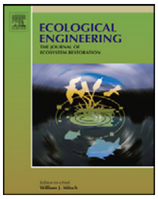
Ecological Engineering 53 (2013) 228–234

Contents lists available at SciVerse ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Numerical assisted assessment of vadose-zone nitrogen transport under a soil moisture controlled wastewater SDI dispersal system in a Vertisol

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ARTICLE INFO

Article history:
Received 11 July 2012
Received in revised form 25 October 2012
Accepted 3 December 2012
Available online 27 December 2012

Keywords:
Decentralized
HYDRUS
Irrigation
Soil moisture
Vertisols
Wastewater

ABSTRACT

A real-time soil moisture controlled wastewater SDI dispersal system was tested in a Vertisol for approximately one year to regulate soil nitrogen from an artificially prepared septic effluent. The control strategy was to allow wastewater hydraulic disposal only when the drain field moisture level was near field capacity. Due to limited field sampling and resulting uncertainty in rate of field nitrification/denitrification, numerical simulation (HYDRUS 2D) was utilized to assess system control over nitrogen concentrations in the drain field. Using nitrification/denitrification rates estimated from cumulative frequency distributions (CFD), simulated drain field moisture levels were found statistically lower than actual field observations over the entire year, suggesting persistent drain field soil swelling which is theoretically favorable to denitrification. Short- and long-term simulations suggest that denitrification level should be 50% higher than 50% CFD (first-order reaction, 0.042 day^{-1}). Although no conclusive results are presented, this study indicates a potential management approach that favors denitrification by regulating nitrogen application using soil moisture. Further study is required to optimize soil moisture to increase wastewater hydraulic disposal while restricting nitrogen concentrations within the managed soil horizon.

1. Introduction

Conventional septic systems, one category of onsite wastewater systems (OWS), consisting of a septic tank and a gravity fed effluent dispersal field (drain field), are of international significance due to their ease of installation and widespread adoption (Liehr et al., 2004; Ho, 2005; Moelants et al., 2008). However, soils with high or very low percolation rate are generally considered unsuitable for this technology (Spicer, 2002; US EPA, 2002).

Vertisols are expansive clay soils that not only form deep cracks during dry seasons (Amidu and Dunbar, 2007; Kishne et al., 2009), but also swell to effectively close soil pores during wet weather conditions (Bouma and Loveday, 1987; Weaver et al., 2005). These features technically make Vertisols generally undesirable for conventional septic systems. The challenge is that unregulated hydraulic disposal can result in nutrient leaching and surface runoff (US EPA, 2002). Nevertheless, there is a need to utilize Vertisols as wastewater disposal drain fields (He et al., 2011a). Therefore, if a hydraulic disposal strategy can be modified to adapt for seasonally changing site conditions, adverse effects previously mentioned might be mitigated (Dabach et al., 2012).

Scheduling irrigation based on field moisture conditions has been shown effective for agriculture due to its effective control of water and nutrient percolation losses and surface runoffs (Phene et al., 1992; Muñoz-Carpena et al., 2003; Meron et al., 1996; Dukes and Scholberg, 2005; Duan and Fedler, 2009; Dabach et al., 2012). With an intention to provide an alternative septic effluent disposal strategy for conventional septic systems, this agricultural concept was adapted in this study to be used together with subsurface drip irrigation (SDI) that can potentially provide an uniformed wastewater distribution throughout drain fields (Jnad et al., 2001), and a properly managed cropping systems that can potentially provide an increased field evapotranspiration (ET) and a reduced drainage loss of dosed water (Askegaard and Eriksen, 2008; Wang et al., 2008). The hydraulic disposal strategy used in the present study allowed wastewater disposal only when the drain field moisture level was near field capacity, a working point theoretically favorable for both nitrification and denitrification (Linn and Doran, 1984).

This hydraulic disposal strategy was tested at pilot scale in a Vertisol for approximately one-year period using an artificially prepared septic effluent (He et al., 2011b, 2012). The hydraulic dosing pump was controlled by real-time drain field moisture levels.

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http://dx.doi.org/10.1016/j.ecoleng.2012.12.048

Water balance analysis of field tests indicate that water percolation might have occurred during summer months (He et al., 2011b) and that nitrate (NO_3-N) leaching could be a long-term environmental concern at the site (He et al., 2012). However, due to limited experiment duration, conclusive system assessment was not provided.

HYDRUS 2D is a PC based modeling environment for analysis of water flow and solute transport in variably saturated/unsaturated porous media (Šimůnek et al., 1999). This program has been utilized successfully in assessing water and nitrogen movement in non-clay soils (Beggs et al., 2004, 2011; Radcliffe and West, 2009). Because HYDRUS 2D also has features that provide modeling of irrigation and drainage it was used to assess system control over soil nitrogen fate and transport in lieu of cost consuming field studies. Thus, the focus of this paper was to assess the short- and long-term fate of applied nitrogen under a soil moisture controlled wastewater disposal strategy.

2. Materials and methods

2.1. Field experiment

The experimental site was at the Alabama Black Belt Research and Extension Center in Marion Junction, Dallas County, Alabama. Five soil horizons were identified to a depth of 1.52 m, all indicating increasing clay content over by depth (Table 1). The field capacities (1/3 bar, SSSA, 2002) of the soil cores sampled at the 46 cm depth of the experimental site ranged between 0.37 and 0.44 $m^3 m^{-3}$ with a field uniformity of 96.9% per the Christiansen uniformity coefficient (Soil Conservation Service, 1970).

The experimental system consisted of 60 drip tubes (Geoflow, CA) of 27-m long installed at approximately 20–25 cm deep. The drip tube lateral distance was set to 61 cm. Two capacitance type volumetric soil moisture sensors (Delta-T, UK) were buried at two depths (20 cm and 46 cm) at one location in the middle of the site for control of the SDI wastewater dosing pump. A data logger/controller (Delta-T, UK) was programmed to record data from the following instruments every 15-min: two soil moisture sensors, one soil temperature sensor buried at 20 cm with the soil moisture sensors, one tipping bucket rain gauge, and one inline vortex flow meter on the main water line from the SDI dosing pump. Soil moisture ($m^3 m^{-3}$) thresholds used for wastewater dosing pump on/off control were set at 0.40 or below (on) and 0.45 or above (off). The SDI dosing pump was initiated for a 5-min period every 55 min when hydraulic dosing was allowed. The septic effluent was made up of clean well water spiked with fertilizer solution to obtain a nitrogen strength of 80 mg N L^{-1} in the form of urea ($(NH_2)_2CO$). Organic carbon level was measured at approximately 100 mg TOC (total organic carbon) L^{-1}.

2.2. HYDRUS simulation

The HYDRUS 2D (version 1.06) simulation domain used was a rectangular soil profile (61 cm wide and 100–500 cm deep depending on each simulation scenario) representing the cross-sectional space between two emitters on adjacent drip laterals (Fig. 1). Emitter facings were represented by two 16 mm semi-circles 20 cm deep at the side boundaries. Each emitter was set with a time variable flux representing daily wastewater applications. The upper boundary was set as a time-variable atmospheric surface associated with daily ET and precipitation. The bottom boundary was set to permit free drainage. The side boundaries, excluding emitters, were set to exclude lateral flux. Two hypothetical observation points were placed at the 20 cm and 46 cm depths in the middle of the modeling space in order to compare with field observed soil moisture data. Two additional hypothetical observation points were placed at the 46 cm and 100 cm depths directly beneath one emitter to monitor the soil water percolation and soil water nitrogen content change over time. Soil hydraulic parameters used for the simulation domain are listed in Table 1. Root mass (dimensionless) was simulated as linearly decreasing over the 100 cm depth. The root water uptake model for forage was used as the predefined HYDRUS 2D routine. The simulation domain was first simulated for field capacity by allowing the simulation domain to drain freely from saturation. Soil domain moisture content was found approximately 0.40 $m^3 m^{-3}$ when “substantial drainage” stopped. This value was within the range of the lab measured field capacity (0.37–0.44 $m^3 m^{-3}$), and therefore was used as the initial soil moisture content for the simulation.

Model inputs included the actual daily SDI hydraulic disposal rate (mm d^{-1}, from field data, corrected from 3D into 2D by dividing the water volume with the surface area of a sphere whose diameter is the same as the drip tube), precipitation (mm d^{-1}, from field data), nitrogen concentration of the applied synthetic wastewater (80 mg N L^{-1}), and daily field Penman method ET (mm d^{-1}, FAO, 2006). Selected chemical/physical reactions for applied nitrogen within the simulation domain were nitrification and denitrification ($NH_4\text{-N} \rightarrow NO_3\text{-N} \rightarrow N_2$), soil adsorption, and crop uptake. Water phase diffusion coefficients were set at 1.60 $cm^2 d^{-1}$ for NH_4-N and NO_3-N (Beggs et al., 2004). Soil adsorption coefficients (K_d, $cm^3 g^{-1}$) were set at 6.0×10^{-6} for NH_4-N and 1×10^{-7} for NO_3-N (Beggs et al., 2004). Since the spatial and temporal variability of nitrification and denitrification rates are highly uncertain (McCray et al., 2005; Heatwole and McCray, 2007), McCray et al. (2005) compiled reported first-order nitrification and denitrification rates for onsite wastewater treatment systems as cumulative frequency distributions (CFDs) (Eqs. (1) and (2)). Using the 10–90% CFD values for nitrification and denitrification, short-term simulation (one-year) was compared with field measurements to evaluate drain field nitrification and denitrification levels during the experimental period. Long-term (ten-year) simulation was conducted to assess the cumulative effect of applied nitrogen.

$$\text{CFD of nitrification rate} = 0.1070 \times \ln(\text{nitrification rate}) + 0.3736 \quad (1)$$

$$\text{CFD of denitrification rate} = 0.1348 \times \ln(\text{denitrification rate}) + 0.9288 \quad (2)$$

3. Results and discussion

3.1. Water movement

Simulated daily soil moisture levels at the 20 and 46 cm depths were graphically compared to the field data for the experiment period (Fig. 2). Although the year-long pattern of simulated soil moisture levels generally conformed to field observation, the simulation process mostly underestimated field moisture levels, in both the summer and winter. Statistically quantified comparison (data not shown) using Percent Bias (PBIAS) method as described by Moriasi et al. (2007) also indicated the same.

It is generally recognized that soil swelling can decrease soil permeability which consequently leads to slower water movement in the soil (Bouma et al., 1981; Amidu and Dunbar, 2007; Kishne et al., 2009). Since the drain field moisture level was proactively managed at field capacity, reduced soil permeability could be one explanation for the numerical underestimation. If this is the case, then the drain field may indeed be providing favorable conditions