MODELING NITROGEN IN ON-SITE WASTEWATER TREATMENT SYSTEMS

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Abstract. State regulatory agencies set standards for minimum lot size for homes on onsite wastewater treatment systems (OWTS) based on the expected nitrogen (N) load to groundwater. However, the data to support these standards are sparse. In a recent field study on a clay soil, we developed a two-dimensional model for N treatment. Our objective was to use this model to predict the N treatment for 12 soil textural classes using two years of weather data from the field experiment. We found that soil texture had a strong effect on OWTS performance. Denitrification losses varied widely among soils, from 1% in the sand class to 75% in the sandy clay class. This was due to the effect of water content on denitrification. Leaching losses to groundwater ranged from 27% in the sandy clay class to 97% in the sand class. It was important to consider differences in recharge among soil textural classes in estimating the minimum lot size to protect groundwater. The lot sizes ranged from 0.26 to 1.13 ha and were largest for medium-textured soils where denitrification and recharge were intermediate.

INTRODUCTION

Drainfield trenches in OWTS are used to distribute septic tank effluent and allow it to infiltrate into the soil. An OWTS can experience hydraulic failure if the effluent loading rate exceeds the infiltration capacity of the soil. Radcliffe and West (2009) proposed dividing soil textural classes into four groups with the design hydraulic loading rate (HLR_D) ranging from 1 to 4 cm d^{-1} based on simulations using a two-dimensional HYDRUS model (Šimůnek et al., 2006). OWTS can experience water quality failure if N concentrations in effluent leaching to groundwater are sufficiently high to cause groundwater concentrations of nitrate (NO_3^-) to exceed drinking water standards (10 mg L^{-1} NO_3^--N). State regulatory agencies have developed minimum lot size recommendations for OWTS based on estimates of N leaching to groundwater (Frimpter et al., 1990; GDPH, 2012; Hantzsche and Finnemore, 1992; NJOSP, 1988). However, estimates of the amount of NO_3^- leaching to groundwater are highly variable (Gold et al., 1990; Cogger and Carlile, 1984).

Recently, we calibrated a two-dimensional HYDRUS model using measured soil pressure head and vadose zone N data from a conventional OWTS installed in a clay soil in the Piedmont region of Georgia (Bradshaw and Radcliffe, 2013). A N chain model with water-content dependent first-order transformation rates for nitrification and denitrification was developed (Bradshaw et al., 2013). The predicted soil pressure heads and solute concentrations were similar to data collected from the field experiment over a two-year period. Our objective was to use this model to predict how well soils of different textural classes would treat N using the two years of weather data from earlier experiment.

METHODS

The OWTS model was developed using HYDRUS version 2.01 (Šimůnek et al., 2011). It is a finite element model that uses a numerical solution to the Richards (1931) equation to simulate variably saturated water flow in soil. We used the van Genuchten (1980) equations for the relationship between soil volumetric water content and pressure head and the unsaturated hydraulic conductivity function. The parameters for these equations for twelve soil textural classes were taken from the HYDRUS database. The OWTS models were run for 740 days using the precipitation and temperature data from 1 April 2009 to 10 April 2011 in the field experiment described by Bradshaw and Radcliffe (2013).

Solute transport in HYDRUS is described by a numerical solution to the advection-dispersion equation (ADE). It was assumed that longitudinal and transverse dispersivities were 15 and 0.5 cm, respectively, based on the calibrated model of Bradshaw et al. (2013). Soil temperature was simulated based on the heat flow equation using default soil heat transport parameters in HYDRUS for a clay, loam, or sand, depending on the soil textural class being modeled.

The OWTS model space consisted of a trench and the surrounding soil with one axis vertical and the other horizontal (Fig. 1). One half of the drainfield was used for the model space assuming the middle of the trench was an axis of symmetry. The model space was 125 cm in the horizontal dimension. This placed the right boundary approximately at the midpoint between two trenches, and assumed trenches were centered at 2.5 m which is the recommended spacing for a conventional OWTS in Georgia. The model space was 150 cm in the vertical direction with the trench bottom placed 72 cm below the soil surface, the depth of the trench bottom in the field experiment of

Bradshaw and Radcliffe (2013) and a typical installation depth for the Georgia Piedmont region. The soil surface formed the top of the model space. The trench was 45 cm in width (half of a full trench) and 30 cm in height.

Table 1. Hydraulic group, design hydraulic load, dose rate, and saturated hydraulic conductivity (K_s) for 12 soil textural classes.

Textural class	Group†	HLR_D† cm d^{-1}	Dose cm d^{-1}	K_s cm d^{-1}
Silt	I	5.40	4	43.74
Sand	I	5.16	4	642.98
Silt loam	I	4.71	4	18.26
Loamy sand	I	4.44	4	105.12
Sandy loam	II	3.31	3	38.25
Silty clay loam	II	2.97	3	11.11
Loam	II	2.79	3	12.04
Sandy clay loam	III	2.08	2	13.19
Clay	III	2.02	2	14.75
Clay loam	III	2.00	2	8.18
Silty clay	III	1.91	2	9.61
Sandy clay	IV	1.48	1	11.35

†From Radcliffe and West (2009).

The model space consisted of three materials representing the soil, trench gravel, and a 2-cm thick biomat at the trench-soil-interface on the bottom and sidewall (Fig. 1). The soil for each model run consisted of one of the 12 textural classes in Table 1. The soil was divided into an upper section from 0 to 90 cm and a lower section from 90 to 150 cm. The only difference between the upper and lower sections was the maximum denitrification rate (discussed later).The boundary condition at the soil surface for water flow was a system-dependent "atmospheric" boundary condition that simulates infiltration and evaporation. The boundary condition at the bottom of the model space represented a deep water table with a unit vertical hydraulic head gradient (gravity flow). The perforated pipe semi-circle was a variable flow boundary condition where effluent entered the model space in three daily doses every eight hours over a half-hour period (using shorter dosing periods made it difficult for the numerical model to converge). The rate was chosen so that the effluent dose, expressed as a volume of effluent per area of trench bottom, was 4, 3, 2, or 1 cm d^{-1}, depending on the soil group category (I, II, III, or IV, respectively) (Table 1).

We used a two-solute N chain model consisting of NH_4^+ and NO_3^-. We assumed all the N in the effluent from the septic tank was in the form of NH_4^+. The transformation of NH_4^+ to NO_3^- (nitrification) was modeled as a single step, first-order reaction. Denitrification was modeled as a first-order reaction loss of NO_3.The values for rate nitrification and denitrifcation rate constants were set at 0.045 and 0.01 h^{-1}, respectively, except in the lower soil horizon which was assigned a denitrification rate of 0.001 h^{-1} to reflect the limiting effect of lower carbon levels deeper in the soil profile. All of these values were based on the calibrated model of Bradshaw et al. (2013).

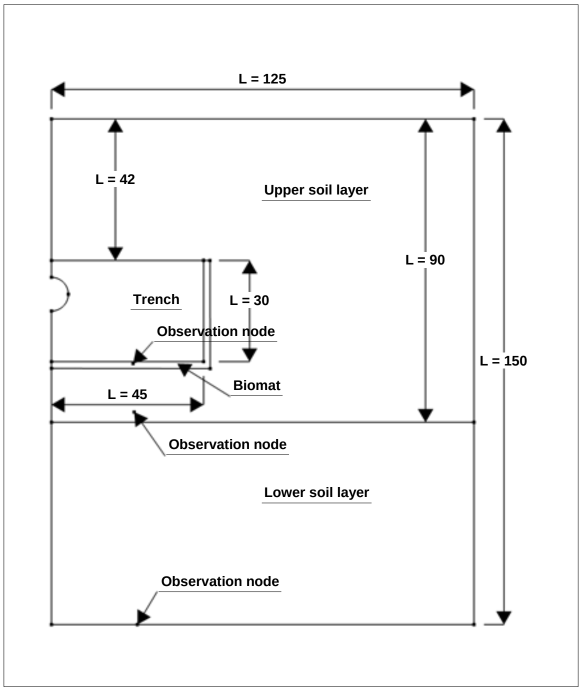

Figure 1. Model space.

HYDRUS incorporates temperature dependence of reaction rates using a modified form of the Arrhenius equation where the user specifies activation energies for a particular reaction. We used functions specially coded into HYDRUS for saturation dependency of reaction rates. These equations are described in detail in Bradshaw et al. (2013).

We assumed that NH_4^+ sorption was linear. McCray et al. (2010) reviewed the literature for wastewater NH_4^+ sorption coefficients. They found that the values could be separated into two groups: for soils with clay contents <30%, a median $K_d = 0.35$ cm^3 g^{-1} and for soils with clay contents >30%, a median $K_d = 1.46$ cm^3 g^{-1}. We used this grouping for our study.

We assumed all the N entering the drainfield from the septic tank was in the form of NH_4^+. We used the average total N concentration in the septic tank effluent over the two-year experiment from Bradshaw and Radcliffe (2013), 47.4 mg L^{-1}, for the concentration in the dose.

To get the initial conditions for N concentrations that would represent a mature OWTS, we first ran the model in a "warm up" mode for the two years of weather data. Using the simulations from the second run, we calculated a N mass balance by tallying the total N that entered the profile via the perforated drain boundary, exited the profile via the bottom boundary, was taken up by roots, was lost through denitrification, and the change in storage within the profile.

As part of the minimum lot size calculation, estimates of the annual groundwater recharge rate (as a percent of annual rainfall) from the lot area that did not contain the OWS drainfield was needed. To get this estimate, each of the soil textural class models were run without any OWTS effluent or trench, keeping all other variables the same.

RESULTS AND DISCUSSION

The simulated pressure heads from the observation node 15 cm below the trench are shown in Fig. 2 for the different soil textural classes. The average pressure head for the simulation period is shown in parentheses in the legend and the soil textural classes are listed in order from high to low pressure heads. Pressure heads became less negative as the soils progressed from Group I to Group IV soils. The Group IV soil, sandy clay, was the wettest soil with an average pressure head of -7 cm. All of the Group III soils had similar pressure heads with averages ranging from -15 to -18. The Group I soils had the most negative pressure heads with averages ranging from -38 to -152 cm. Pressure heads rose with rainfall events and were higher in the winter. This was especially evident in the silt and silt loam soils.

The N mass balance for each soil class based on the two-year simulation of a mature OWTS is shown in Fig. 3. The soil textural classes are listed from left-to-right in the order of decreasing HLR_D (Table 1) progressing from Group I to Group IV soils. The mass balance was good in that the residual was less 2% for all classes. There was a wide range in leaching losses (27-97%) and denitrification losses (1-75%), but plant uptake (1-4%) and change in storage (0-2%) were small and in a narrow range. The small change in storage indicated that the OWTS had indeed reached a mature state after the first two-year cycle. For the most part, leaching losses decreased and the denitrification losses increased from left to right in the order of decreasing HLR_D and progressing from Group I to IV soils. Since decreasing HLR_D is associated with less negative pressure heads below the trench (Fig. 2), the Group I and II soils were dryer than the Group III and IV soils and the pressure heads were in the range that denitrification was inhibited. Since plant uptake was low, this resulted in most of the N being leached from the profile (as NO_3^-). However, HLR_D did not explain the entire pattern.

In Georgia, county health departments have the authority to set minimum lot sizes for homes with OWTS to prevent NO_3^- contamination of groundwater. The Georgia OWTS manual (GDPH, 2012) uses an equation to estimate the NO_3^- concentration in groundwater recharge from a home lot that can be written as follows:

$$n_r = \frac{V_w}{V_w + V_r}(1-d)n_w \qquad [1]$$

where n_r is the NO_3^--N concentration in mg L^{-1} in the recharge water, n_w is the total N concentration in the OWTS effluent, V_w is the wastewater discharge rate in L d^{-1},V_r is the background groundwater (effluent-free) recharge rate in L d^{-1}, and d is the fraction of OWTS N that is lost to denitrification. V_r is the product of the lot area (cm^2) and the groundwater recharge rate (cm d^{-1}). The manual assumes that each bedroom generates 568 L d^{-1} (150 gal d^{-1}), the wastewater total N concentration (n_w) is 60 mg L^{-1}, and denitrification results in a loss of 50% of the effluent total N. Annual rainfall in Georgia is approximately 127 cm and the manual assumes that one half of this total becomes recharge. With these assumptions, the manual recommends a minimum lot size of 0.41 ha (1 acre) for a 4-bedroom home because the estimated groundwater recharge NO_3^--N concentration using Eq. [10] is 7.4 mg L^{-1} and less than the drinking water standard of 10 mg L^{-1}.

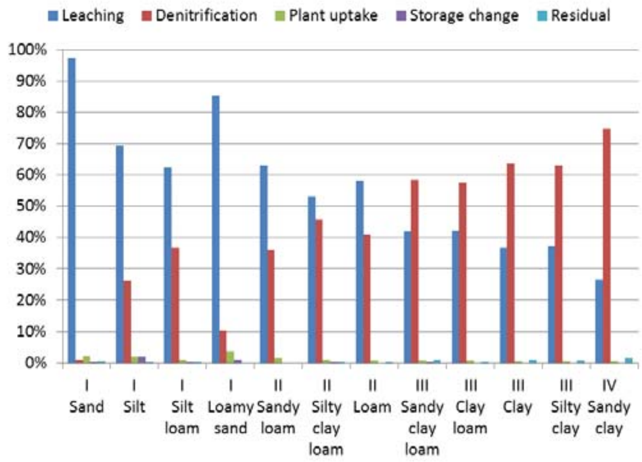

Figure 3. Nitrogen mass balance for the various soil textural classes in the two-year simulation for a mature OWTS.

We used Eq. [1] to calculate the minimum lot size for a 4-bedroom home for each soil textural class that would result in a recharge concentration (n_r) of 10 mg L^{-1}. We assumed the same total N concentration for wastewater (60 mg L^{-1}) and discharge rate per bedroom (568 L d^{-1}) as the Georgia OWTS manual, but used the denitrification loss percentages that we found in the simulations (Fig. 3). We used two estimates of the groundwater recharge rate: 1) 50% of annual rainfall as in the OWTS manual and 2) the percentage of rainfall found in the recharge simulations for each soil textural class where the models were run without any input of OWTS wastewater. We used the average annual rainfall from the experiment by Bradshaw and Radcliffe (2012), 122 cm.

The minimum lot sizes are shown in Table 3. Using the first method, lot sizes ranged from 0.07 to 0.65 ha. Lot size decreased steadily from Group I to Group IV soils as the simulated denitrification percentage increased. The recommended minimum lot size of 0.41 ha in the Georgia OWTS manual was a reasonable estimate for all soil classes except the sand and loamy sand. Using the second method where differences in recharge rates among soil textural classes were considered resulted in higher values for the minimum lot size (ranging from 0.26 to 1.13 ha) and the pattern among soil groups was more complicated. Recharge percentages were highly variable and ranged from 13 to 44%. The highest recharge percentages occurred in the Group I soils with high K_s. The high recharge rates in this group offset the low denitrification rates in some cases so that the minimum lot size was similar to the Group III and IV soils. The largest lot sizes occurred in the medium-texture Group II soils where recharge and denitrification percentages were intermediate. Using the second method of calculating the minimum lot size, the Georgia OWTS manual recommendation is too low for all soils except the sandy clay and clay classes. This analysis shows the importance of accounting for differences among soil textural classes in recharge as well as denitrification.

CONCLUSIONS

Our simulations showed that N treatment varied widely among the soil textural classes with denitrification losses that ranged from 1 to 75% and leaching losses that ranged from 26 to 97% of the total N input. The HLR_D grouping was a good predictor of N treatment in that the sandy Group I soils had the lowest denitrification (and highest leaching) losses and the Group IV clayey soils had the highest denitrification (and lowest leaching) losses. The primary reason for the denitrification differences was the difference in hydraulic performance and its effect on denitrification. Plant uptake and sorption accounted for 4% or less of the N input.

Minimum lot sizes designed to prevent groundwater concentrations of NO_3^--N above 10 mg L^{-1} varied widely among the soil textural classes, ranging from 0.26 to 1.13 ha, and were higher for most soil classes than the minimum lot size recommended in Georgia (0.41 ha). Our simulations showed that it was important to consider the effect of soil texture on recharge as well as denitrification and that the loamy textured soils had the largest lot size requirement.

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Table 2.Minimum lot size for 12 soil textural classes calculated in two ways: 1) assuming that recharge is 50% of rainfall and 2) using recharge percentage of rainfall from model simulations. Model recharge percentage and denitrification percentage are also shown.

Textural class	Group	Minimum Lot Size		Model Recharge	Model Denitrification
		50% Rainfall ha	Model Rainfall ha	%	%
Sand	I	0.65	0.74	44	1
Silt	I	0.45	0.54	42	26
Silt loam	I	0.37	0.68	27	37
Loamy sand	I	0.58	1.13	26	9
Sandy loam	II	0.38	0.98	19	35
Silty clay loam	II	0.30	0.74	20	46
Loam	II	0.33	0.85	20	41
Sandy clay loam	III	0.19	0.56	17	60
Clay loam	III	0.20	0.68	14	59
Clay	III	0.14	0.41	17	66
Silty clay	III	0.13	0.51	13	66
Sandy clay	IV	0.07	0.26	13	75

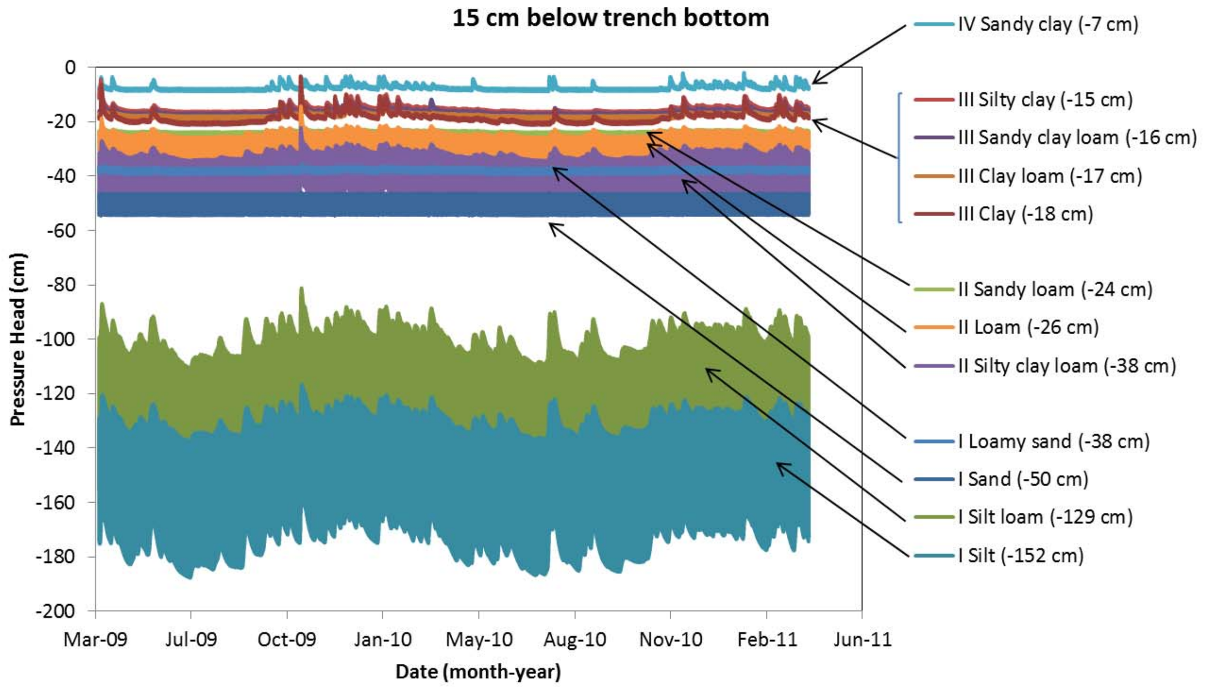

Figure 2. Soil pressure heads at the observation node 15 cm below the trench for the various soil textural classes.