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Internal hydraulics of an agricultural drainage denitrification bioreactor

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ABSTRACT

Denitrification bioreactors to reduce the amount of nitrate-nitrogen in agricultural drainage are now being deployed across the U.S. Midwest. However, there are still many unknowns regarding internal hydraulic-driven processes in these engineered treatment systems. To improve this understanding, the internal flow dynamics and several environmental parameters of a denitrification bioreactor treating agricultural drainage in Northeastern Iowa, USA were investigated with two tracer tests and a network of bioreactor wells. The bioreactor had a trapezoidal cross section and received drainage from approximately 14.2 ha at the North East Research Farm near Nashua, Iowa. It was clear from the water surface elevations and the continuous pressure transducer data that flow was attenuated within the bioreactor (i.e., reduction in peak flow as the hydrograph moved down gradient). Over the sampling period from 17 May to 24 August 2011, flow conditions and internal parameters (temperature, dissolved oxygen, oxidation reduction potential) varied widely resulting in early samplings that showed little nitrate removal ranging to complete nitrate removal (7–100% mass reduction; 0.38–1.06 g N removed per m^3 bioreactor per day) and sulfate reduction at the final sampling event. The bioreactor's non-ideal flow regime due to ineffective volume utilization was a major detriment to nitrate removal at higher flow rates. Regression analysis between mass nitrogen reduction and theoretical retention time (7.5–79 h) suggested minimum design retention times should be increased, though caution was also issued about this as increased design retention times and corresponding larger bioreactors may exacerbate detrimental by-products under low flow conditions. Operationally, outlet structure level management could also be utilized to improve performance and minimize detrimental by-products.

1. Introduction

Deteriorating water quality in the U.S. Midwest associated with subsurface agricultural drainage nitrate-nitrogen (NO_3^--N) loads has caused multi-scale environmental concern. From impaired local water bodies in this region (IDNR, 2006) to the national challenge of the Hypoxic Zone in the Gulf of Mexico (USEPA, 2007, 2011), new options are needed to mitigate N losses from agricultural drainage systems. Denitrification bioreactors, sometimes referred to as woodchip bioreactors, denitrification beds, or biofilters, are being trialed in the U.S. Midwest as an on-farm strategy to reduce N loads from field-sized areas (Van Driel et al., 2006; Jaynes et al., 2008; Christianson et al., 2009; Schipper et al., 2010; Woli et al., 2010). Recent work with these enhanced denitrification systems has shown promising N-removal with annual load reductions as high as 98% (Verma et al., 2010), though more typical reductions have been in the range of 42–54% in Illinois (four site-years from Verma et al., 2010; Woli et al., 2010) with a mean of 32% N reduction for seven site-years in Iowa (Christianson et al., 2012).

Because denitrification bioreactors for agricultural drainage are still considered an emerging technology (Christianson et al., 2009), there is much to be learned not only about design and overall annual performance, but also about the internal dynamics of these engineered treatment systems. As many recently installed bioreactors have long and narrow orientations (i.e., "trench" designs with length to width ratios, L:W, of at least ≈5:1; Christianson and Helmers, 2011; Christianson et al., 2011a; University of Illinois, 2011), it would be beneficial to have greater understanding of how flow and physical/chemical parameters (e.g., temperature, dissolved oxygen (DO), oxidation reduction potential (ORP), and NO_3^--N concentrations) change along the length of these reactors during drainage events or throughout the drainage season. Because denitrification is a microbially mediated, anoxic process where

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NO_3^- and subsequent nitrogenous oxides are reduced, this knowledge may help optimize the design of these reactors for different conditions (Korom, 1992; Metcalf and Eddy, 2003).

Tracer testing is one common method to investigate internal reactor hydraulics and such tests in related work have been used to approximate in situ wood media porosity, average hydraulic retention times, and pore water velocity (Schipper et al., 2005; Van Driel et al., 2006). Tracer testing of enhanced denitrification systems can also be a valuable tool for elucidating reasons for poor performance such as testing by Schipper et al. (2004) that confirmed groundwater bypassed underneath a denitrification wall rather than through. Most recently, Cameron and Schipper (2011) used tracer testing to investigate the effect of inlet and outlet position upon short circuiting of flow in denitrification systems. Short circuiting is technically defined as a nonideal flow regime occurring when a portion of the flow exits the reactor outlet before the bulk of the flow that it entered with (Metcalf and Eddy, 2003); this can be a serious detriment to reactor performance as it decreases the interaction time between water and denitrification sites and indicates inefficient use of the reactor volume. Potential causes of such non-ideal flow regimes include poor mixing, inadequate design, and location of inlets and outlets (Metcalf and Eddy, 2003; Cameron and Schipper, 2011).

To quantify non-ideal flow performance in reactors, several measures have been developed based upon tracer residence time distribution curves. Originally, Thackston et al. (1987) defined "hydraulic efficiency" (later, more precisely termed "effective volume") as the ratio of mean tracer residence time to theoretical hydraulic retention time (Eq. (1)):

$$e = \frac{t}{T} = \frac{t}{V\rho/Q} \tag{1}$$

where e is the effective volume, t is the mean tracer residence time, T is the theoretical retention time, V is the active flow volume, Q is the flow rate through the reactor, and with the addition of wood media porosity (ρ) here to reflect the porous woody media. The mean tracer residence time is calculated:

$$t \approx \frac{\sum t_i c_i \Delta t_i}{\sum c_i \Delta t_i} \tag{2}$$

where t_i and C_i are the time and tracer concentration, respectively, of the ith sample, and Δt_i is the time increment between measurements (Metcalf and Eddy, 2003). Zones preferentially avoided due to by-passing flow short circuiting (i.e., dead zones) cannot truly be considered part of the reactor volume, thus making the tracer residence time less than the theoretical retention time and the effective volume less than the actual volume (Thackston et al., 1987). Thackston et al. (1987) also indicated that a "hydraulic efficiency correction factor" of $1/e$ could be used as a design tool to correct for differences in residence and retention times.

Plug flow reactors can be modeled in part as a series of continuously stirred tank reactors (CSTRs) where an infinite number of completely mixed CSTRs in series reflects plug flow conditions (Kadlec and Knight, 1996). Considering this, a hydraulic efficiency metric needs to include factors describing a reactor's extent of mixing (i.e., number of CSTRs in series or dispersion of tracer curve) as well as the reactor's ability to distribute flow evenly (i.e., uniform flow profile across entire volume) (Persson et al., 1999). Persson et al. (1999) combined both an effective volume term and a mixing component into a newer, more descriptive hydraulic efficiency term (Eq. (3)).

$$\lambda = e\left(1 - \frac{1}{N}\right) = \frac{t_p}{T} \tag{3}$$

where λ is hydraulic efficiency, N is the theoretical number of CSTRs in series, and t_p is the time the peak tracer concentration eluted. The number of CSTRs in series (N) has been defined by Kadlec and Knight (1996) as:

$$N = \frac{t}{t - t_p} \tag{4}$$

Persson et al. (1999) defined "good", "satisfactory", and "poor" hydraulic efficiency as $\lambda > 0.75$, $0.5 < \lambda \leq 0.75$, and $\lambda \leq 0.5$, respectively. A specific measure of short circuiting, S (Ta and Brignal, 1998; Eq. (5)), has also been developed for tracer information.

$$S = \frac{t_{16}}{t_{50}} \tag{5}$$

where t_{16} and t_{50} are the times at which 16% and 50%, respectively, of the tracer eluted. An S nearer to zero indicates the reactor may be experiencing short circuiting whereas more ideally performing reactors have S values nearer to 1.0. Additionally, the Morrill Dispersion Index (MDI) is an indicator of mixing that was endorsed by Teixeira and Siqueira (2008) in an assessment of such indices (Eq. (6)).

$$\mathrm{MDI} = \frac{t_{90}}{t_{10}} \tag{6}$$

where t_{10} and t_{90} are the times at which 10% and 90%, respectively, of the tracer eluted (Metcalf and Eddy, 2003). A theoretically ideal plug flow reactor would have an MDI of 1.0, but an MDI less than two is indicative of "effective" plug flow (Metcalf and Eddy, 2003).

In addition to conservative tracer testing, well or piezometer networks have been used to monitor internal bioreactor dynamics (Van Driel et al., 2006; Chun et al., 2010; Warneke et al., 2011). These networks allowed documentation of changing NO_3^-, DO, and ORP within the reactors but past studies only report this information on only one date (Van Driel et al., 2006) or during specific testing conditions (Chun et al., 2010). Moreover, all these tracer- and piezometer-monitored systems differed in design from more current long and narrow Midwestern bioreactors that use flow controlling structures. Additionally, while work by Warneke et al. (2011), Schipper et al. (2004, 2005), and Cameron and Schipper (2011) provided insight into the benefits of tracer and well-based monitoring, these reports investigated treatment of hydroponic waste water, groundwater, and municipal waste water, each of which are distinct from agricultural drainage water chemically and in regard to flow-regime.

There is clearly a need for tracer testing and well-based monitoring of drainage bioreactors in the U.S. Midwest as there have been very few studies of hydraulics and efficiency in denitrification systems (Cameron and Schipper, 2011). Here, a bioreactor in Northeastern Iowa, USA with low NO_3^- removal performance was chosen for a study of its internal dynamics and flow hydraulics with such tests. These contributions are unique as, while other authors have indicated this "emerging technology" shows promise, this work allows insight into changing flow and environmental characteristics inside a bioreactor over a drainage season, clarifies reasons for sub-optimal NO_3^- removal performance of this reactor, and provides an evaluation of design parameters.

2. Materials and methods

2.1. Site description

A woodchip denitrification bioreactor with a trapezoidal cross section (1:1 sides, 36.6 m $L \times$ 4.6 m top $W \times$ 1.0 m D, unlined) was installed at the North East Research Farm near Nashua, Iowa in April 2009 (Fig. 1). Inflow and outflow flow manifolds consisted of