Developing a GIS-Based Model for Estimating Nitrate Fate and Transport from Septic Systems in Surficial Aquifers

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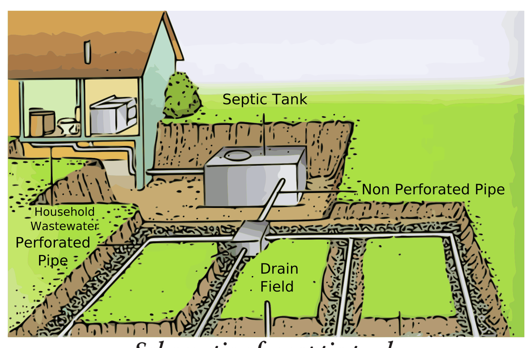
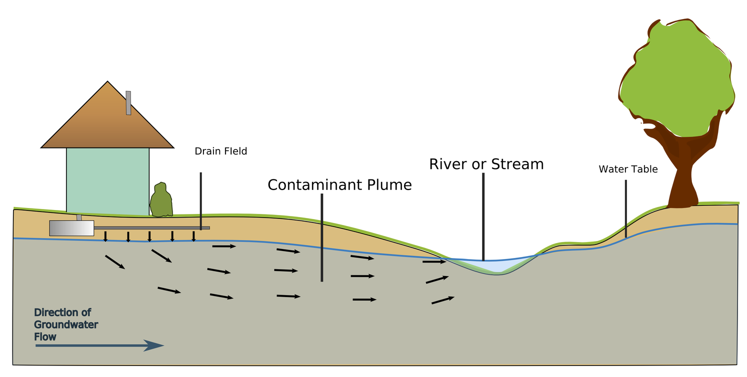
Background



Schematic of a septic tank

- Estimating nitrate fate and transport in groundwater is an important task in water resources and environmental management, because excess nitrate load on ground and surface waters may cause negative impacts on human and environmental health. High levels (>10 mg/l according to EPA standards) of nitrates can cause fatal poisoning in infants causing methemoglobinemia (blue baby syndrome) where cells are starved of oxygen. It is also a possible carcinogenic agent causing gastric cancer. Elevated levels harm livestock, fish and aquatic ecosystems. In aquatic ecosystems, elevated levels can lead to algae blooms and excessive plant growth, the decay of which can cause eutrophication. There is more than one source of nitrates. This model will focus on nitrates originating from septic tanks.

- This project aims to develop simplified groundwater flow and denitrfication models in the surficial aquifer, each having reduced input data requirements and enhanced ease of use compared to conventional models (e.g. MODFLOW, AgriFlux). This simplified model is intended to be used as a screening tool and as such, it is meant only to give an overall picture.



Schematic of plume movement in the surficial aquifer

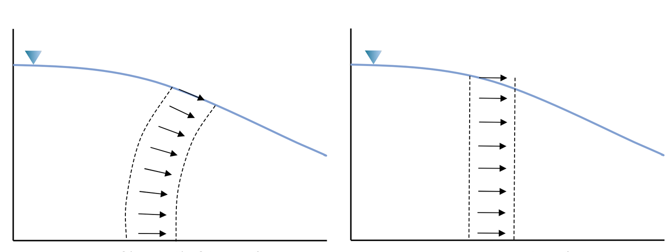
- Summary of project objectives: The model/software should (1) reduce input data demands compared to conventional models (2) consider the spatial location of the septic tank (this is often ignored in other simplified models) (3) incorporate nitrate removal in the form of denitrification (4) be easy to use and have a GIS (Geographic Information System) -based interface.

Conceptual Model

- Model is separated into three sub-models: the flow model, transport model and denitrification model.

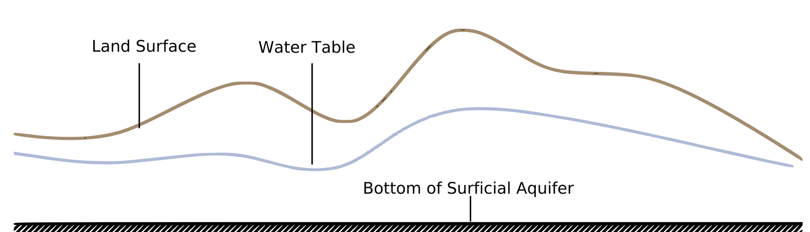
Flow Model:
- The model considers only steady state groundwater flow. There is no change in flow due to seasons or recharge events. This model is only concerned with long term nitrate loads therefore a steady state condition is sufficient.

- Only two dimensional flow is considered. This is known as the Dupuit approximation and is valid in when the slope of the water table is small and the aquifer is not too thick. Under the Dupuit approximation, flow lines are horizonal and hydraulic head equipotentials vertical. Additionally, the hydraulic gradient is considered to be the slope of the water table and is invariant with depth.



3D flow (left). The Dupuit Approximation (right)

- The water table is a subdued replica of the topography. Valid in relatively flat or gently rolling terrain with shallow water tables (Haitjema and Mitchell-Bruker, 2005). This is valid for the Jacksonville Study area.



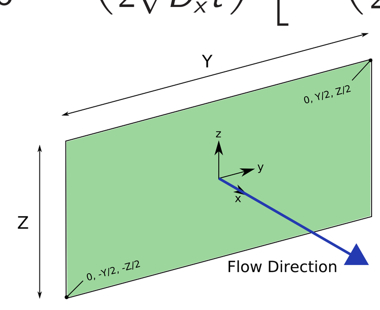
A subdued replica of the topography

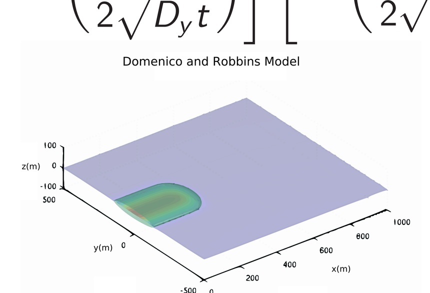
- A Digital Elevation Model (DEM) will be used to approximate the water table.

- The groundwater seepage velocity is calculated via Darcy's Law $v = -\frac{K\nabla h}{\theta}$

Transport Model:
- Contaminant plume is calculated via the analytical solution to the advection-diffusion equation presented by Domenico and Robbins (1987). This equation has been used by the U.S. EPA in groundwater remediation models such as BIOCHLOR and BIOSCREEN

$$C(x,y,z,t) = \frac{C_0}{8} erfc\left(\frac{x-vt}{2\sqrt{D_x t}}\right)\cdot\left[erf\left(\frac{Y+\frac{1}{2}y}{2\sqrt{D_y t}}\right) - erf\left(\frac{Y-\frac{1}{2}y}{2\sqrt{D_y t}}\right)\right]\left[erf\left(\frac{Z+\frac{1}{2}z}{2\sqrt{D_z t}}\right) - erf\left(\frac{Z-\frac{1}{2}z}{2\sqrt{D_z t}}\right)\right]$$





Denitrification Model:
- Given the denitrification volume V_{aq} (i.e. the volume of the plume) obtained from the transport model and the initial nitrate load N_0 , the amount of nitrate at time t is calculated by

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

where R_{dn} is the denitrification rate, obtained from a separate model via a) a linear regression, b) a multivariate linear regression, or c) a neural network.

Method

- The model is being implemented as a plug-in to the commercial GIS software package ArcGIS from ESRI using the Visual Basic .NET programming language from Microsoft. The software is fully object oriented with a modular approach to the GUI.

Flow Model:
- Given a topographic map, a map of water bodies and a map of hydraulic conductivity and porosity, the software outputs two files representing the groundwater flow velocity vector (direction and magnitude) calculated using Darcy's Law.

- A subdued replica of the topography is obtained by applying a 7 x 7 averaging filter. The x and y components of the hydraulic gradient are calculated by applying a Sobel filter to the smoothed DEM.

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

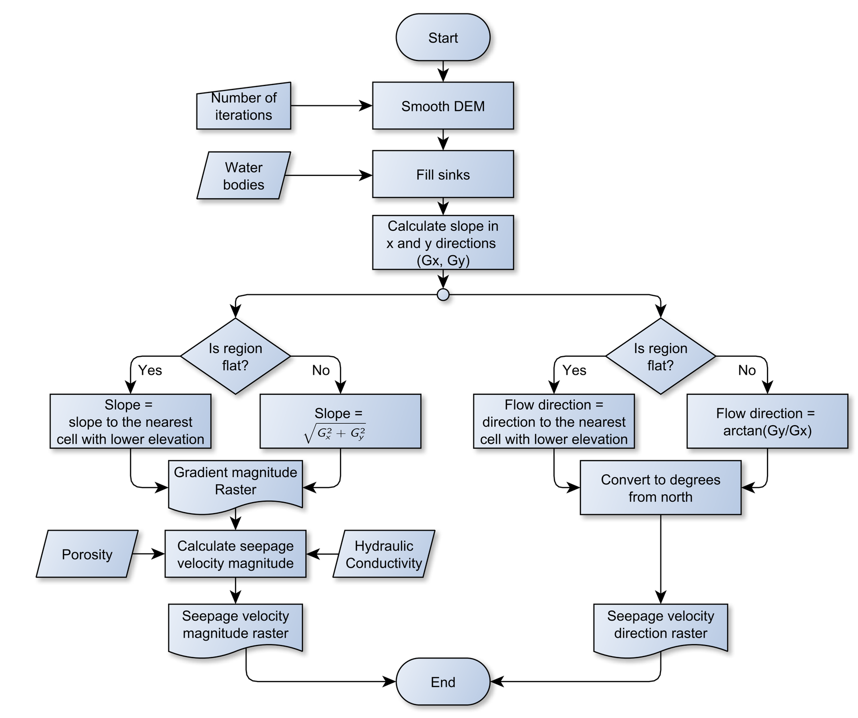
$*$ is the convolution operator.

Method (Cont.)

- Due to the use of a DEM in approximating the water table, sinks and flat areas in the DEM are problematic for calculating the flow vector. In reality, a depression in the water table usually corresponds to a lake or stream. If a depression occurs where there is no such water body, the sink must be filled. Sinks are filled by raising the elevation of the sink until there is a downslope path. Flat areas (caused by limited DEM resolution or by sink-filling) are dealt with by finding the path to the nearest downslope cell.

- Given the groundwater flow direction and magnitude, a separate module conducts particle tracking given a set of starting points.

Transport & Denitrification Model:
- These are in the process of being implemented



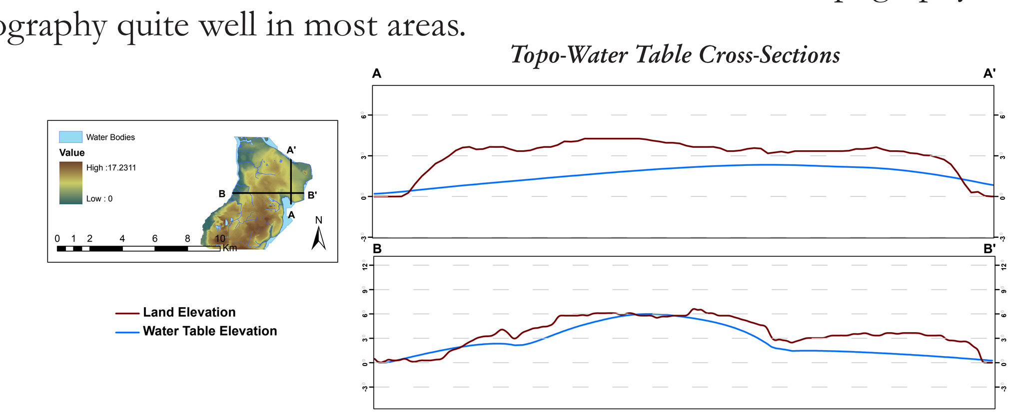
Flow model flowchart

Validation - Flow Model

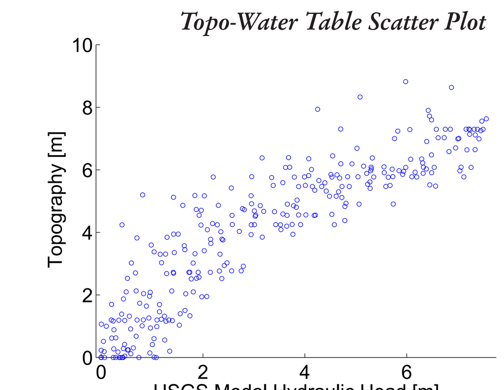
- The model was validated using a calibrated MODFLOW model of the U.S. Naval Air Station in Jacksonville, Florida which is based on a study by the USGS (Davis 1996, 1998).

- The rank correlation between the water table and the topography is 0.91 indicating the water table follows the topography quite well in most areas.

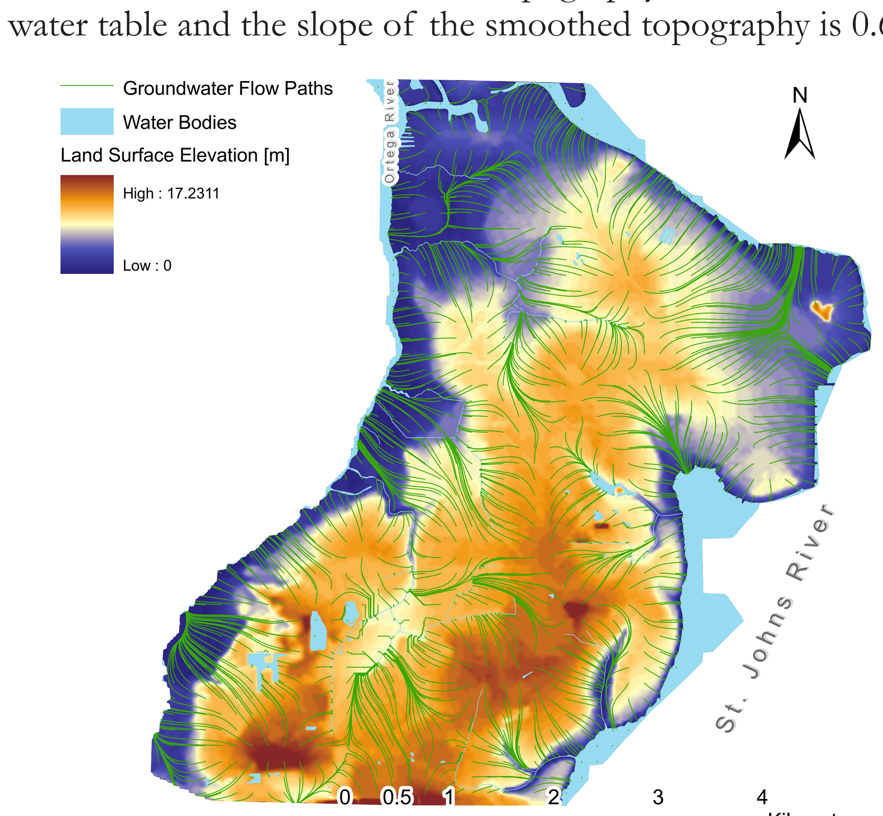
Topo-Water Table Cross-Sections



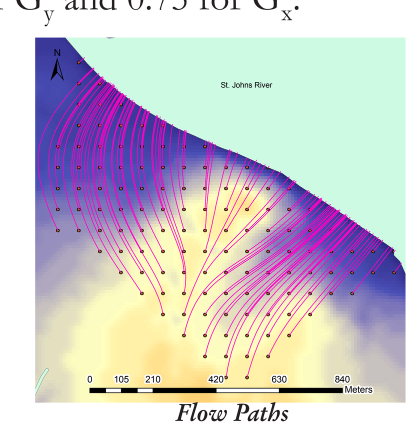
Topo-Water Table Scatter Plot



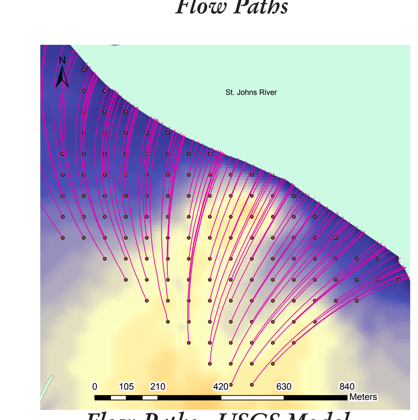
- The model was run with 50 smoothing iterations, a hydraulic conductivity of 2.113 m/day and a soil porosity of 0.25. The correlation between the smoothed topography and the water table is 0.93 and the correlation between the slope of the water table and the slope of the smoothed topography is 0.60 for G_y and 0.75 for G_x.



Flow Paths

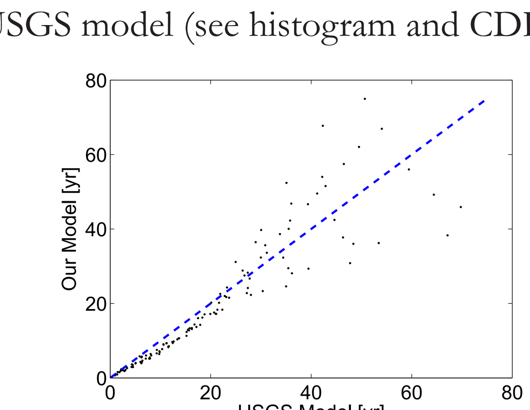


Flow Paths

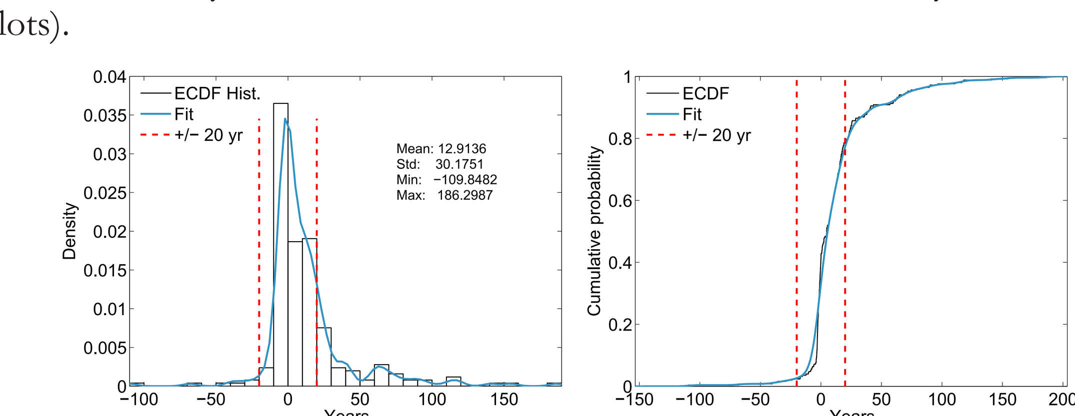


Flow Paths - USGS Model

- Two smaller subdomains were selected and compared with the USGS results. Statistics from this comparison indicate that the mean difference in travel times is 13 years. 75% of the time, our model is within 20 years of the USGS model (see histogram and CDF plots).



Scatter plot of travel time estimates for the sub area shown above. Line indicates y=x.



Difference in travel time between our model and the USGS model

Conclusions

- The water table has been determined to be a subdued replica of the topography for the U.S. Naval Air Station, Jacksonville and surrounding area.

- The simplified flow model has reduced data requirements compared to conventional models by using a DEM to approximate the water table.

- The simplified flow model provides a reasonable estimate of groundwater flow compared to a more detailed conventional model. For two smaller test areas within the simulation domain, the estimated travel times are within 20 years of the travel times estimated by the more detailed model, 75% of the time.

- Future work consists of implementing the transport and denitrification modules.

Acknowledgements

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