Developing an ArcGIS Extension for Estimating Nitrate Fate and Transport in the Surficial Aquifer

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Presentation Outline

- Problem statement and background information
- Conceptual models of flow, transport, and denitrification
- Verification and validation study of the flow model.
- Conclusions and future work

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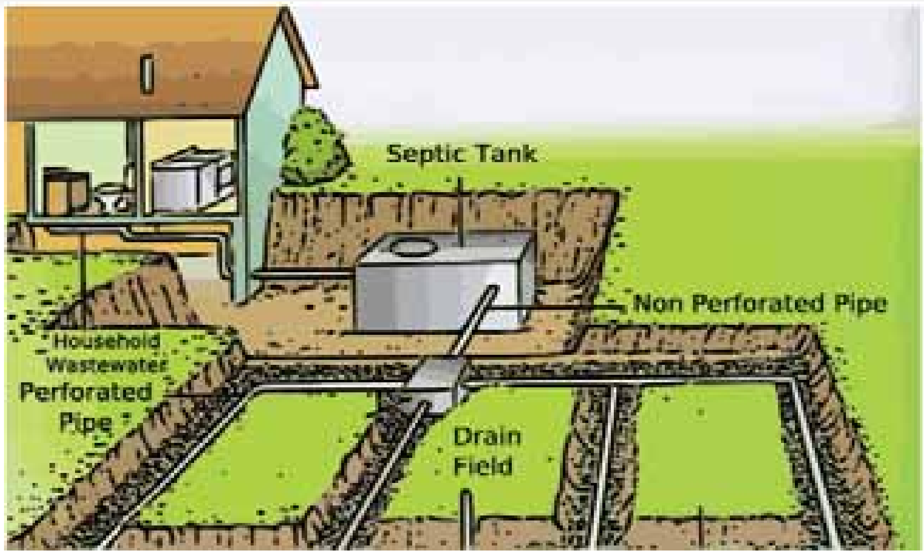
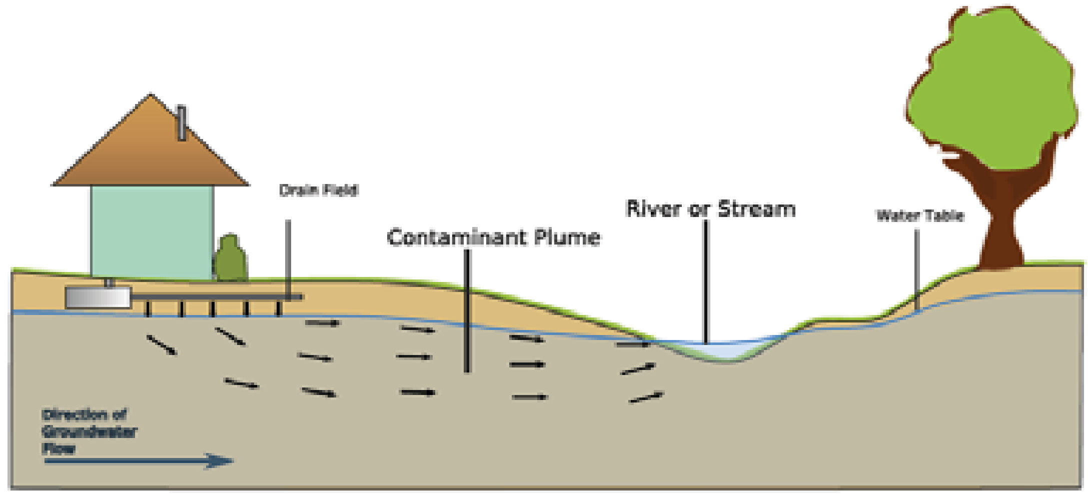
Overview





- Septic tanks are a source of groundwater contaminants

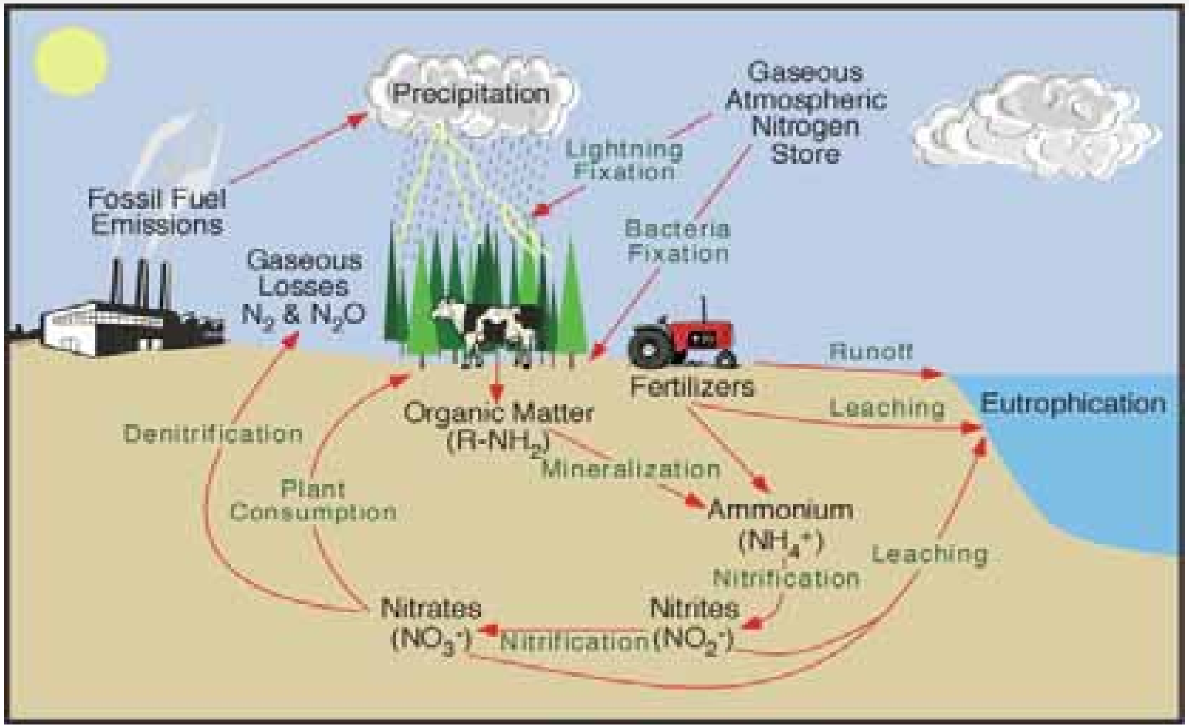
Motivation

- 1/3rd of Florida's population uses Onsite Wastewater Treatment Systems (OWTS) for treating waste water (Brown et al 2001; Ursin and Roeder, 2008, FDOH)

- Nitrate loading due to OWTS negatively affects water resources quality
  - Environmental issues
    - algae blooms, excessive plant growth
  - Health issues
    - Possible carcinogenic agent – gastric cancer
    - High levels can cause blue baby syndrome

- Local regulators must determine whether new developments utilizing OWTS will increase nitrate loads beyond an acceptable limit.

Nitrates and OWTS



- Several sources of nitrogen
  - Focus on septic tanks
- Undergoes nitrification
- Several nitrate attenuation mechanisms
  - Focus on denitrification

Existing Models

- Traditional (i.e. numerical) models while useful, require large amounts of input data
  - Examples of “traditional” models: MODFLOW, MT3DMS, RT3D
  - Difficult to use, steep learning curve

- A simplified model is appropriate for use as a screening tool. If a detailed analysis is required, a more advanced model should be used

- Existing simplified models do not simultaneously take into account the spatial location of the septic tank and the effect of denitrification.

Project Goals

- Want a tool that
  - Estimates nitrate loads to surface water bodies due to septic tanks at a development scale
  - Has low input data requirements
  - Is easy to use
    - Data management
    - Visualization
    - Runs as an extension to ArcGIS
  - Incorporate the effects of OWTS location (e.g. topography)
  - Incorporate the effects of denitrification
  - The tool should be able to handle many sources simultaneously
  - incorporates management functionality to aid in regulatory decisions

- Apply the tool initially to neighborhoods in Jacksonville, Florida

Project Structure

- Project is divided into modules
  - Groundwater flow
  - Transport
  - Denitrification
  - Management

- In this presentation focus will be more towards the flow model however the other modules will also be discussed

Flow Model

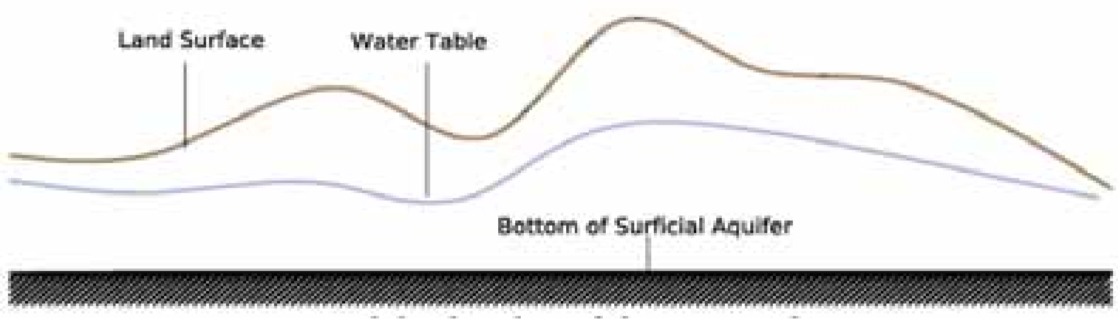
- Flow model predicts groundwater flow direction and travel time to a target water body

- Steady state flow
  - Intended application scenario is not concerned with seasonal variations

- Dupuit Approximation
  - Flow is horizontal
  - Hydraulic gradient is assumed to be the slope of the water table

Flow Model

- Water table is a subdued replica of the topography



- As a result, can feed a digital elevation model (DEM) into a processing routine to generate a water table

- With maps of porosity and hydraulic conductivity, can then apply Darcy's Law to find groundwater seepage velocity: $v = -\frac{K \nabla h}{\theta}$

Transport Model

- Simulating contaminant transport requires solving the advection-dispersion equation

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

- To simplify, use an analytical solution (Domenico & Robbins 1985)

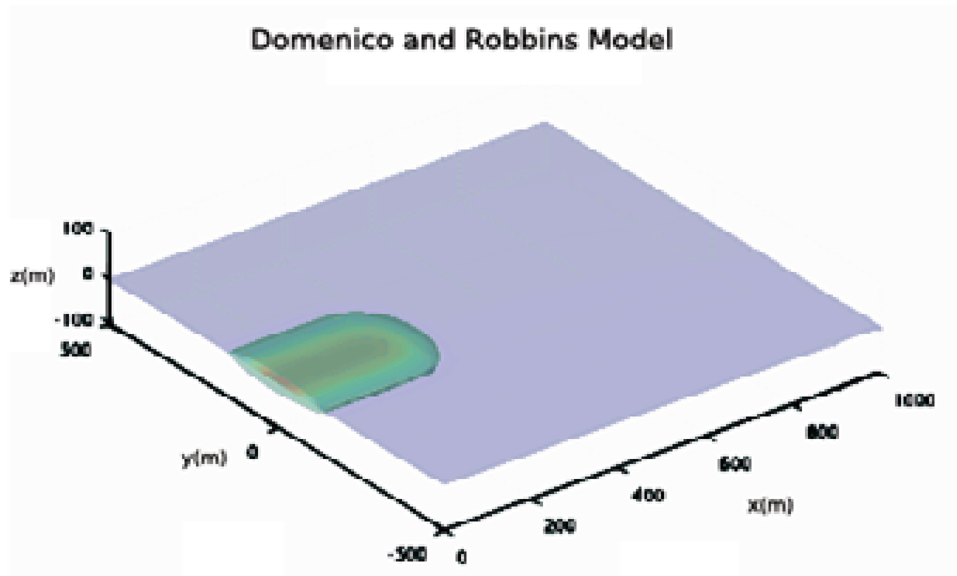
$$C(x,y,z,t) = \frac{C_0}{8} erfc\left(\frac{x - vt}{2\sqrt{D_x t}}\right) \cdot$$

$$\left[erf\left(\frac{Y + \frac{1}{2}y}{2\sqrt{D_y t}}\right) - erf\left(\frac{Y - \frac{1}{2}y}{2\sqrt{D_y t}}\right)\right] \cdot$$

$$\left[erf\left(\frac{Z + \frac{1}{2}z}{2\sqrt{D_z t}}\right) - erf\left(\frac{Z - \frac{1}{2}z}{2\sqrt{D_z t}}\right)\right]$$

Transport Model

- Flow velocity is obtained from the flow model.
- Considers only transport in the saturated zone
- Domenico solution is widely used
  - E.g. BIOSCREEN, BIOCHLOR, FOOTPRINT, REMChlor (EPA)



Denitrification Model

- Nitrate reduction is modeled using

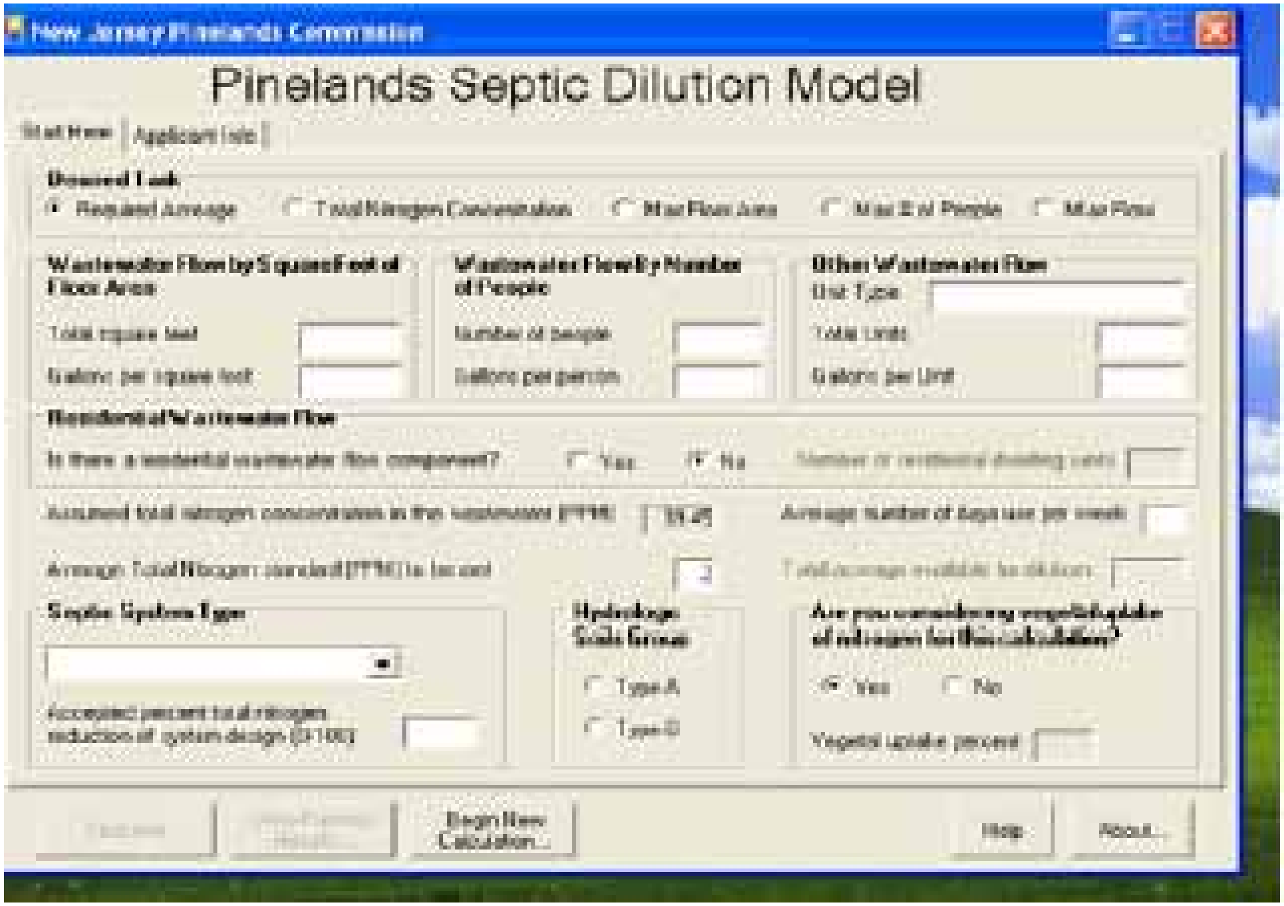
$$N_t = N_0 - R_{dn} V_{aq}$$

- V_{aq} is obtained from the transport model.

- Rate is obtained from a separate model being developed by collaborators in the geology department at FSU.
  - Univariate and multivariate regression models
  - Neural network

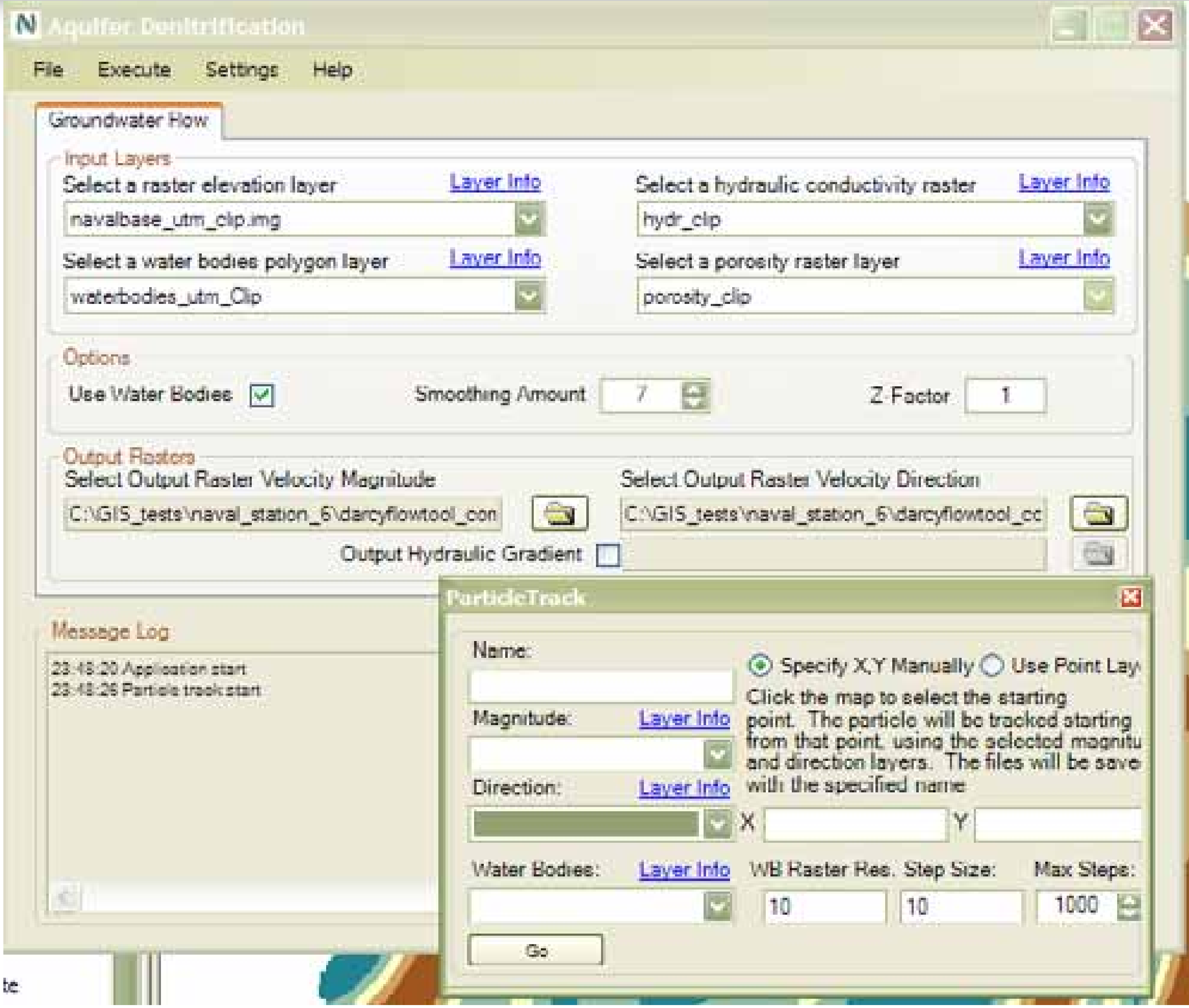
Management Module

- Similar idea as NJ Pinelands Commission tool



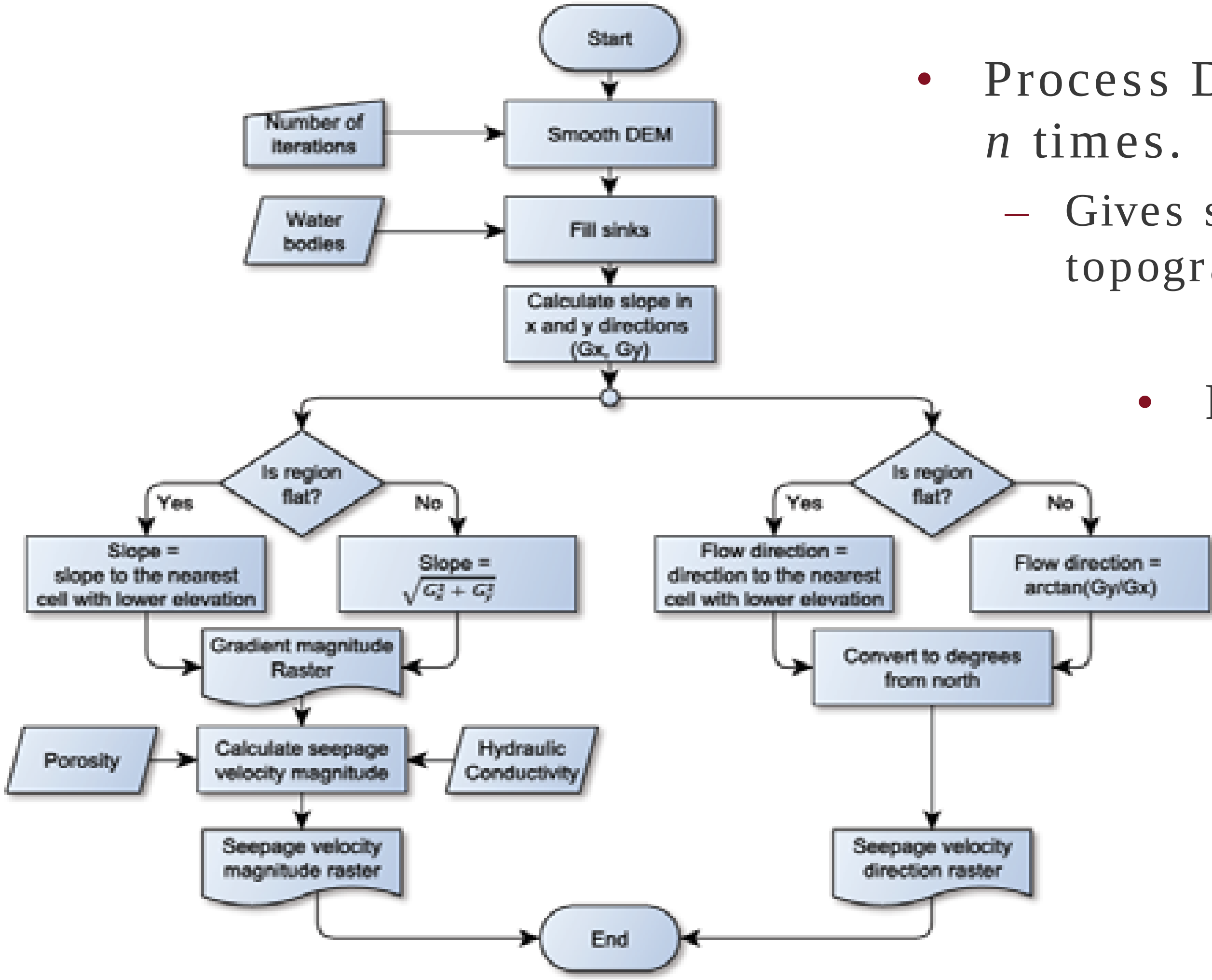
User Interface

- The software is implemented in Visual Basic .NET using the ArcObjects API
- Accessible from the ArcMap toolbar



Flow Model

- The purpose of the flow module is to generate two rasters, representing the groundwater flow magnitude and direction



- Process DEM with an averaging filter *n* times.
  - Gives subdued replica of the topography

- Fill sinks
  - If flow enters a sink, it will never escape
  - Fill sink if no water body exists at that location
  - Use ArcGIS sink fill tool

Flow Model

- Calculate the hydraulic gradient
  - Apply a Sobel filter (similarly for $\partial h / \partial y$)

$$\frac{\partial h}{\partial x} \approx G_x * A, \quad G_x = \frac{1}{8\Delta x}\begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix}$$

$*$ is the convolution operator.

  - Magnitude of the gradient is: $\sqrt{\left(\partial h / \partial y\right)^2 + \left(\partial h / \partial y\right)^2}$
  - Direction is: $tan^{-1}\left(\frac{\partial h / \partial x}{\partial h / \partial y}\right)$

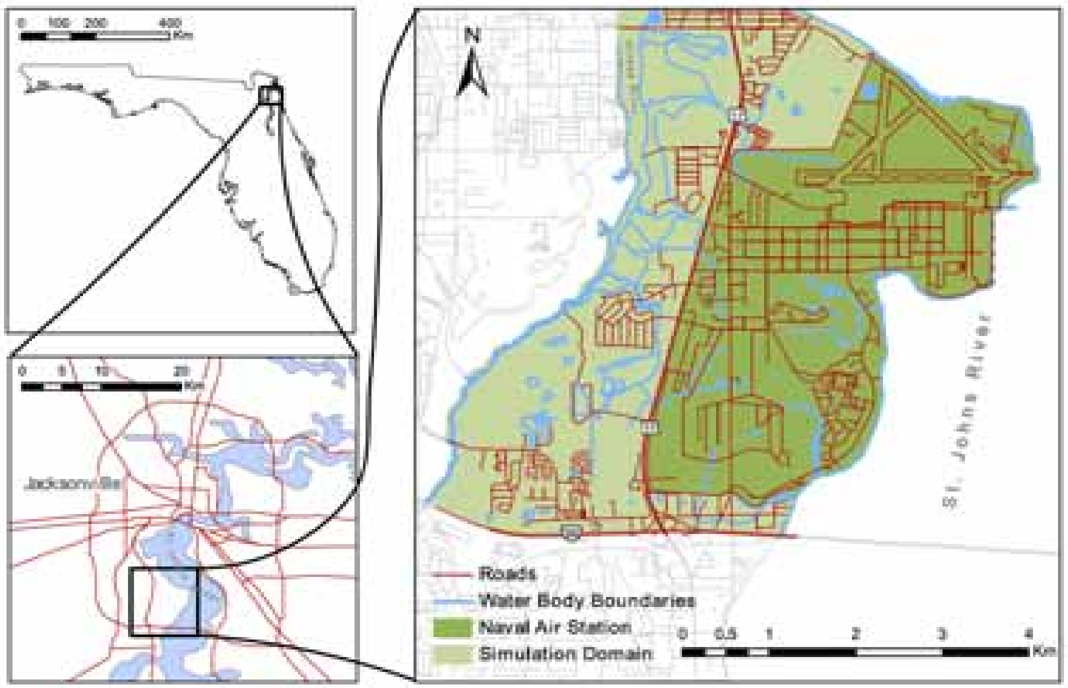
- A subtle problem with flat areas must be dealt with
  - Flat areas in the water table cause the hydraulic gradient to be zero
  - Assign a slope equal to the cell elevation divided by the distance to the nearest downslope cell (Jenson & Domingue, 1988) – Flow Direction tool

Transport & Denitrification

- Transport
  - Given a set of septic tank locations, track groundwater flow to water body
  - Solve the Domenico Robbins equation for a given starting concentration and time
    - Time may be the groundwater travel time but it can by any time
  - Sum the total contributions for each source on the target water body

- Denitrification
  - Subtract the removed nitrates from the total plume concentrations
  - Similar approach taken in BIOSCREEN (calculate plume first then subtract a certain amount

Test Site

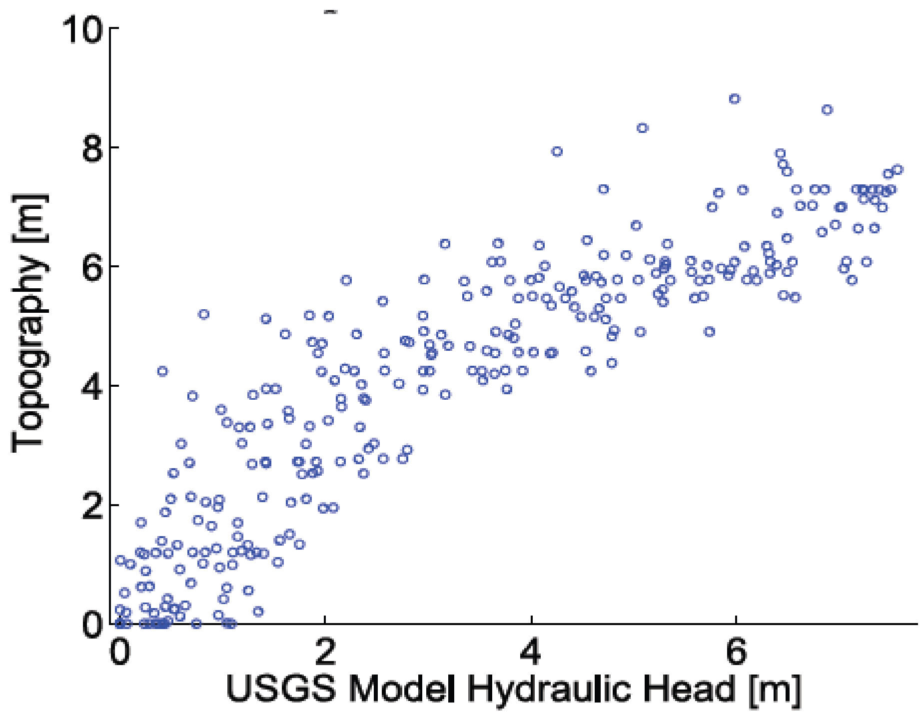


- U.S. Naval Air Station (NAS) Jacksonville
- Quite flat
- Shallow water table
  - 0 – 1.5 m
- Surficial Aquifer
  - 12 – 30 m thick
  - Medium to fine grain unconsolidated sands

- A MODFLOW model was constructed by the USGS (Davis et. al 1996, Davis 1998)
  - Steady state, single layer model
  - Calibrated with 128 well measurements

Analysis of the Water Table-Topography Relationship

- Important to determine whether the water table is reasonable approximated by the topography
  - Model applicability



- Rank correlation: 0.9

Analysis of the Water Table-Topography Relationship

- Under normal circumstances, won't have water table
  - How to determine model applicability?

- Rule of thumb (Haitjema & Mitchell-Bruker, 2005)

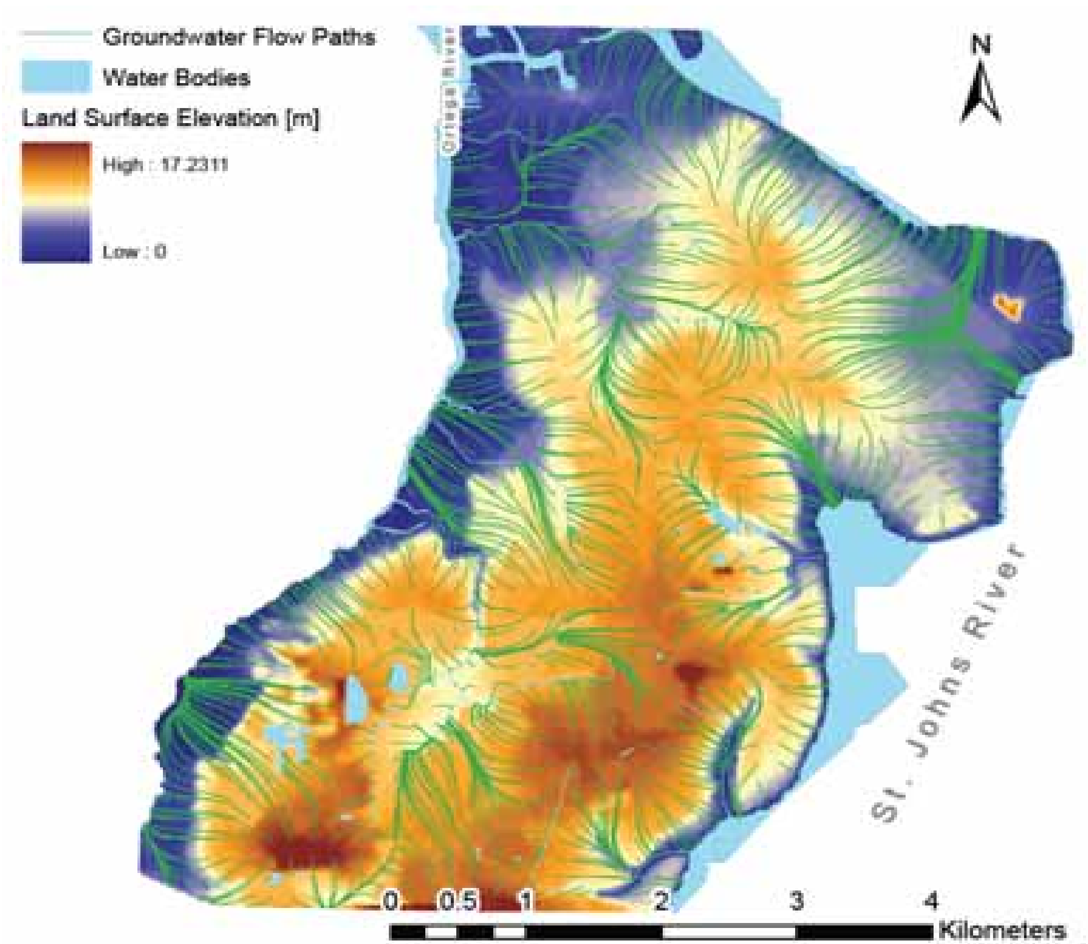
$$\phi = \frac{RL^2}{mKHd} \begin{cases} > 1 & \text{Topography controlled} \\ < 1 & \text{Not topography controlled} \end{cases}$$

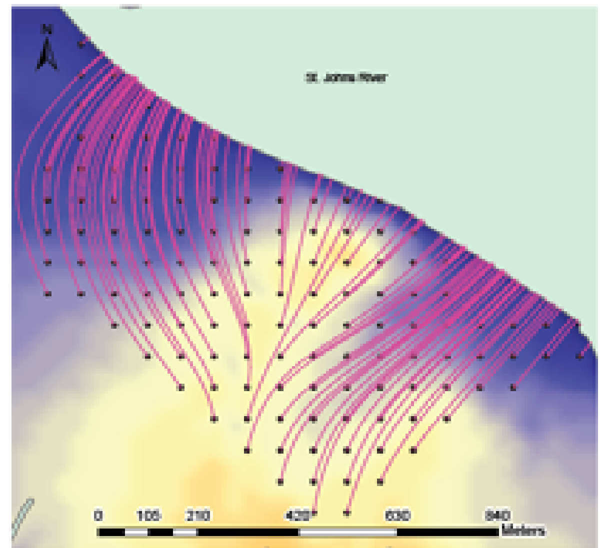
R=Recharge
L=Avg. dist between surface waters
m=factor accounting for geometry
K=hydraulic conductivity
H=Avg. aquifer thickness
d=Max. distance between avg. water level in surface water bodies and the elevation of the terrain

- Φ=6.2

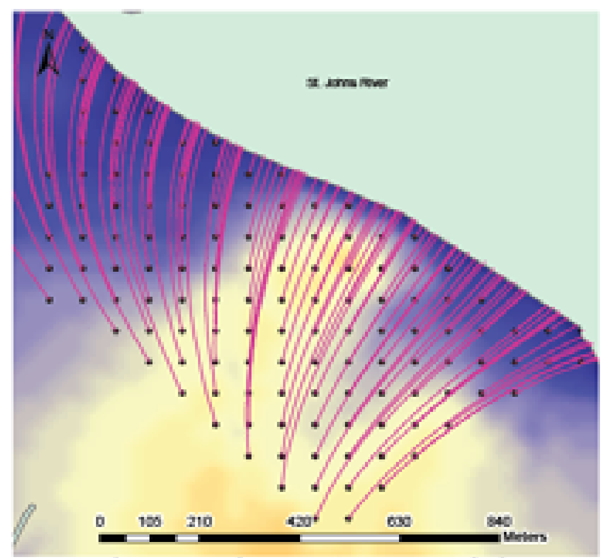
Flow Model Results

- Flow paths





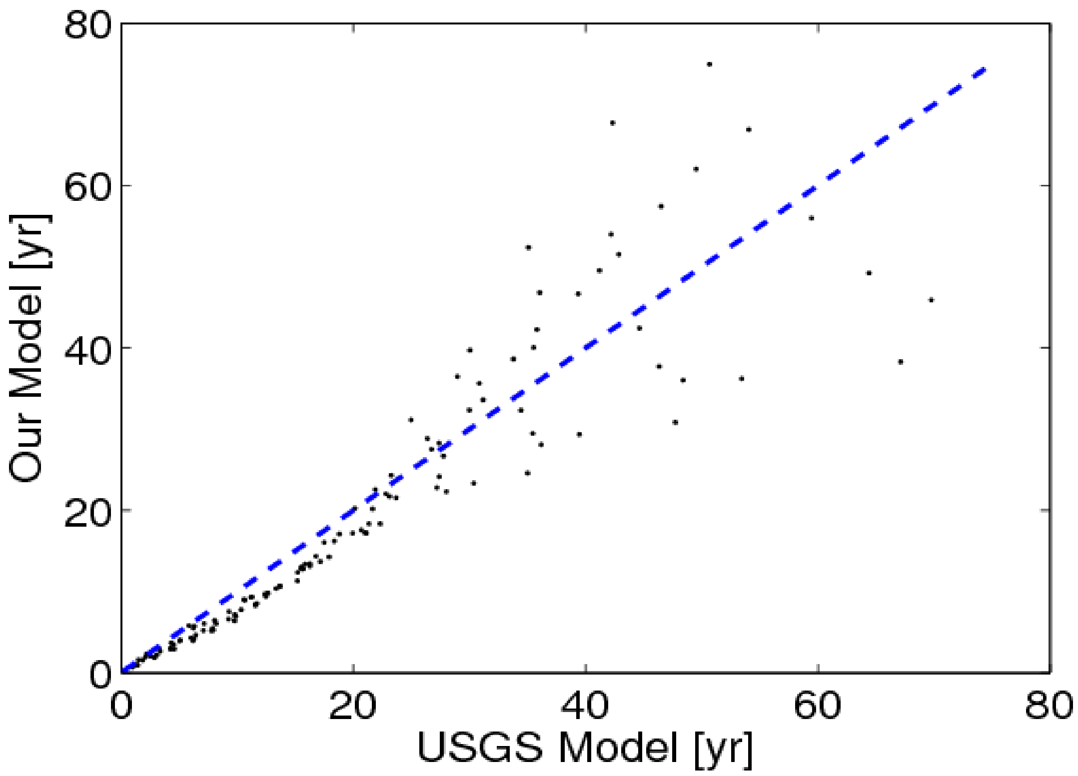
Flow Paths



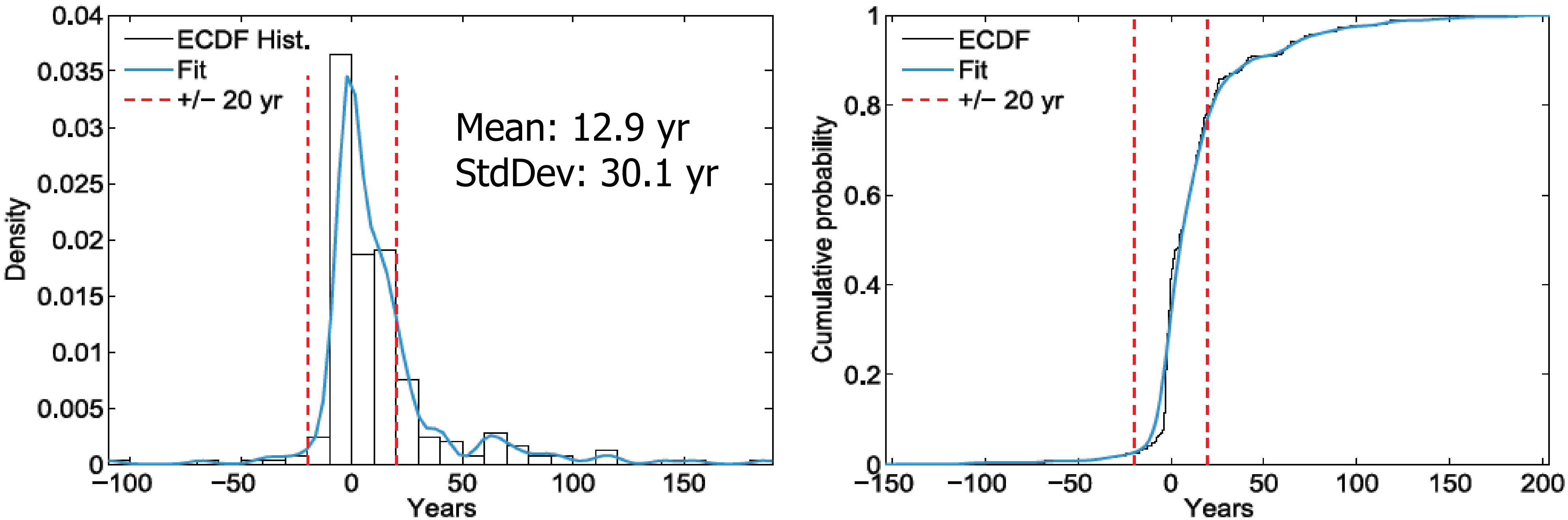
Flow Paths - USGS Model

Flow Model Results

- Travel time analysis



Flow Model Results



Difference in travel time between our model and the USGS model

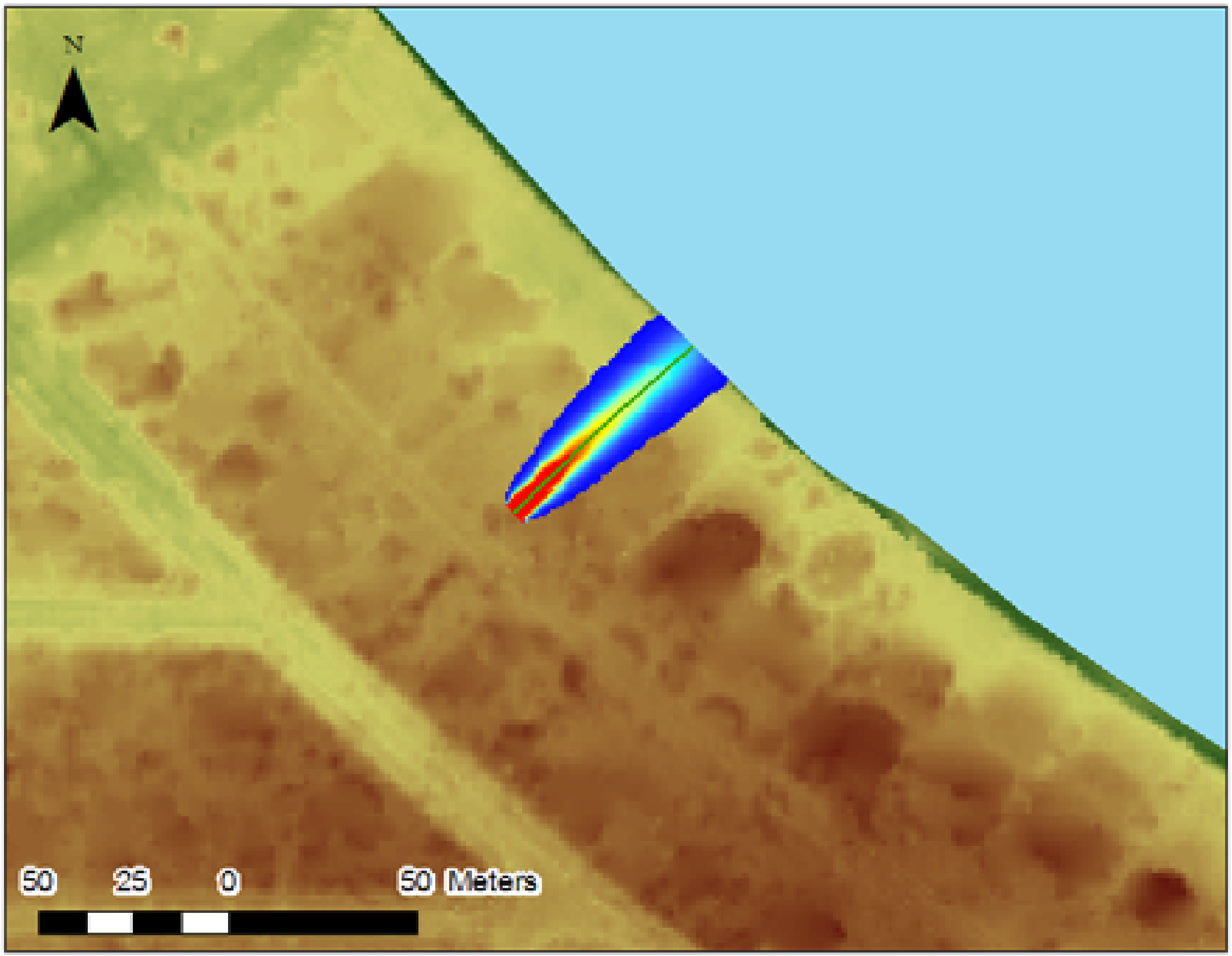
- Mean difference is 13 years
- 75% of the time our model is within 20 years of the USGS model

Conclusions

- The first module (Flow) was developed and tested.
- Model applicability was determined for the NAS
  - Water table in the vicinity of the NAS is a subdued replica of the topography
- The simplified flow model was compared to a detailed model (USGS model) on a smaller scale
  - Mean difference was 13 years.
- ArcGIS makes managing input data and visualizing model results easier.

Transport Module

- Adapt the analytical solution to a curved path
  - Preliminary results show this method is feasible, with some limitations



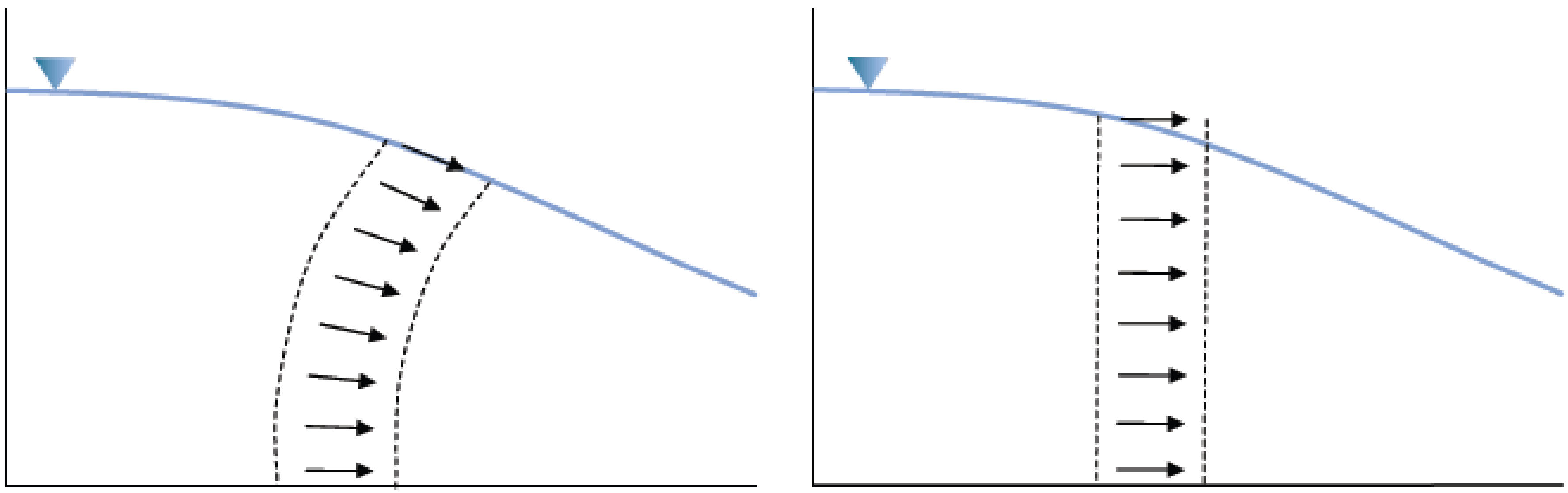
Denitrification and Management Modules

- An appropriate denitrification rate must be determined
  - work closely with collaborators in geology to implement the proposed statistical models.

- Management module
  - Work closely with the FDEP to determine appropriate management and/or decision support functionality.

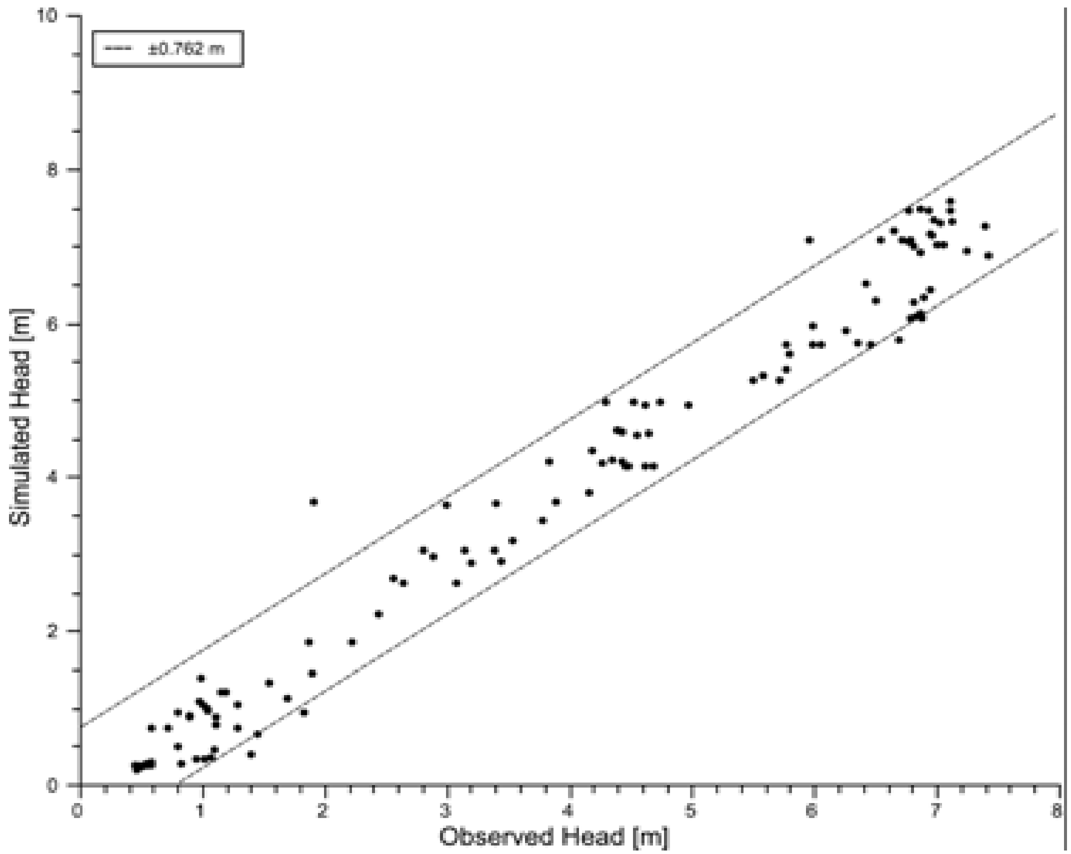
Questions?

- Dupuit Approximation
  - Flow is horizontal
  - Hydraulic gradient is assumed to be the slope of the water table

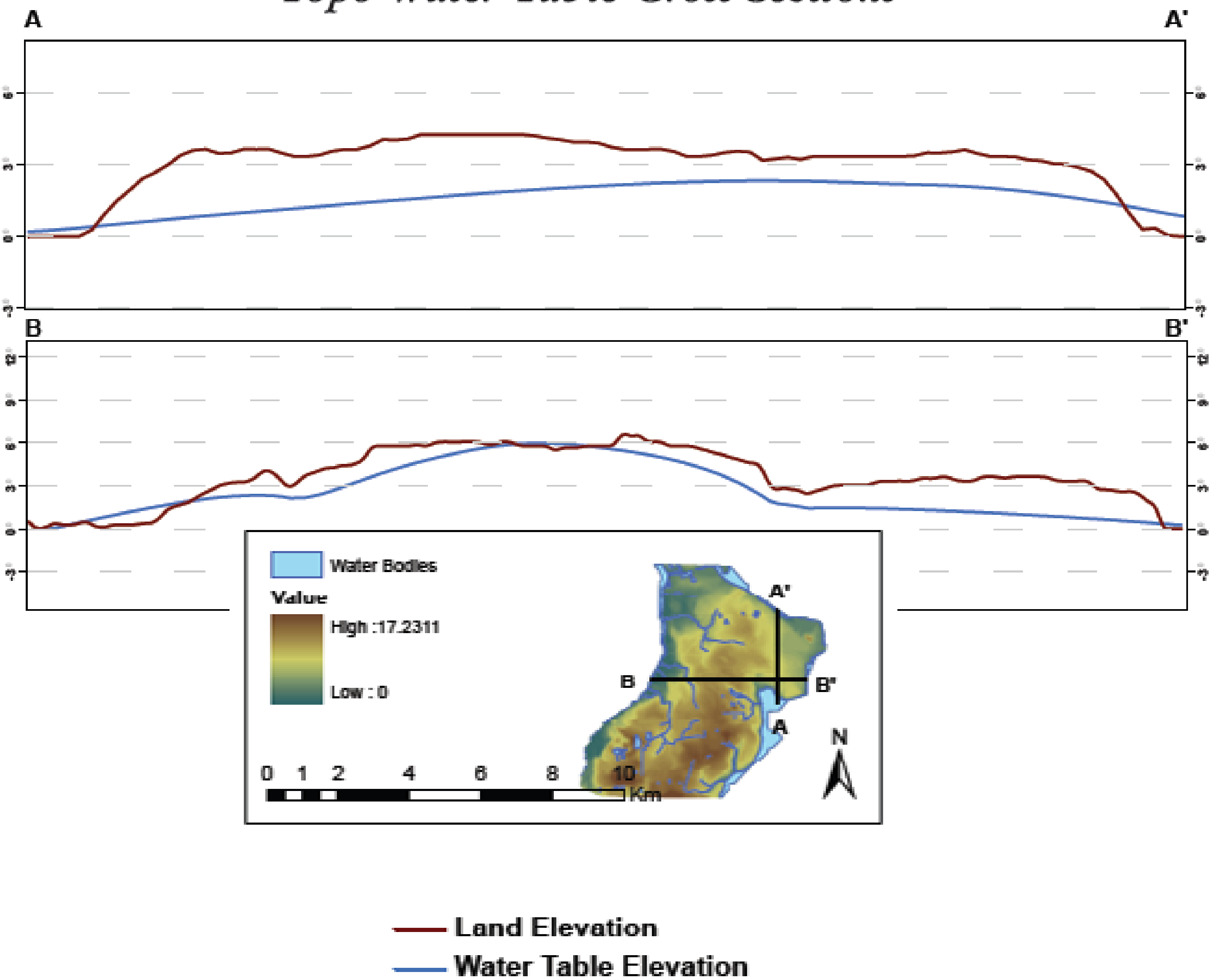


USGS Model

- The USGS model was calibrated with 128 well measurements



Topo-Water Table Cross-Sections

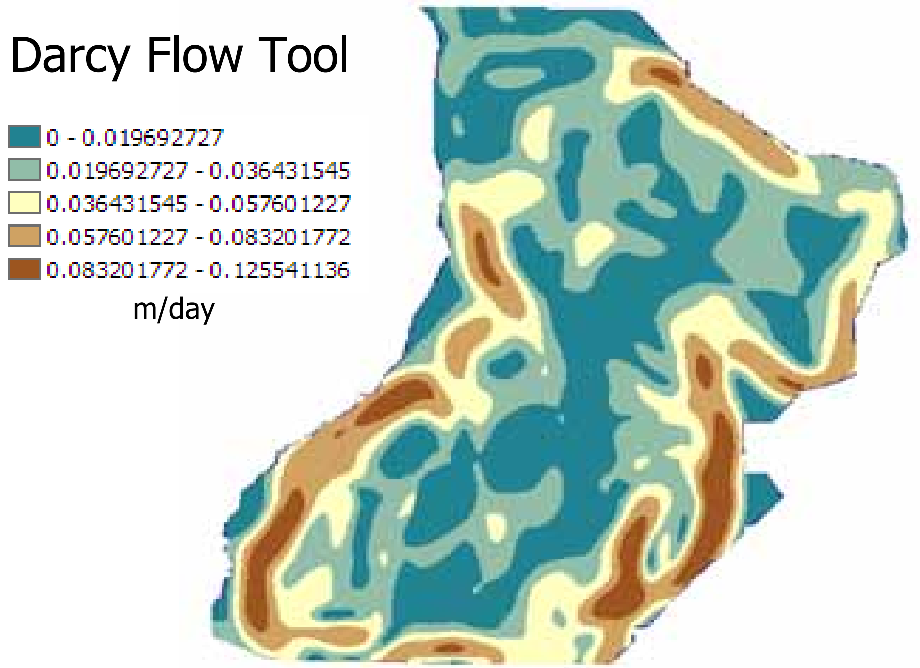


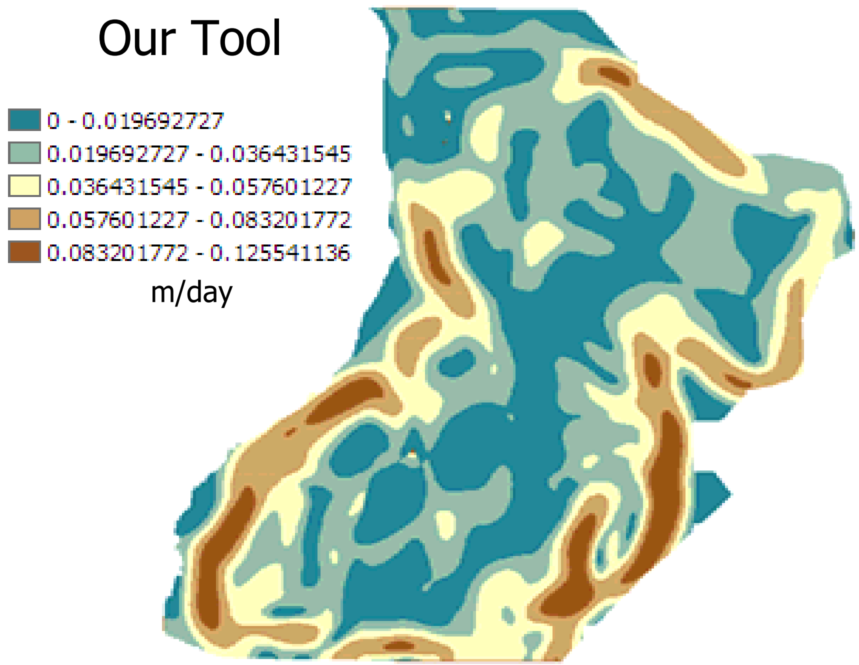
Analysis of the Water Table-Topography Relationship

- Relationship between the *slope* of the topography and *slope* of the water table is somewhat weaker.
  - Due to smoothness of the simulated water table
  - After smoothing DEM
    - X-direction: 0.75
    - Y-direction: 0.60

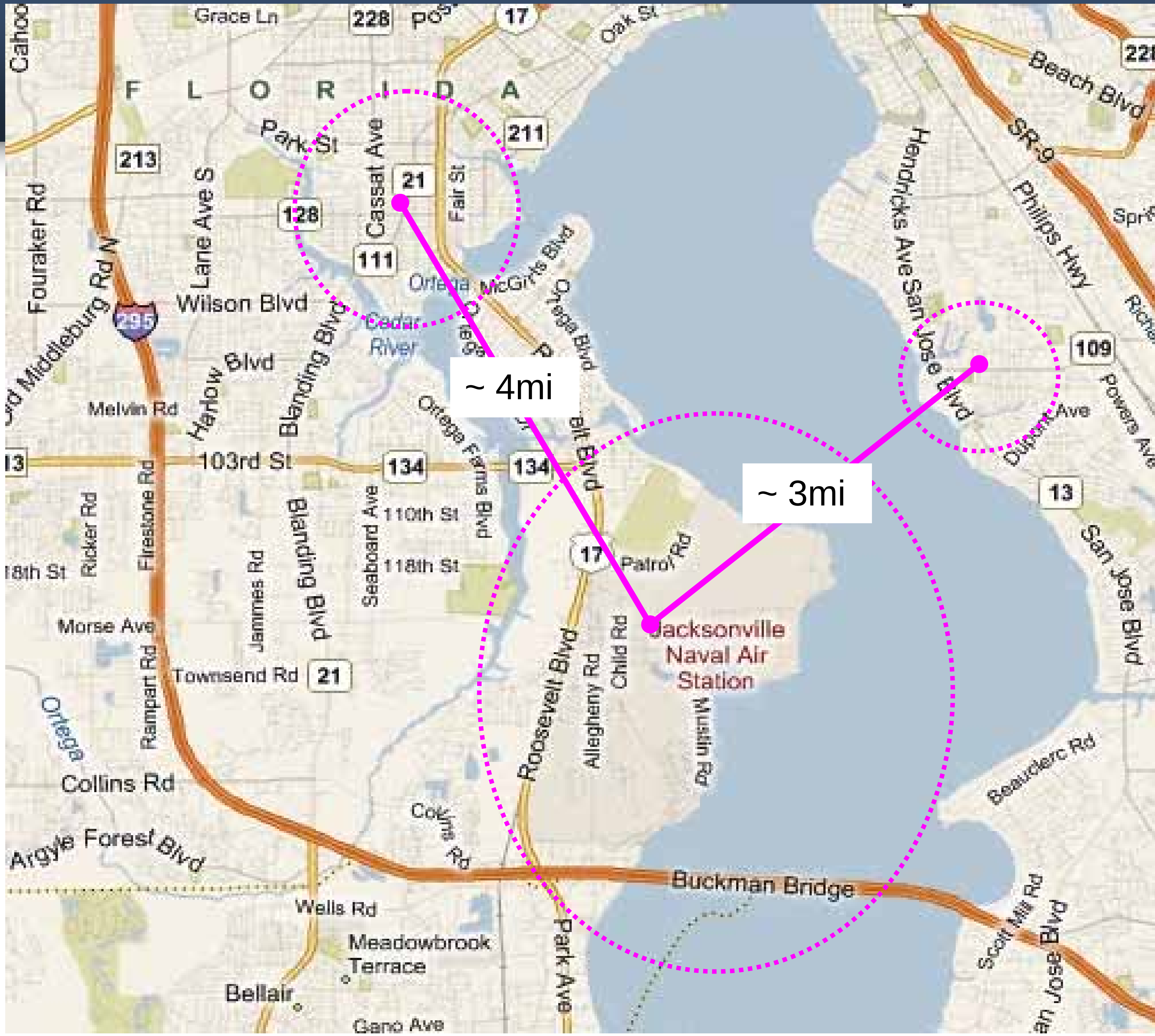
Correctness

- Need to check whether the software calculates the "correct" values
- Compare with SA Darcy tool





- Virtually identical except in flat areas (not handled by Darcy Flow tool)
- Mean difference is 9E-6 m/day Std. dev. 1.57E-5 m/day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~ 3mi
F L O R I D A
Jacksonville Naval Air Station
Buckman Bridge
Park St
Cassat Ave
Fair St
Wilson Blvd
Harlow Blvd
Blanding Blvd
103rd St
110th St
118th St
Seaboard Ave
Ortega Farms Blvd
Roosevelt Blvd
Allegheny Rd
Child Rd
Patrol Rd
Mustin Rd
Hendricks Ave
San Jose Blvd
Philips Hwy
Beach Blvd
SR-9
Powers Ave
Dupont Ave
Beauclerc Rd
Scott Mill Rd
Park Ave
Collins Rd
Argyle Forest Blvd
Wells Rd
Meadowbrook Terrace
Bellair
Gano Ave
Morse Ave
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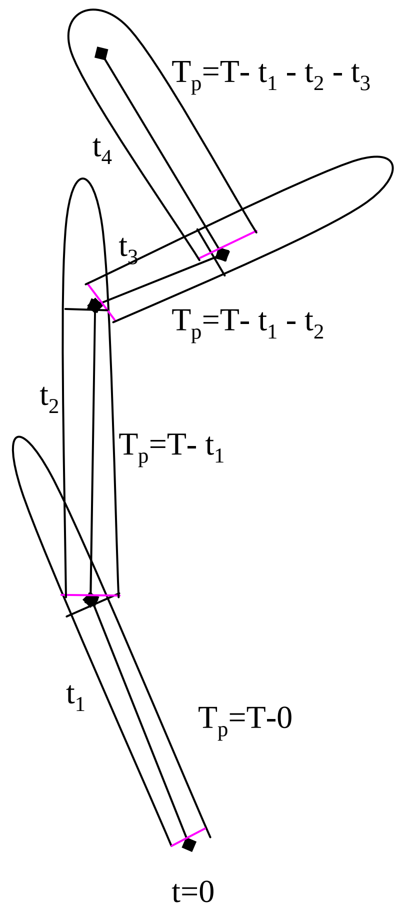

- Segment based calculation