A NITROGEN MODEL FOR ONSITE WASTEWATER SYSTEMS

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Abstract. A constructed wetland two-dimensional model developed by Langergraber and Simunek (2005) was adapted to onsite wastewater systems (OWS). The model is an optional module in the HYDRUS (2D3D) variably saturated flow model. It predicts the fate and transport of nitrogen (N) species in the drainage trench and surrounding soil of an OWS. It is a multi-component reactive transport model that simulates 12 components and 9 processes. Concentrations of ammonium, nitrite, nitrate (NO_3), nitrogen gas (N_2), dissolved oxygen (DO), and three forms of organic matter are predicted. The model simulations showed that conditions are dynamic in an OWS as water levels in the trench respond to daily dosing, precipitation, and evapotranspiration. The simulations indicated that NO_3 losses occurred during dryer periods when DO concentrations were high enough in the trench for ammonium conversion to NO_3, and outside the trench the high DO concentrations slowed denitrification, especially in the dryer area to the side of the trench. Predictions of NO_3 losses compared well with an experimental OWS at Griffin, GA.

INTRODUCTION

Most nutrient total maximum daily loads (TMDLs) in watersheds that include suburban areas attribute part of the non-point source N load to OWSs (e.g. Georgia DNR, 2009). However, the exact contribution from these systems is unknown because the extent to which denitrification (the conversion of NO_3 to nitrite and N_2) reduces the load has not been documented. In a review of the literature on modeling of OWSs, Mcray et al. (2008) concluded that the biggest question in modeling N in OWSs was under what conditions and to what extent does denitrification occur.

Most of the N models for OWSs that have been developed are simple models designed to predict the NO_3 concentration in groundwater. These models typically specify a denitrification rate (Hantzsche and Finnemore, 1992) or assume there is no loss due to denitrification (Eichner et al., 1992; Frimpter et al., 1990; NJOSP, 1988; and Taylor, 2003).

Only a few studies have measured the losses of N from OWSs or shown conclusively that N from OWSs is, or is not, contributing to groundwater N levels. Gold et al. (1990) measured NO_3 concentrations in samplers 1 m be-

low OWS trenches in New England. The average NO_3 concentration was 68 mg L^{-1} and the annual NO_3 load was 47.5 kg ha^{-1}. They estimated that 21% of the N was removed in OWSs. Postma et al. (1992) measured NO_3 in shallow groundwater wells installed 2-6 m from OWS trenches in shore-side homes in New England and found concentrations often exceeded 30-40 mg L^{-1} in the summer.

Soil moisture conditions in the drainage field of OWSs are dynamic and within the range near saturation where ammonification (the conversion of organic N to ammonium), nitrification (the conversion of ammonium to nitrate) and denitrification are possible. Systems commonly use dosing which results in short-term alternating wet and dry periods. Seasonal changes in precipitation and evapotranspiration cause long-term wet and dry periods.

This type of system may require a more complex model capable of simulating soil processes. An example is the HYDRUS (2D/3D) model developed by Šimůnek et al. (2006). HYDRUS is a finite element numerical model capable of simulating saturated and unsaturated water flow, solute transport, and heat flow in soil in two and three dimensions. Langergraber and Šimůnek (2005) developed a microbial growth module for HYDRUS (2D/3D) to simulate N fate and transport in constructed wetlands.

Our objective was to adapt the constructed wetlands module for OWSs and calibrate the model using data from an OWS experiment in Griffin, Georgia. In the future, we will use the HYDRUS model to modify simple N models for OWSs.

MATERIALS AND METHODS

The wetland module consists of a reactive transport model that simulates 13 components:
- DO;
- three pools or organic matter: readily biodegradable (ROM), slowly biodegradable (SOM), and inert (IOM);
- four forms of N: ammonium (NH_4), nitrite (NO_2) , NO_3, and N_2 gas;
- three groups of bacteria: heterotrophic bacteria responsible for hydrolysis, aerobic metabolism, and anoxic metabolism; autotrophic *Nitrosomonas* re-

sponsible for producing NO_2 autotrophic *Nitrobacter* responsible for producing NO_3;
- inorganic phosphorus (IP); and
- a tracer of choice.

Hydrolysis (the conversion by enzymes of SOM into ROM and a small fraction into IOM and the release of NH_4) takes place independent of the oxygen condition. Aerobic metabolism consumes DO, ROM, and NH_4. Anoxic metabolism uses ROM, NO_3, and NO_2 and produces N_2 (denitrification). Adsorption is included for NH_4 and IP. Autotrophic bacteria are strictly aerobic in the model.

In the wetland module, the reaction rate for a given process is a sum of the products of the stoichiometric factors and the reaction rates for the components. The zero order reaction rate for denitrification is a function of the maximum denitrification rate; the Michaelis-Menten equation saturation/inhibition coefficients for DO, NO_3, NO_2, ROM, NH_4, and inorganic P; and the concentrations of DO, NO_3, NO_2, ROM, NH_4^+, IP, and heterotrophic bacteria. The exchange of oxygen from the gas phase to the aqueous phase is a function of the oxygen re-aeration rate (h^{-1}).

The wetland model was developed to simulate a subsurface constructed wetland used in Austria where domestic wastewater infiltrates vertically through a sand bed. It was based on an activated sludge model and contains over 50 parameters. The model space consisted of a single stage or double stage configuration of infiltration beds. In the single stage configuration, the bed was one m in width and 60 cm deep with a 10-cm layer of gravel at the bottom above a drain. The surface was an "atmospheric" boundary condition modified to allow ponding and the bottom was a seepage boundary condition.

We adapted the model to simulate N fate and transport in a conventional OWS installed at the Ellis Road Research Farm in Griffin, GA. This system is described by Bradshaw and Radcliffe (2011). Briefly, the system consisted of a septic tank connected to a drainfield consisting of three 10-m long trenches, 2.5 m apart from center-to-center. Piezometers were installed in the trenches to record water levels. Tensiometers were installed near each trench to monitor the pressure head of soil water in the drainfield. Suction lysimeters were installed beneath and adjacent to trenches to collect soil water for chemical analysis. Each trench was dosed three times per day at the design loading rate of 2.5 cm d^{-1}.

The model space consisted of a two-dimensional region with the soil surface at the top extending to a depth of 150 cm below the surface (Figure 1). Symmetrical flow was assumed on either side of the trench so that the left side of the model space coincided with the centerline of the trench and perforated pipe. The space extended 125 cm in the horizontal direction so that the right side coincided with the midpoint between the trenches. The trench bottom was positioned 72 cm below the surface to conform to the experimental site average depth. The trench width (half the actual width) was 45 cm and the height was 30 cm. The 10-cm perforated pipe was positioned 47 cm below the soil surface. The finite element mesh was designed to place most of the nodes in and around the trench where water entered from the perforated pipe and near the soil surface where precipitation and evapotranspiration took place. Observation nodes were placed at the bottom of the trench and 15 cm below and to the side of the trench (Figure 1).
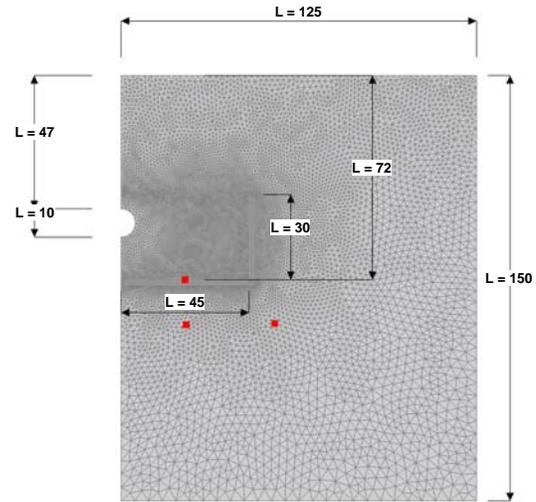
Figure 1. Model space for the HYDRUS (2D/3D) simulation. Dimensions are in cm. The space is a vertical cross-section with the soil surface at the top and the centerline of the trench on the left boundary. Observation nodes (red squares) were placed at the bottom of the trench and 15 cm below and to the side of the trench.

Six different regions were included in the model space with different hydraulic (and potentially chemical) properties:
- gravel within the trench,
- 1-cm thick biomat layer on the bottom and side of the trench,
- Ap horizon extending from the soil surface to a depth of 10 cm,
- Bt1 horizon between the depths of 10 and 70 cm,
- Bt2 horizon between the depths of 70 and 80 cm, and
- BC horizon between the depths of 80 and 150 cm.

Soil water retention and hydraulic conductivity were described in the model using the van Genuchten (1980) equations. The soil hydraulic parameters in these equations include:
- θ_s (cm^3 cm^{-3}), saturated volumetric water content,
- θ_r (cm^3 cm^{-3}), residual volumetric water content,

- α (cm^{-1}), a fitting parameter,
- n (-), a fitting parameter, and
- K_s (cm h^{-1}), the saturated hydraulic conductivity.

The soil hydraulic parameters for each region in the model are shown in Table 1. The parameters were based on measurements of water retention on soil cores and borehole measurements of K_s from the site. These were used as initial estimates and then α, n, and K_s were adjusted manually in simulations by comparing the predicted pressure heads to those observed in automated tensiometers.

The boundary conditions for water flow were zero flux on the vertical boundaries except for the perforated pipe where a variable flux condition was used that represented the daily dosing (three times per day at 8-hour intervals). The boundary condition on the bottom of the model space was a "free drainage" or unit gradient condition (pressure head gradient of zero). At the soil surface, an "atmospheric" boundary condition was used that simulated precipitation, runoff, infiltration, and evaporation. Daily precipitation and pan evaporation data for Griffin, GA were obtained from the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net). Plant uptake of water was simulated for a grass cover with roots extending to a depth of 100 cm (N. Hill, Crop and Soil Sciences Dept., UGA, personal communications).

The boundary condition for solutes at the perforated pipe was that concentrations during the dose would be NH$_4$-N = 60, NO$_3$-N = 0.1, NO$_2$-N = 0.1, ROM = 160, SOM = 120, IOM = 20, DO = 1, and Cl = 42 mg L^{-1} based on measurements at the septic tank outlet. The boundary condition for solutes at the soil surface was that all concentrations were zero in precipitation except for DO which was 8 mg L^{-1}.

It was assumed that NH$_4$ sorption was linear with an adsorption coefficient of 3.5 cm^3 g^{-1} for soil based on batch sorption measurements on samples from the site. It was also assumed that no sorption occurred within the gravel-filled trench. None of the values of the 50-plus parameters in the wetland module were modified in our simulations, except for the initial values of microbial populations and solute transport dispersivity. We adjusted the initial populations so that they were near the steady-state simulated values. We also adjusted dispersivity based on the observed Cl distribution (Bradshaw and Radcliffe, 2011).

The simulation was run for 2000 hours from April 1, 2009 when dosing began until July 22, 2009.

RESULTS AND DISCUSSION

In Figure 2, the predicted pressure heads are compared to the observed values during the first 2000 hours after dosing began. An inset shows that the simulated pressure heads responded to the tri-daily dosing regime.

Trench piezometers indicated that water was ponding in the trench. The simulated values also showed ponding, but predicted that between doses the pressure head became negative during periods with low rainfall. Pressure heads measured with tensiometers 15 cm directly below the trench were near zero for most of the period and those measured to the side and below the trench were generally in the range of 0 to -50 cm. The simulated pressure heads agreed reasonably well with the observed values during wet periods, but were too negative during dry periods.
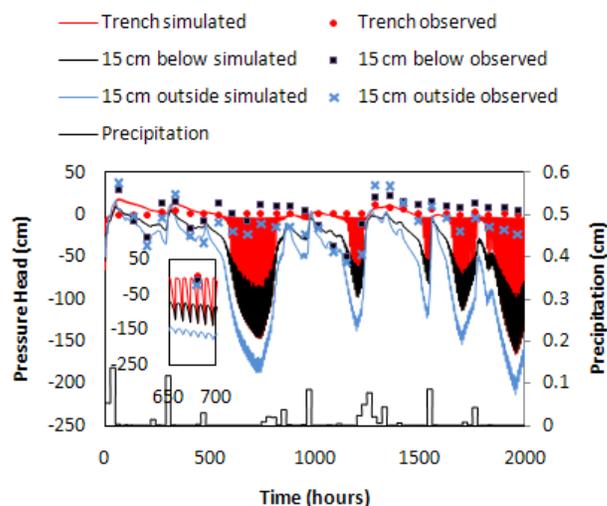
Figure 2. Simulated and observed pressure heads (left vertical axis) at the three observation nodes shown in Fig. 1 during the first 2000 hours after dosing began. Precipitation is shown on the right vertical axis. In an inset, oscillations in the simulated pressure heads are apparent over a short time interval (650-700 h).

Various outputs from the model simulations are shown in Figure 3 on day 1848 as contour plots. On this day (June 16, 77 days after dosing began), Cl concentrations were high throughout the model space indicating that the OWS effluent had time to move to the deepest depths and up near the soil surface.

Readily degradable organic matter was highest in the trench, but present in areas farther away from the trench (Figure 3). This seemed to indicate that ROM had been transported throughout the model space but consumed in areas closer to the trench (by high populations of heterotrophic bacteria). Slow degradable organic matter was also highest in the trench, but absent in areas farther away from the trench.

Ammonium was confined to a small area just below the trench (Figure 3). This indicated that ROM and SOM were converted to NH$_4$ within the trench and that NH$_4$ movement outside of the trench was limited due to sorption outside the trench and conversion to NO$_3$. The high NH$_4$ concentration below the trench may have been due to

the fact that this was the area was wettest most of the time and redox conditions were unfavorable for conversion to NO_3.

Nitrate concentrations were highest at the lower corner and to the side of the trench (with a small area just above the trench; Figure 3). Concentrations were as high

Cl (mg L^{-1})   ROM (mg L^{-1})   SOM (mg L^{-1})

NH$_4$ (mg L^{-1})   NO$_3$ (mg L^{-1})   DO (mg L^{-1})
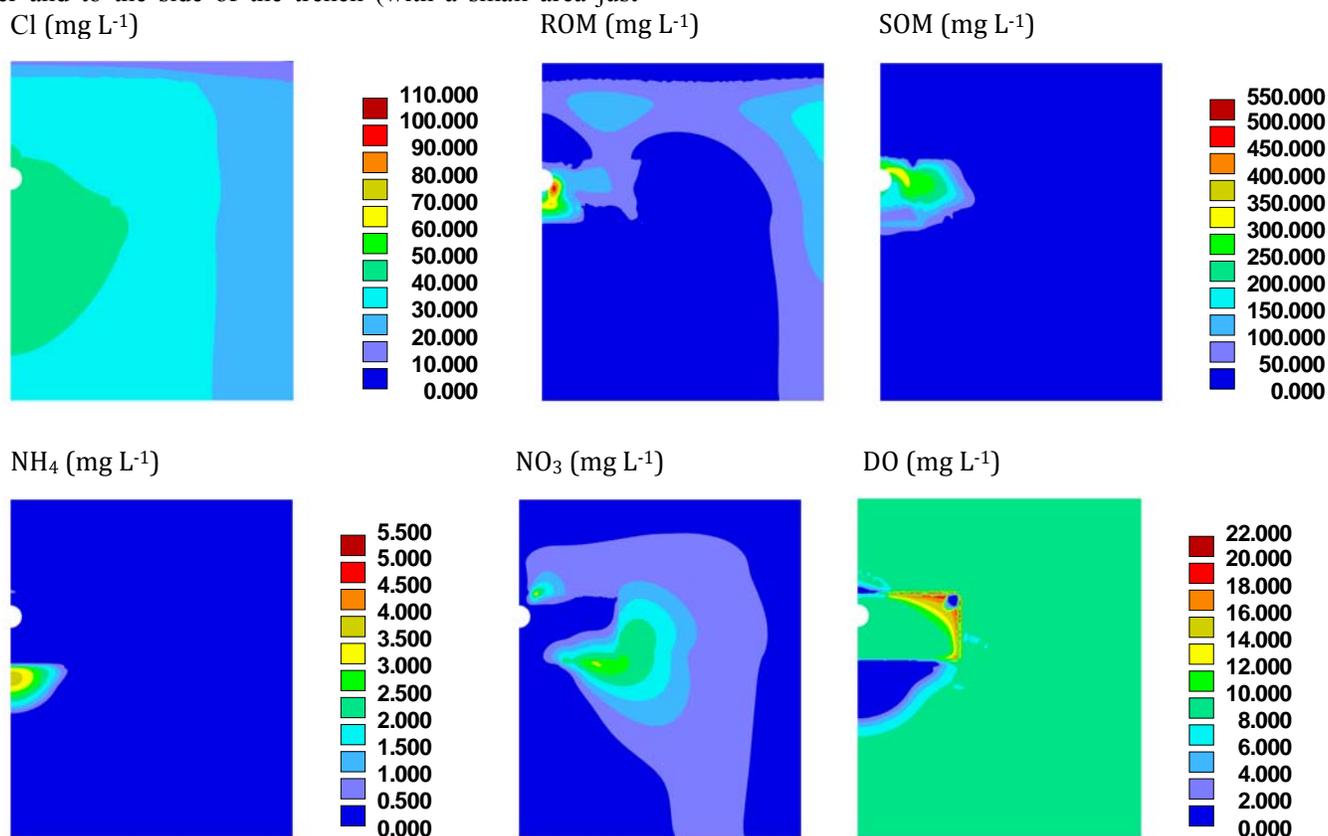
Figure 3. Simulated output after 1848 hours in the model space (see Figure 2 for dimensions). Top row left to right: Cl, ROM, and SOM concentrations in mg L^{-1}. Bottom row left to right: , NH$_4$, NO$_3$, and DO concentrations in mg L^{-1}. The applicable scale bars are to the right of each graph.

as 12 mg L^{-1} within the plume. As shown in the simulated and observed pressure heads (Figure 2), the area to the side of the trench was dryer than the area immediately below the trench. The plume extended to the lower boundary of the model space indicating NO_3 loses to deeper depths.

Dissolved oxygen was lowest immediately below the trench (Figure 3). This area coincided with the area where high concentrations of NH$_4$ were simulated. In the upper left corner of the trench there was an area of very high DO (20 mg L^{-1}). There is no simulated process to generate DO in this system other than reaeration and that process should not cause DO to exceed the saturation concentration of 9.18 mg L^{-1}. Therefore, the area of high DO may indicate numerical instabilities and require shorter time steps (a maximum time step of 0.01 h was used in these simulations).

Time series graphs of the NO_3 concentrations at the three observations nodes (at the bottom of the trench, 15 cm below the trench, and 15 cm below and to the side of the trench) for the 2000 hours of simulation are shown in Figure 4. Concentrations at the node at the bottom of the trench were the most dynamic. The concentrations were near zero during four intervals that corresponded to the first four of five "wet" intervals (when pressure heads were positive) at this node in Figure 2. The last wet interval was the shortest and had little effect on the NO$_3$ concentrations. In the first three "dry" intervals (when pressure heads were negative), NO_3 concentrations were in the 2-5 mg L^{-1} and in the fourth interval they increased to the 4-12 mg L^{-1} range. Within the dry intervals, concentrations declined during each dose and rose between doses indicating that nitrification occurred at the bottom of the trench as it drained between each dose. The decline during the doses could have been due to dilution

due to the dose input or denitrification during the dose when water levels rose in the trench. The absence of NO_3 during the wet periods indicated that nitrification did not occur when water failed to drain from the trench between doses.

Nitrate concentrations at the node 15 cm below the trench were the lowest of the three observation nodes (Figure 4). They did not show a response to daily dosing but did show a similar response to wet and dry periods. Nitrate concentrations at the node below and to the side of the trench did not show a response to dosing but they increased steadily with each dry interval until they were nearly as high as the concentrations at the node at the trench bottom. These results indicated that during the dryer periods, NO_3 escaped from the trench area. This was probably because DO concentrations were high enough in the trench for NH_4 to be converted to NO_3, and outside the trench the high DO concentrations slowed denitrification, especially in the dryer area to the side of the trench.
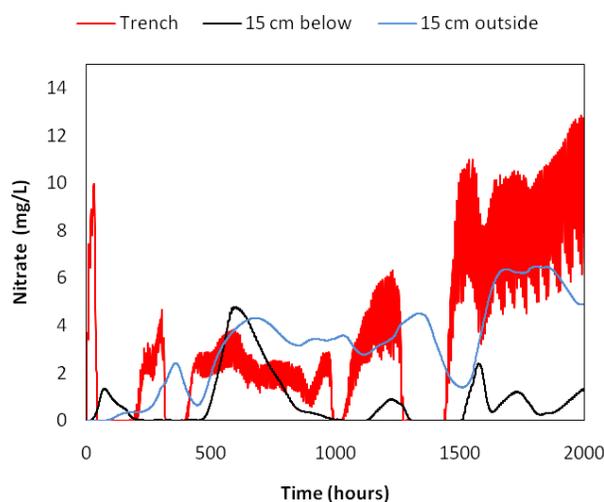
Figure 4. Simulated NO_3 concentrations at the 3 observation nodes shown in Figure 1 during the first 2000 hours after dosing began.

The model simulations produced nitrate concentrations that were similar to those observed at the field site after 3 months (Bradshaw and Radcliffe, 2011). The estimated loss below the drain field in the experiment after one year was 1.86 kg ha^{-1}. The model simulations predicted a loss of 0.45 kg ha^{-1} after 2000 hours so this may be on track to predict a similar loss after one year.

CONCLUSIONS

The contribution of OWSs in nutrient TMDLs is largely unknown due the lack of information on denitrification in these systems. Our model simulations showed that moisture conditions were dynamic in and surrounding an OWS trench as water levels in the trench responded to daily dosing as well as precipitation and evapotranspiration. These conditions, combined with the high levels of organic matter and nutrients in the effluent, make it very difficult to predict NO_3 losses using a simple model with a constant denitrification rate. The simulations indicated that NO_3 losses occurred during dryer periods when DO concentrations were high enough in the trench for NH_4 conversion to NO_3, and outside the trench the high DO concentrations slowed denitrification, especially in the dryer area to the side of the trench.

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