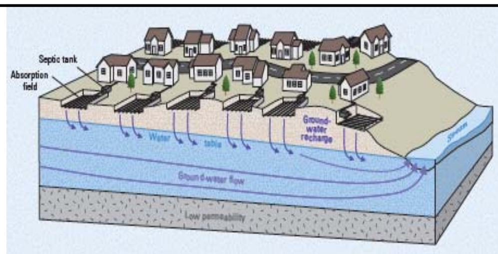

Picture from USGS Scientific Investigations Report 2008–5220

Arc NLET: Nitrate Load Estimation Toolkit

Developing a GIS-Based Software for Estimating Nitrate Fate and Transport in Surficial Aquifers: from Septic Systems to Surface Water Bodies

March 29th, 2011

Presentation at the SHRUG Symposium

Project Team Members

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  - Hal David (USGS)
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Presentation Outlines

- Background and overview
- Development of groundwater flow and nitrate fate and transport models
- Demonstration of Arc NLET
- Applications to Eggleston Height neighborhood in Jacksonville
- Conclusions

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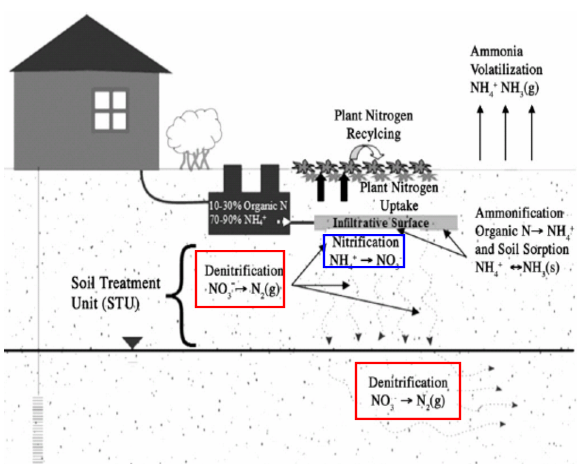
Schematic of an Onsite Wastewater Treatment System (OWTS) and Subsurface Nitrogen Transformation and Removal Processes



From Heatwole and McCray (2007)

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

Denitrification rates are much smaller than nitrification rates in natural soils.

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

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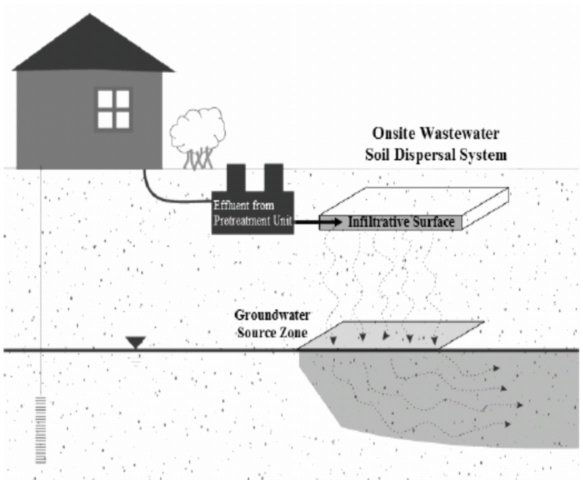
Nitrate Fate and Transport in Groundwater



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).

From Heatwole and McCray (2007)

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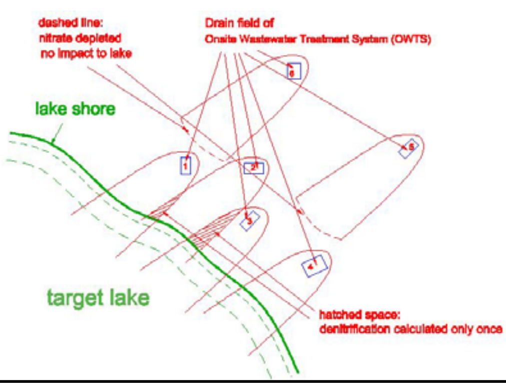
Motivations

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



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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).

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Project Goal

Goal: To develop a simplified model and software to support the TMDL.

- 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

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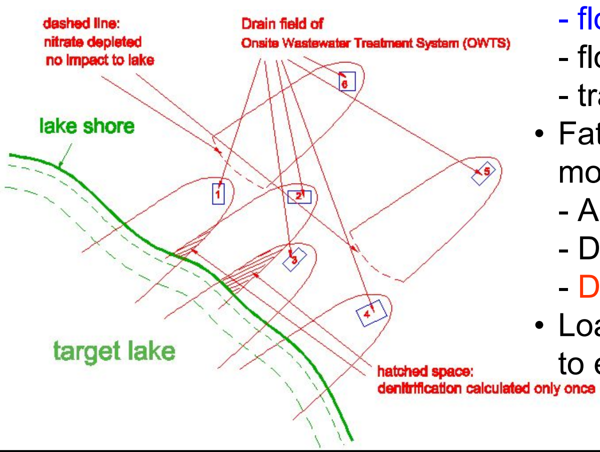
Project Objectives

- Develop a simplified model 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
- Apply this software to nitrate transport modeling at the Lower St. Johns River basin to facilitate DEP environmental management and regulation.
- Disseminate the software and conduct technical transfer to DEP staff and other interested parties.

Conceptual Model

Take into account of nitrate contribution from working septic tanks.



- Groundwater flow model to estimate
  - flow path
  - flow velocity
  - travel time
- Fate and transport model to consider
  - Advection
  - Dispersion
  - Denitrification
- Load calculation model to estimate nitrate load

Denitrification

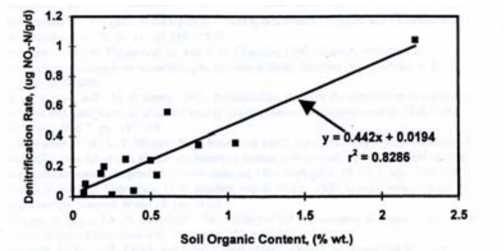
Denitrification refers to the biological reduction of nitrate to nitrogen gas.

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

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

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).

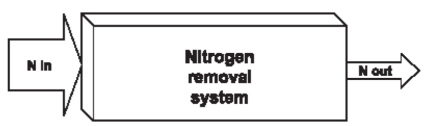
A fairly broad range of heterotrophic anaerobic bacteria are involved in the process, requiring an organic carbon source for energy as follows



Anderson (1989)

Estimation of Nitrate Load

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



- M_l (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

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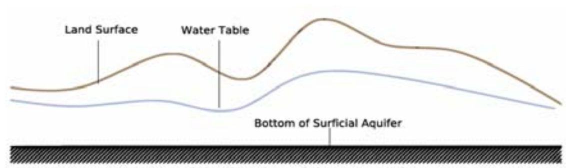
Groundwater Flow Modeling

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



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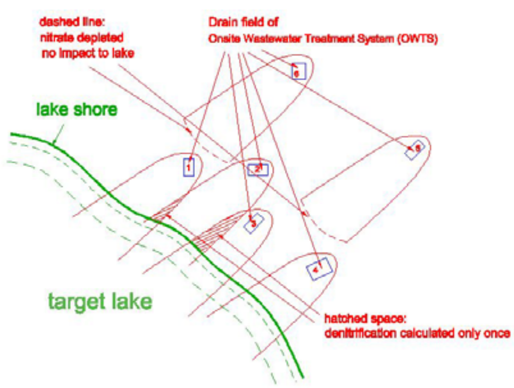
Outputs of Groundwater Flow Modeling



- 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

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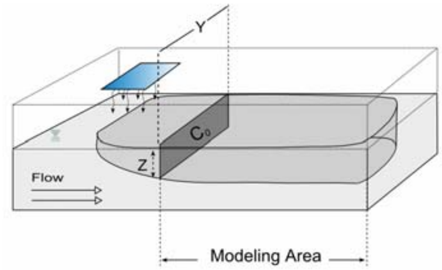
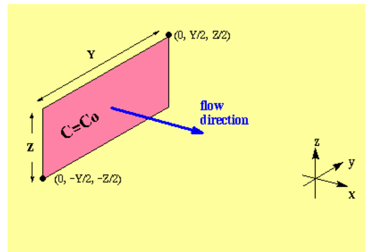
Nitrate Transport Modeling

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

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

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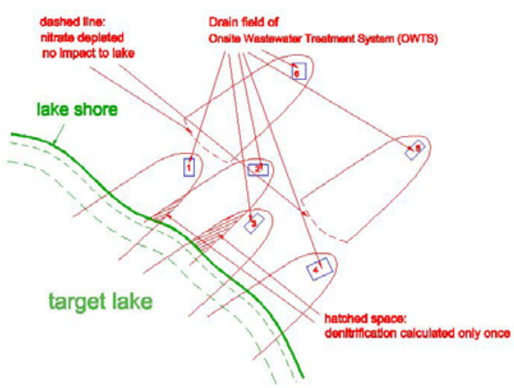
Outputs of Nitrate Transport Modeling and Calculation of Nitrate Load

- 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



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

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

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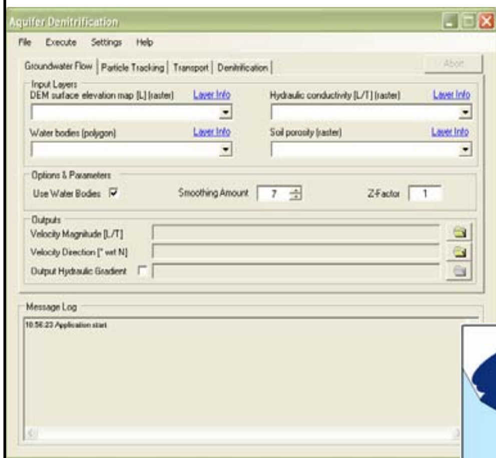
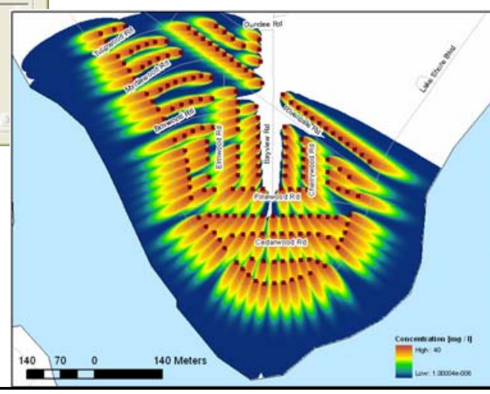
Software Demo





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.

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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

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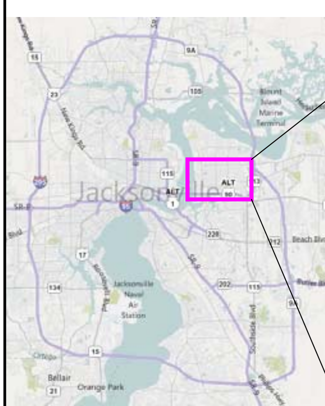
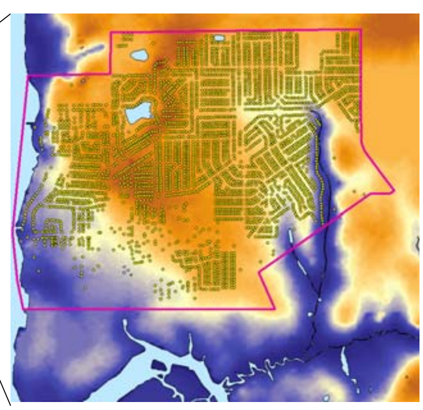
Eggleston Heights





Approximately 3500 septic tanks

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Modeling Procedure

- Gather updated data sources such as DEM, LIDAR, and NHD.
- Collect field observations of hydraulic heads and concentration for model calibration
- Conduct sensitivity analysis to identify the most sensitive parameters
- Calibrate the model
- Estimate nitrate load

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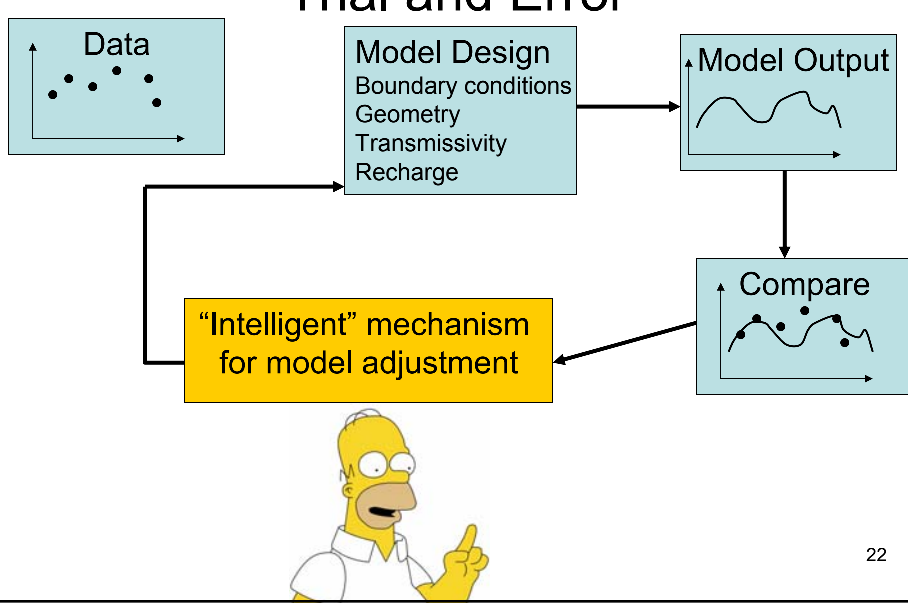
Model Calibration
Trial and Error



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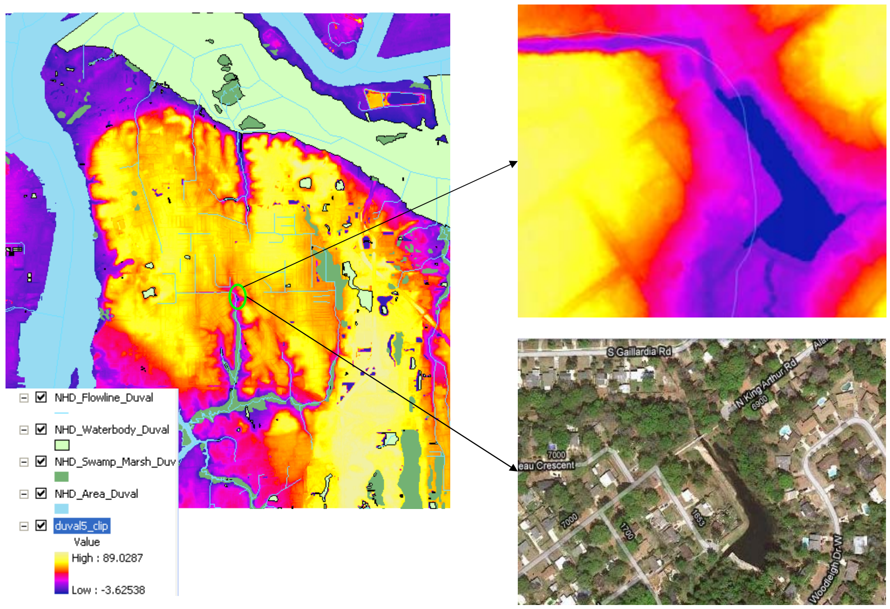
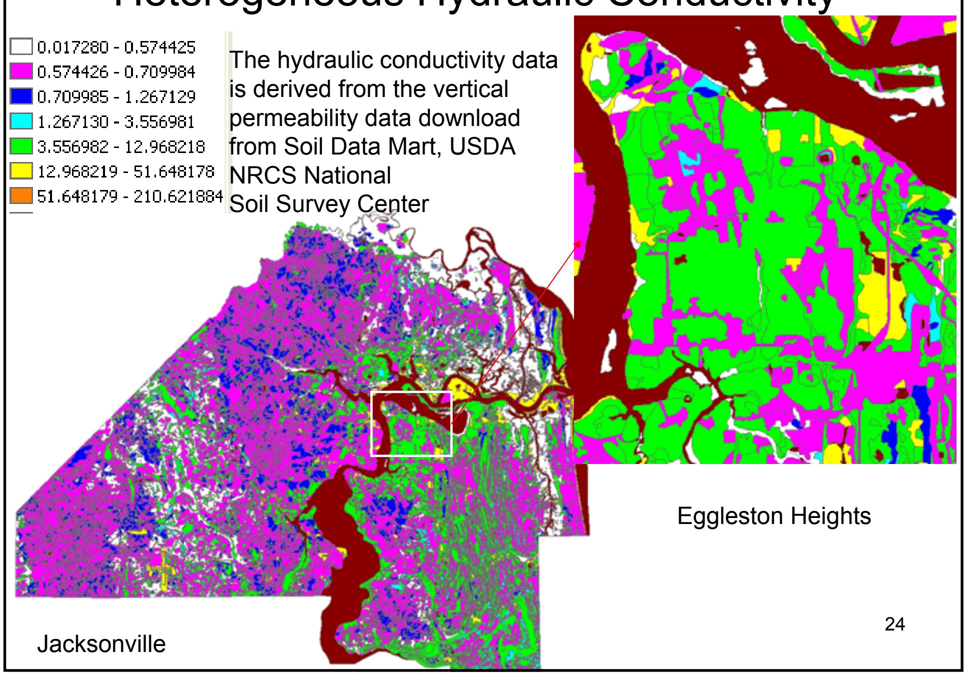
Use LiDAR Data to Update NHD Data



Heterogeneous Hydraulic Conductivity

- 0.017280 - 0.574425
- 0.574426 - 0.709984
- 0.709985 - 1.267129
- 1.267130 - 3.556981
- 3.556982 - 12.968218
- 12.968219 - 51.648178
- 51.648179 - 210.621884

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



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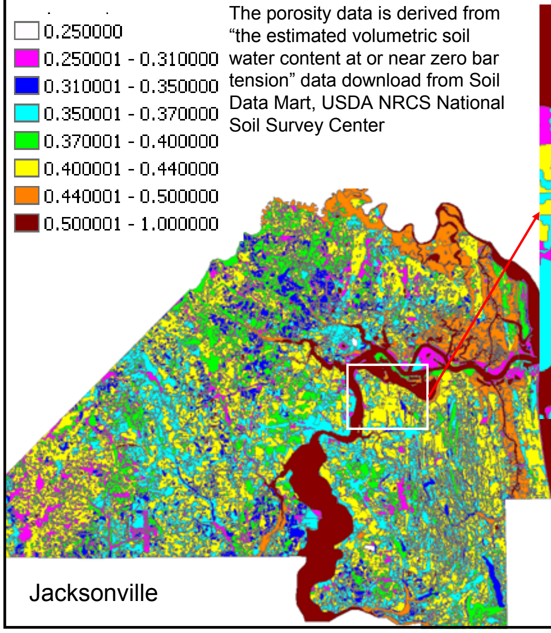
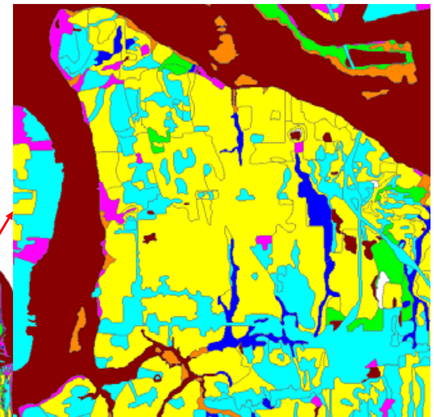
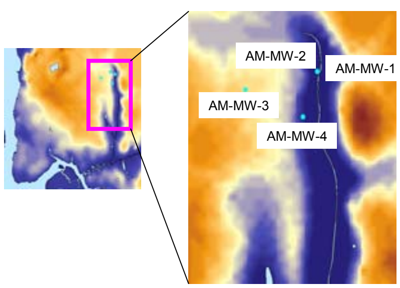
Heterogeneous Porosity

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

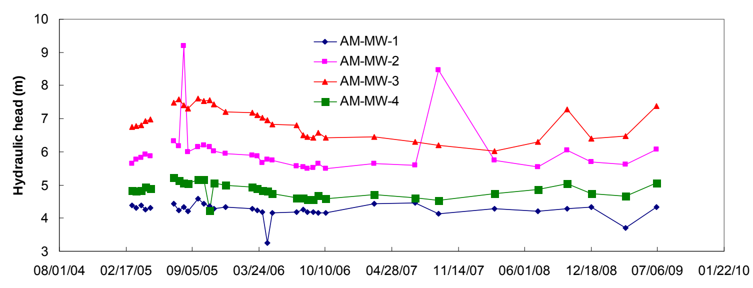




Observations of Hydraulic Head

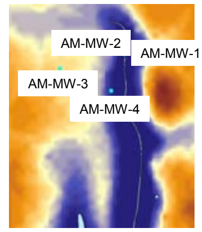


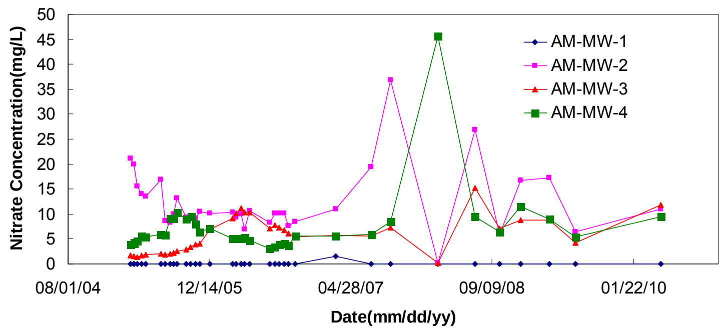
- Four monitoring wells
- Monitoring data from 2005 to 2009
- Water table is relatively stable



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.





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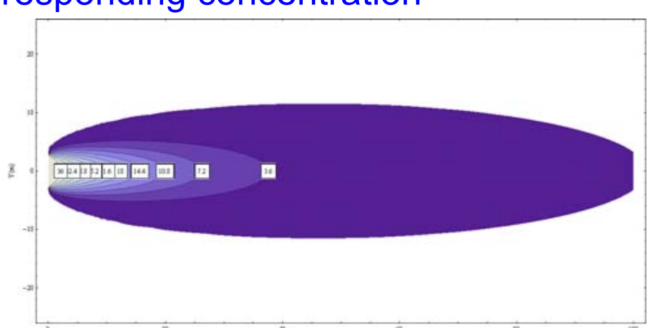
Sensitivity Analysis

- 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

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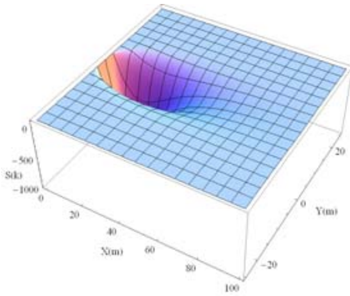
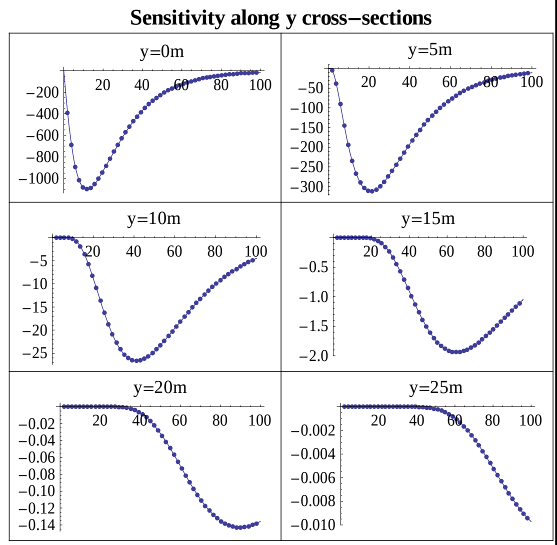
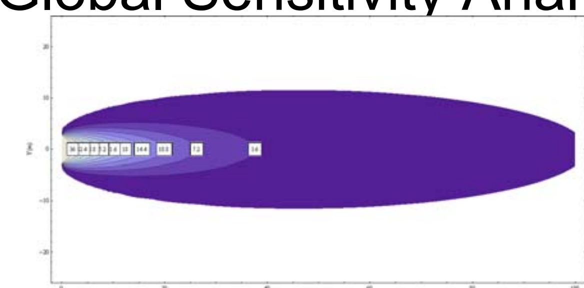
Sensitivity to k at Different Horizontal Cross-Sections





- 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.

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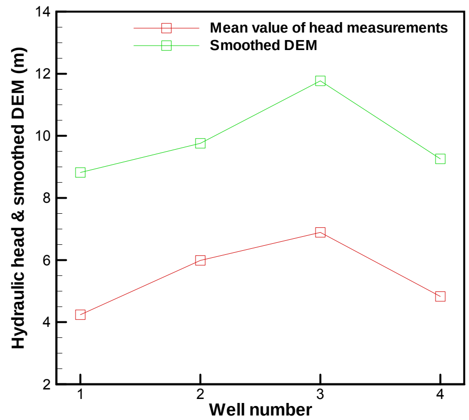
Calibration Results: Heads

Smoothed DEM agree well with mean observed hydraulic head with correlation coefficient of 0.93.



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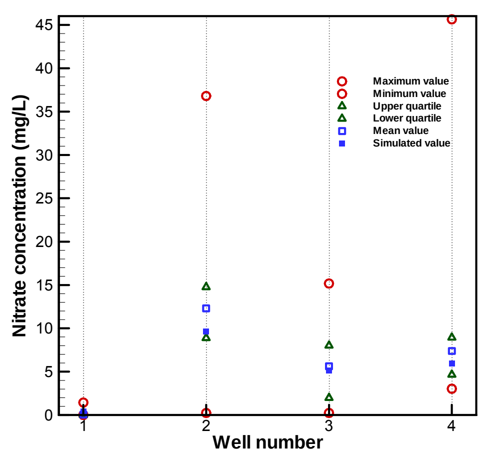
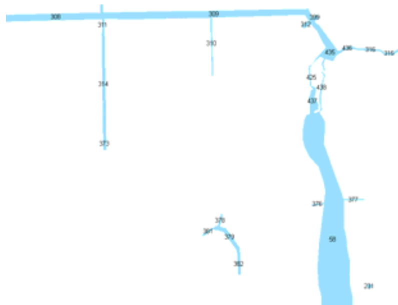
Calibration Results: Concentrations

Simulated concentrations are close to the mean observations and are within



Nitrate Load Estimation



Estimated load to the Red Bay Branch.

Outputs

Waterbody FID	Mass Output Load [M/T]	+ Mass removal rate [M/T] =	Mass Input Load [M/T]
0437	**2,133,221.00**	3,355,981.00	5,489,202.00
0310	**2,191,942.00**	2,088,461.00	4,280,404.00
0058	**9,060,189.00**	9,802,528.00	18,862,720.00
0435	**2,766,620.00**	1,935,365.00	4,701,985.00
0312	**656,354.10**	269,644.10	925,998.10
0309	**683,581.60**	278,356.40	961,938.10
0381	**2,450,713.00**	9,036,498.00	11,487,210.00
0378	**933,768.80**	815,566.10	1,749,335.00
0379	**802,179.90**	542,008.90	1,344,189.00
0373	**887,182.40**	390,788.20	1,277,971.00

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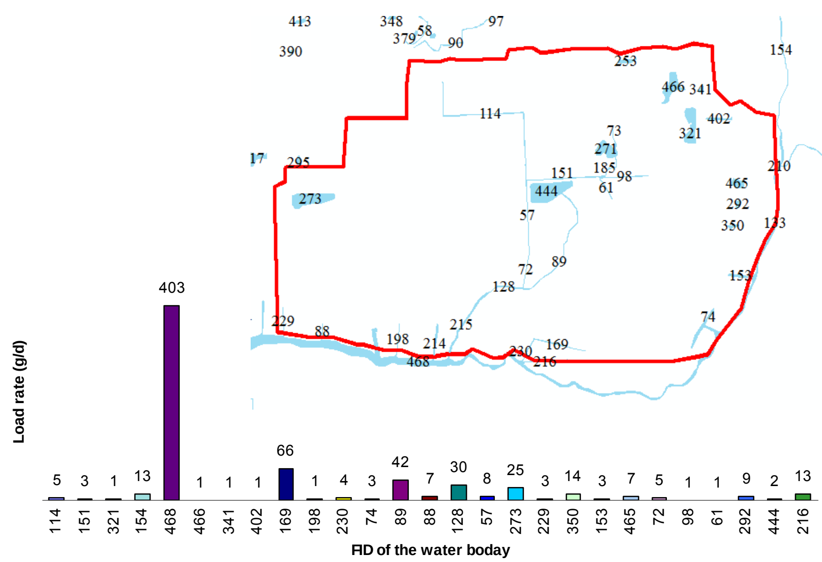
Mass unit is mg/day

Estimated Nitrate Load at Julington Creek



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Conclusions

- A GIS-based software, Arc NLET, has been developed for estimation of nitrate load from septic tanks to surface water body.
- The software is user friendly and easy to operate.
- It is capable of simulating field observations after being calibrated.
- We will give workshops and training courses in Summer to FDEP staff and the public who are interested in this software.

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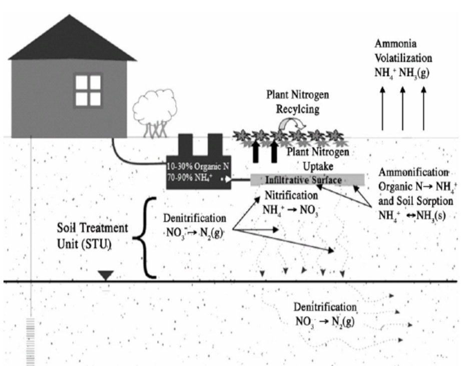
Prospective Research

- 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)

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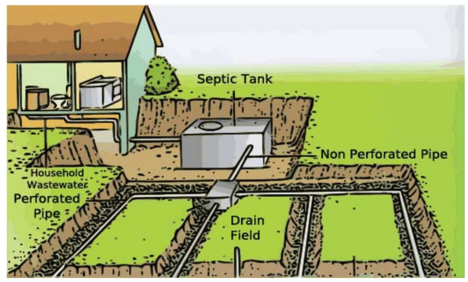
Questions?



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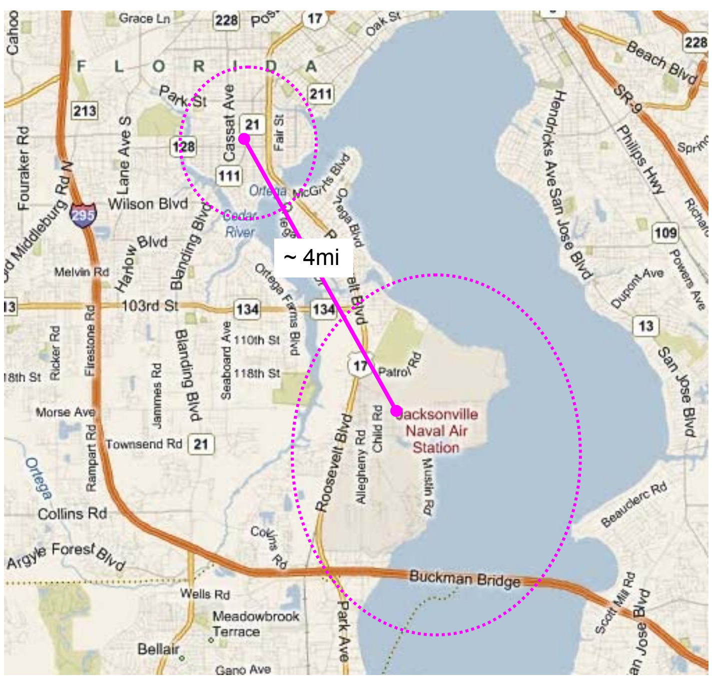

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Nonlinear Relationship

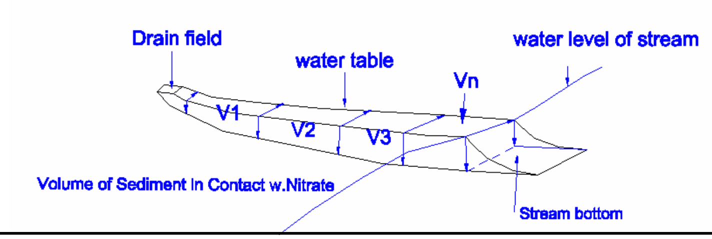
$$M_l = M_{in} - R_{dn}V_g$$

The volume is determined by

- Advection of groundwater flow
- Dispersion of nitrate transport
- Denitrification due to biological processes

All these affect nitrate concentration and nitrate concentration in turn affect denitrification rate.

V1, V2,.. Vn are volumes of plume in contact with sediment in equal travel time



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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.

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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.

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