Use of an Arc-GIS Based Software for Estimation of Nitrate Loads from Septic Systems to St. Johns River in Jacksonville, FL

Picture from USGS Scientific Investigations Report 2008–5220

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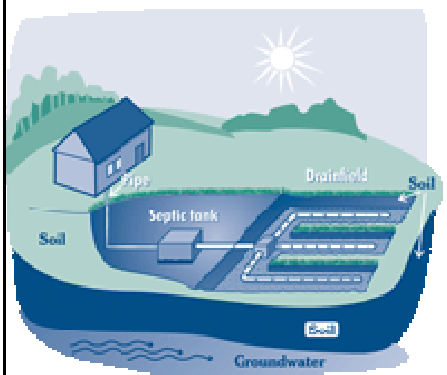
Problem Statement

- In Florida, nearly 1/3 of households are served by septic systems and approximately 92% of Florida's drinking water comes from groundwater (Briggs et al. 2007). The negative impacts of nitrogen due to septic systems in Florida are of wide concern. Taking the Lower St. Johns River Basin (LSJRB) as an example, nitrate due to septic systems is believed to be one important nitrogen source that causes nutrient enrichment (Leggette et al. 2004).

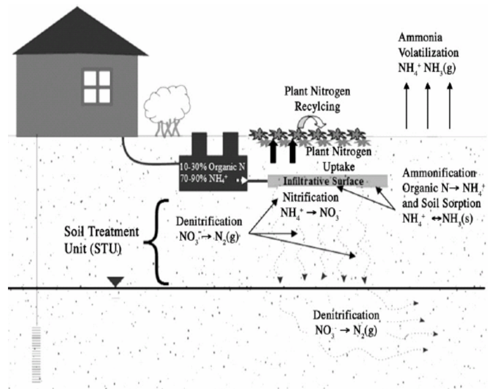
- Traditional models such as MODFLOW and MT3DMS usually have steep learning curves. Sometimes their setup can be quite complex, requiring a large amount of input data and the execution time can be quite long.

- The goal of this study is to develop an ArcGIS-based, easy-to-use software (with friendly user interface) by using simplified conceptual models and readily available soil and topographic GIS layers

Schematic of A Septic Systems and Subsurface Nitrogen Transformation Processes



From EPA website

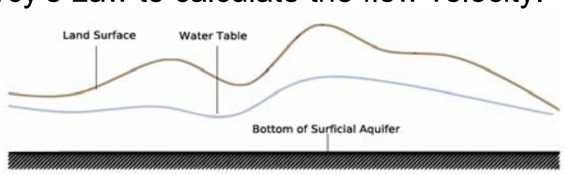


From Heatwole and McCray (2007)

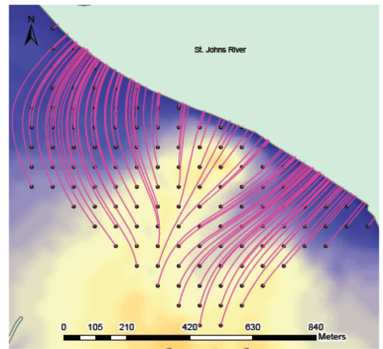
This software simulates fate and transport of nitrate in groundwater. The nitrate load from the unsaturated zone is treated as a constant concentration boundary for the transport model.

Groundwater Flow Modeling

- 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 digital elevation model (DEM) and use it to approximate water table.
- Use Darcy's Law to calculate the flow velocity.



Outputs of Groundwater Flow Modeling

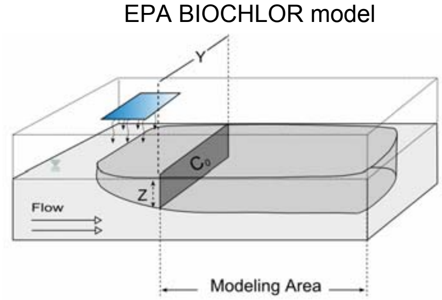


Flow Paths

- 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

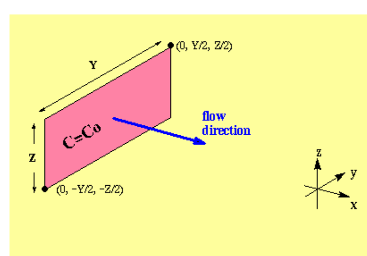


$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} - v\frac{\partial C}{\partial x} - kC$$

Dispersion Advection Decay

Domenico & Robbins (1985), Domenico (1987), Martyn-Hayden & Robbins (1997)

Domenico analytical solution



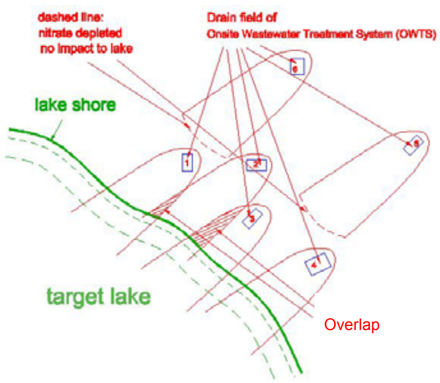
$$C(x,y) = \frac{C_0}{2} F_1(x) F_2(y,x)$$

$$F_1 = \exp\left[\frac{x}{2\alpha_x}\left(1 - \sqrt{1 + \frac{4k\alpha_x}{v}}\right)\right]$$

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

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 using analytical solutions and denitrification.
- Calculate load to rivers by mass balance method

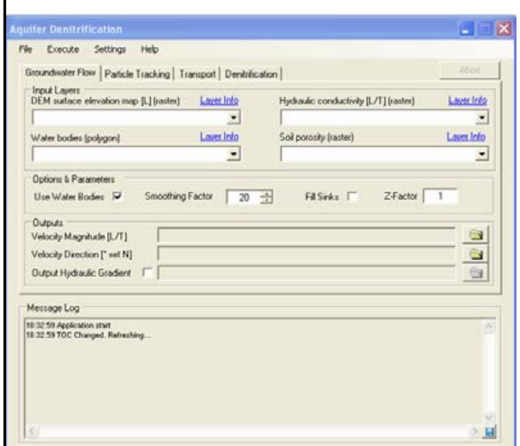


$$M_l = M_{in} - M_{dn}$$

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

Software Demo

The software is developed as an ArcGIS 9.3 extension



Graphical User Interface

Output of Groundwater Flow Module :

- Direction of seepage velocity
- Magnitude of seepage velocity

Output of particle Tracking Module:

- Flow path
- Average velocity along the path

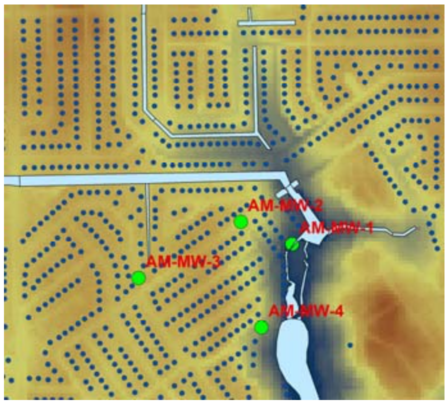
Output of Transport Module:

- Nitrate concentration
- Source input mass
- Denitrification mass

Denitrification Module:

- Nitrate loads to target waterbody

Calibration Domain for Eggleston Heights and Julington Creek Neighborhoods, Jacksonville, FL



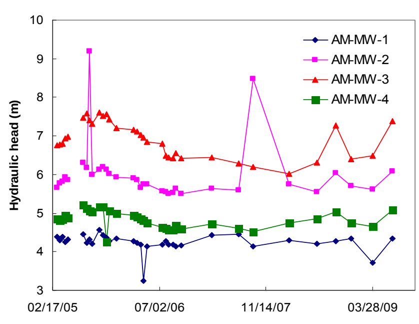
Eggleston Heights

Julington Creek

The isotope study within this two neighborhoods shows that

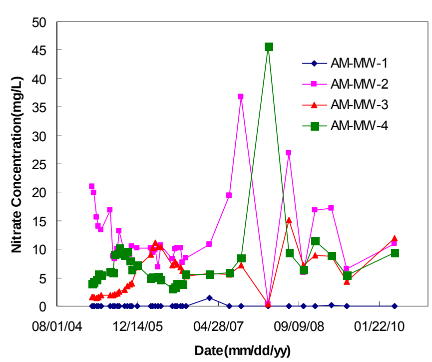
- nitrate due to septic systems is the major source of nitrate and
- significant denitrification occurs.

Observations of Hydraulic Head and Nitrate Concentration



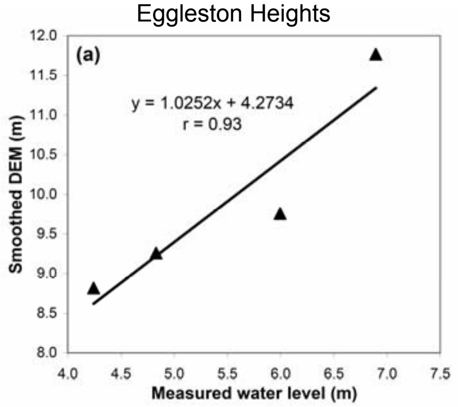
- The observed water tables are relatively stable.
- Only the mean values are used as calibration targets.

- The observed concentrations have large fluctuation due to complicated nitrogen transport and transformation mechanism.
- The ranges between upper and lower quartile are used as the calibration targets.

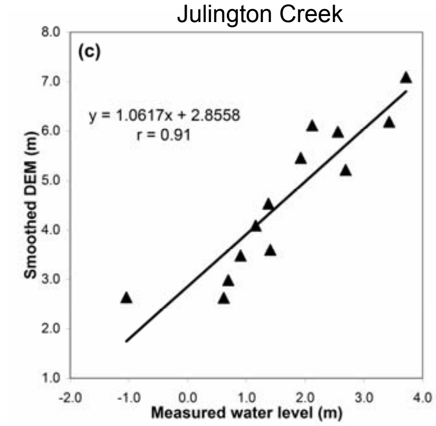


Calibration Results of Hydraulic Gradient

Eggleston Heights



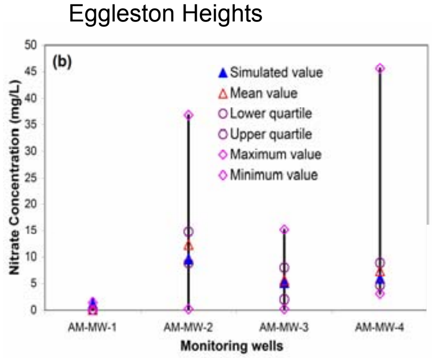
Julington Creek



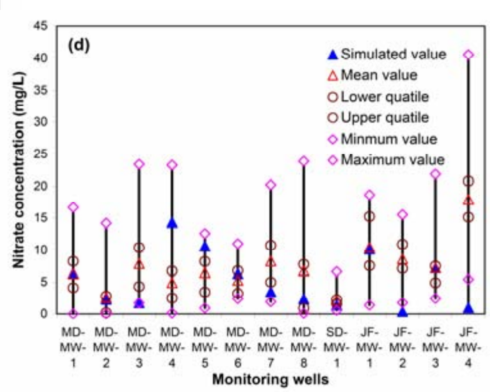
The smoothed DEM agree well with the observed water table shape with a linear correlation coefficient of more than 0.9 and slope of the linear regression close to 1.0

Calibration Results of Nitrate Concentration

Eggleston Heights

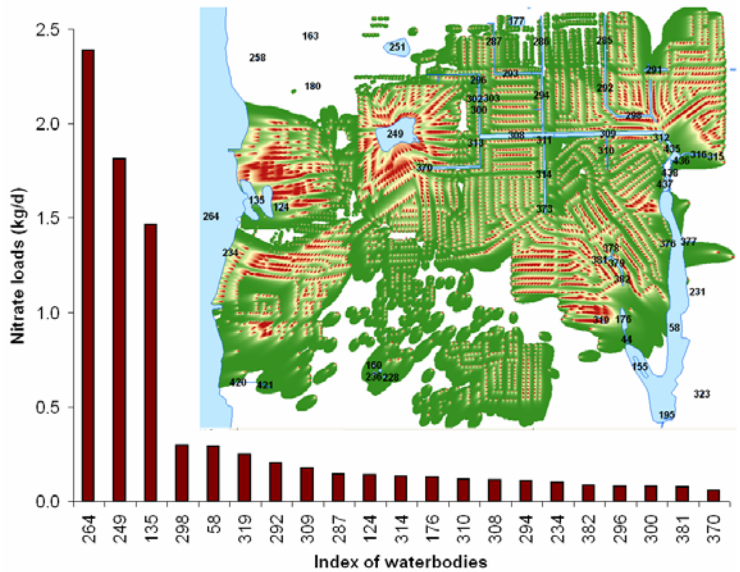


Julington Creek



The simulated nitrate concentrations are close to the mean observations and within the inter-quartile of the observed concentrations in more than half of the monitoring wells.

Nitrate Loads Estimation for Eggleston Heights Neighborhood



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.

Conclusions

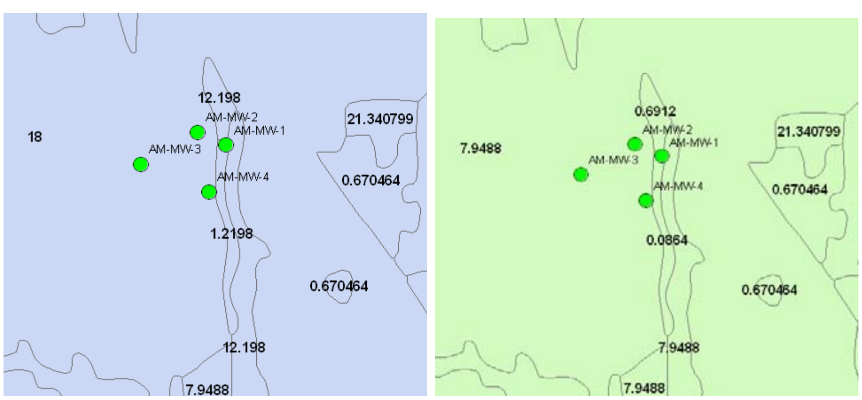
- The ArcGIS-based software has been developed for simulation of nitrate transport and estimation of nitrate load from septic systems to surface water bodies.
- The software is user friendly and easy to operate.
- After being calibrated, it can yield acceptable simulations of field observations.
- The software gives reasonable estimation of source input mass flux, which is comparable with the estimate base on Anderson (2006).

Thank you

Calibrated Parameters

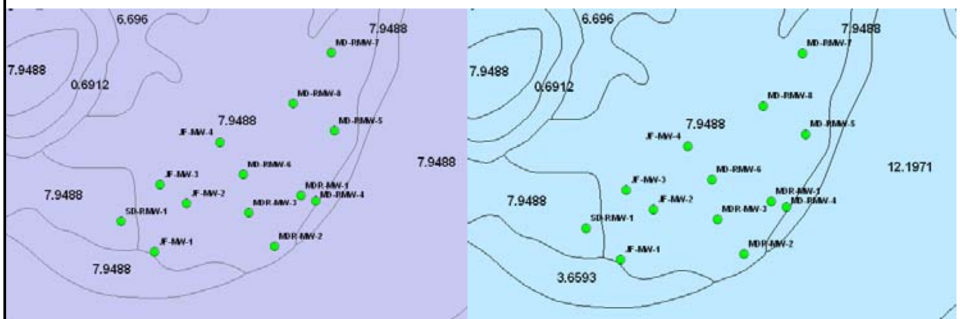
Parameters for Eggleston Heights
–Width of the source plain Y=6m
–Decay coefficient: k = 0.005 /d
–Dispersivity: α_x = 10.0 m, α_y =1.0 m .
–Soil porosity: Φ = the original values from the soil survey data

Calibrated Hydraulic Conductivity (Eggleston Heights)



Zonal values of original (left) and calibrated (right) hydraulic conductivity

Calibrated Hydraulic Conductivity and Other Parameters (Julington Creek)

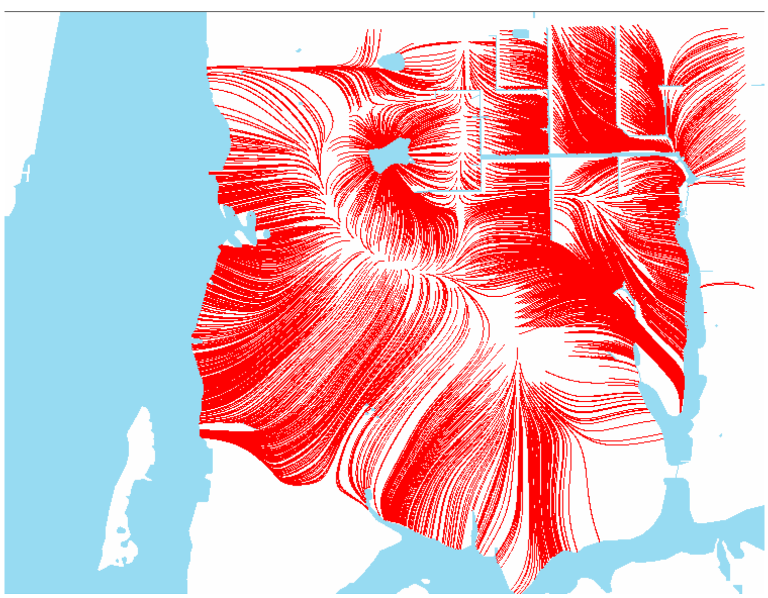


Zones of original hydraulic conductivity (left) and after calibration (right)

Other parameters

- Width of the source plain Y=6m
- Decay coefficient: k = 0.012 /d
- Dispersivity: α_x = 10.0 m, α_y =1.0 m.
- Soil porosity: Φ = the original values from the soil survey data
- Initial source concentration: C_0=100mg/L (fertilizer effect is considered)

Simulated Flow Path for Eggleston Heights Neighborhood

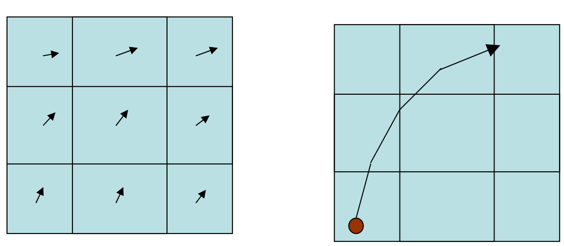


Development of the ArcGIS Extension

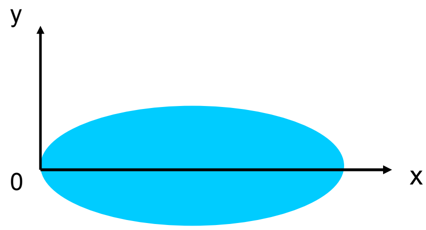
- All the development is within ArcGIS, including pre-processing, post-processing, and computation.
- We developed a user-friendly interface using Visual Basic.
  - The .NET framework is used to expedite development.
- The software development is for ArcGIS 9.3.
  - The software can be updated with newer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

Flow Model

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



Global Sensitivity Analysis



Calibrated parameters include:

– Groundwater velocity: v
  - ✓Smoothing factor: s
  - ✓Soil porosity: Φ
  - ✓Hydraulic conductivity: K

– First-order decay coefficient: k

– Dispersivity: α_x and α_y

– Source concentration: C_0

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

Two most critical parameters for selected location