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Bioreactor Design Geometry Effects on Nitrate Removal

Laura Christianson

Iowa State University, Ames, Iowa, United States; laurac@iastate.edu

Matt Helmers

Iowa State University, Ames, Iowa, United States; mhelmers@iastate.edu

Alok Bhandari

Iowa State University, Ames, Iowa, United States; alokb@iastate.edu

Abstract. *Denitrification bioreactors for nitrate removal in agricultural drainage have recently gained attention for their low cost and effectiveness. While research continues to investigate the optimal sizing of these systems, little work has been done on the optimal design geometry (Length to width ratio and cross sectional shape). To address this lack, pilot-scale (1/10th scale) work performed in Iowa during the summer of 2009 explored three shapes of potential bioreactor designs. The objective was to study the nitrate removal effectiveness of each design at various retention times. The pilot bioreactors had a standard volume (0.71 m3) and depth (0.61 m) and different dimensions of 0.76 m x 1.5 m (rectangle), 0.38 m x 3.0 m (channel), and 1.5 m x 1.2 m (trapezoidal). Steady state experiments consisted of the bioreactors being allowed to run at a given retention time for several days/weeks before being changed to a different retention time. A hydrograph flush experiment simulated a drainage hydrograph moving through the bioreactor over the course of a few days. Preliminary results indicated little significant difference between the designs though the*

channel design seems to provide the most consistent results between the two experiments. Further analysis of this data is expected to guide future full-scale denitrification bioreactor designs.

Keywords. Water quality, Drainage, Nitrate, Bioreactor, Denitrification, Design.

Introduction

Intensively drained agricultural systems in the US Midwest have precipitated water quality concerns in the Mississippi River basin. Nitrate losses from these systems lead to decreased water quality locally (Keeney and DeLucca, 1993) as well as nationally. The seasonal hypoxic zone in the Gulf of Mexico is thought to be due in large part to nitrate losses from Midwestern agriculture (Rabalais et al. 1996; USGS 2000).

In order to reduce this local and national concern, water quality, commodity and governmental groups have recently shown interest in denitrification bioreactors, a new field-scale nitrate reduction technology. This technology is promising in terms of nitrate removal with Chun et al (2009) finding nearly 50% mass nitrate-N reduction for a square bioreactor and Jaynes et al (2008) reporting a 55% mass reduction for agricultural denitrification walls. Moreover, Van Driel et al. (2006) noted bioreactors could provide nitrate removal rates an order of magnitude higher than wetlands. Because there have been a variety of denitrification designs implemented in the Midwest, it may be difficult to compare results due to this variability.

Current design procedures in Iowa allow determination of a required bioreactor volume, but there has been no evaluation of bioreactor design geometry (i.e. length to width ratio or cross-sectional shape). As interest in denitrification bioreactors continues to grow, design standardization is necessary to improve effectiveness of field scale reactors. Field data has shown that long, narrow bioreactors and wider, more rectangular bioreactors are both able to remove nitrate but it is not known which design provides greatest efficiency per given volume or retention time. Moreover, it is possible that a trapezoidal cross-section would provide more consistent retention times than a rectangular cross-section due to higher flow velocities at low flow rates. The objective of this study was to investigate the nitrate removal effectiveness of different design geometries at various retention times and hydraulic loadings.

Methods

Three pilot scale designs were constructed with plywood and installed on ISU's Agronomy/Agricultural Engineering Research Farm, Ames, Iowa to test the effectiveness of different bioreactor geometry (Figure 1). These pilot bioreactors were 1:10 field scale based on surface footprint and had a standard total woodchip volume (0.71 m3) and depth (0.6 m). The flow rates were controlled using valves and the water depth was controlled using an upturned PVC elbow and extension piece at the outlet side of the boxes. The 60 cm depth of woodchips in each box was covered with geofabric and approximately 10 cm soil. Between five and twelve 1.5 inch diameter PVC monitoring
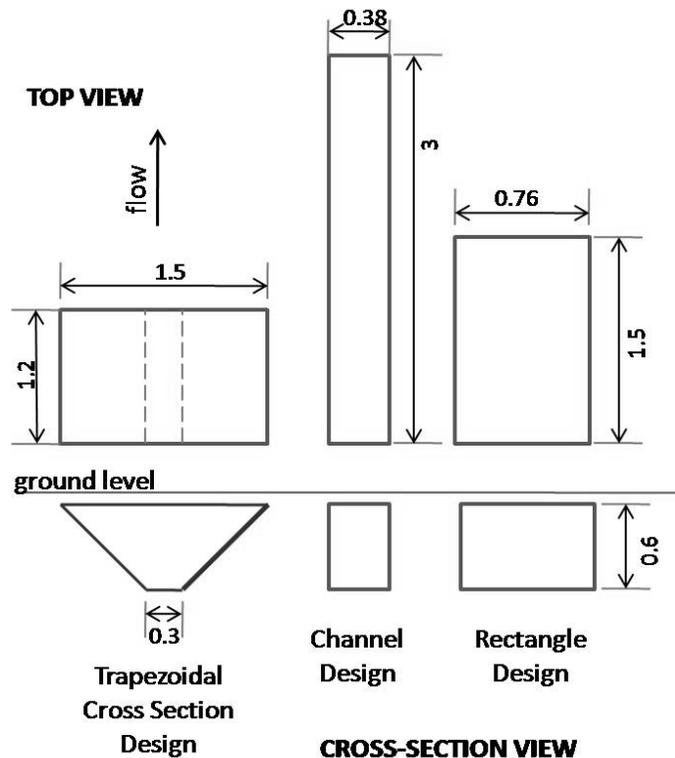
Figure 1. Schematic of three pilot bioreactors (all dimensions are in meters).

wells were installed in each bioreactor. Flow to the bioreactors was supplied from an underground tile drainage reservoir with a submersible pump and buried PVC plumbing. Flow meters (Neptune™ T-10) were used at the outlet side of the bioreactor to determine total outflow. The experiments used for this work were performed during June - August 2009.

The steady state experiment, consisted of allowing all three bioreactors to equilibrate for at least a week at the retention times of 1.5, 4, 8, and >10 hours. Flow into the reactors was gradually decreased over the course of several months to provide a range of retention times and evaluate associated nitrate removal rates. Note the cross-sectional area and, therefore, the active flow volume of the trapezoidal design was smaller at the evaluated flow depth (approximately 28 cm) than the other two designs. Thus, the flow rate for this design had to be lower in order to obtain a consistent retention time among all three designs. Effluent and monitoring well samples were collected and analyzed for nitrate and sulphate (Lachat™ Quick-Chem 8000), while probes were used to measure ORP, DO, pH, temperature and the depth to water surface in the wells (WTW® 3300i pH/mV Field Meter and WTW® SenTix ORP Electrode Probe, Fisher Scientific Accumet® AP74; Solinst® water level meter Model 101). The main transformative process of the influent nitrate-nitrogen was assumed to be denitrification. The presence of denitrifying conditions was verified by the oxidation-reduction potential measurements as well as dissolved oxygen measurements (data not shown).

The hydrograph experiment was modeled after a drainage hydrograph from a monitored site in Iowa. Retention times of less than 4 hours to greater than 10 hours were used over the approximately three day simulated event.   Each retention time was maintained for at least one pore volume before the flow rate was changed to simulate the next stage of the hydrograph. Influent and effluent samples were taken before the retention time was changed for the next hydrograph stage and were analyzed for nitrate.

The data from these experiments were statistically analyzed using the general linear model in sas with significance determined using a tukey-kramer analysis ($\alpha = 0.05$). Least squares means (lsms) were used rather than a simple means procedure because of the unbalanced experimental design caused by unequal numbers of samples at each retention time for each design geometry. The lsm procedure allows for datasets to be centered to account for an unbalanced design.

Results and Discussion

For the steady state experiment, the nitrate removals between the three designs did not appear to be different based on a graph of the retention time versus percent nitrate mass reduction. However, considering each hour of retention separately, there were significant differences between the designs (table 1). Each categorical hour of retention was obtained by rounding the actual retention times; the value of 1 hour of retention consisted of data from 0.50 to 1.49 hours. At three and four hours of retention the trapezoidal design removed significantly more nitrate than the channel design. There were no significant differences for the other retention time values between the designs.

The steady state experiment results showed a positive linear correlation between retention time and percent nitrate mass reduction. As the retention time increased, the least squares means also increased for each design. The only exception to this is the channel design at

Table 1. Percent mass no_3^-n reduction by categorical retention time values for the steady state pilot bioreactor experiment (lsm is least squares mean averages; lsms with the same letter are not significantly different within a given row).

Approximate retention time (hr)	Lsm percent no_3^-n mass reduction		
	Channel design	Rectangle design	Trapezoidal design
2	Na	12.7 (a)	10.6 (a)
3	20.3 (a)	Na	28.4 (b)
4	25.1 (a)	30.9 (ab)	35.5 (b)
5	23.0 (a)	34.4 (a)	45.0 (a)
6	Na	45.1 (a)	44.9 (a)
8 to 11	78.6 (a)	73.6 (a)	86.4 (a)

Four to five hours though these values of 25.1 and 23.0% may not be significantly different from each other.

Averaging across all retention times using the lsms procedure, the steady state experiments showed the channel and trapezoidal designs did not differ in percent reductions, but they both had significantly higher removals than the rectangular design (table 2). Though at 4-5 hours of retention (table 1), the rectangular design removals were numerically greater than the channel design's, these differences weren't significant. When additional data from retention times not included in table 1 (i.e. One hour and twelve hours of retention), were added for the analysis in table 2, a difference in removal for the channel and rectangular designs became apparent.

The hydrograph experiments showed the channel and rectangular designs were not different but had significantly higher removals than the trapezoidal design (table 2). In this case, the trapezoidal design showed lower percent reductions rather than higher as shown in table 1 at three and four hours of retention.

When these percent mass removals were normalized by the hours of retention time (table 2), the steady state results indicated no difference in the designs while the hydrograph results indicated all the designs had significantly different percent reductions per hour. With the relatively rapid changes in retention time of the hydrograph tests, the rectangle design showed the best performance measured by percent per hour and the trapezoidal design the worst.

For steady state conditions, the trapezoidal design appeared to provide the highest numerical (non-significant) nitrate removal, however under the rapidly changing flow conditions inherent to drainage systems, this design might actually provide the least removal. Moreover, the trapezoid design's high removals under the steady state conditions were not significantly different from the channel design's removals. The rectangular design provided the lowest percent reduction (significant) for the steady state test but the highest percent per hour for the hydrograph test (significant). The channel design appeared to be the most consistent performer considering both experiments.

Table 2. Percent mass NO_3^-N reduction and percent reduction per hour of retention averaged over all retention times for two pilot bioreactor experiments (LSM is least squares mean averages over all retention times; LSMs with the same letter are not significantly different within a given column).

	Steady State Experiment		Hydrograph Experiment	
	LSM of Mass Percent Reduction (%)	LSM of Percent Reduction per Retention (%/hr)	LSM of Mass Percent Reduction (%)	LSM of Percent Reduction per Retention (%/hr)
Channel Design	37.8 (a)	7.0 (a)	99.0 (a)	10.1 (b)
Rectangle Design	32.8 (b)	6.8 (a)	111.6 (a)	13.5 (a)
Trapezoidal Design	38.7 (a)	7.9 (a)	70.2 (b)	5.4 (c)

Conclusion

Denitrification bioreactors are a new option for field-scale nitrate removal from agricultural drainage. Though various bioreactor design geometries have been implemented throughout the US Midwest and Canada, there has been no evaluation of design geometry effects on nitrate removal performance. Three pilot scale denitrification bioreactors were used to address the question regarding bioreactor geometry effects on performance.

Though there were significant differences in nitrate removal for the three cross-sectional designs at various retention times or during different experiments, it remained difficult to conclude whether one design was better than the others. The rectangular design appeared to have the highest nitrate removal during the hydrograph tests while the trapezoidal cross-section had higher numerical removal percentages at certain retention times. Overall, the channel design provided the most consistent results among all the tests. In designing a bioreactor it may be that it is far more important to design for the correct retention time and hydraulic properties than for a specific shape. With further work investigating full scale designs, knowledge of bioreactor performance will be increased and designs will continue to be improved.

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