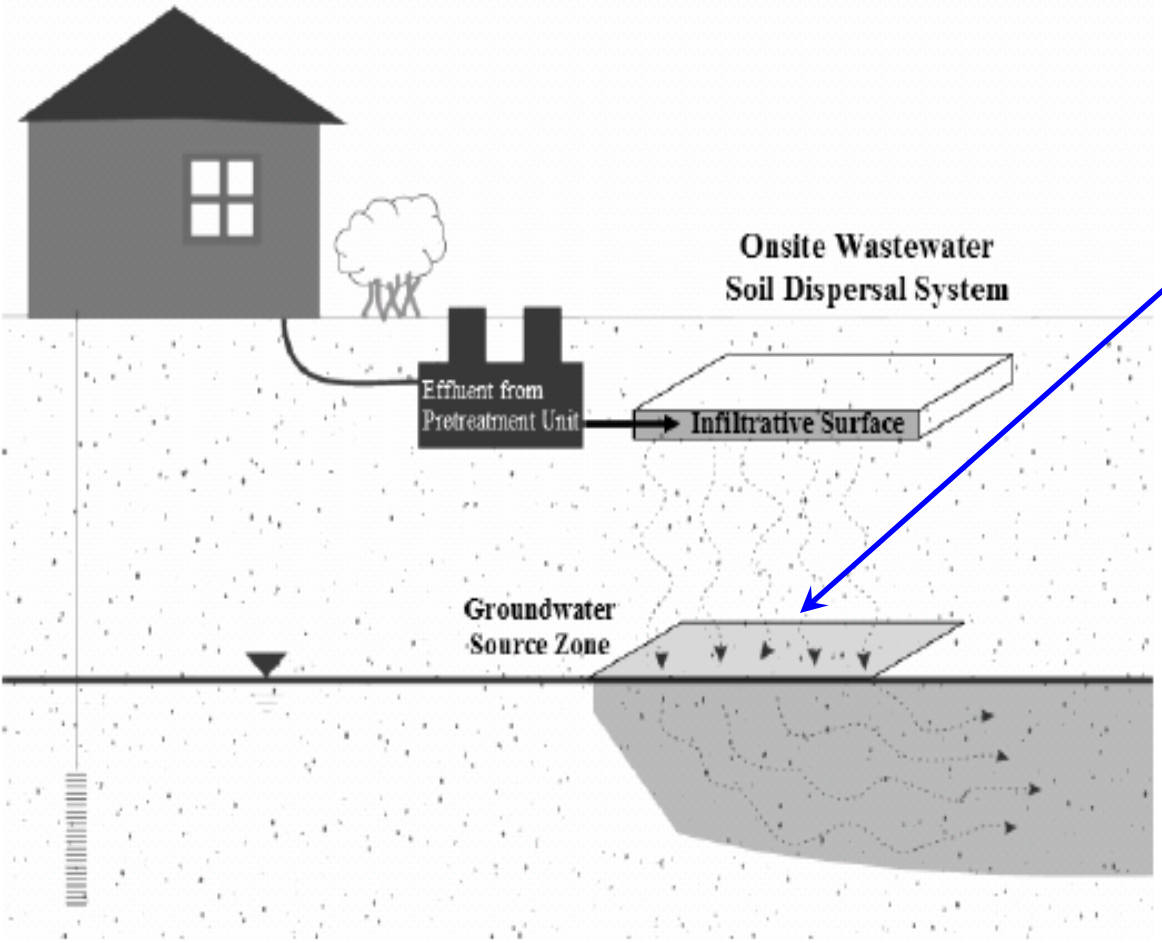
Estimation of Nitrate Load from Septic Systems to Surface Water Bodies Using ArcNLET: an ArcGIS-Based Nitrate Load Estimation Toolkit

Richard W. Hicks (FDEP) and Ming Ye (FSU)

2011 Environmental Symposium

Project WM956 Supported by FDEP

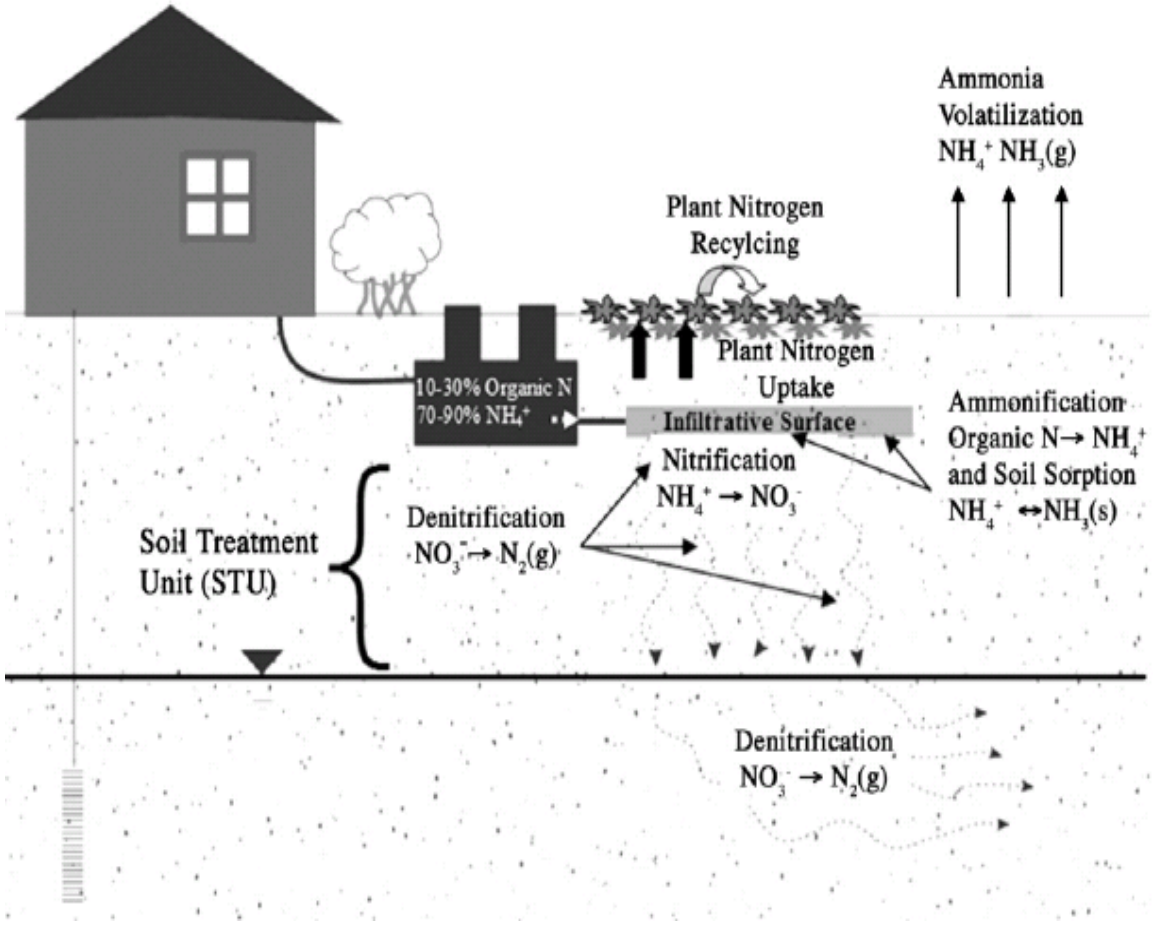
Nitrate Fate and Transport in Groundwater



Due to nitrification in the vadose zone, OSTDS can generate NO_3-N concentration at the water table from 25 to 80 mg N/L in most situations (McCray et al., 2005).

From Heatwole and McCray (2007)

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)

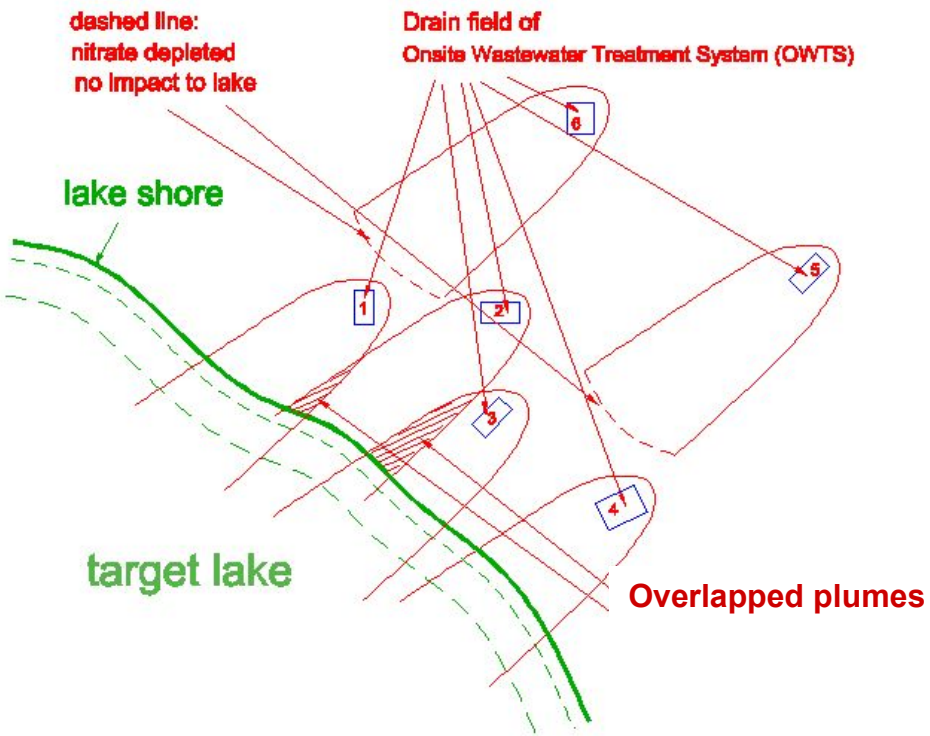
Ninety percent of the water used for drinking comes from the ground water. (FDEP, 2006)

From Heatwole and McCray (2007)

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

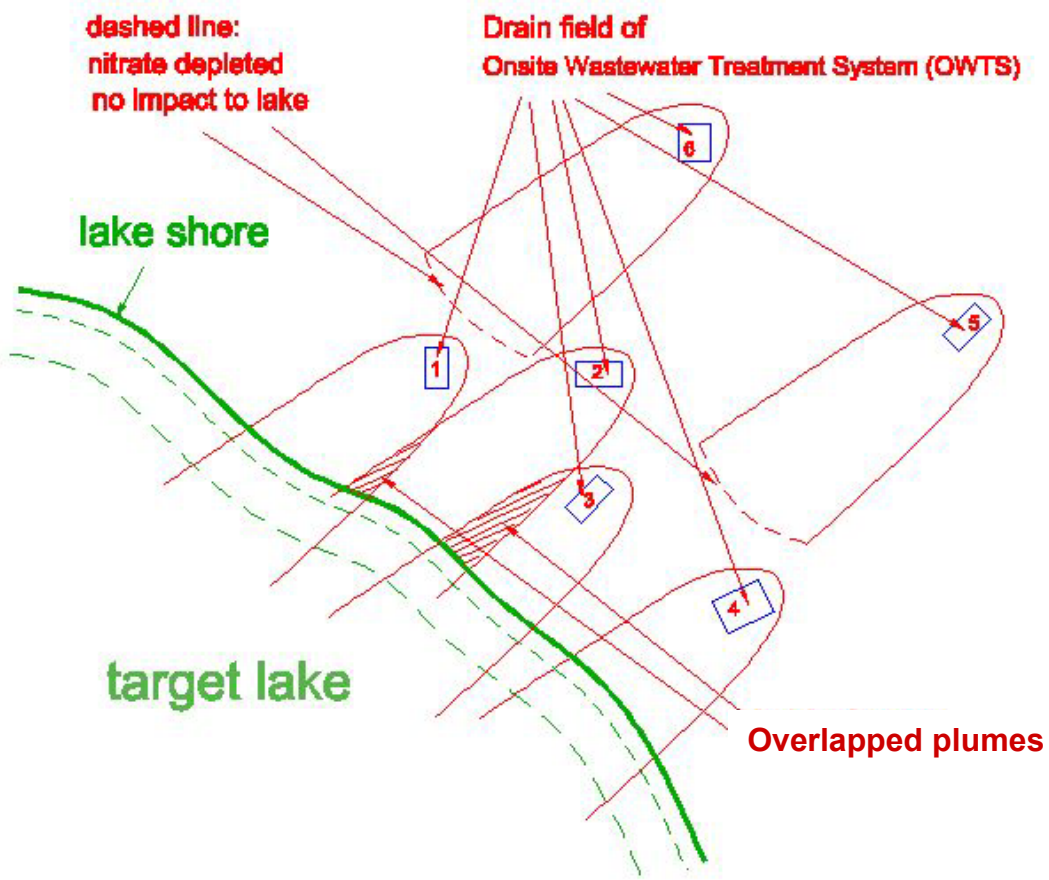
Project Goal

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

Denitrification

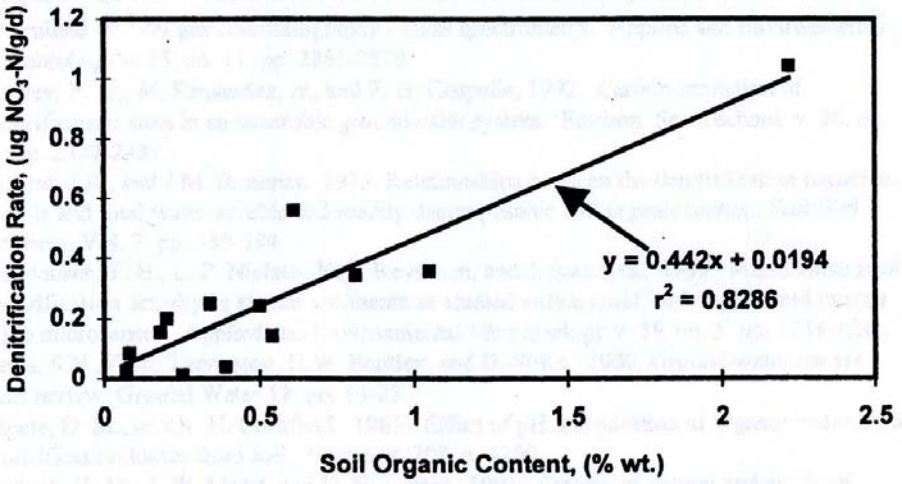
Denitrification refers to the biological reduction of nitrate to nitrogen gas.

$$NO_3^- + \text{Organic carbon} \rightarrow NO_2^- + \text{Organic carbon} \rightarrow N_2 + CO_2 + H_2O$$

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

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)

Estimation of Nitrate Load

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

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

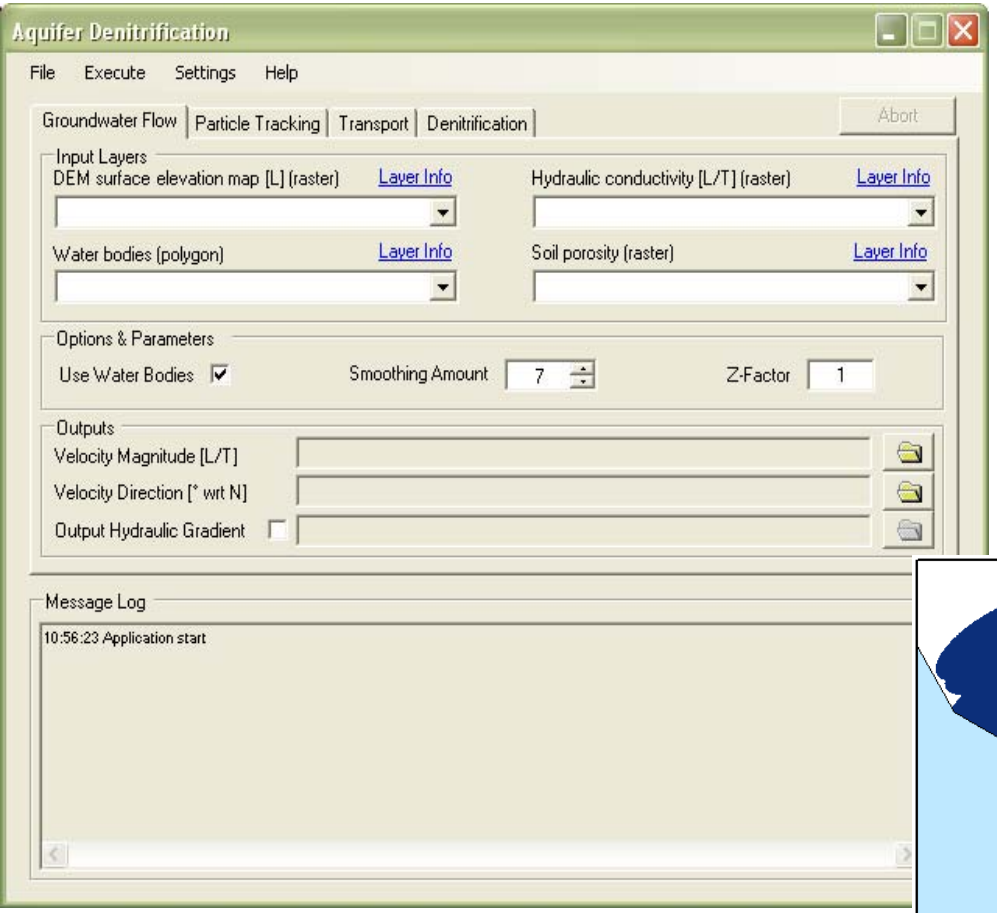
- M_{out} (M/T): nitrate load to rivers
- M_{in} (M/T): nitrate from septic tanks to surficial aquifer
- M_{dn} (M/T): nitrate loss due to denitrification

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

R_{dn} ($M/T/L^3$): denitrification rate

V_g (L^3): volume of groundwater solution, estimated from groundwater flow and reactive transport modeling

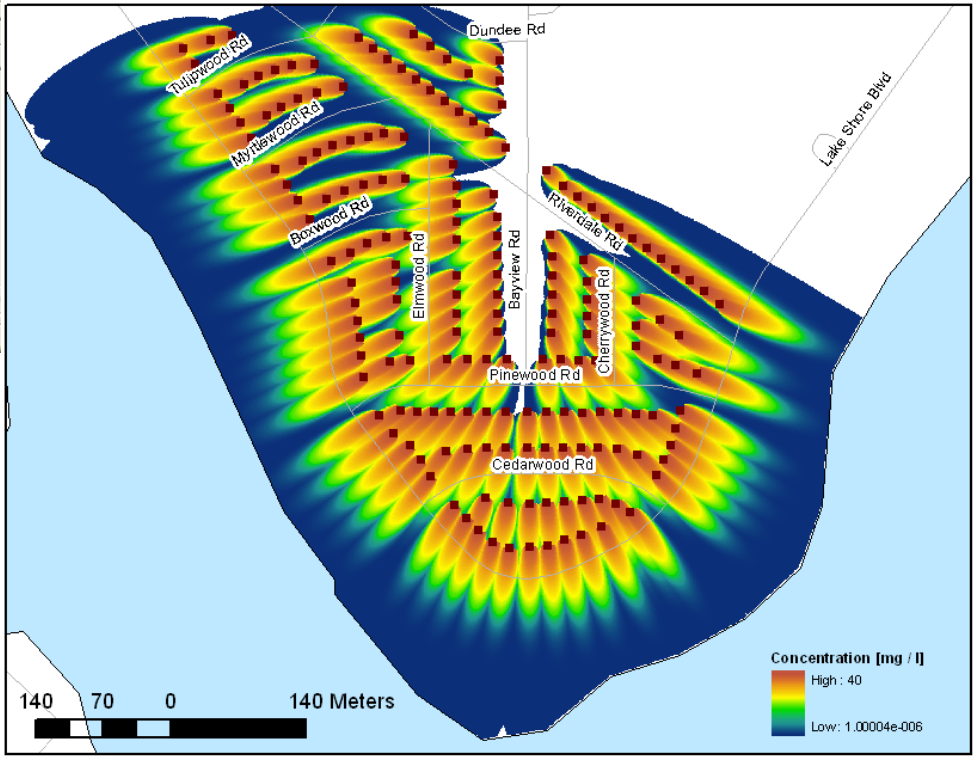
Graphic User Interface (GUI)



ArcNLET

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

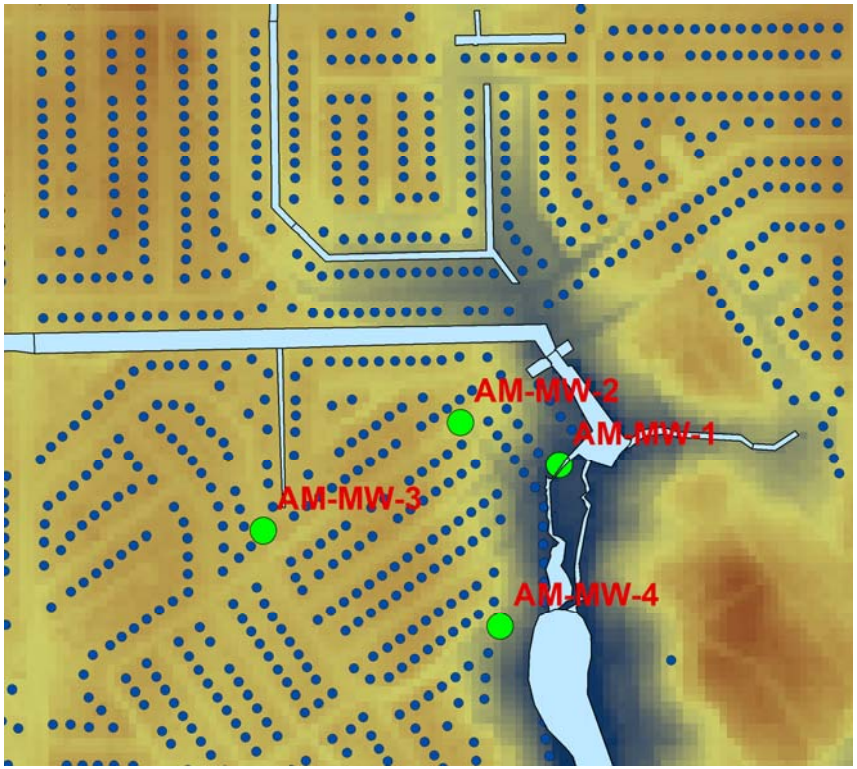
Free download at
http://people.sc.fsu.edu/~mye/ArcNLET/



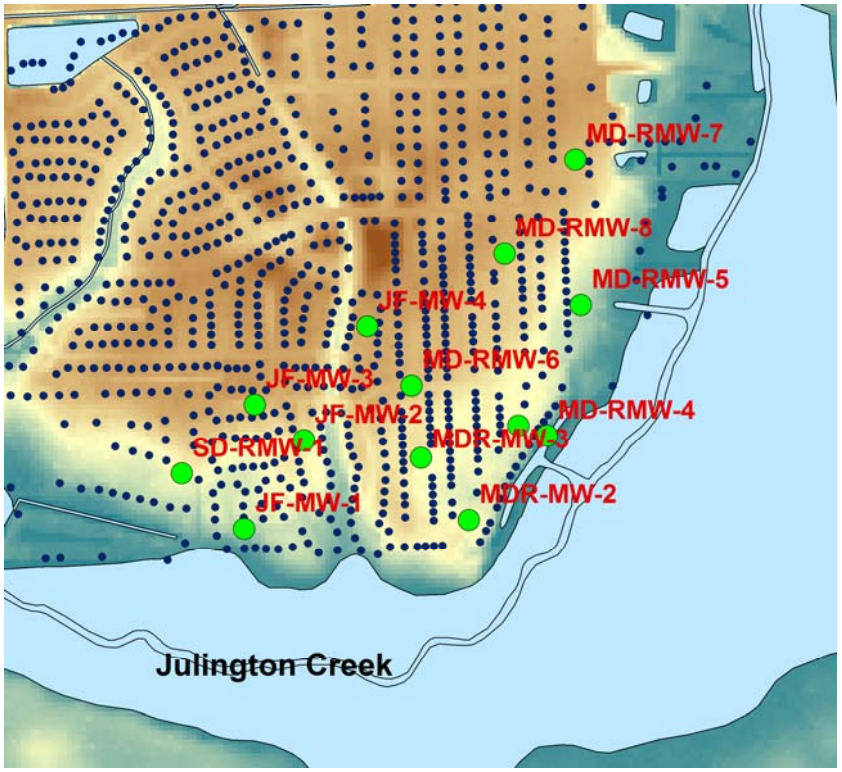
Example of simulated nitrate plumes

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

Eggleston Heights with 3500 OSTDS



Julington Creek with 1978 OSTDS



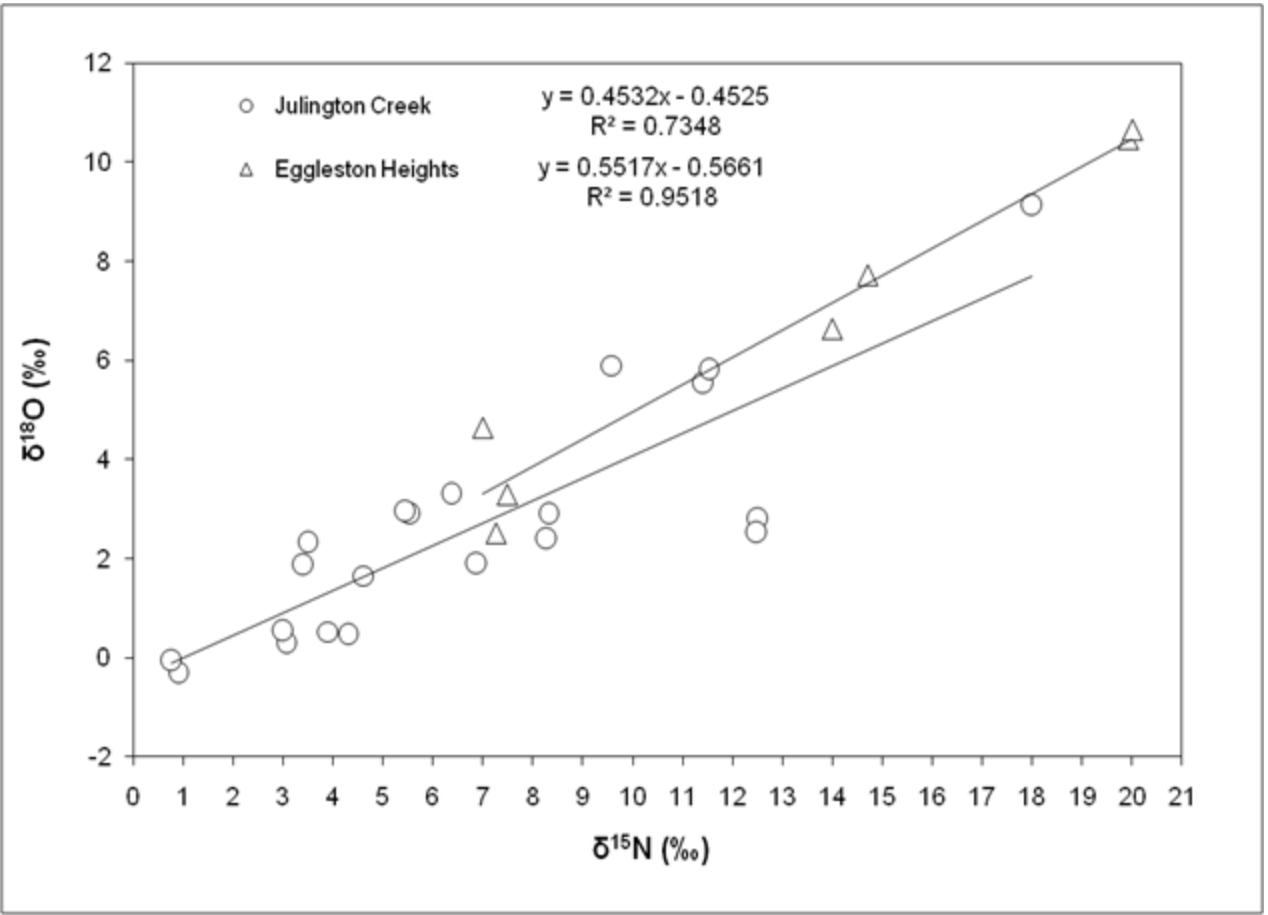
Reasons of selecting the two sites:

- 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.

Isotope Signature of Denitrification

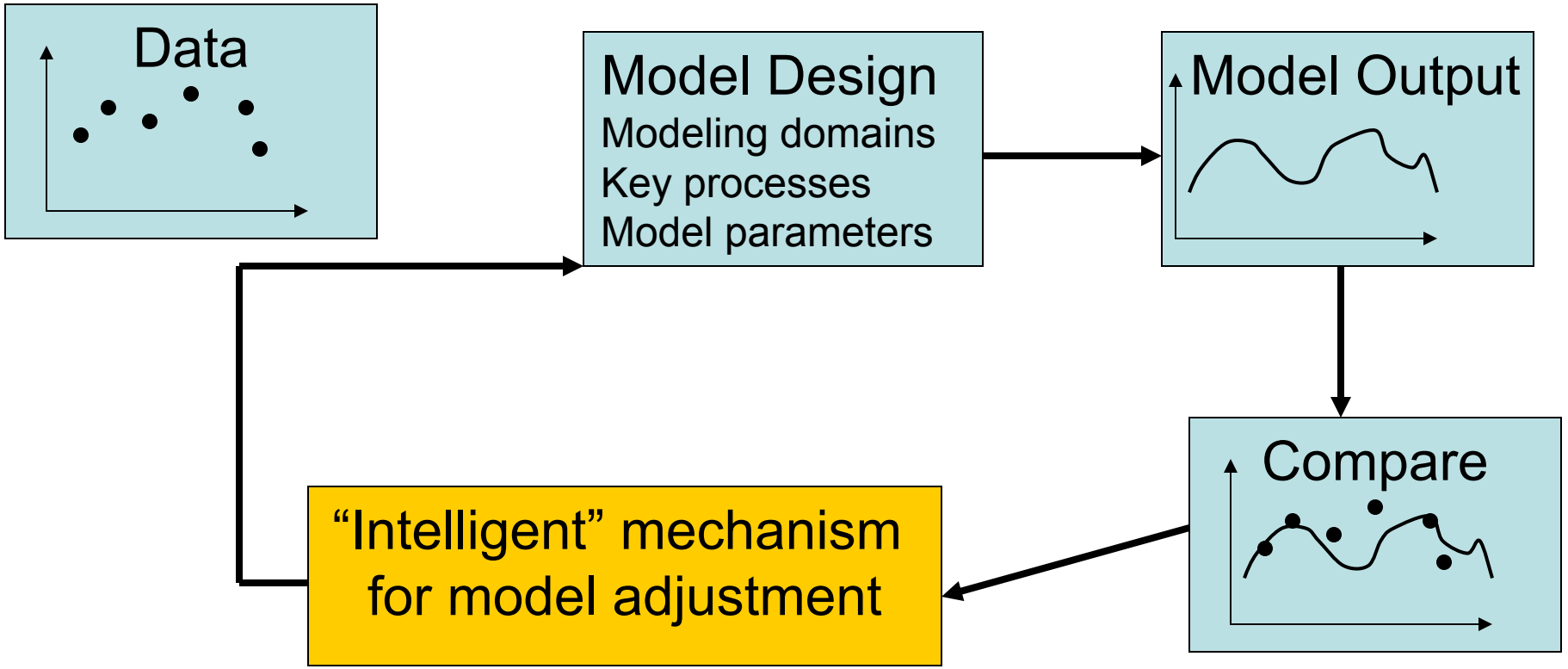
Indication of denitrification occurrence (Chen and Mcquarrie , 2005) :

- Linear relationship
- Slope close to 0.51



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

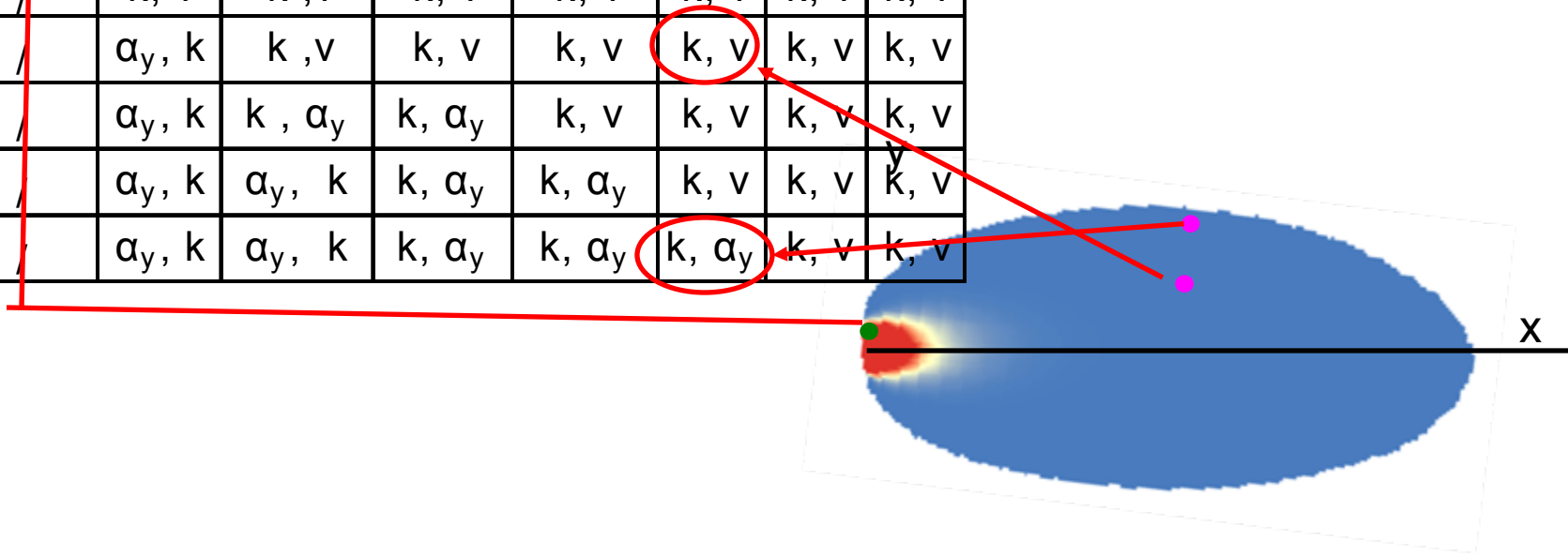
Model Calibration: Trial and Error



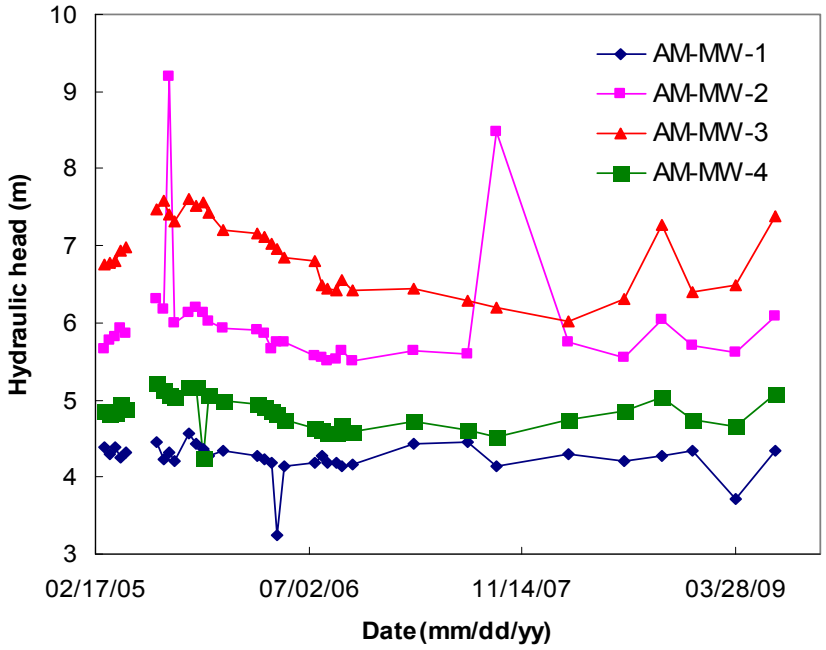
Global Sensitivity Analysis

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	k, v	k, v	k, v	k, v
6	/	α_y, k	k ,v	k, v	k, v	k, v	k, v	k, v
8	/	α_y, k	k , α_y	k, α_y	k, v	k, v	k, v	k, v
10	/	α_y, k	α_y, k	k, α_y	k, α_y	k, v	k, v	k, v
12	/	α_y, k	α_y, k	k, α_y	k, α_y	k, α_y	k, v	k, v

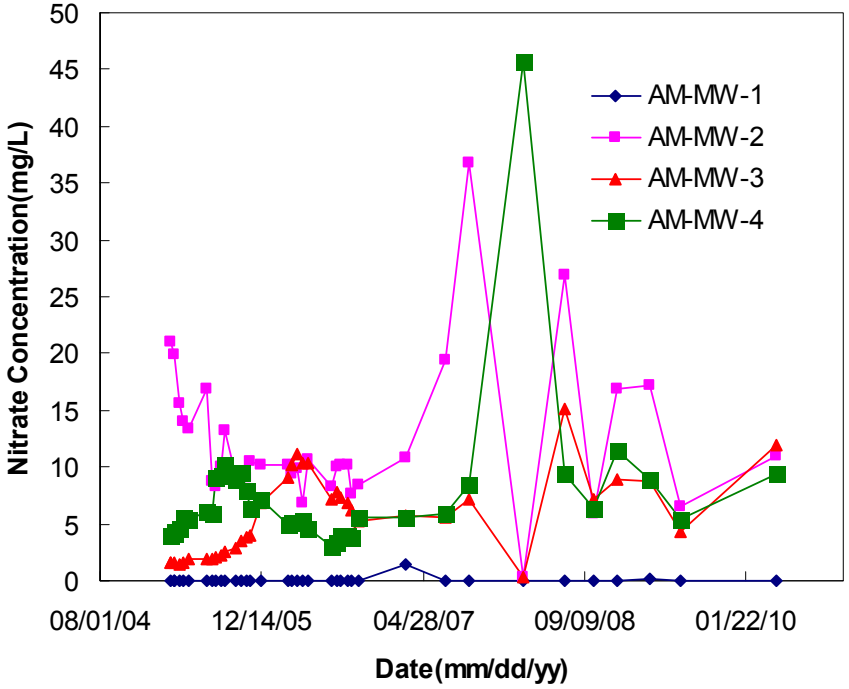


Observations of Hydraulic Head and Nitrate Concentration



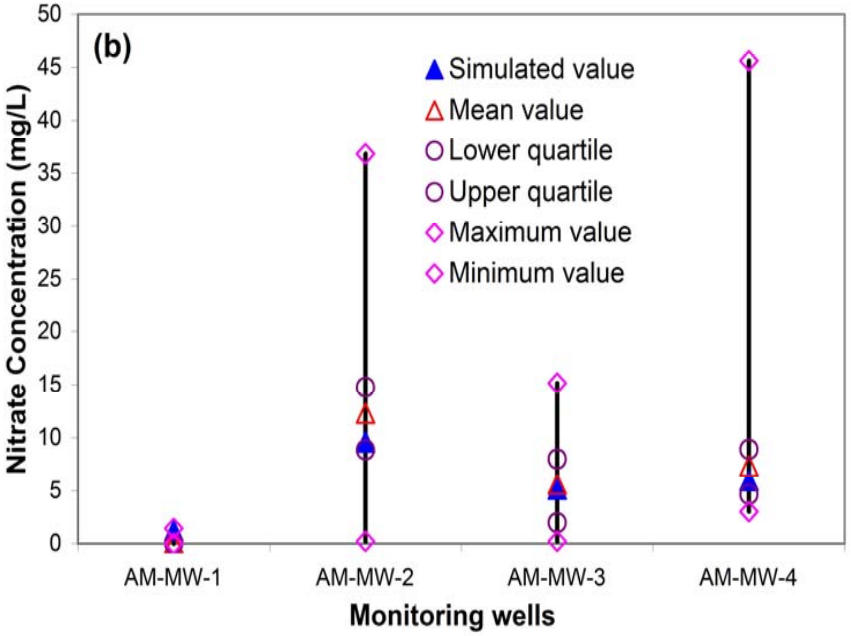
- The observed concentrations have large fluctuation due to complicated nitrogen transport and transformation mechanisms.
- No trend is observed.
- The mean value and ranges between upper and lower quartile are used as the calibration targets.

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



Calibration Results of Nitrate Concentration

Eggleston Heights



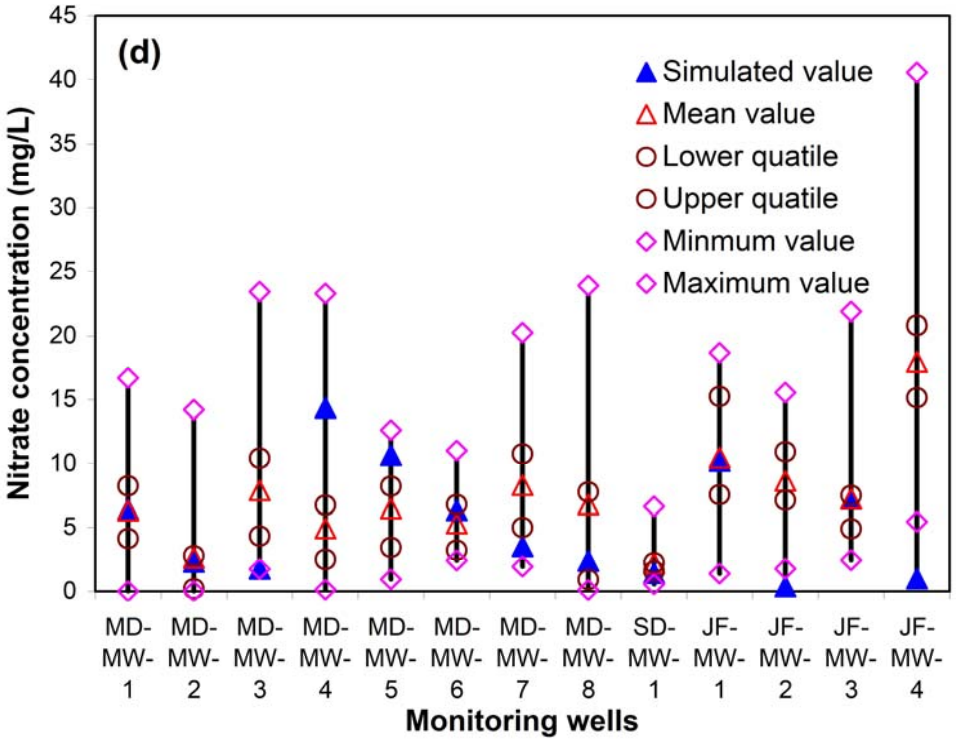
The simulated nitrate concentrations are

- 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.

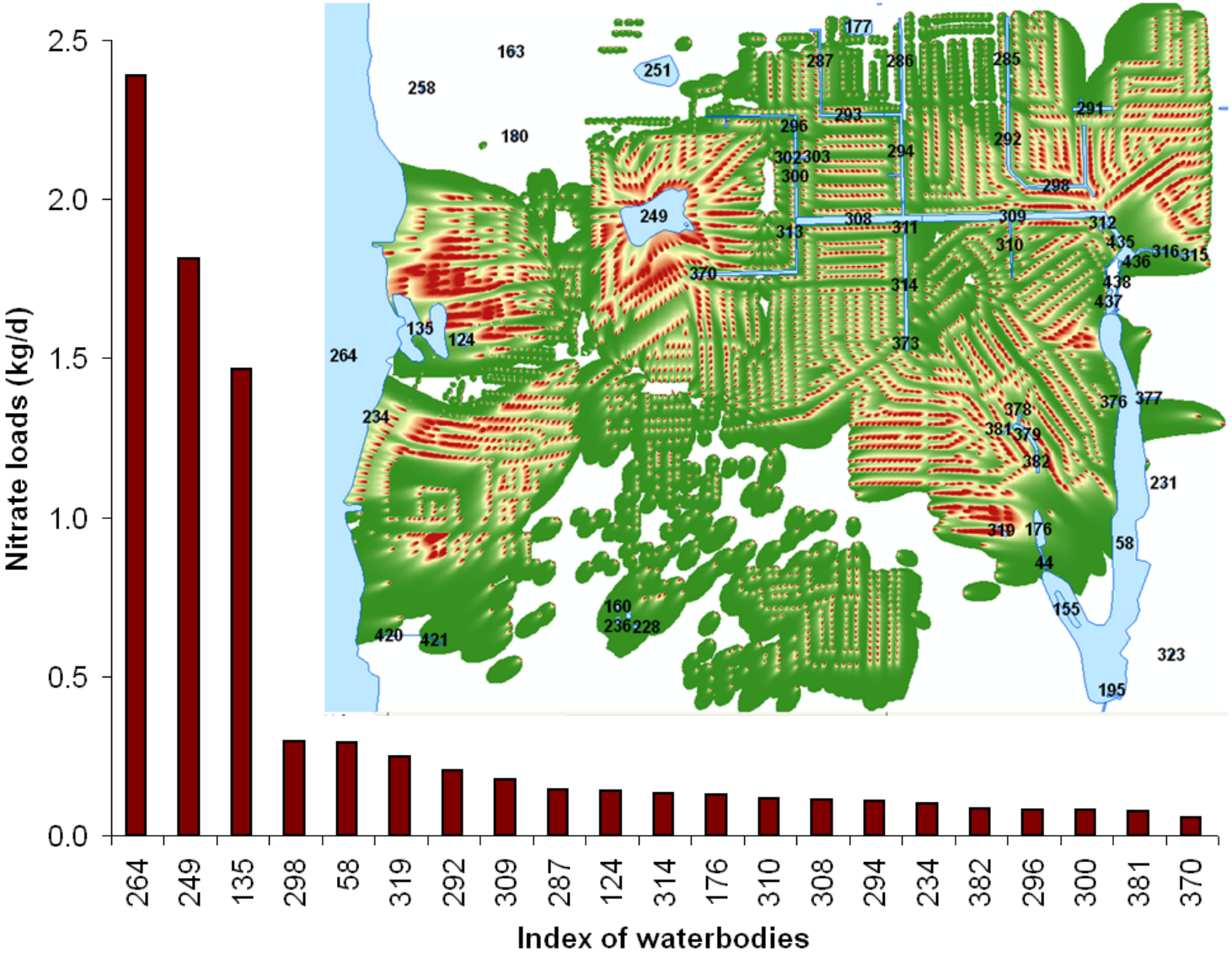
The simulated nitrate concentrations are

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

Julington Creek



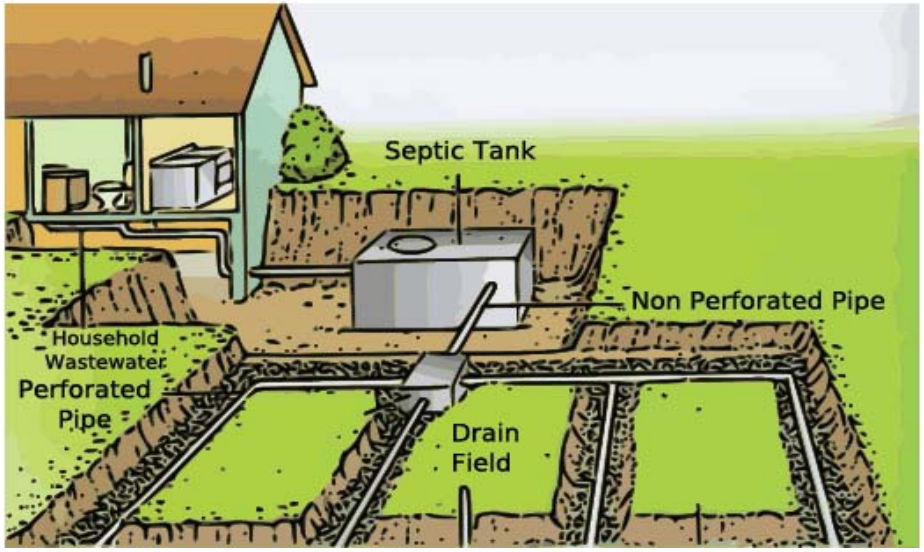
Nitrate Loads Estimation for Eggleston Heights Neighborhood



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 if interested.

Questions?


Septic Tank
Non Perforated Pipe
Household
Wastewater
Perforated
Pipe
Drain
Field

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.

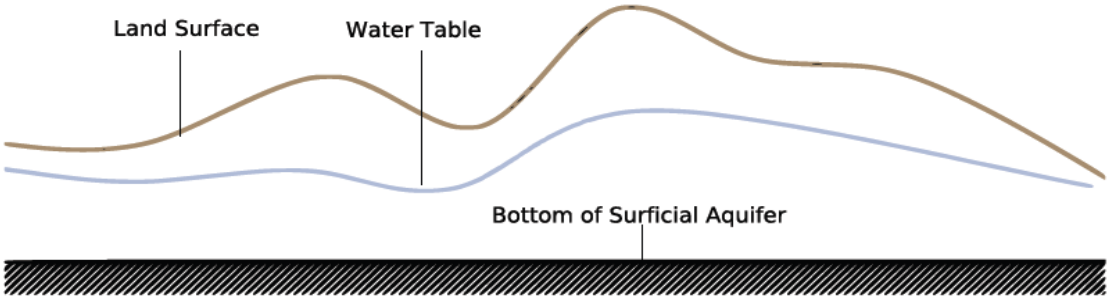
Modeling Procedure: Estimation

- 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.

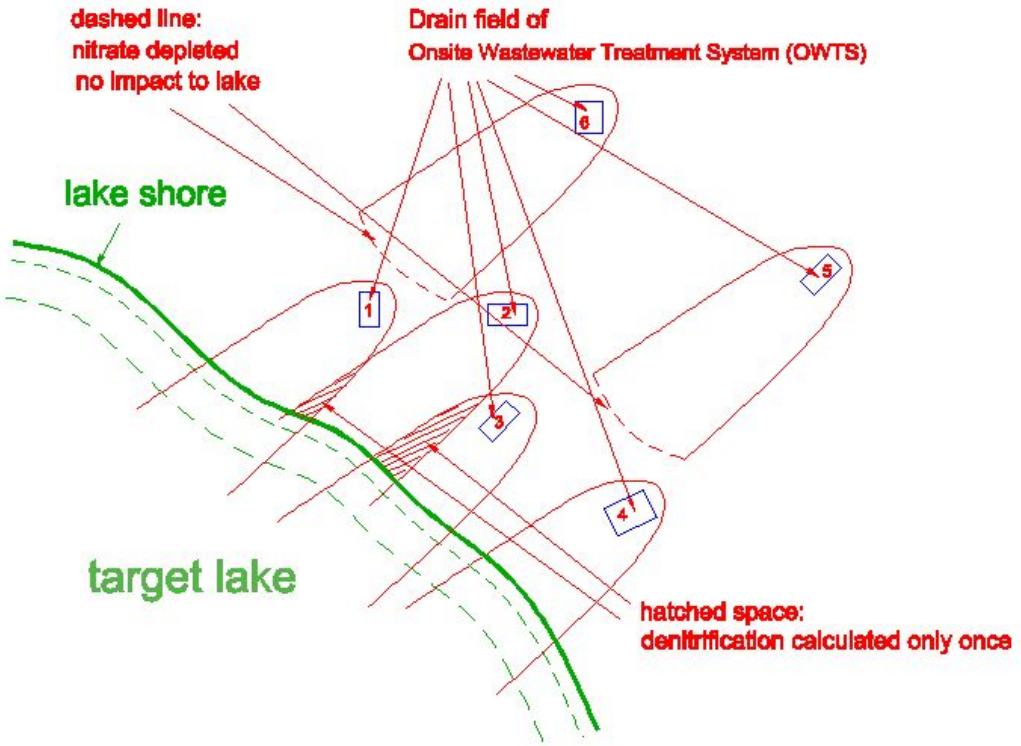
Groundwater Flow Modeling

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



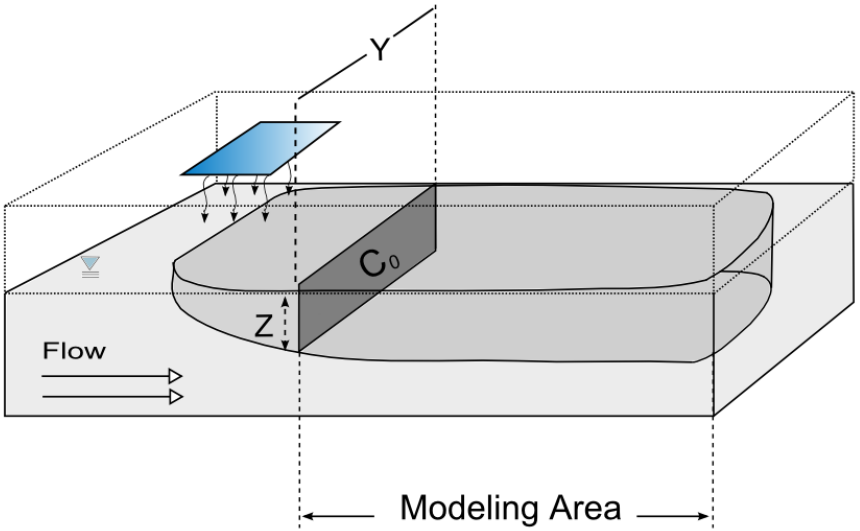
Outputs of Groundwater Flow Modeling



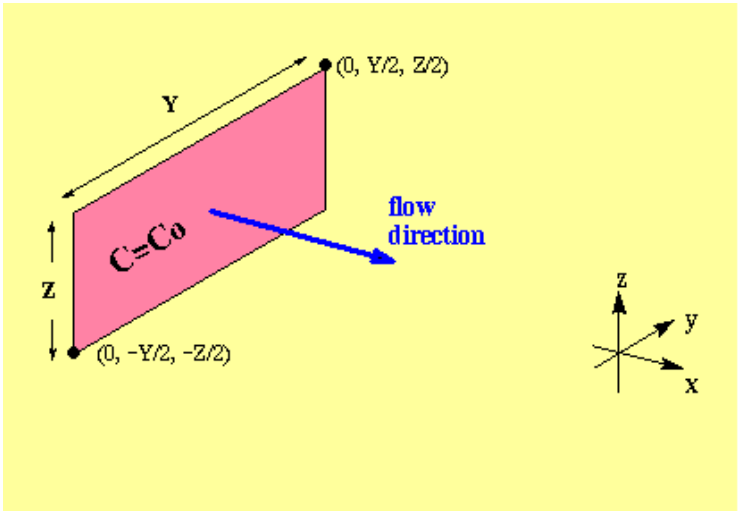
- Flow paths from each septic tank to surface water bodies
- Flow velocity along the flow paths. Heterogeneity of hydraulic conductivity and porosity is considered.
- Travel time from septic tanks to surface water bodies

Nitrate Transport Modeling

EPA BIOCHLOR model



Domenico analytical solution



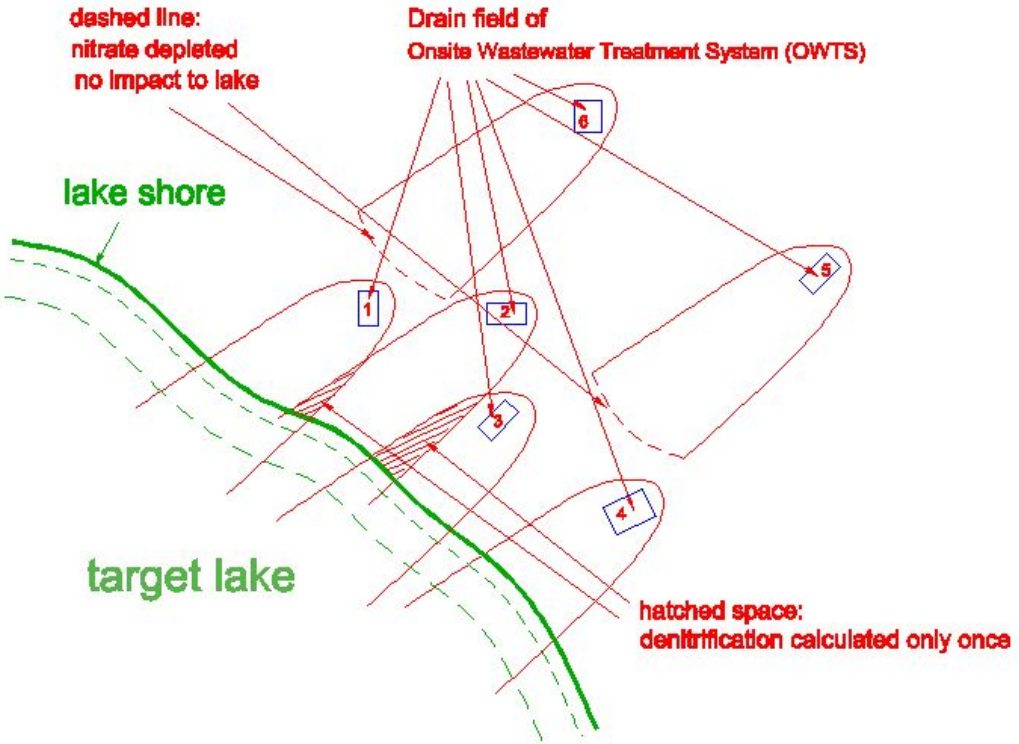
$$\frac{\partial C}{\partial t} = \alpha_\ell v \frac{\partial^2 C}{\partial x^2} + \alpha_{T_h} v \frac{\partial^2 C}{\partial y^2} + \alpha_{T_v} v \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial x} - kC$$

Dispersion Advection Decay Denitrification

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

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



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

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

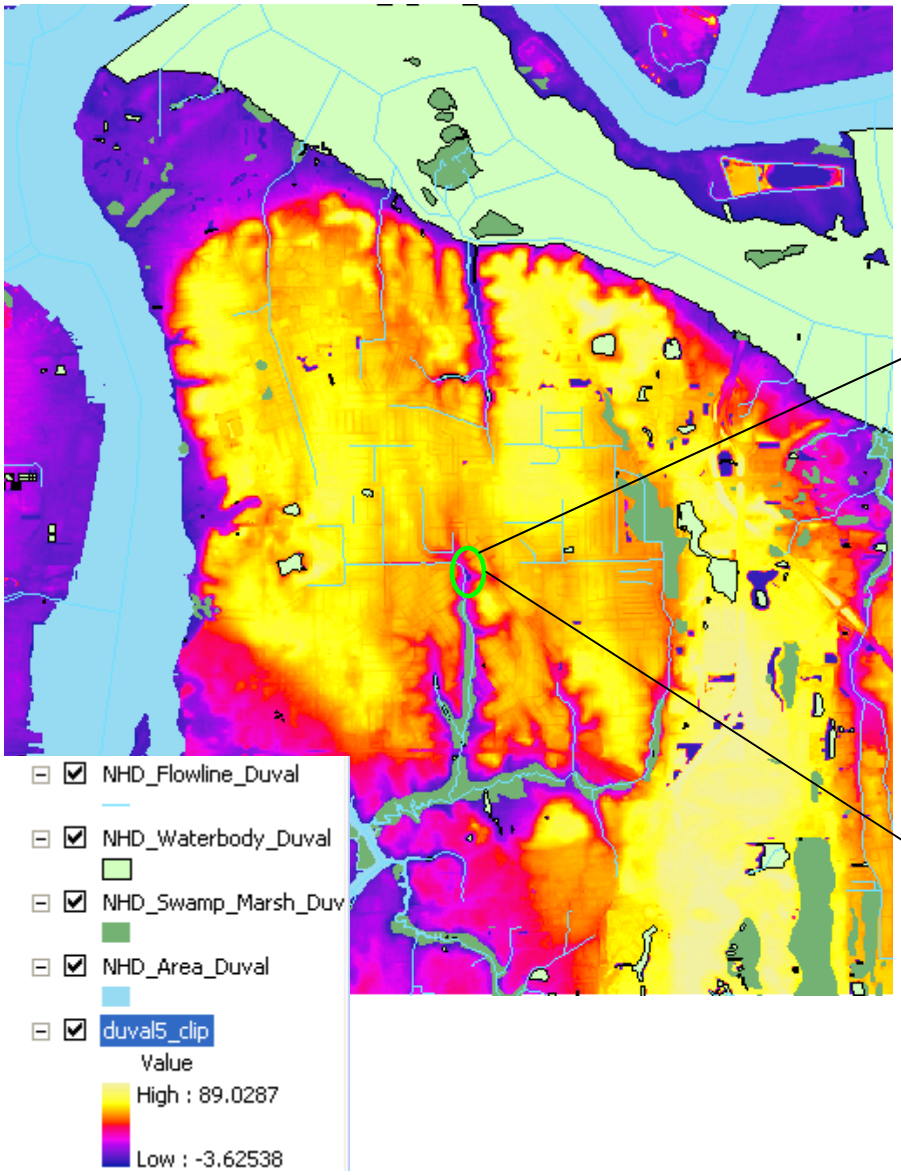
Development of the ArcGIS Extension

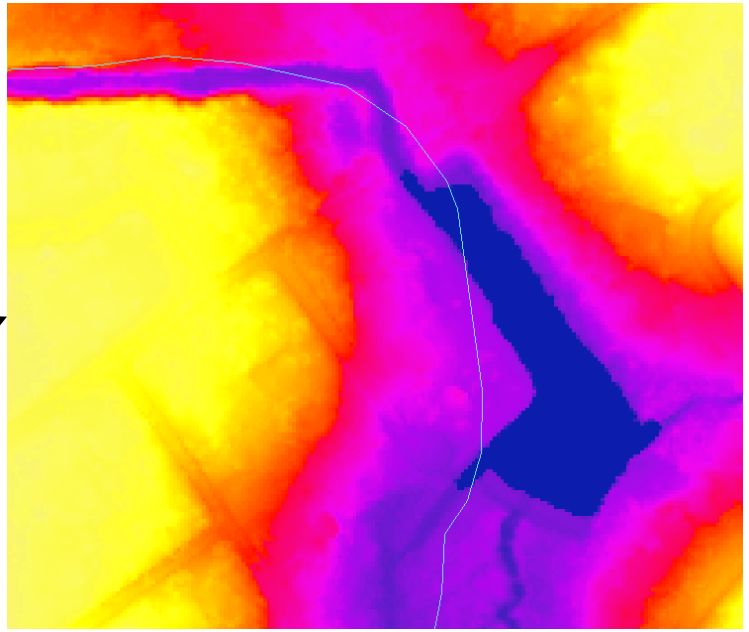
- All the development is within ArcGIS, including pre-processing, post-processing, and computation.
- We developed a user-friendly interface using Visual Basic.
  - The .NET framework is used to expedite development.
- The software development is for ArcGIS 9.3.
  - The software can be updated with newer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

Summary of Model Inputs and Outputs

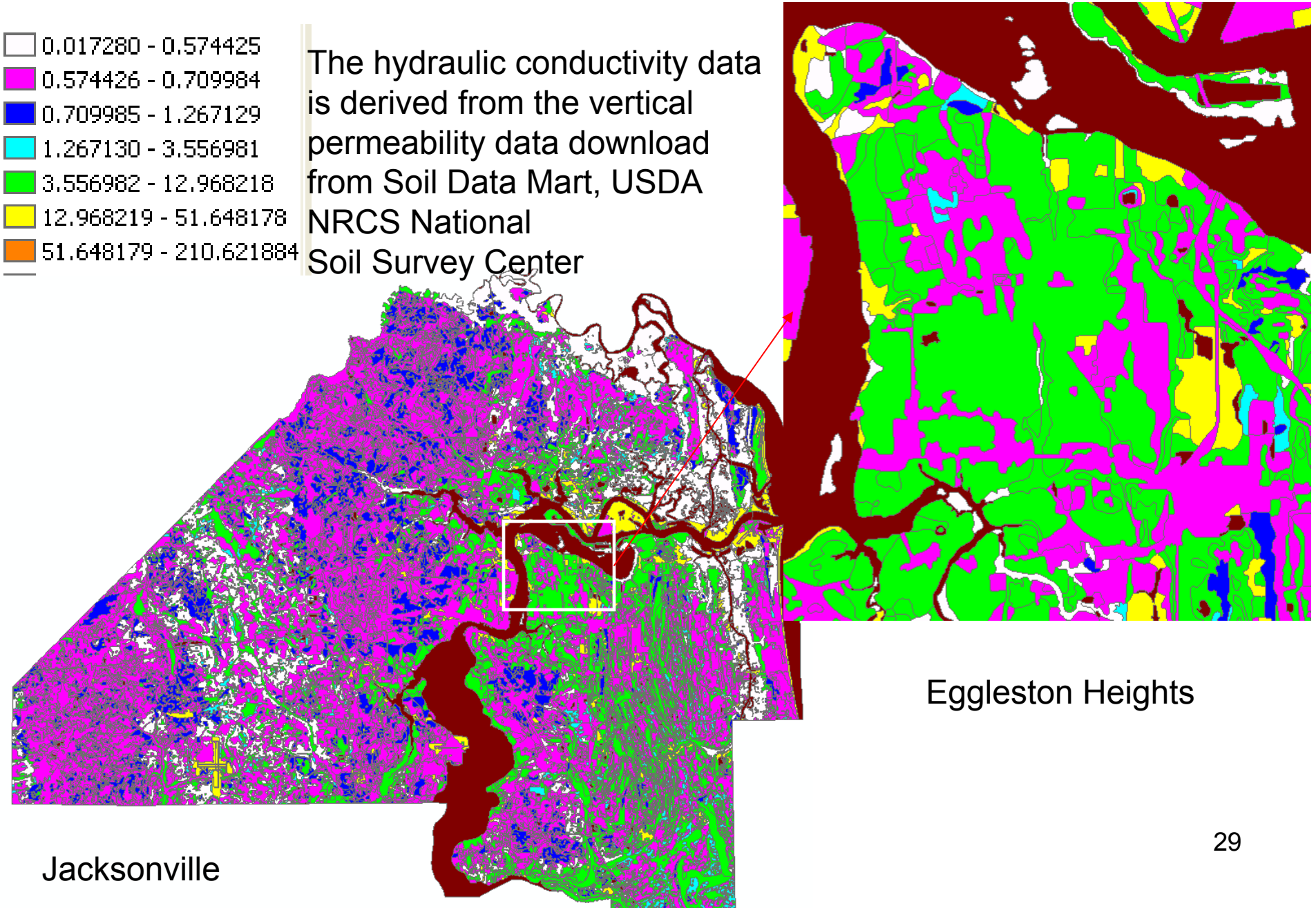
- Model Inputs
  - Flow module: DEM, Water bodies, Hydraulic conductivity, and Porosity
  - Transport module: Source nitrate concentration, Dispersivity, and Decay coefficient
  - Denitrification module: none
- Model Outputs
  - Flow module: Flow velocity and path
  - Transport module: Nitrate plume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

Use LiDAR Data to Update NHD Data





Heterogeneous Hydraulic Conductivity

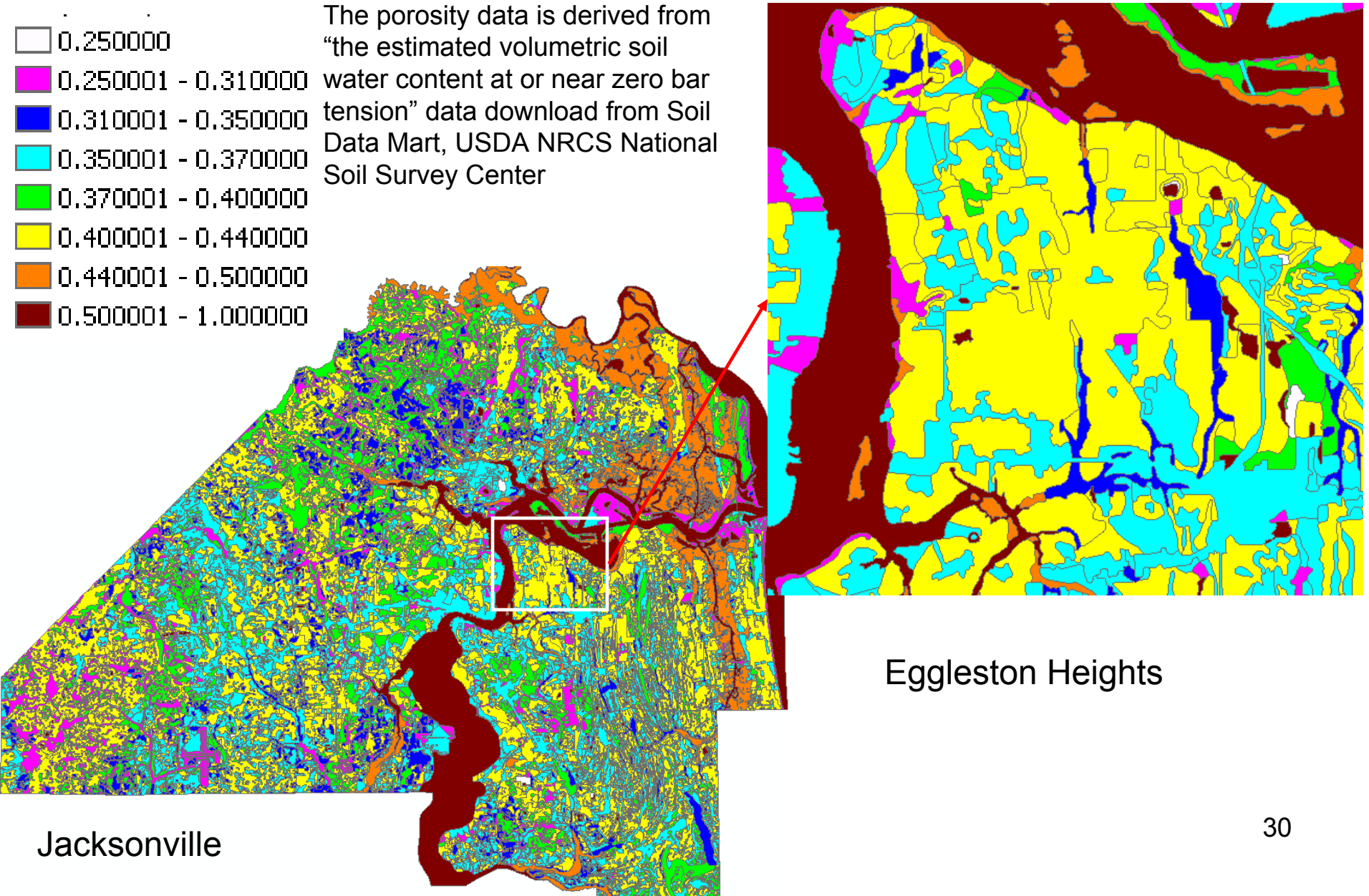


The hydraulic conductivity data is derived from the vertical permeability data download from Soil Data Mart, USDA NRCS National Soil Survey Center

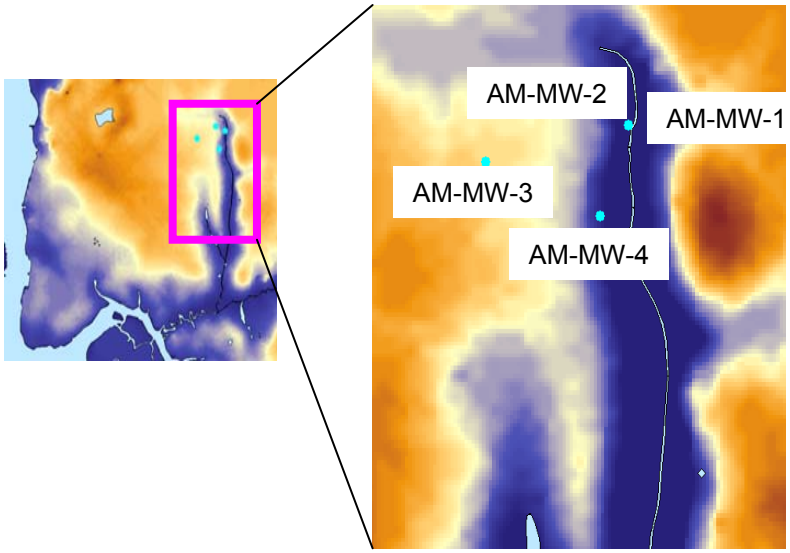
Eggleston Heights

Jacksonville

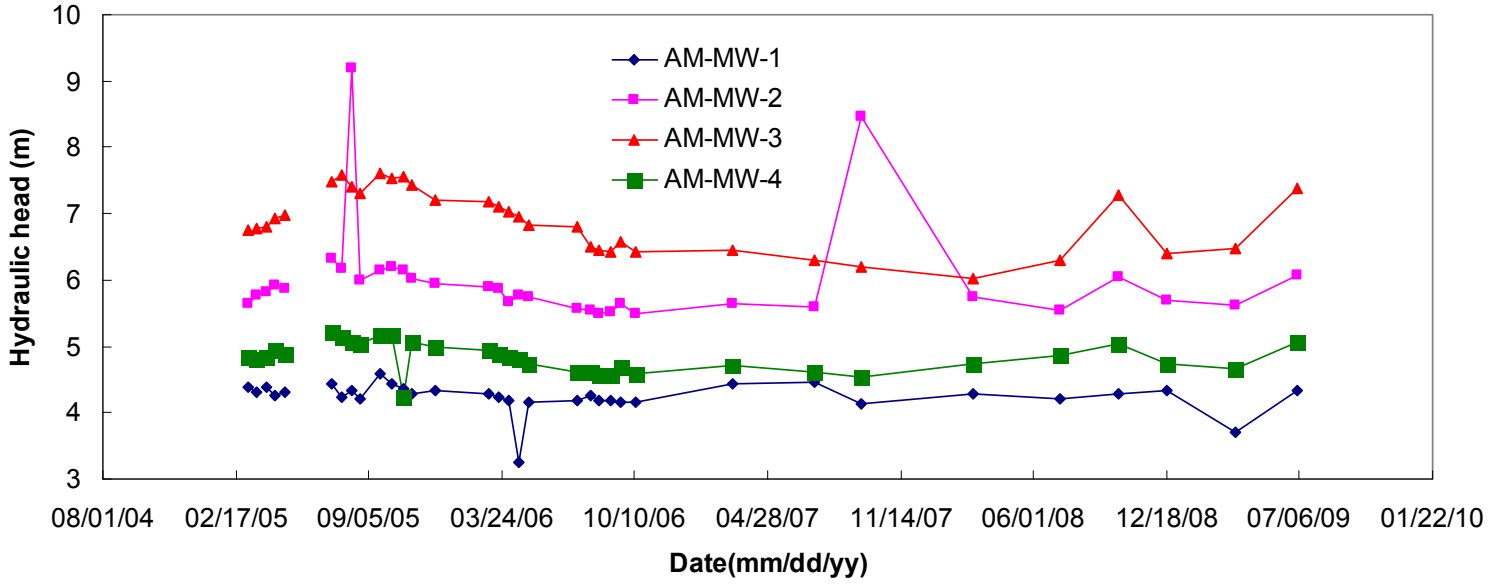
Heterogeneous Porosity



Observations of Hydraulic Head

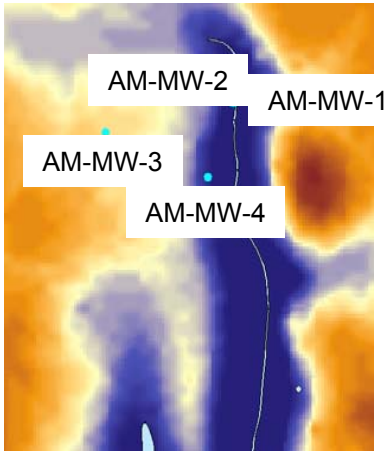


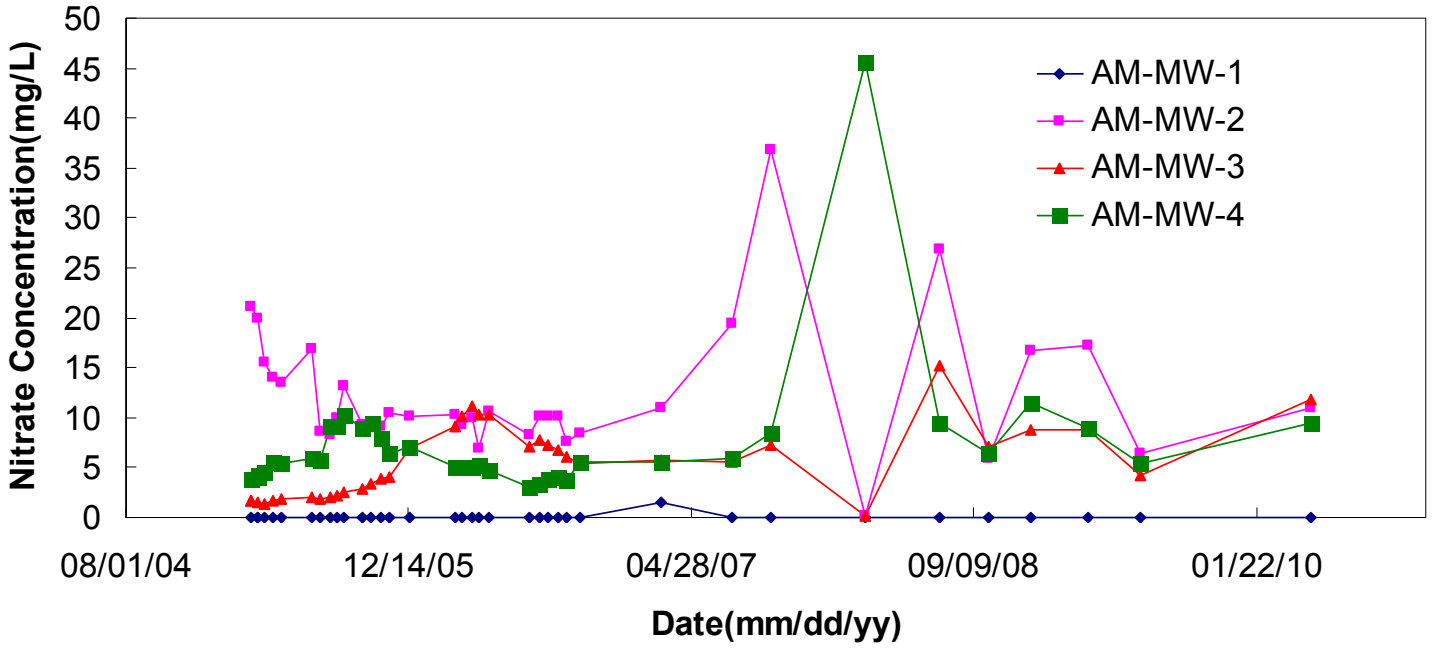
- Four monitoring wells
- Monitoring data from 2005 to 2009
- Water table is relatively stable



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.

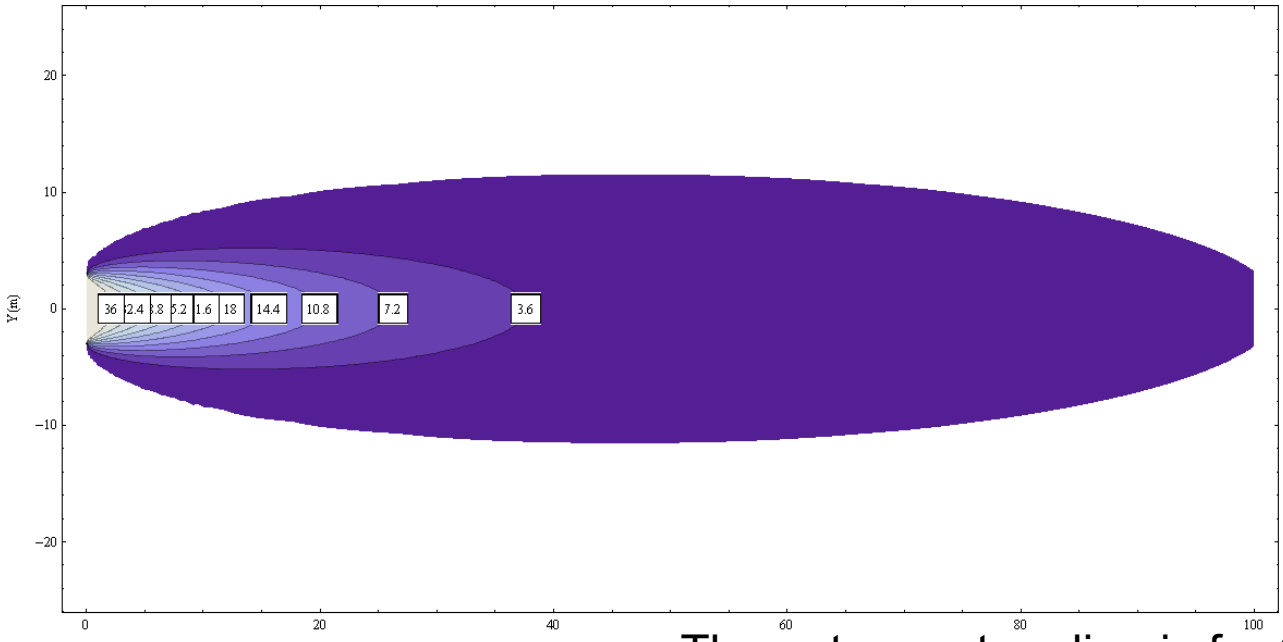




Sensitivity Analysis

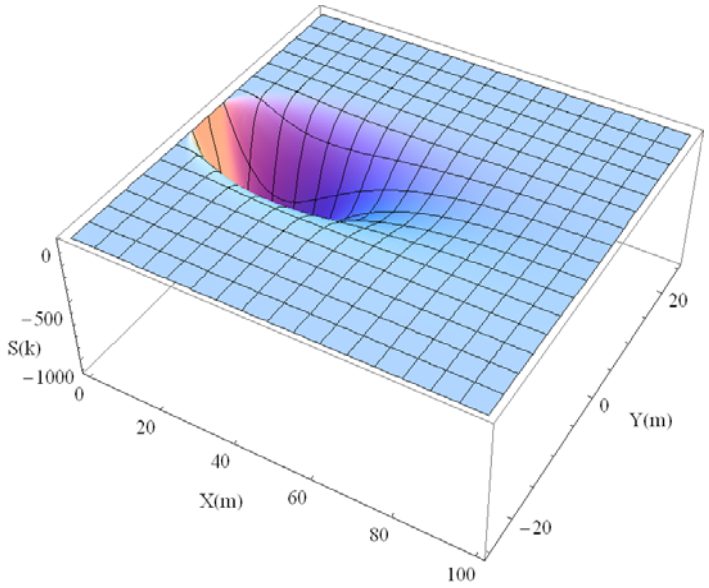
- What control plume size and nitrate concentration?
- Nominal parameters:

  C_0=40mg/L, v=0.15m, α_x=2m, α_y=0.2m, and k=0.008/d
- Corresponding concentration

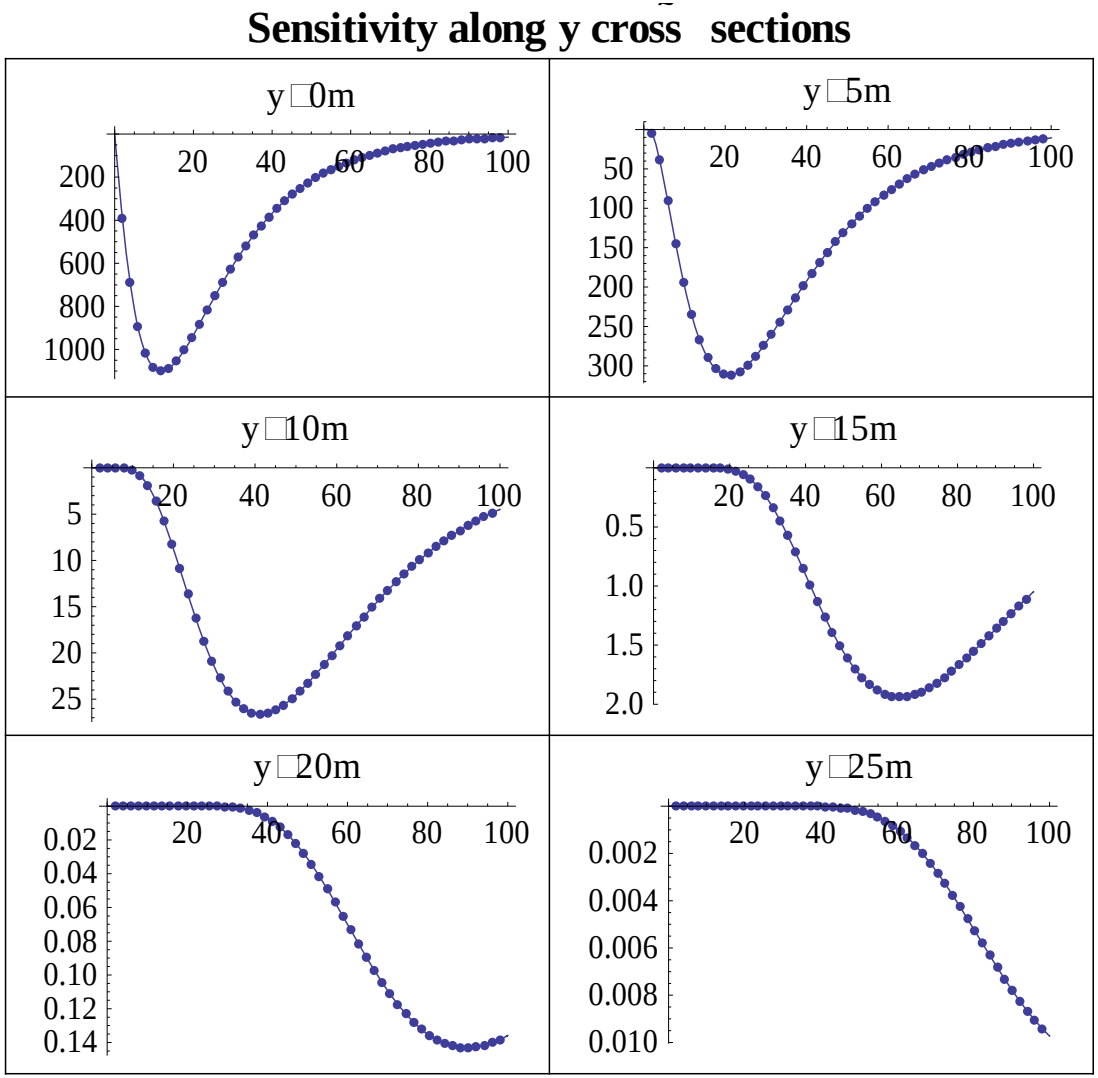


The outer contour line is for C=0.1 mg/L

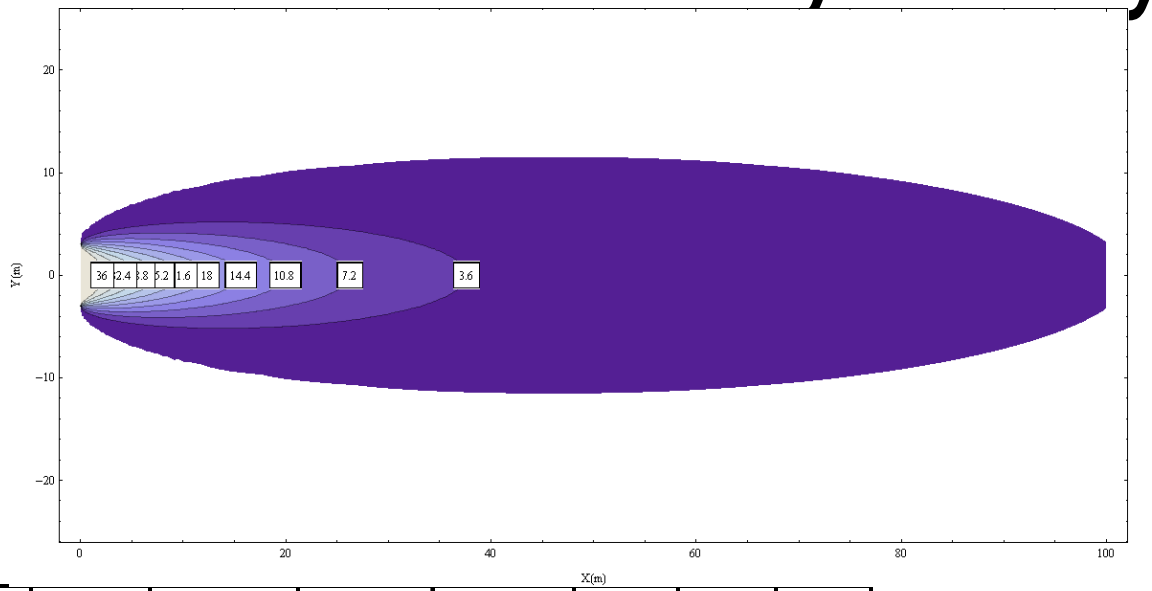
Sensitivity to k at Different Horizontal Cross-Sections



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



Global Sensitivity Analysis



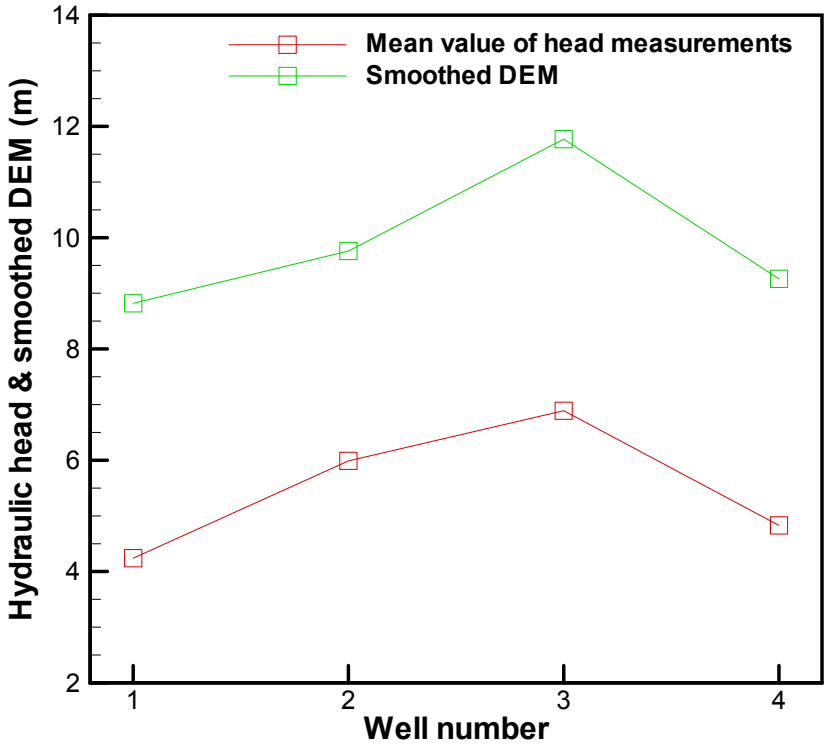
x(m) / y(m)	0.0001	5	10	15	20	30	40	50
0	C_0, v	k, v	k ,v	k, v	k, v	k, v	k, v	k, v
1	C_0, v	k, v	k ,v	k, v	k, v	k, v	k, v	k, v
2	C_0, v	k, v	k ,v	k, v	k, v	k, v	k, v	k, v
3	C_0, v	k, v	k ,v	k, v	k, v	k, v	k, v	k, v
4	/	k, v	k ,v	k, v	k, v	k, v	k, v	k, v
6	/	a_y, k	k ,v	k, v	k, v	k, v	k, v	k, v
8	/	a_y,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

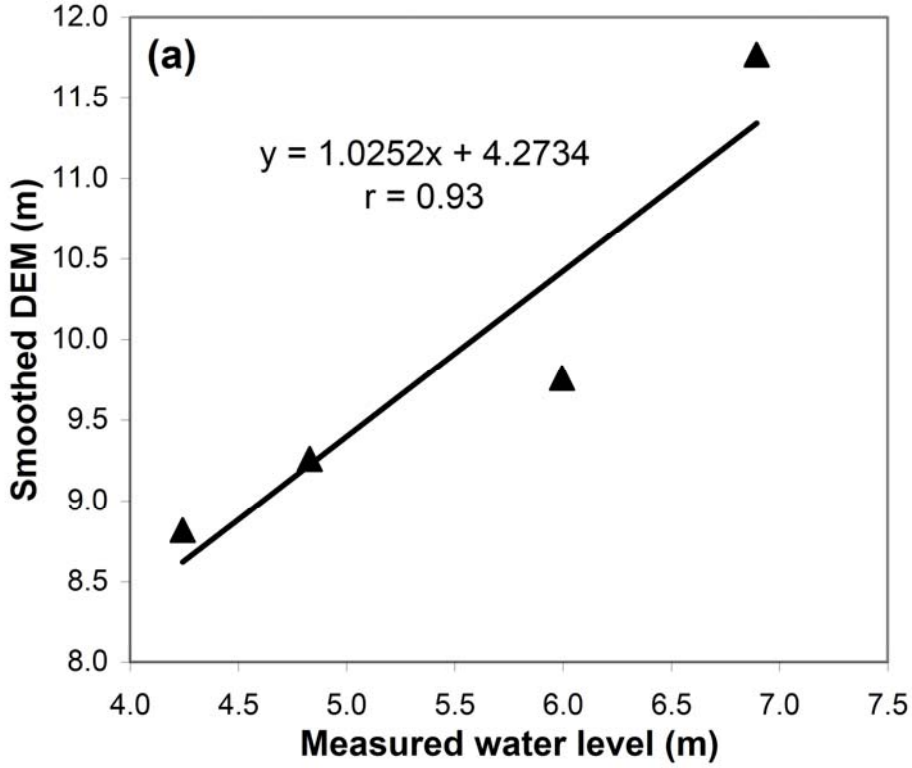
Two most critical parameters to simulated nitrate concentration at every location.

Calibration Results: Heads

Smoothed DEM agree well with mean observed hydraulic head

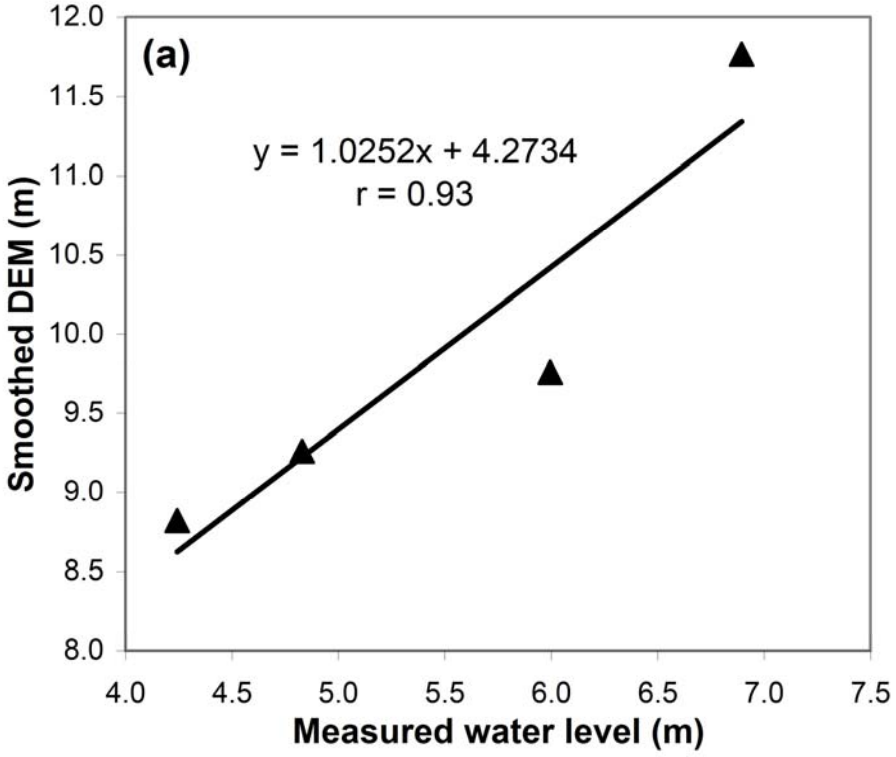
- correlation coefficient of 0.93 and
- the slope of linear regression close to 1.



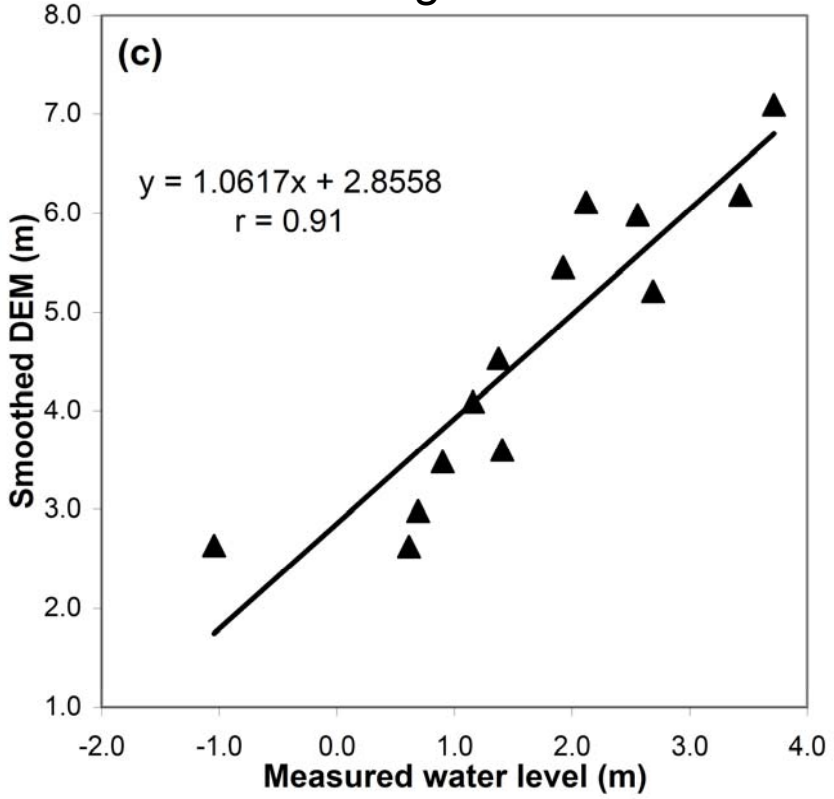


Calibration Results of Hydraulic Gradient

Eggleston Heights



Julington Creek

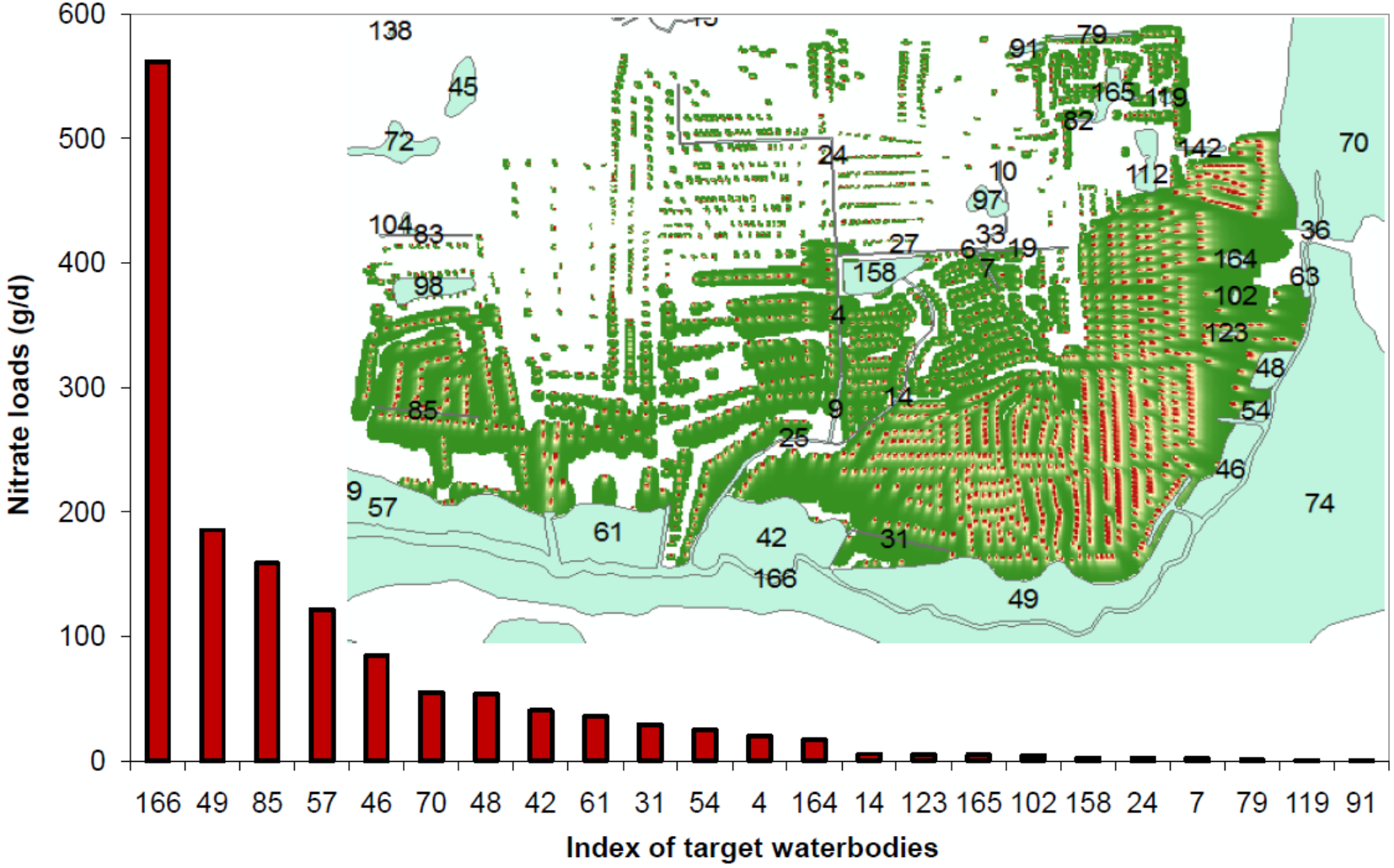


The smoothed DEM agree well with the observed water table shape with a linear correlation coefficient of more than 0.9 and slope of the linear regression close to 1.0

Estimated Source Input Mass Flux and Loads

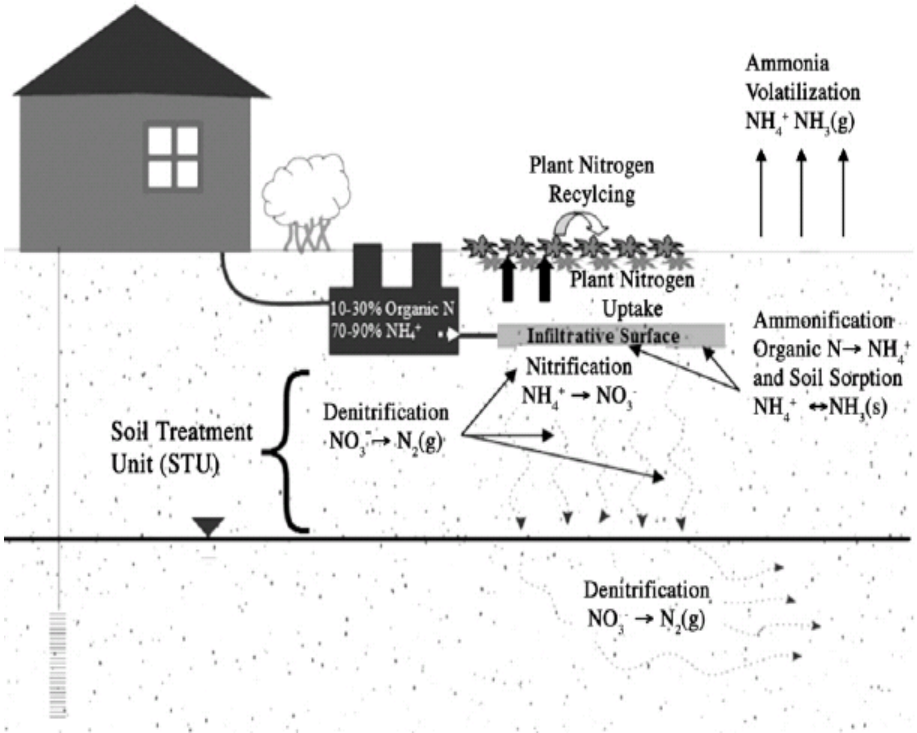
- Based on the summary report of Anderson (2006) for Florida, average source input mass flux is estimated as 20 g/sep/day.
- For Eggleston Heights, the estimated source input mass flux from 3495 septic systems is 115.4kg per day (33g/sep/day), about 92.5% of which is lost due to denitrification and 7.5% 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 NO_3-N concentration at the water table from 25 to 80 mg N/L in most situations. (McCray et al., 2005)