Project

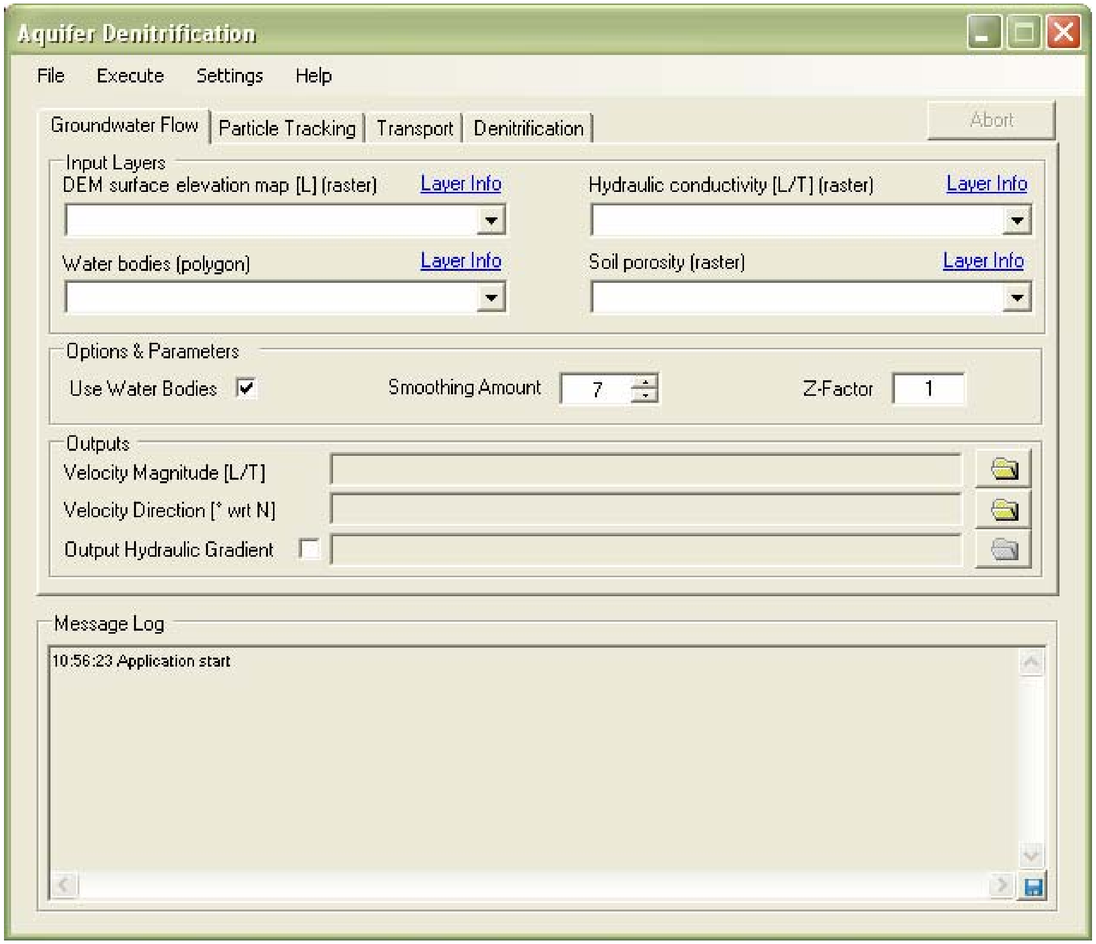
- Modules
  - Flow
  - Transport
  - Denitrification

- Flow, transport and denitrification modules have been developed.

- Flow module has been tested with a (MODFLOW) model of the NAS Jacksonville created by the USGS.

- Transport and nitrate estimation modules have been tested using a contaminant transport model (MT3DMS)

- Demo
  - Flow transport and denitrification



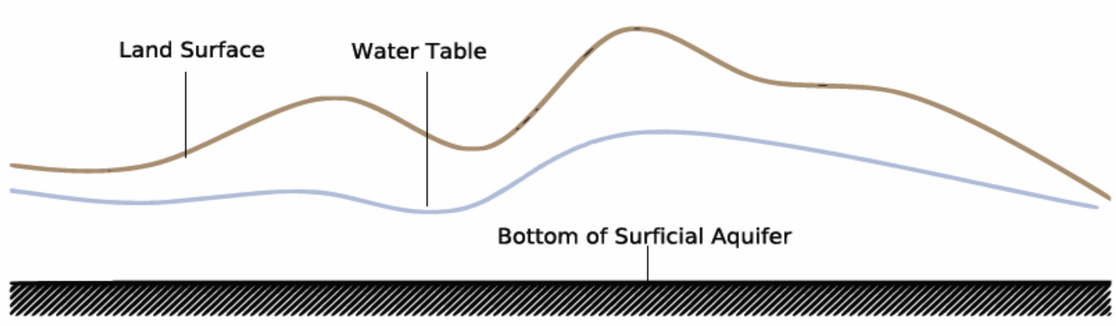
Flow Model

- Flow model estimates groundwater flow velocity and travel time to a target water body using various approximations
  - Steady state flow
  - Dupuit Approximation
    - Flow is horizontal
    - Hydraulic gradient is assumed to be the slope of the water table
  - Water table is a subdued replica of the topography

- Process an input DEM and use it to approximate water table.

- Use Darcy's Law to calculate the flow velocity.

Flow Model



$$v_s = -\frac{K}{\theta}\nabla h$$

- Apply a smoothing algorithm (an averaging filter) to the DEM to get water table

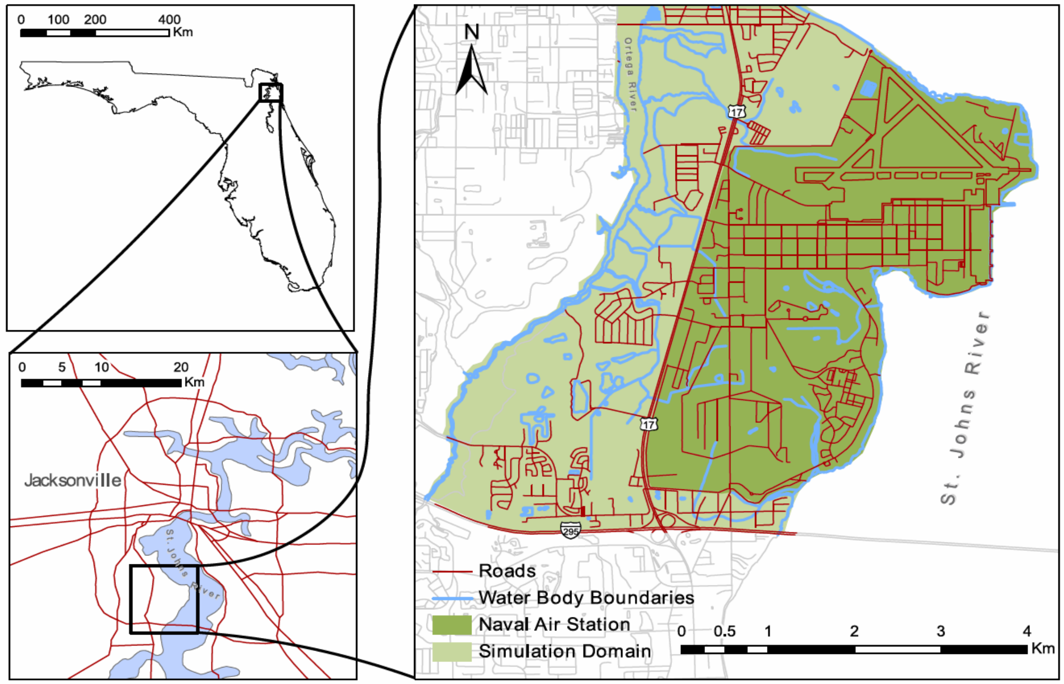
- Calculate the hydraulic gradient
  – Apply a Sobel filter (similarly for $\partial h / \partial y$)

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

$*$ 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: $tan^{-1}\left(\frac{\partial h / \partial x}{\partial h / \partial y}\right)$

Analysis of the Water Table-Topography Relationship



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

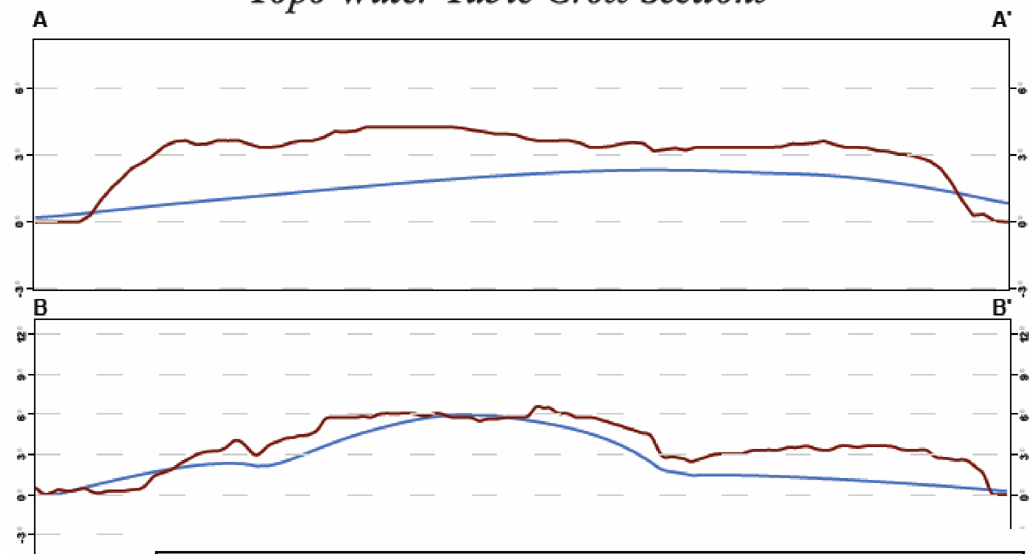
- A MODFLOW model was constructed by the USGS (Davis et. Al, 1996; Davis, 1998)
  - Steady state, single layer model
  - Calibrated with 128 well measurements

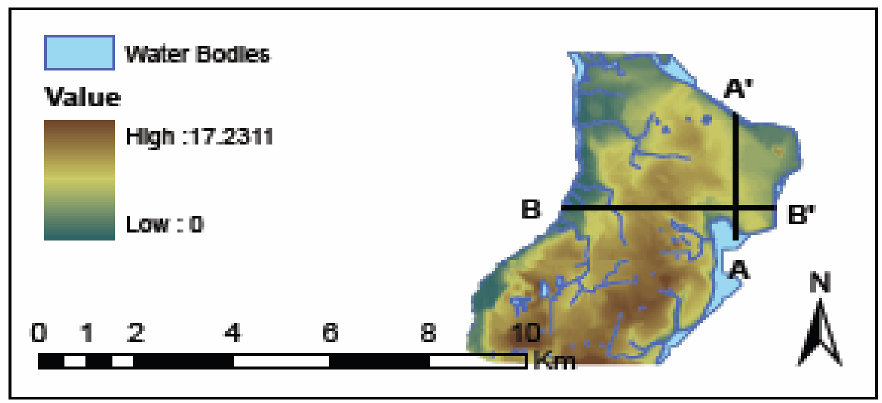
Analysis of the Water Table-Topography Relationship

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

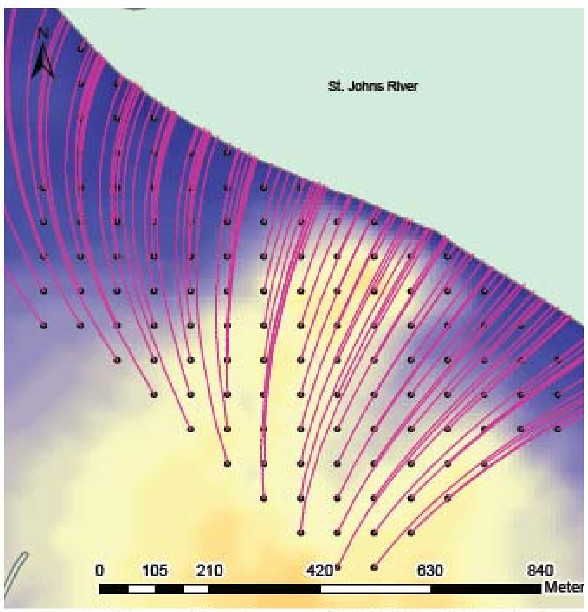
- Compare with USGS model of NAS Jacksonville

Topo-Water Table Cross-Sections

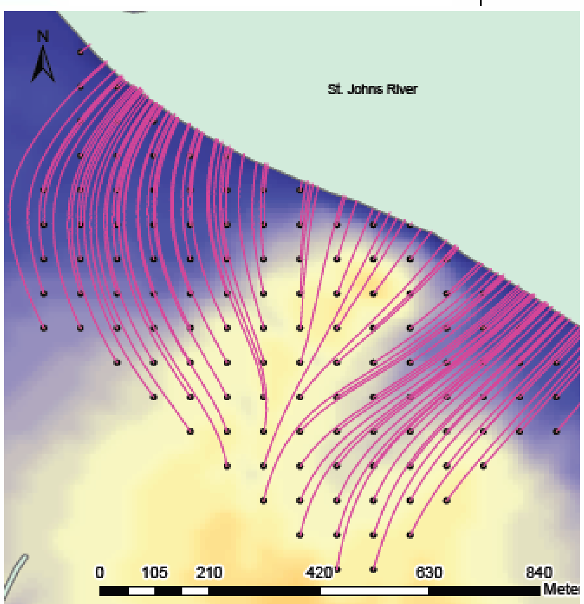




Path length correlation: 0.9

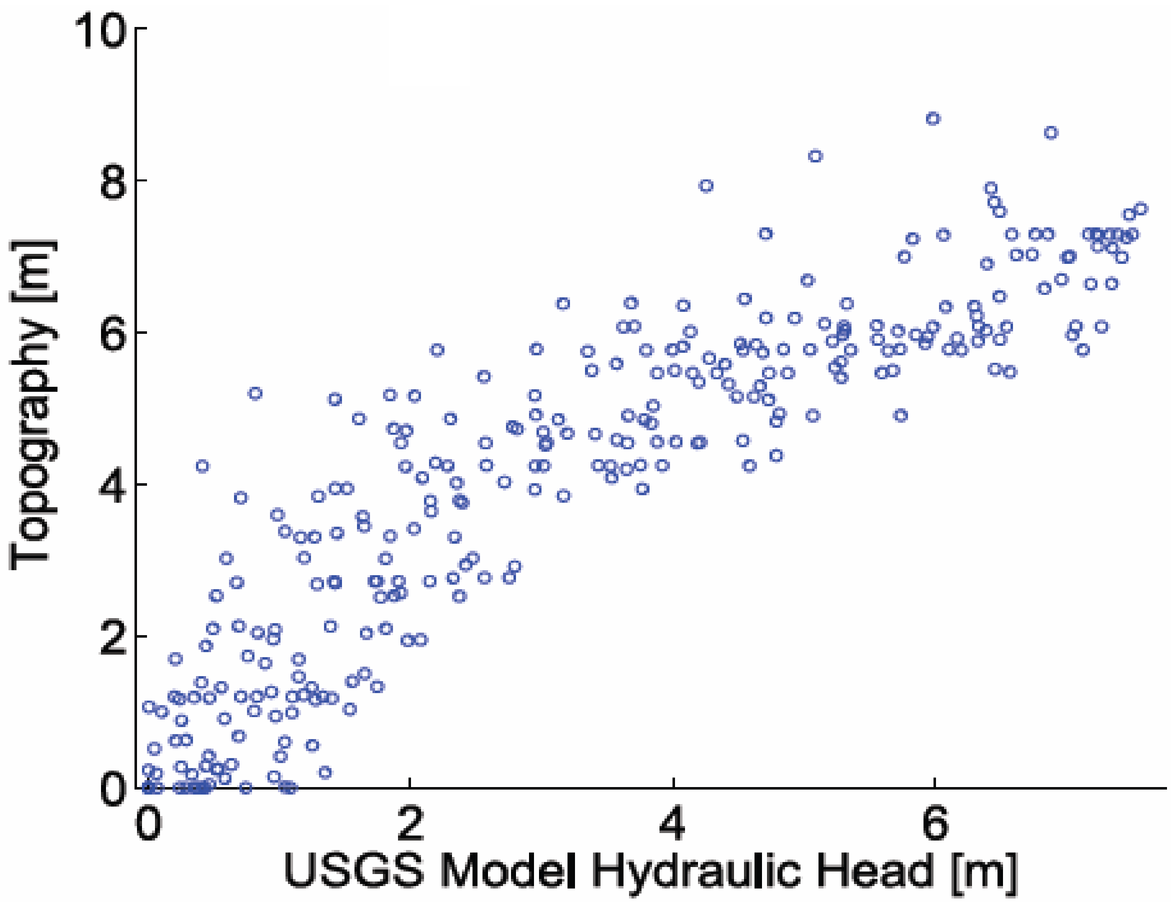


Flow Paths - USGS Model



Flow Paths

Analysis of the Water Table-Topography Relationship



- correlation: 0.87

Transport

- General idea:
  - Given a set of septic tank locations, track groundwater flow to water body
  - Use analytical solution for a given nitrate concentration at a septic tank to calculate concentration at point (x,y).

- The effect of denitrification on plume size is taken care of by 1st order decay.

Transport Model

- Simulating contaminant transport requires solving the advection-dispersion equation

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

- To simplify, use an analytical solution (Domenico & Robbins (1985), Domenico (1987), Martyn-Hayden & Robbins (1997))
  - Used in other models e.g. BIOSCREEN, BIOCHLOR, FOOTPRINT, REMChlor (EPA), SWLOAD.xls (Pennsylvania DEP)

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

$$\begin{aligned} F_1 = \; & exp\left[\frac{x}{2\alpha_x}\left(1 - \sqrt{1 + \frac{4k\alpha_x}{v}}\right)\right] \times erfc\left[\frac{x - vt\sqrt{1+\frac{4k\alpha_x}{v}}}{2\sqrt{\alpha_x vt}}\right] + \\ & exp\left[\frac{x}{2\alpha_x}\left(1 + \sqrt{1 + \frac{4k\alpha_x}{v}}\right)\right] \times erfc\left[\frac{x + vt\sqrt{1+\frac{4k\alpha_x}{v}}}{2\sqrt{\alpha_x vt}}\right] \end{aligned}$$

$$F_2 = erf\left(\frac{y + Y/2}{2\sqrt{\alpha_y x}}\right) - erf\left(\frac{y - Y/2}{2\sqrt{\alpha_y x}}\right)$$

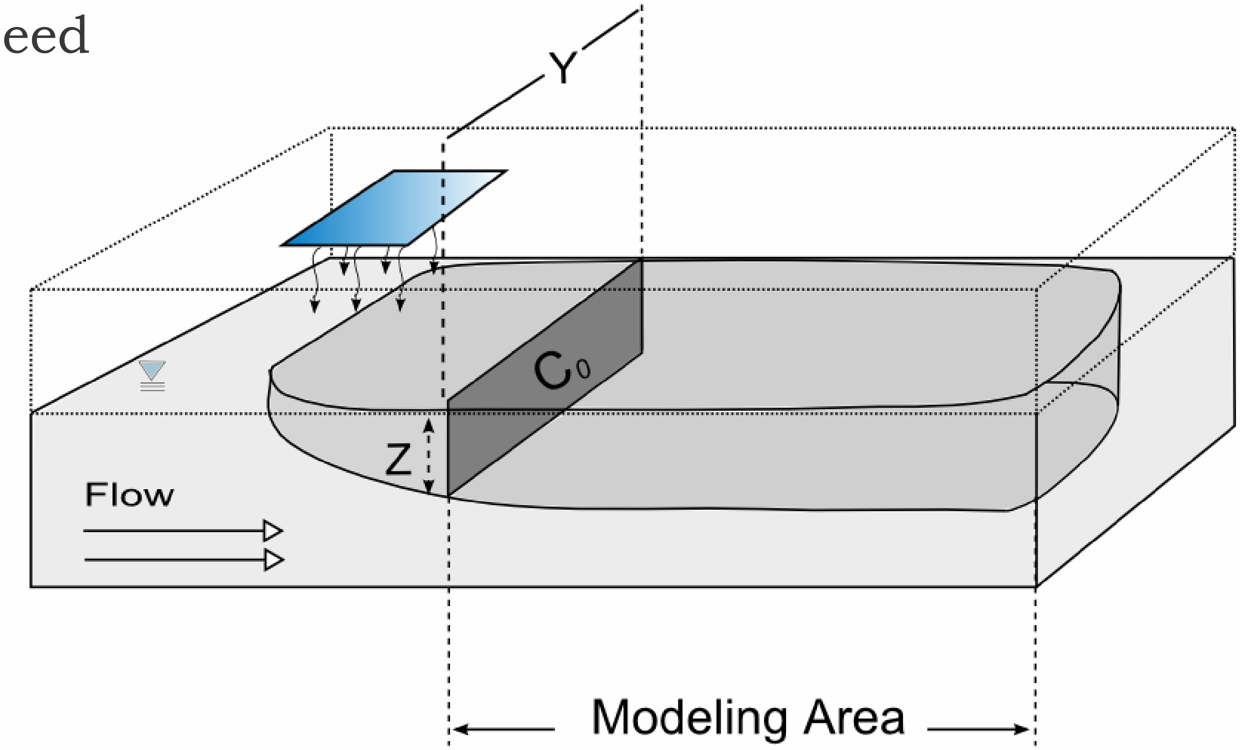
$$F_3 = erf\left(\frac{z + Z/2}{2\sqrt{\alpha_z x}}\right) - erf\left(\frac{z - Z/2}{2\sqrt{\alpha_z x}}\right)$$

Transport

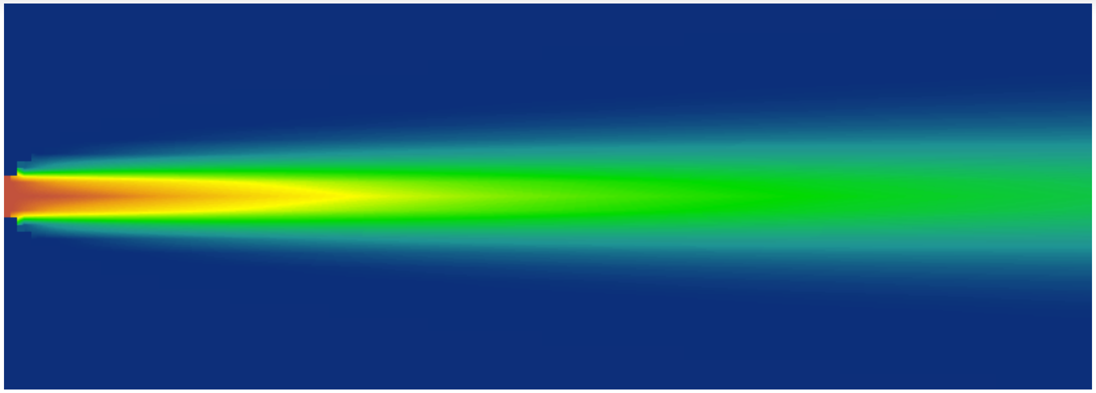
- Use a steady-state, 2-D version of the Domenico solution
  - Greatly reduces memory requirements and increases computation speed

- BIOCHLOR uses a similar approximation for computing mass loads

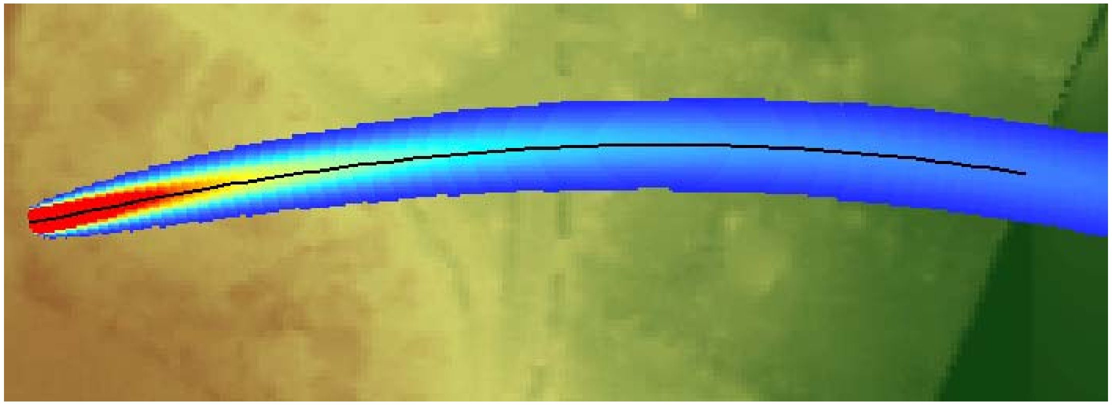
- Is reasonable if vertical dispersion is small



Transport



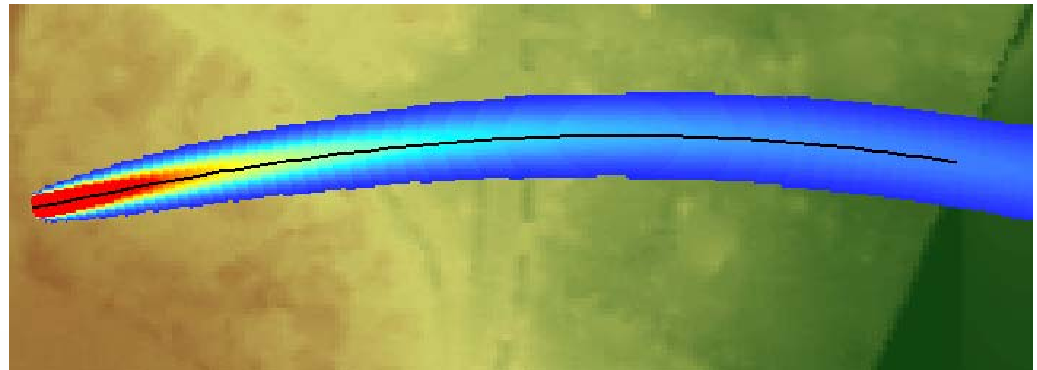
- Plumes are mapped to the flow path using a user selectable transformation



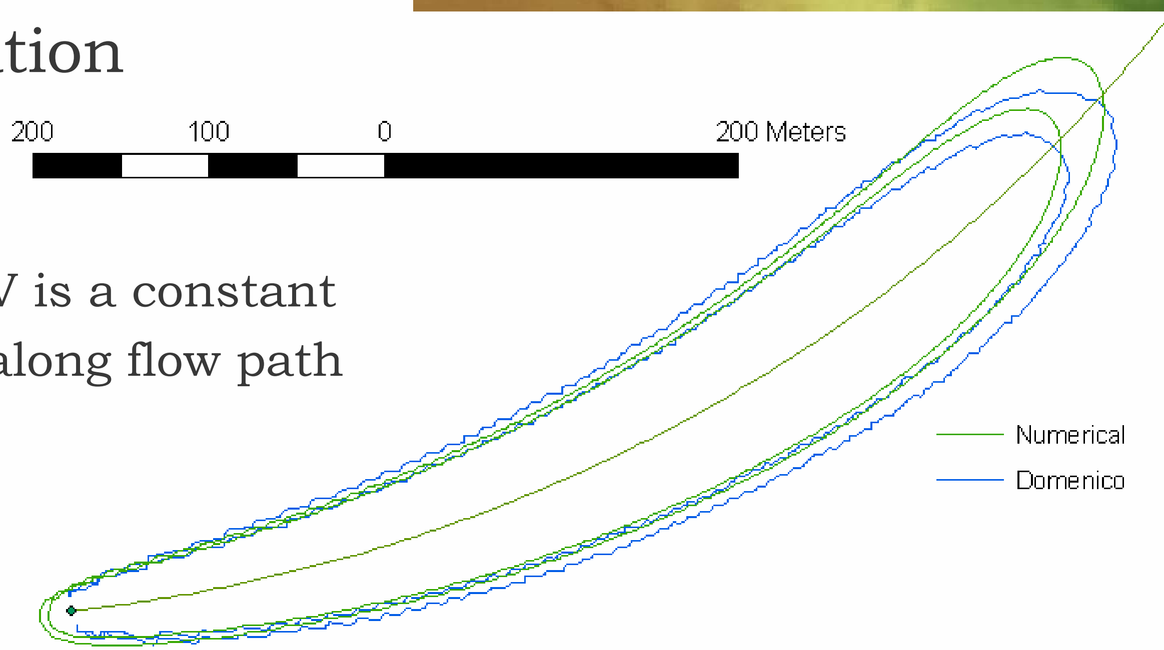
- Velocity, porosity are averaged along the flow path

Synthetic Tests

- Domenico solution considers only a single plume with a straight flow path



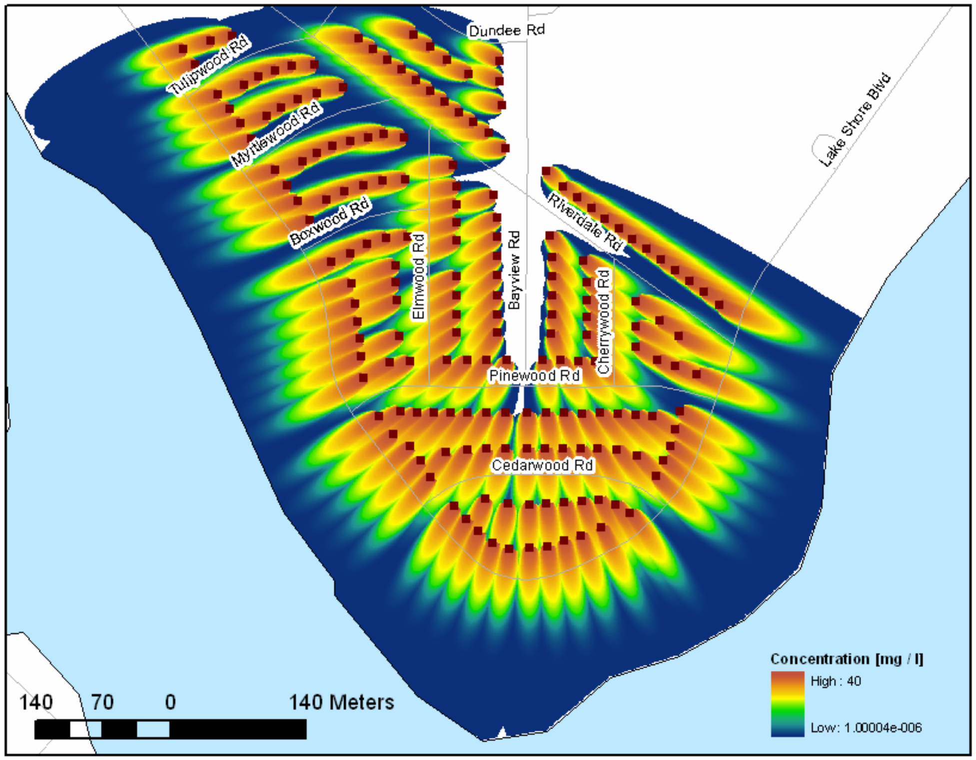
- Plumes are mapped to curved flow paths using a user-selectable transformation



V is a constant along flow path

Transport

- Domenico solution considers only a single plume in isolation
  - Our tool can handle many plumes



- Plume overlap will affect the concentration measured at a specific location

Load Calculation

- Denitrification is incorporated in the transport module using a first-order reaction.
- The load is determined by mass balance.
- In the steady state:

Nitrate Load = Mass Rate In – Mass Rate Out

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

Load Calculation

- M_{in} is calculated based on the mass flowing into the system from the constant concentration boundary
  - Advection and dispersion are taken into account

$$M_{in} = C_0 \Delta y \Delta z \theta v - \alpha_L \Delta y \Delta z \theta v \frac{\partial C}{\partial x}$$

- M_{dn} is calculated from the definition of a first order reaction and the volume of the calculation cell. The coefficient k is obtained from literature.

$$M_{dn} = kC\theta \Delta x \Delta y \Delta z \beta$$

Model Limitations

- Steady-state models.
- Only surficial aquifer considered
  - Saturated zone only
  - No Karst
- No recharge → mounding due to STE not considered.
- Plume evolves in an isolated, semi-infinite domain
  - $x \rightarrow [0, +\infty)$, $y \rightarrow (-\infty, +\infty)$, $z \rightarrow (-\infty, +\infty)$
  - Influences from other plumes or contaminants cannot be considered directly.
- Only consider uniform flow in the longitudinal direction
  - Flow field should not deviate too much from this assumption or results may be inaccurate.
- Other parameters (e.g., dispersivity and decay rate) are assumed constant throughout each plume (can vary plume by plume)
- Contaminant source is modeled as a constant concentration plane
  - A constant concentration will remain at the source for all time.

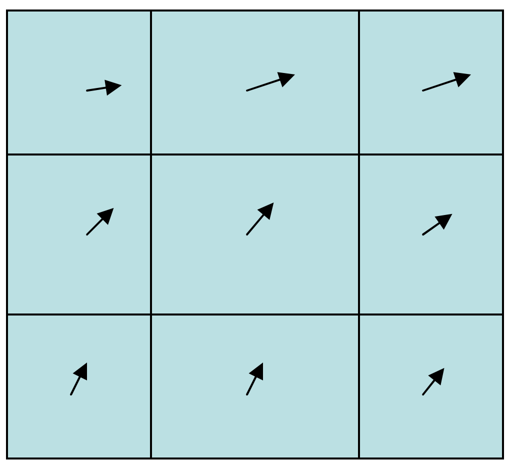
Final Remarks

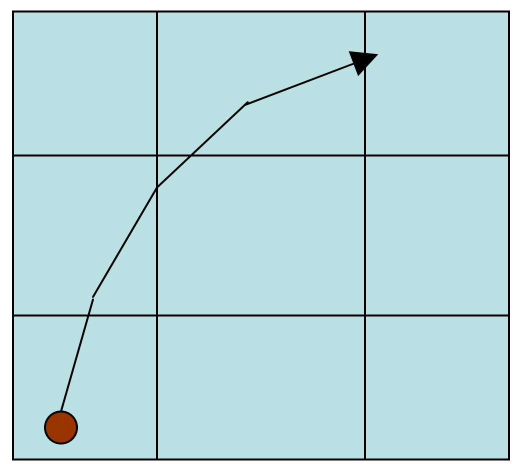
- Flow, transport and load estimation modules have been implemented: ArcNLET
- The water table is a subdued replica of the topography at the NAS
  - Likely in many areas in Jacksonville as well.
- Domenico solution with warping and velocity averaging provides a satisfactory approximation of plume size and shape compared with a more advanced simulation.
- Modeling results in the Julington Creek and Eggleston Heights neighborhoods in Jacksonville look promising.
  - More detailed comparison entails model calibration and the collection of site specific parameters.

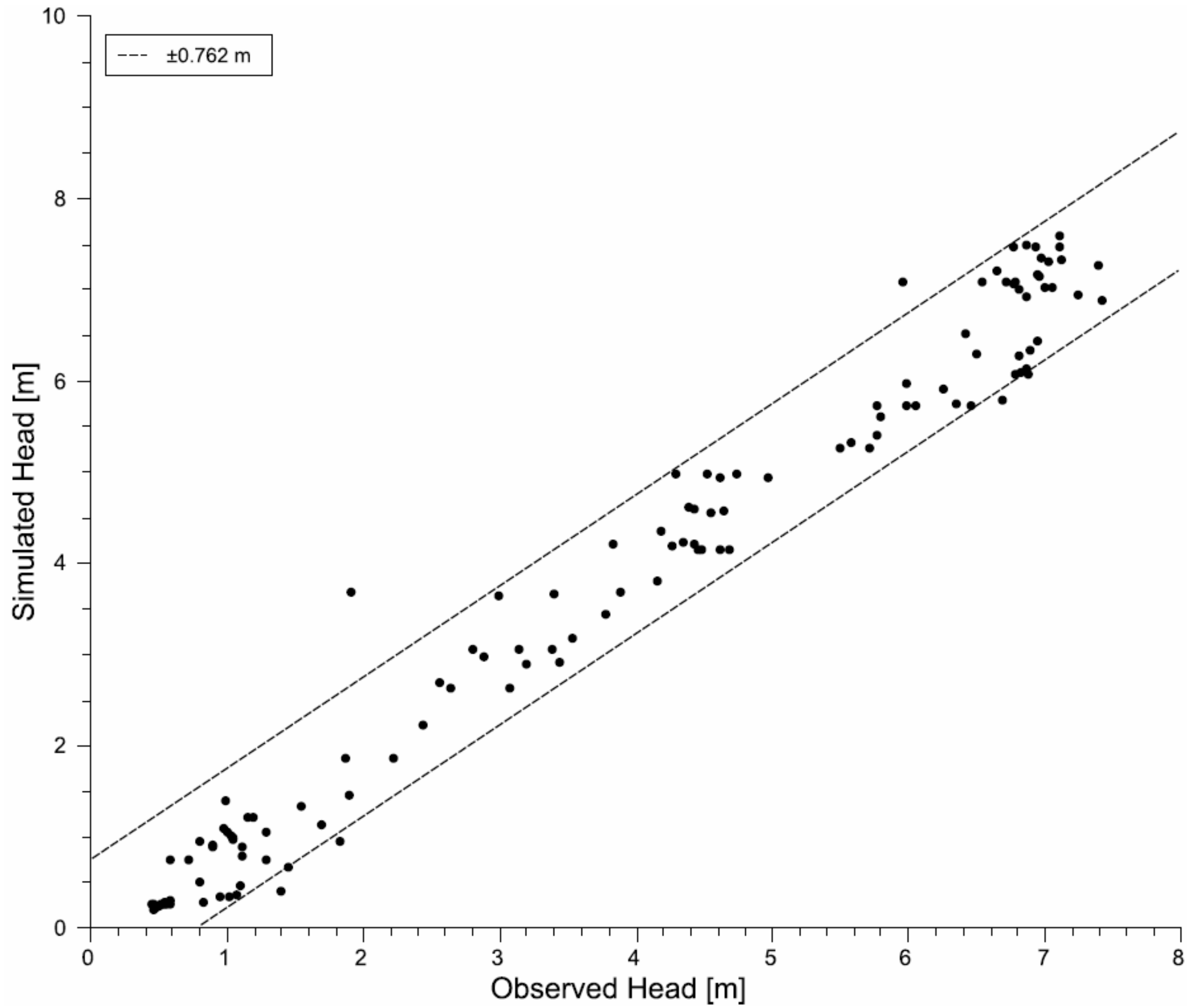
Questions?

Flow Model

- Particle tracking
  - Visualize flow field
  - Used by transport module to calculate plume centerline location

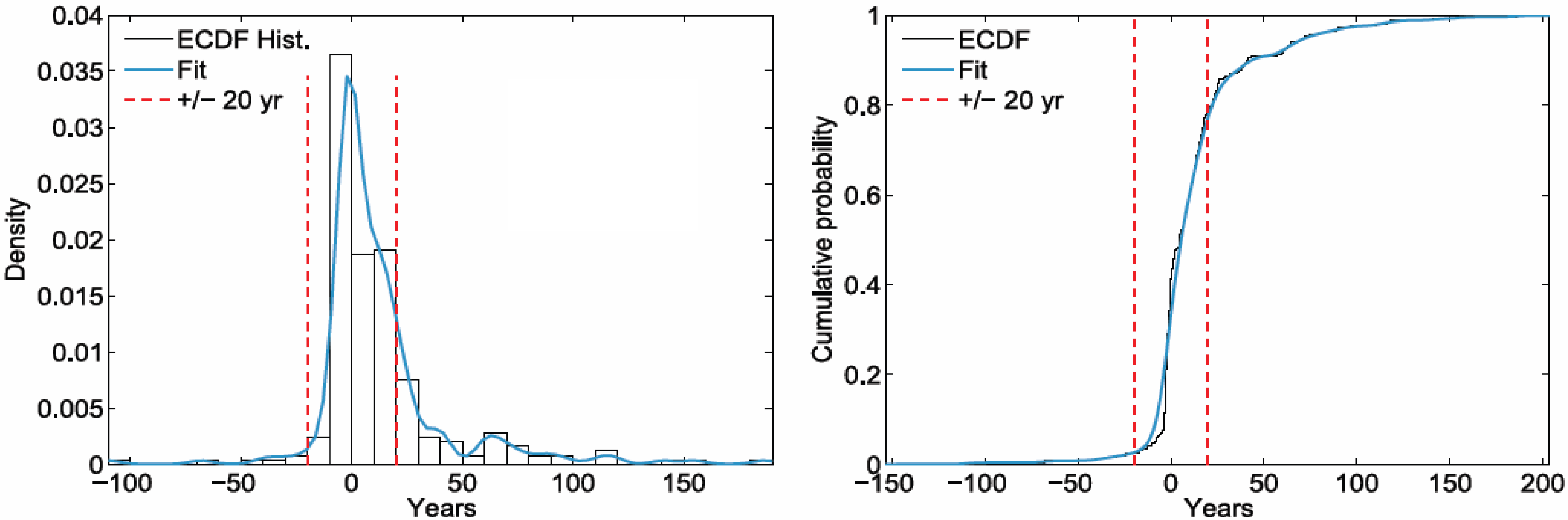






±0.762 m
Simulated Head [m]
Observed Head [m]
0
2
4
6
8
10
0
1
2
3
4
5
6
7
8

Analysis of the Water Table-Topography Relationship

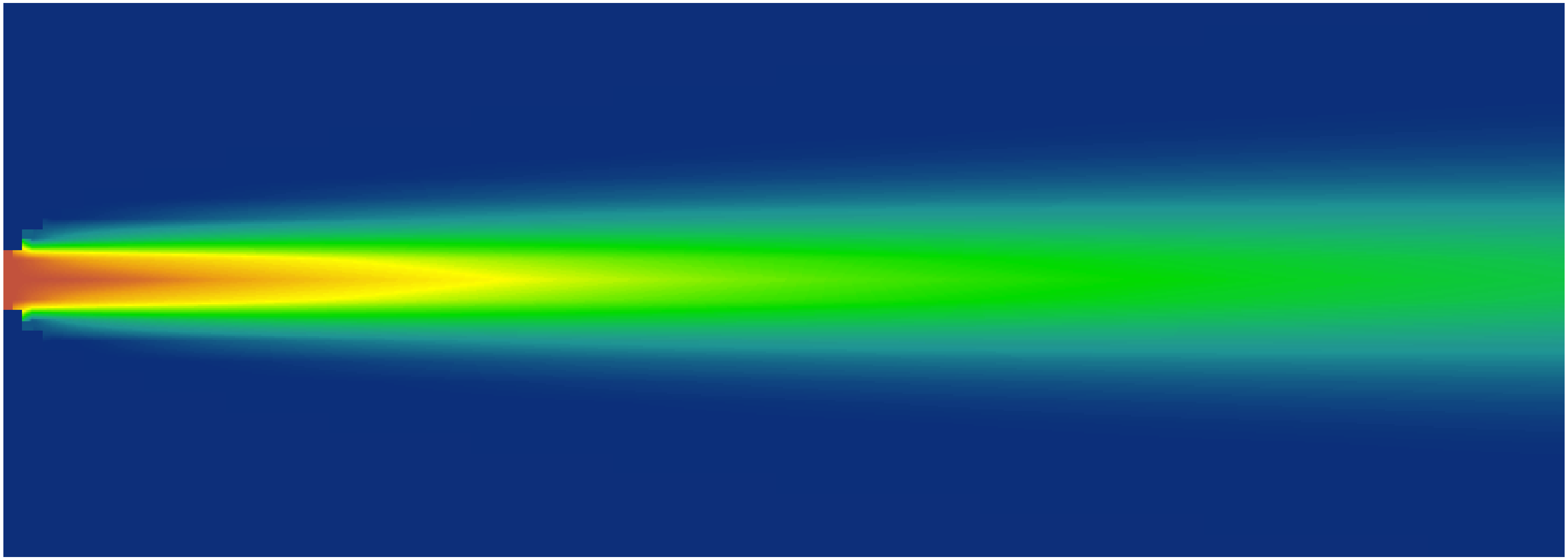


Difference in travel time between our model and the USGS model

- Mean difference is 13 yr

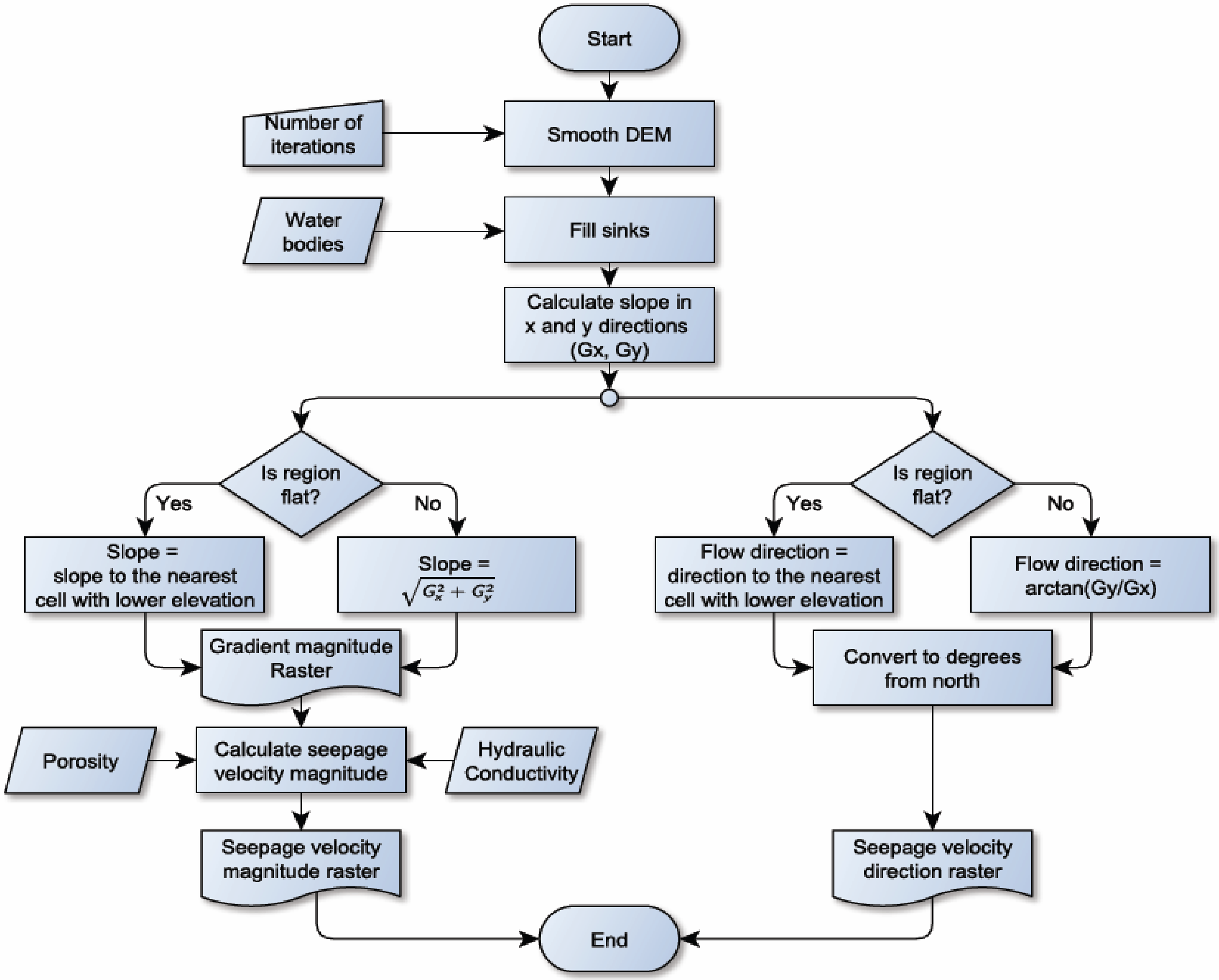
Transport – Domenico Solution

- Domenico solution visualization

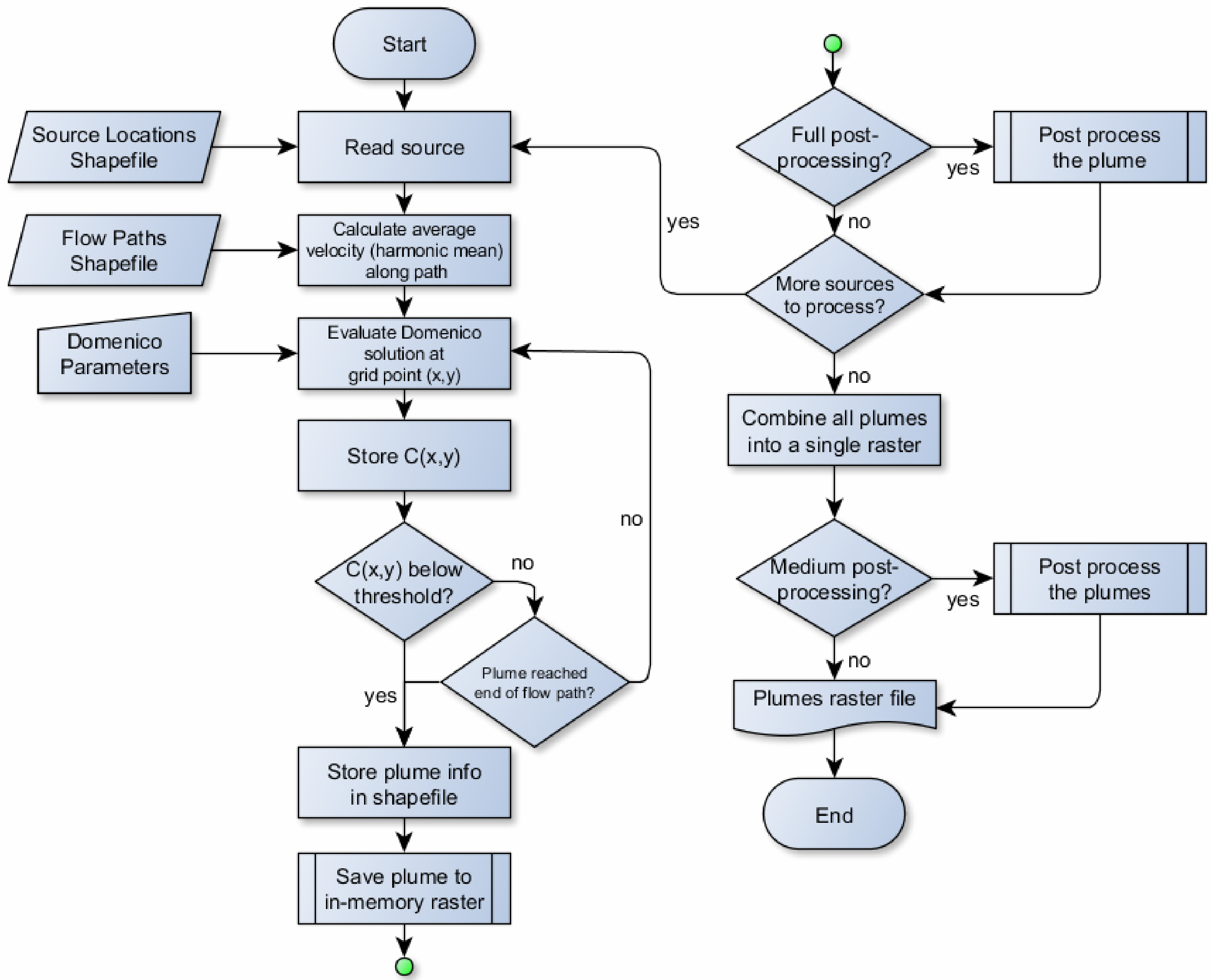


Flow Model

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



Transport


Start
Source Locations Shapefile
Read source
Flow Paths Shapefile
Calculate average velocity (harmonic mean) along path
Domenico Parameters
Evaluate Domenico solution at grid point (x,y)
Store C(x,y)
C(x,y) below threshold?
no
Plume reached end of flow path?
no
yes
Store plume info in shapefile
Save plume to in-memory raster
Full post-processing?
yes
Post process the plume
no
More sources to process?
yes
no
Combine all plumes into a single raster
Medium post-processing?
yes
Post process the plumes
no
Plumes raster file
End

Synthetic Tests

- Effect of velocity averaging
  - Depends on the form of the flow field