Simulation of Nitrogen Transport in Surficial Aquifer and Estimation of Nitrogen Load from Septic Systems in the Indian River Lagoon Area, Florida

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ABSTRACT

Onsite sewage treatment and disposal system (OSTDS) or septic systems, is one of the significant sources of nitrogen in groundwater and surface water, poseing serious threats to human health and the environment. The ArcGIS-based Nitrate Load Estimation Toolkit (ArcNLET) has been used to simulate nitrogen transport and estimate nitrogen load from septic systems to surface waterbodies through the surficial aquifer. It is based on a simplified conceptual model of groundwater flow and nitrogen transport. This study utilizes the ArcNLET tool for the Main-South Canal (MSC) drainage basins of Indian River County (IRC) area which discharge to the Indian River Lagoon (IRL), FL. The purpose of this study is to estimate the nitrogen load from 12,735 septic systems to the IRL and other surface waterbodies in MSC drainage basins. This study found, all the waterbodies (574 in number) including the IRL have been receiving a total nitrogen load of 13,742 lbs/yr. Twenty out of the 574 watebodies receive 50.5% (6,802 lbs/yr) of the total load. Among the 12,735 septic systems, only 358 septic systems contributed nitrogen load directly to the IRL, which is 2.01% (271 lbs/yr) of the total load. It is also found that the estimated ground water load of nitrogen to the southern drainage basin is greater than the estimated septic tank load to the main drainage basin. The estimation of nitrogen load exhibits spatial variability, which is useful to facilitate decisions on the sewering of residential areas served by OSTDS to reduce nitrogen load to the canals and the IRL. The modeling results may change when new data are available for model calibration.

KEYWORDS
ArcNLET; Indian River Lagoon; nitrogen load; septic system; spatial variability.

INTRODUCTION

Nitrite NO_2^-, nitrate NO_3^-, and ammonium NH_4^+ are the common contaminant forms of nitrogen, identified in groundwater and surface water, causing negative impacts on human and environmental health. Nitrate-N higher than 10 mg/L in drinking water may cause methemoglobinemia, also known as blue baby syndrome. Nitrogen transported from groundwater to surface water bodies can lead to fish kills, algal growth, hypoxia, eutrophication, and outbreaks of toxic bacteria (Kumar et al. 2011). Onsite sewage treatment and disposal systems (OSTDS) known as septic systems, are significant sources of nitrogen especially in urban areas (U.S. Environmental Protection Agency (EPA) 1993, 2002). In the state of Florida, nearly one-third of households use septic systems (Hazen and Sawyer 2009). The combined Main-South Canal (MSC) drainage basin of Indian River County (IRC) area, which discharges to the Indian River Lagoon (IRL), are considered to be impaired due to excessive loads of nitrogen (Gao and Rhew, 2012). Almost 35~40% of the MSC drainage area is characterized as urban land (Gao and Rhew, 2012) and much of this area is served by septic systems. Understanding the magnitude of nitrogen loadings from the septic systems to the canal system and IRL in this area via groundwater discharge is important for restoration planning purposes.

An Arc-GIS based Nitrate Load Estimation Toolkit (ArcNLET) model has been established by Rios et al. (2013) to focus on nitrate transport and loads at small scale with point sources such as septic systems. Two important benefits of the use of ArcNLET as an estimating tool are that: (1) it can provide useful results with smaller datasets, without compromising the estimating accuracy and (2) it can be constructed by moderately skilled technical users within a reasonable timeframe (Rios et al., 2013). ArcNLET includes a simple conceptual groundwater model to estimate the groundwater hydrologic process, and uses analytical equations to describe nitrate transport with site-specific septic systems. This model has been successfully applied to estimate nitrate load from thousands of septic systems to surface water bodies in several neighborhoods of the Lower St. Johns River Basin (LSJRB) in Florida, USA (Wang et al., 2013) as well as many other less complex scenarios. With the above mentioned advantages, ArcNLET is ideally suited to estimate nitrogen transport in the MSC drainage basins area.

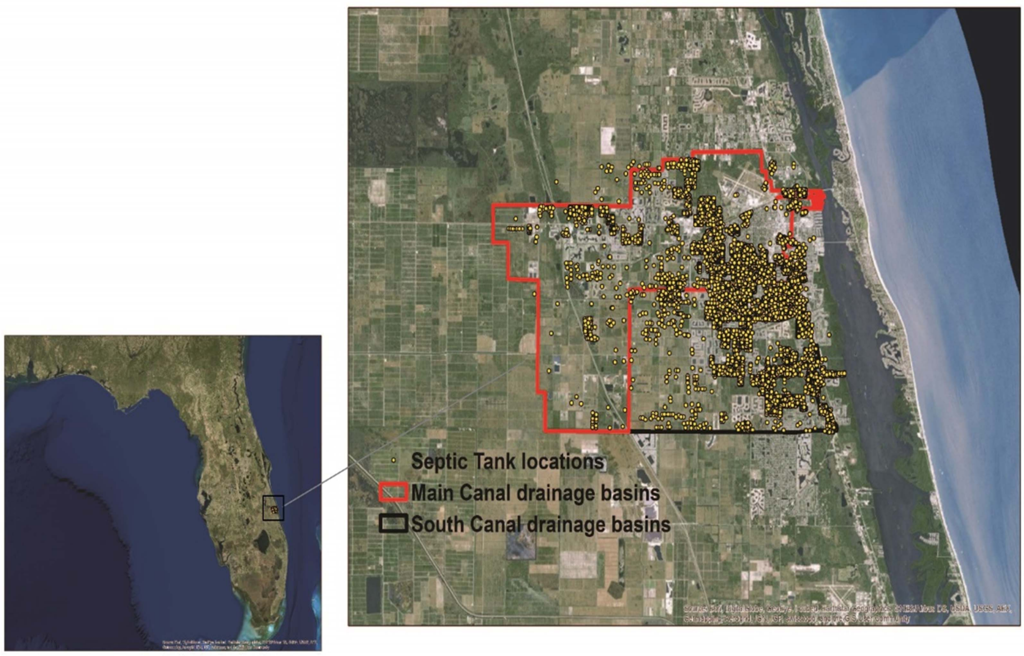

Figure 1. Locations of septic systems (yellow dot) in the modeling area, the MSC drainage basins.

MODELLING AREA AND INPUT DATA

Figure 1 shows the MSC drainage basins area of IRC and the locations of the septic systems. Septic system locations are provided by IRC. ArcNLET is used to estimate nitrate load from septic systems to surface water bodies in MSC drainage basins in IRC, which identified as impaired (Gao and Rhew, 2012). The targeted surface water bodies of nitrate load include rivers, creeks, lakes, ponds, ditches/canals, swamps, and reservoirs. Figure 2 shows the datasets of this modeling. Figure 2a shows the locations of the surface waterbodies (river, lake, pond, swamp/marsh etc) downloaded from the NHD website (http://nhd.usgs.gov/) and ditch/canal data provided by IRC. Figure 2b shows the LiDAR elevation data downloaded from the SJRWMD (http://www.sjrwmd.com/gisdevelopment/docs/themes. html). The resolution of this LiDAR data is 5ft × 5ft, thus it can well capture details of the topography. Figure 2c and Figure 2d show the heterogeneous porosity and hydraulic conductivity values, respectively, which were obtained from the Soil Survey Geographic database (SSURGO) database. For groundwater flow calibration, five monitoring wells datasets of the ground water level (GWL) at the area of interests were collected from the SJRWMD website (http://webapub.sjrwmd.com/agws10/hdsnew/map.html). For the transport parameters calibration (dispersivities, denitrification coefficient), nitrogen ground water quality datasets were obtained from the Florida Department of Environmental Protection's Storage and Retrieval (STORET) data base.

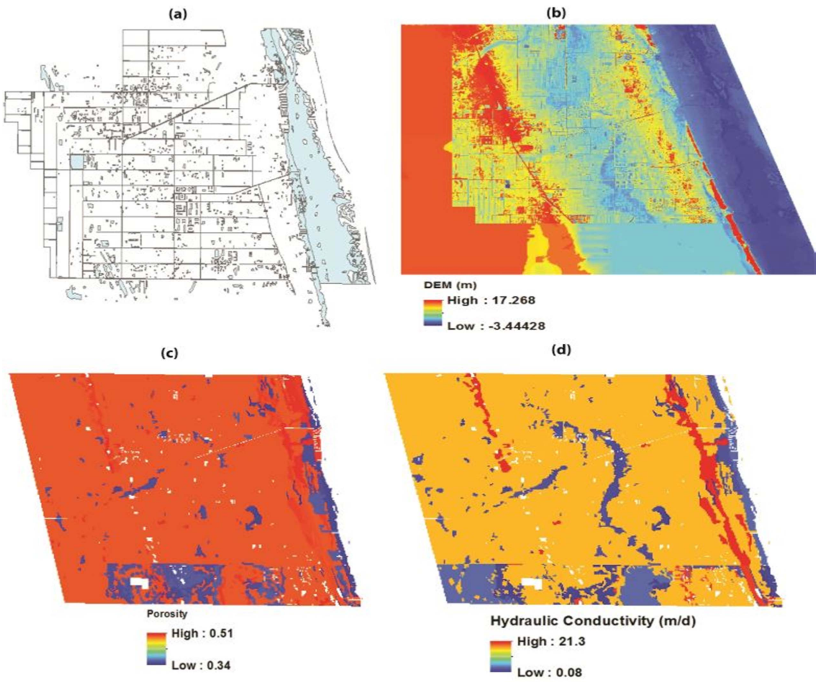

Figure 2. Modeling datasets of (a) surface water bodies, (b) digital elevation model (DEM), (c) heterogeneous porosity, and (d) heterogeneous hydraulic conductivity of the modeling domain.

ARCNLET: FLOW, TRANSPORT AND LOAD ESTIMATION MODEL

ArcNLET is composed of three submodels: the groundwater flow model, the nitrate transport model, and the denitrification/load estimation model.

The ArcNLET flow model generates a map of ground water flow velocity (direction and magnitude) using a minimal amount of data by making several simplifications. The simplifying assumptions made in the flow model are: (1) the water table assumed to be subdued replica of the topography, (2) the steady state flow conditions, (3) only saturated flow in porous media is considered, (4) flow occurs under Dupuit conditions, and (5) 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. Details of this modeling can be found in Rios et al. (2013).

The transport model of ArcNLET estimates the nitrate concentration distribution from septic tanks once it enters groundwater. The model is simplified by using an analytical solution of the governing equation for modelling contaminant transport and fate, known as the advection-dispersion equation (ADE) with decay of nitrate through denitrification. ArcNLET adopts a two-dimensional, steady-state version of the full Domenico solution. These results in significant memory saving, accelerated computational speed, and reduced amount of input data demands. Detailed description of this modeling can be found in Rios et al. (2013).

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. Details of this model can be found in Rios et al. (2013).

RESULTS AND DISCUSSION

Results of Groundwater Flow Modeling
With the data and information described above, the ArcNLET groundwater flow module and particle tracking module were executed. The flow model provides magnitude and direction of seepage velocity (Darcy velocity divided by porosity) at the individual raster cells in the modeling domain. They are used in the particle tracking module to evaluate flow paths from individual septic systems to receiving waterbodies of particles placed at the septic system locations. Smoothing factor is an important parameter specific to ArcNLET and is used to smooth the topography to generate the shape of the water table. The parameter is site specific and strongly correlated to site topography. It affects the magnitude of the flow velocity, and ranges to be 40–120 based on the reference of Wang et al. (2013). In this study, the calibrated smoothed DEM is obtained using the smoothing factor of 65, i.e., the smoothing (through spatial average) is performed 65 times for the entire modelling domain. Figure 3a represents the shape of the water table (GWL) and the elevation of the smoothed topography (S65). Figure 3b shows that the smoothed DEM data agree well with the observed water table with a linear correlation coefficient of 0.90 and the slope of the linear regression close to 1.0. So even the smoothed DEM is higher than the real water table, the hydraulic gradient can be approximated by the smoothed DEM, and it can be used to calculate the velocity.

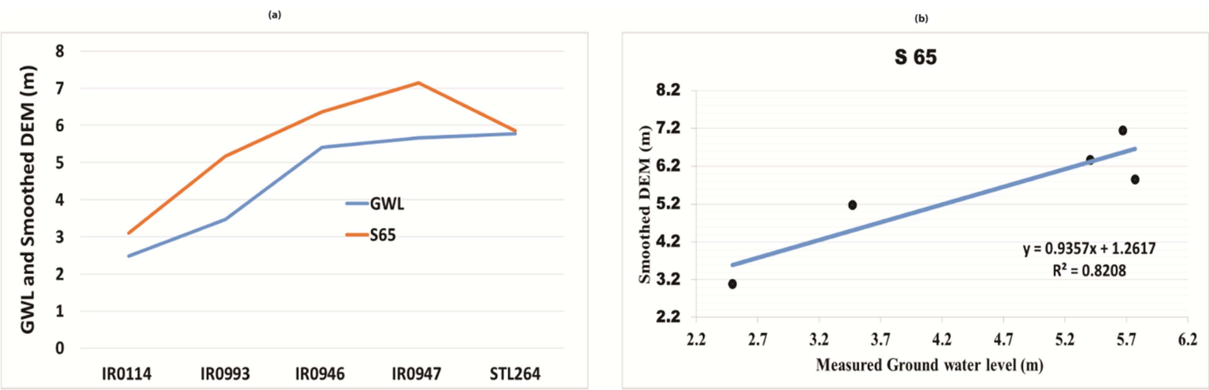

Figure 3. (a) Similarity of the shape of water table and the smoothed DEM, and (b) the correlation of the measured water table with the smoothed DEM at the five monitoring wells.

Results of Nitrogen Transport Modelling

The transport model calibration was conducted prior to using the transport module of ArcNLET. Data from three monitoring wells were provided by FDEP and used in this modelling to calibrate the transport parameters (denitrification, longitudinal and transverse dispersivity). Figures 4a through 4c represent the monitoring well (black circles) and the extent of nitrogen plumes. Figure 4d shows the simulated and measured nitrogen concentration for three sets of parameters. Calibration 3 represents the highest coefficient correlation 0.94, thus longitudinal dispersivity = 1m, transverse dispersivity = 0.10m and denitrification = 0.00055 day^{-1} was selected. ArcNLET transport module was executed using those parametric values. The simulated nitrogen plumes in the model domain are plotted in Figure 5. Waterbodies in Main Canal and South Canal receive 2,063 and 4,046 lbs/yr of nitrogen, respectively and have 5,343 and 7,392 contributing septic tanks, respectively. Generally speaking, the South Canal drainage area receives a higher load of nitrogen from septic systems than the Main Canal drainage area. The South Canal receives 1.21 lbs/yr/septic tank while the Main Canal receives 0.85 lbs/yr/septic tank. The 20 surface water (canal and pond) segments that receive the highest loads from septic systems and the spatial locations of the segments are shown in Figure 6a and Figure 6b, respectively. The 20 segments with the highest loads received a total of 6,802 lbs/yr from septic systems, which is 50.5% of total loads and from 22% of contributing septic tanks. Out of the 20 segments receiving the highest loads, 16 contributed to the South Canal basin and 4 contributed to the Main Canal basin. Understanding the relative contributions of nitrogen from septic tanks to these segments may help in planning decisions to address the areas of highest priority for reducing nitrogen load to surface water bodies.

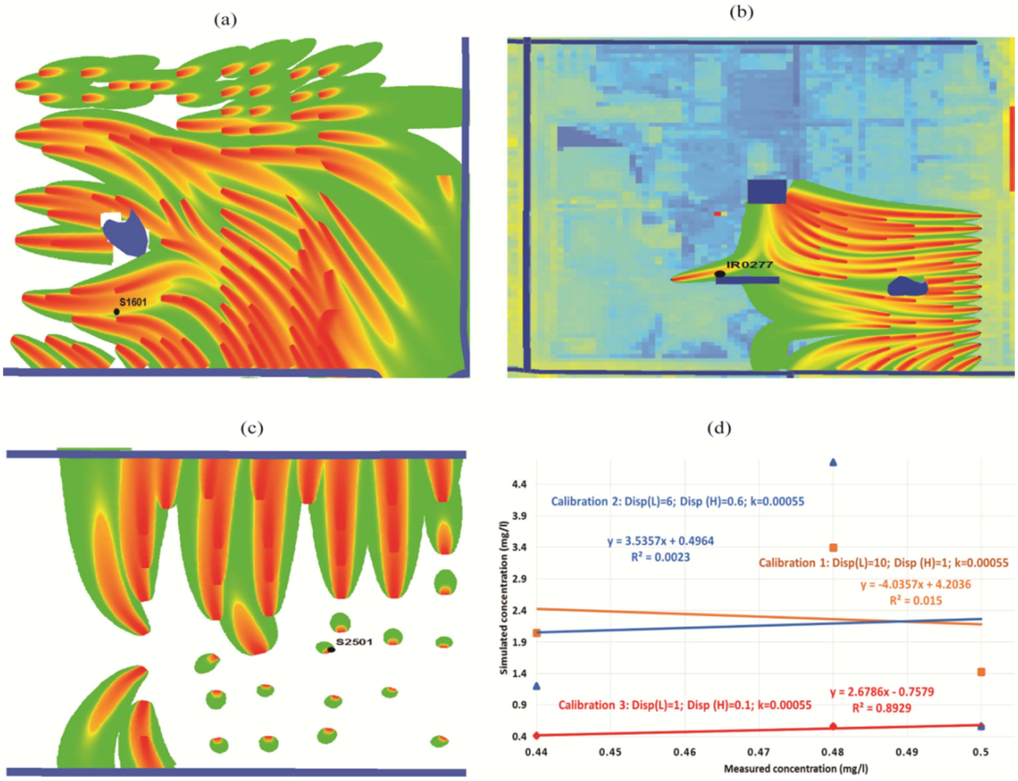

Figure 4. (a) Well S1601 situated in between plumes, (b) Well IR0277 is in the range of one septic systems, (c) Well S2501is in the vicinity of one stations, and (d) correlation of the simulated and measured nitrogen concentration (mg/l).

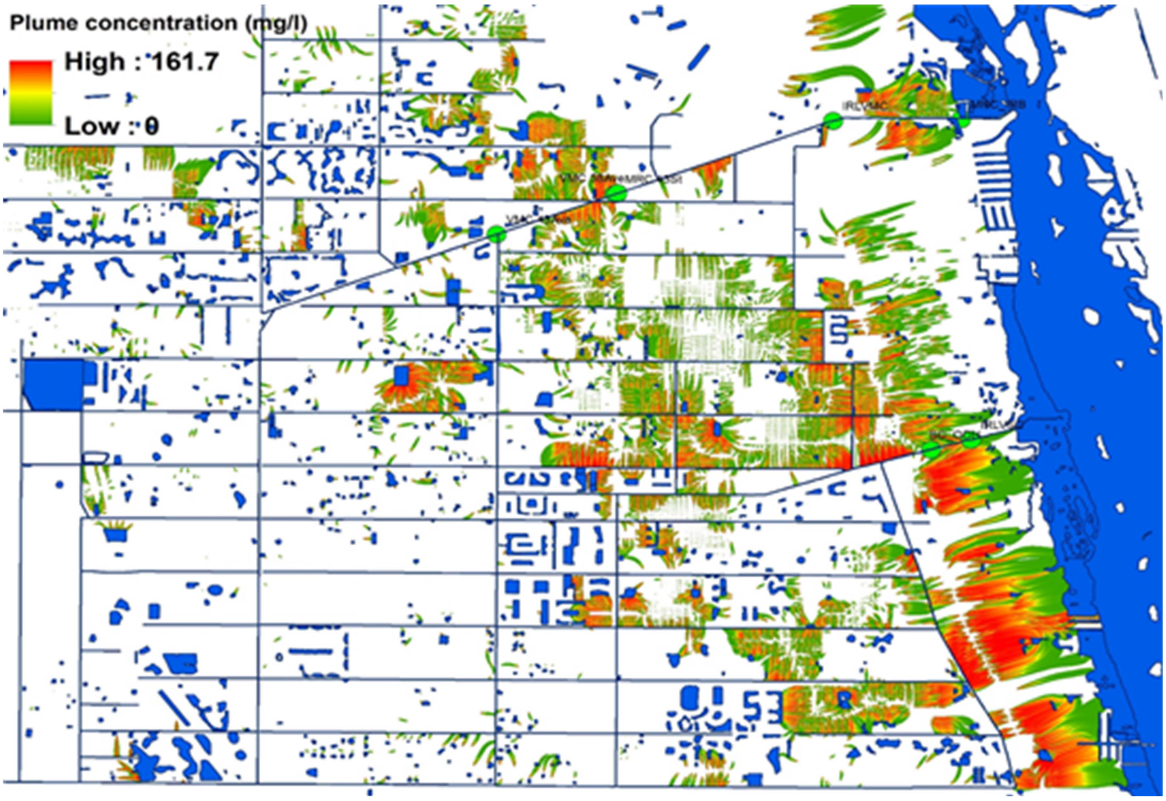

Figure 5. Simulated nitrogen plumes from the septic systems in the SMC drainage basins of IRC.

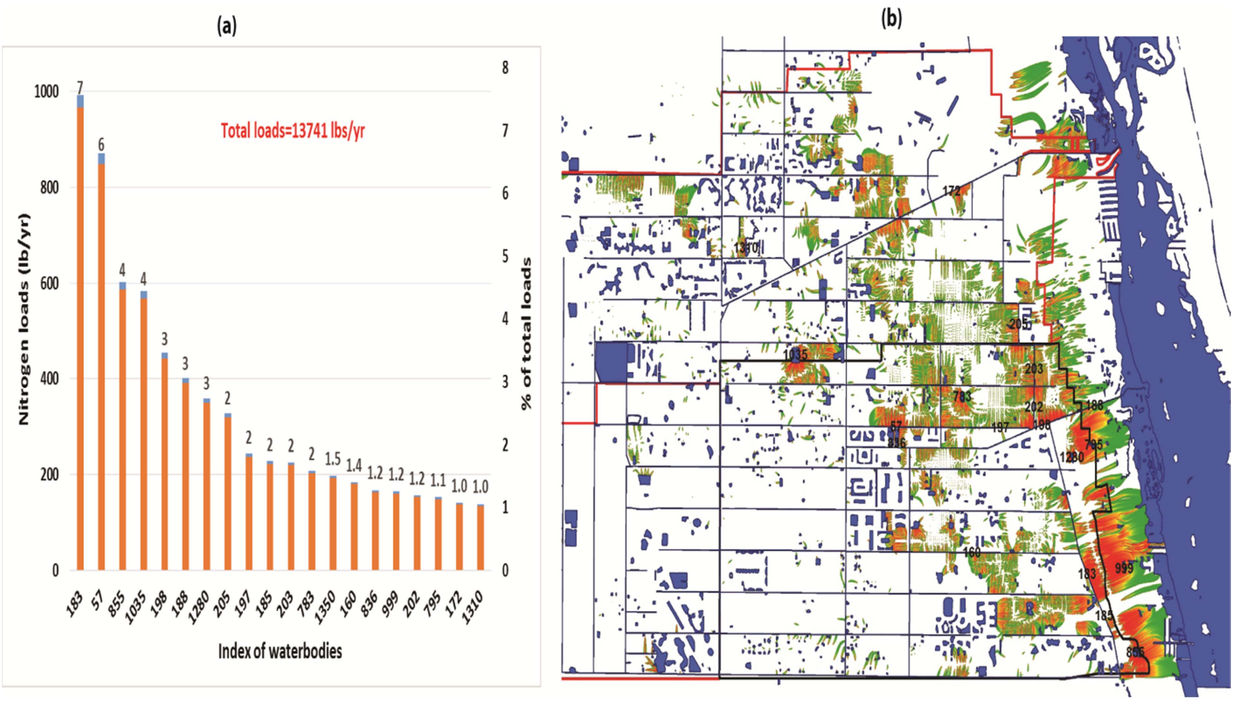

Figure 6. The highest 20 loadings of receiving waterbodies: (a) magnitude of the highest nitrogen loads (lbs/yr) with the index of waterbodies, and (b) locations of the waterbodies (marked in blank) receiving the highest 20 loadings.

Controlling factors of load estimate:

The two controlling physical factors affecting the ArcNLET-modeled load from septic systems to surface water are the length of ground water flow paths and the flow velocity. The length of flow paths is important, because shorter flow paths from septic systems to the receiving waterbody result in greater loads and longer flow paths result in smaller loads due to the amount of denitrification occurring along the pathway. Similarly, higher flow velocities allow for less residence time for denitrification than do lower velocities. Figure 7 shows this relationship for the Main Canal and South Canal drainage basins. Therefore, in the management of nitrogen pollution, it is important to consider spatial variability of the distance between septic systems and surface water bodies as implemented in ArcNLET.

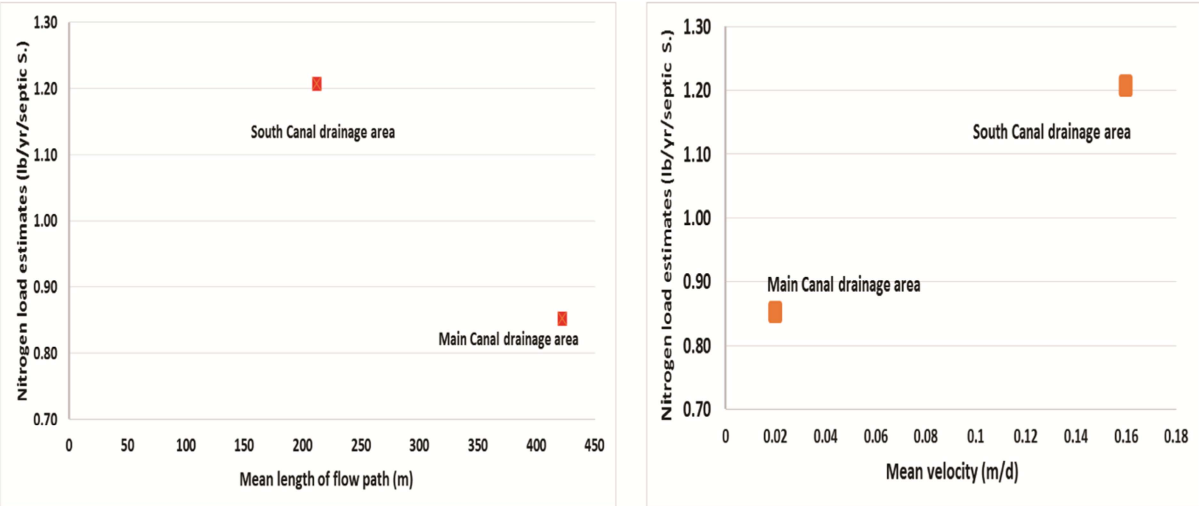

Figure 7. Variation of nitrogen load estimate per septic systems in the south canal and main canal drainage basins with (a) mean lengths of flow path and (b) mean seepage velocity.

CONCLUSIONS

This study utilizes ArcNLET to estimate nitrogen load from septic systems to surface water bodies in Main South Canal (MSC) drainage basins of Indian River County, Florida. A total 13,742 lbs/yr nitrogen is contributed by septic systems to the 574 surface water segments modeled in this study area, which includes canals, ponds and part of the IRL. Among the 12,735 septic systems, only 358 septic systems contributed nitrogen load directly to the IRL, which is 2.01% (271 lbs/yr) of the total load. The South Canal drainage basin receives a higher load of nitrogen from septic systems than the Main Canal drainage basin, with the difference in load received being related with the mean lengths of ground water flow path from septic tank sources to receiving waters and the mean ground water velocities. Differences of mean velocity within these two areas are related to the ground water gradients within the areas and soil drainage conditions. Nitrogen concentrations in the surface water in these two basins are elevated and is of concern in the IRL. Thus these estimations of nitrogen loadings from the septic systems will provide useful information to local governments and water managers in the area who are involved in implementing restoration actions.

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