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

Liying Wang[1], Ming Ye[1], J. Fernando Rios[2], Paul Z. Lee[3]
[1]*Florida State University, lwang3@fsu.edu, mye@fsu.edu, Tallahassee, FL, USA*
[2]*State University of New York at Buffalo, jfernand@buffalo.edu, Buffalo, NY, USA*
[3]*Florida Department of Environmental Protection, Paul.Lee@dep.state.fl.us, Tallahassee, FL, USA*

ABSTRACT

Nitrate contamination in water is a national concern, as it poses serious threats to human health and environments. In Florida, approximately one third of population use onsite sewage treatment and disposal systems (OSTDS) (also known as septic systems) for treating domestic wastewater. Nitrate from septic systems comprises a significant portion of the nitrogen load to groundwater and surface water in Florida. It is therefore important to accurately simulate nitrate fate and transport from septic tanks in water resources and environmental management. We developed an easy-to-use and user friendly software, as an ArcGIS extension, for estimating long-term nitrate loads from septic systems to surface water bodies. While this software is based on a simplified groundwater flow and nitrate transport model, the model takes into account nitrate attenuation mechanisms (e.g., dispersion and denitrification) as well as spatial variability of hydraulic parameters and septic systems. This software was used for estimating nitrate loads to the St. Johns River from about 3900 septic tanks in the Eggleston Heights neighborhood in Jacksonville, Florida. Before the estimation, local and global sensitivity analyses were performed, and they indicate that the most critical parameters are hydraulic conductivity, decay coefficient related to denitrification, and dispersivity. Hydraulic and transport parameters were calibrated against observed hydraulic head and nitrate concentrations. Despite the fact that the model is simple, the calibration led to satisfactory match to field observations. This software is being used by the Florida Department of Environmental Protection for estimating nitrate load in other neighborhoods in Jacksonville, FL.

INTRODUCTION

Nitrate contamination in water is a national concern, as it poses serious threats to human health and environments. In Florida, approximately one third of population use onsite sewage treatment and disposal systems (OSTDS, a.k.a. septic systems) for treating domestic wastewater. Nitrate from septic systems comprises a significant portion of nitrogen load to groundwater and surface water in Florida. Taking the Lower St. Johns River (LSJR) basin as an example, nutrient enrichment with nitrogen and phosphorus originating from non point source runoff has been identified as an important environmental concern. Among all the sources, nitrate due to septic systems is believed to be important (Leggette, Barshear, and Graham, Inc., 2004). Therefore, accurate simulation of nitrate fate and transport from septic systems is an important task in water resources and environmental management.

Although many sophisticated models and computer codes have been developed for simulating fate and transport of contaminants, including nitrate, they always have steep learning curves and require specialists for model setup and calibration. In addition, they may lack user friendly components for pre- and post-processing. These limit the use of sophisticated models and codes in environmental permitting and regulation. With recognition of this, there has been a trend of developing simplified models and user friendly software. The New Jersey Department of Environmental Protection developed a tool to determine effects of dilution on nitrate contamination from OSTDS (Hoffman and Canace, 2004). Its goal was to determine the average area required per OSTDS in order to dilute the septic tank effluent to acceptable levels. The model SepTTS (Schecher, 1997; Lee et al., 1998) is a simplified model that focused on fate and transport of household chemicals from OSTDS (not nitrogen or nitrate). Using GIS-based software associated with simplified models has been popular for groundwater flow and/or transport modeling. Ye et al. (1996) presented a map-based subsurface flow modeling tool that integrated directly with GIS. The models reviewed by McCray (2009) are simplified GIS-based screening models for nitrogen fate and transport. Schilling and Wolter (2007) developed a GIS-based model specifically for the simulation of

nitrate pollution from agricultural sources; in the model, groundwater travel time map was estimated by using a DEM (digital elevation model) to approximate the hydraulic gradient.
In order to support environmental regulation activities of the Florida Department of Environmental Protection, we developed a simplified groundwater flow and nitrate transport model, and implemented this model by forging a software tool as an ArcGIS extension using the VB .NET programming language. The software is easy to use and user friendly; the pre- and post-processing and execution are all performed within ArcGIS. By making assumptions and simplifications to the system being modeled, this software significantly reduces complexity of the modeling process and computational burden, and can be used to predict nitrate concentration in groundwater and provide quick estimates of nitrate loads to surface waterbodies due to septic systems. Local and global sensitivity analyses were performed based on the simplified model. The model was calibrated against field observations of head and concentration collected at the Eggleston Heights neighborhood in Jacksonville, FL, and used to estimate nitrate load from septic systems of this neighborhood to surface water body within and around the neighborhood including the St. Johns River.

SIMPLIFIED GROUNDWATER MODEL AND SOFTWARE DESIGN

The groundwater has three submodels: the groundwater flow model, the nitrate transport model, and the denitrification model. In comparison with conventional groundwater flow models that solve for hydraulic heads the heat equation with given initial and boundary conditions, our groundwater flow model is simplified by assuming that flow occurs only in the surficial aquifer (unconfined) and that water table is a subdued replica of the topography. Based on the latter assumption, the shape of water table can be obtained by processing (e.g., smoothing) topography given for example by the digital elevation model data (DEM), which substantially reduces the amount of work required for flow modeling. Therefore, hydraulic gradient can be approximated by the gradient of the smoothed topography, based on which flow velocity is estimated using Darcy’s law. Although this assumption is conditionally valid, it is found reasonable in the working area. Another major assumption is that the Dupuit approximation is valid. In other words, vertical flow can be ignored, and the slope of the water table is equal to the hydraulic gradient. This assumption for two-dimensional flow saves a large amount of memory in our software development. Other assumptions and approximations are as follows: (1) flow conditions are in the steady state; (2) the surficial aquifer does not include karsts or conduits; (3) mounding on water table due to recharge from OSTDS is not considered. These assumptions and approximations reduce the amount of input data to the flow model and the amount of work needed for modeling.

The purpose of the transport model is to estimate the migration of nitrate from septic tanks once it enters the saturated zone. The model is simplified by using an analytical solution to the governing equation for modeling contaminant transport and fate, known as the advection-dispersion equation (ADE) with decay of nitrate through denitrification. The analytical solution used in this model is the general form of the Domenico solution, the three-dimensional transient solution of Martin-Hayden and Robbins (1997), which is based on the work by Domenico and Robbins (1985) and Domenico (1987). Due to constraints regarding execution speed and memory limitations on desktop computers, as well as the inefficient handling of three-dimensional data within GIS, by ignoring transport in the vertical direction, the two dimensional steady-state form of the Domenico solution can be used

$$C\left(x,y\right)=\frac{C_0}{8}F_1\left(x\right)F_2\left(y,x\right), F_1=\exp\left[\frac{x}{2\alpha_x}\left(1-\sqrt{1+\frac{4k\alpha_x}{v}}\right)\right], F_2=erf\left(\frac{y+Y/2}{2\sqrt{\alpha_y x}}\right)-erf\left(\frac{y-Y/2}{2\sqrt{\alpha_y x}}\right) \quad (1)$$

Where $C(x,y)$ [ML^{-3}] is nitrate concentration at location (x,y), α_x and α_y [L] are longitudinal and horizontal transverse dispersivity, respectively, k [T^{-1}] is the first order decay coefficient, v [LT^{-1}] is groundwater seepage velocity in the longitudinal direction, Y [L] is the width of the source plane respectively, C_0 [ML^{-3}] is the source nitrate concentration at the source plane

The denitrification model determines the amount of nitrate removed due to the process of denitrification and determines the nitrate load to the target water body. The denitrification is calculated using first-order dynamics equation, and a mass balance approach is taken in order to calculate the nitrate load, i.e.,

$M_{load} = M_{in} - M_{Rdn}$, where M_{load} [MT^{-1}] is mass load rate to the target waterbody, M_{in} [MT^{-1}] is mass inflow rate from septic systems to the modeling system, and M_{Rdn} [MT^{-1}] is mass removed rate due to denitrification. The mass inflow rate consists of inflow due to advection and dispersion and is evaluated in the same manner of MT3DMS (Zheng and Bennett, 2002). The mass removal rate is estimated via $F_{dn} = \sum_i kC_i V_i \phi_i$, where C_i, V_i, and Φ_i are concentration, volume, and porosity of each cell of the modeling domain, and kC is denitrification rate assuming that denitrification is the first-order kinetic reaction.

The simplified groundwater flow and nitrate transport model was implemented as an extension of ArcGIS using the VB. NET programming language. In keeping with the object oriented paradigm, the code project was structured in a modular fashion with flow module, transport module, and denitrification module. A particle tracking module is added for visualizing flow paths from septic systems to the targeted waterbody. The user friendly GUI elements were kept separate from the model elements, with further modularization within the GUI and model submodules. The main panel of the model GUI (Fig. 1) serves to illustrate some of this modularization. The main component of the window is the tab panel where each tab represents a separate model component. Programmatically, each tab is a self-contained module that has been separated into its own class and is capable of executing individually of the other modules (tabs). The input files are ArcGIS raster (e.g., hydraulic conductivity) or polygon (e.g., waterbody) files that are prepared outside of the developed software but within ArcGIS. Model execution and post-processing (e.g., visualization of flow paths and plumes) are performed within ArcGIS. More details of the model and software development, including verification and validation, are referred to Rios (2010).

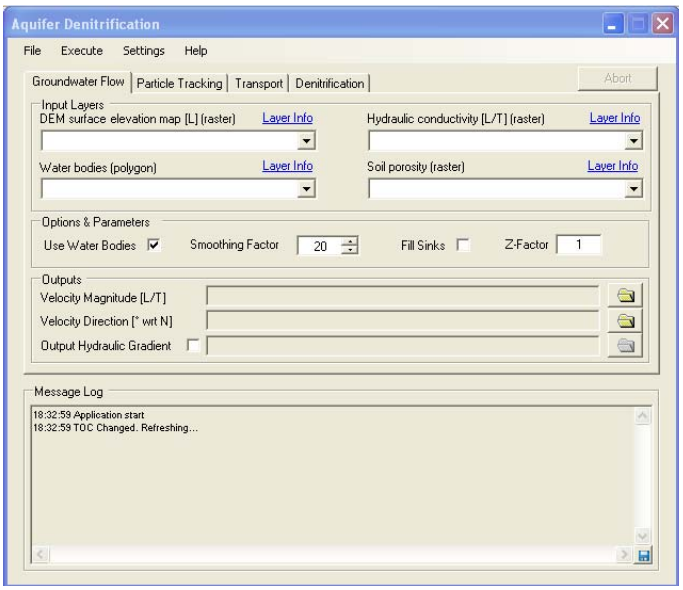

Figure 1. Graphic user interface of the software.

SENSITIVITY ANALYSES AND MODEL CALIBRATION

The conceptual model involves a total of seven parameters: smoothing factor for processing DEM to obtain the shape of water table, hydraulic conductivity, porosity, longitudinal and horizontal transverse dispersivity, first-order decay coefficient, and source nitrate concentration. Both local and global sensitivity analyses were performed to determine the most critical parameters that control the size and concentration within an individual plume. In the local sensitivity analysis, due to the use of the analytical solution (Eq 1), derivatives of concentration to the parameters are estimated directly using the software Mathematica. Although the derivatives to the smoothing factor, hydraulic conductivity, and porosity are not available, sensitivity of these parameters is implicitly obtained from the derivative to groundwater velocity. It was found the sensitivity varies substantially for different parameters and at different locations within the plume. A global sensitivity analysis Morris method (Morris, 1991) analysis was conducted to further identify important parameters in space. Both the local and global sensitivity analyses indicate that the simulated concentration is most sensitive to the first-order decay coefficient, flow velocity, and horizontal transverse dispersivity.

The developed model was calibrated against observations of hydraulic head and concentration obtained from Eggleston Heights (also called Arlington Manor), one of neighborhoods that located within the LSJR basin. By 2008, a total of 3,517 septic tanks had been installed in this area. Part of the neighborhood and

393 out of 3517 septic systems are shown in Figure 2. There were reported high concentrations of nutrients in water samples from the Red Bay Branch, the stream at the right boundary of Figure 2. Nitrogen isotope analyses conformed that the septic systems are the major source of the nitrate in this area and that nitrate contribution from lawn fertilizer is small.

Four monitoring wells (Figure 2) were installed in this area during 2003 to 2004 under the project entitled "Quantification of the Role of Shallow Groundwater Nutrient Enrichment on Exporting Nutrient into the Lower St. Johns River Basin" funded by the St. Johns River Water Management District. Wells AM-MW-1 and AM-MW-4 are adjacent to the Red Bay Branch. A total of 136 observations of water level depth and 143 observations of nitrate concentration from the four monitoring wells were collected during the period from 03/08/2005 to 04/27/2010. Time series of the data for every well are plotted in Fig. 3, in which water level depth were converted into hydraulic head. Despite of fluctuations, the head observations (Fig. 3a) are relatively stable, indicating that it is reasonable to assume steady-state flow for this area. While the concentration observations have more significant fluctuation due to the complex nitrogen transport and transformation mechanism, there is no trend observed. During the model calibration, the means of head and concentration are used as calibration targets. For the nitrate concentration, minimum and maximum as well as lower and upper quartile of the observations were also used to evaluate calibration results. The trial-and-error methods were used by adjusting the most sensitive parameters identified in the sensitivity analyses above. Heterogeneity of hydraulic conductivity and porosity were incorporated in the modeling by using the SSURGO database. The representative values of hydraulic conductivity and porosity were used as the initial values, and hydraulic conductivity was adjusted during the calibration to achieve best goodness-of-fit to the mean observations.

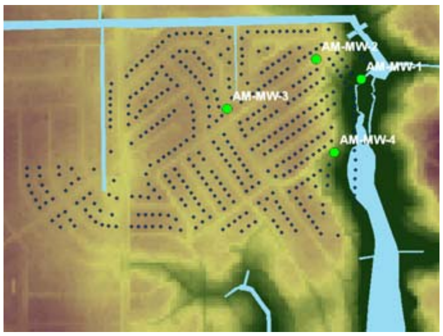

Figure 2. Locations of monitoring wells (green circles) and septic tanks (black).

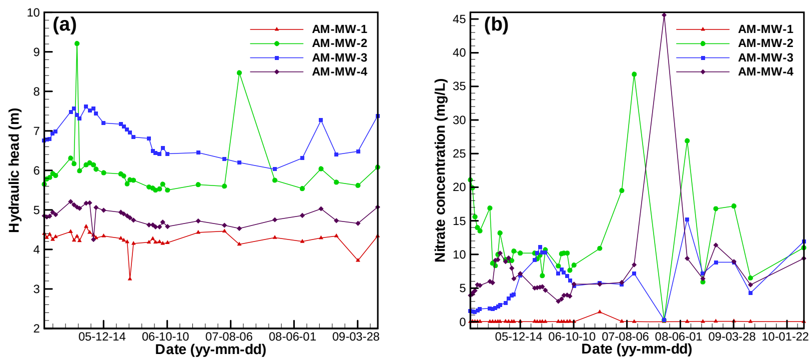

Figure 3. Time series of observations of (a) hydraulic head and (b) nitrate concentration.

Fig. 4 plots the simulated values and mean observations of hydraulic head and nitrate concentration. The smoothed DEM agree well with the mean observed head with a linear correlation coefficient of 0.93 (Fig. 4a). The simulated nitrate concentrations of the four monitoring wells are close to the mean observations and within the inter-quartile of the observed concentrations. The calibrated model was used to estimate nitrate load from 3517 septic systems in the Eggleston Heights

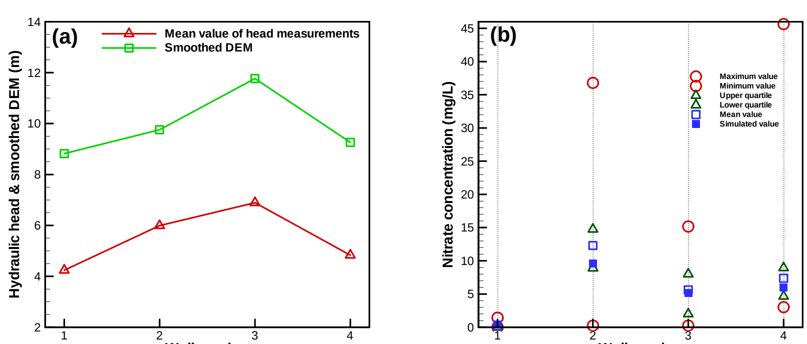

Figure 4. Comparison of simulated values and mean observations of (a) hydraulic head and (b) nitrate concentration.

neighborhood. The estimation results are not shown due to limit of space.

CONCLUSIONS

A simplified groundwater flow and nitrate fate and transport model was developed for estimating nitrate load from septic systems to surface water bodies. The model has three modules for simulating groundwater flow, nitrate transport, and denitrification and nitrate load. Although this model was developed for the estimation in Jacksonville, FL., the model should be applicable to areas with similar hydrogeologic settings. Based on the model, a software was developed as an ArcGIS extension using the VB. NET programming language. The software is easy to use and user friendly; model execution and post-processing are performed within ArcGIS. The model was calibrated against mean field observations of hydraulic head and nitrate concentration. The calibration and prediction results show that the model has the potential to be a useful tool for providing quick estimates of nitrate loads to surface water bodies due to its ease of use and low data requirements. Initial feedback from the FDEP and others involved in subsurface contamination in Florida has been positive. However, it is important to note that due to the simplified nature of this model, results should be taken as a bulk estimate and not an exact prediction.

ACKNOWLEDGEMENT

This work is supported by contract WM956 with the Florida Department Environmental Protection. Help from Rick Hicks, Hal Davis, Tingting Zhao, and Eberhard Roeder is greatly appreciated.

REFERENCES

Domenico, P. A. 1987. An analytical model for multidimensional transport of a decaying contaminant species, Journal of Hydrology, 91, 49–58.

Domenico, P. A. and Robbins, G. A. 1985. A new method of contaminant plume analysis, Ground Water, 23, 4, 476–485.

Hoffman, J. L. and Canace, R. J. 2004. A Recharge Based Nitrate Dilution Model for New Jersey, New Jersey Geological Survey Open File Report OFR 04-1, New Jersey Department of Environmental Protection, Trenton, NJ.

Lee, S., McAvoy, D. C., Szydlik, J., and Schnoor, J. L. 1998. Modeling the fate and transport of household chemicals in septic systems, Ground Water, 36, 1, 123–132.

Leggette, Brashears, and Graham, Inc. 2004, Quantification of the Role of Shallow Groundwater Nutrient Enrichment on Exporting Nutrient into the Lower St. Johns River Basin, Jacksonville, FL.

Martin-Hayden, J. M. and Robbins, G. A. 1997. Plume distortion and apparent attenuation due to concentration averaging in monitoring wells, Ground Water, 35, 2, 339–346.

McCray, J. E. 2009. Modeling Onsite Wastewater Systems at the Watershed Scale: A User's Guide, Water Environment Research Foundation, Alexandria, VA.

Morris, M.D. 1991. Factorial Sampling Plans for Preliminary Computational Experiments, Technometrics, 33(2), 161-174.

Newell, C. J., McLeod, K. R., and Gonzales, J. R. 1996. BIOSCREEN, Natural Attenuation Decision Support System, User's Manual, Version 1.3, EPA/600/R-96-087, U.S. Environmental Protection Agency. Available online at http://www.epa.gov/ada/csmos/models/bioscrn.html.

Rios, J.F. 2010. A GIS-Based Model for Estimating Nitrate Fate and Transport from Septic Systems in Surficial Aquifers, Master Thesis, Florida State University, Tallahassee, FL.

Schecher, W. 1997. Septic Tank Treatment System (SepTTS) Model for Cleaning Product Chemicals, User's Manual, v1.0, The Soap and Detergent Association.

Schilling, K. and Wolter, C. 2007. A GIS-based groundwater travel time model to evaluate stream nitrate concentration reductions from land use change, Environmental Geology, 53, 2, 433–443.

Ye, Z., Maidment, D. R., and McKinney, D.C. 1996. Map-based surface and subsurface flow simulation models: an object-oriented and GIS approach, Center for Research in Water Resources, University of Texas at Austin, CRWR online report 1996-05, Available online at http://hdl.handle.net/2152/6746.

Zheng, C. and Bennett, G.D. 2002. Applied Contaminant Transport Modeling, A John Wiley&Sons, Inc.