HYDRAULIC EVALUATION OF A DENITRIFYING BIOREACTOR WITH BAFFLES

BY

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THESIS

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ABSTRACT

Denitrifying 'woodchip' bioreactors are an effective conservation practice to reduce nitrate-nitrogen (NO_3-N) loss from tile drained agricultural areas. They enhance the naturally occurring denitrification process via the addition of woodchips and maintenance of anoxic conditions. Bioreactors tend to be one of the most cost-effective options for treatment of tile drainage NO_3-N, but considering the scale of water quality goals, new approaches to bioreactors are needed to provide the most practical benefit, while limiting the amount of land taken out of production. Current bioreactor design considerations include a bypass flow pipe to prevent significant reduction of drainage capacity in the field. This practical need for a bypass pipe results in a portion of the annual flow volume being untreated which limits a bioreactor's overall N removal performance. Bioreactors designed to be wider would potentially have greater flow capacity, minimizing this untreated water. To maintain a consistent surface area footprint and not encroach on cropped areas, a wider and shorter bioreactor could use baffles to elongate the flow path, forcing more effective reactor volume utilization. To test this, a new bioreactor (LWD: 16.8 x 10.7 x .91 m; drainage treatment area: 14.2 ha) which included two flow-routing baffles was installed at the University of Illinois Dudley Smith Research Farm (Christian County, IL, USA) in October 2016. A series of potassium bromide conservative tracer tests were performed on this new design during 2018 as well as at three conventionally designed bioreactors to evaluate how the baffles impacted bioreactor hydraulic functioning. This new bioreactor had greater effective volume, lower dispersion, and less short-circuiting compared to the conventionally designed bioreactors. However, this did not necessarily translate into improved NO_3-N removal. Overall N load reductions of 23-24% at the edge of the field were similar to many other published studies for bioreactors without baffles. There was 62-64% N removal for water treated in the bioreactor which translated into removal rates of 1.30-1.25 g N m^{-3} d^{-1} which were also similar to other studies. Additionally, while this bioreactor was relatively wide to maximize the percentage of flow treated, only 40-41% of the annual flow volume was treated. Although bioreactors are meant for N removal, there was unexpected dissolved P removal (23-24%), mechanisms of which should be investigated further. While the baffles did not lead to increased N removal compared to conventionally designed bioreactors, they did improve bioreactor volume utilization, and thus, the idea of bioreactors with baffles is an idea meriting further exploration at additional sites.

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TABLE OF CONTENTS

1. INTRODUCTION

Nitrogen (N) is one of the essential macronutrients required by all plants and thus plays a key role in many agricultural systems. One specific form of N, nitrate-nitrogen (NO_3-N), is often of environmental concern as it is highly susceptible to leaching from soils. Environmental health (e.g., N is the limiting factor for eutrophication in marine waters) and human health (e.g., methemoglobinemia/blue baby syndrome) are both threatened by excess NO_3-N in water bodies. The presence of artificial subsurface drainage pipes (i.e., "tile" pipes) exacerbates NO_3-N leaching and its transport to downstream waters.

Artificial agricultural drainage systems are typically installed for one or a combination of three reasons: to improve trafficability especially in the early spring, to improve crop growth and yield, and to prevent salt accumulation in irrigated areas (Skaggs et al., 1994). The U.S. Midwest region's naturally high water tables and poorly drained soils have required an extensive network of subsurface tile drainage since early settlement in the mid-1800's (Kalita et al., 2007). The state of Illinois alone contains approximately 4 million ha of tile-drained soils (IEPA and IDOA, 2015). Tile drainage on agricultural lands provides environmental benefits including reduced runoff and sediment losses (Skaggs et al., 1994). However, tile drainage also increases losses of dissolved nutrients such as NO_3-N, with the magnitude of these losses dependent upon land use, management practices, soil type, and climate (Skaggs and van Schilfgaarde, 1999; Skaggs et al., 1994).

In the U.S. Midwest, there is currently no water quality regulation for discharge from agricultural subsurface drains in the United States (USEPA, 2017). State-based nutrient loss reduction strategies across the Mississippi River Basin support a voluntary approach to reduce nutrient loss from agricultural areas (e.g., IDALS, 2014; IEPA and IDOA, 2015). As a result, all nutrient loss solutions must be cost-efficient and practical to encourage their implementation (Christianson and Tyndall, 2011). Recommended agricultural conservation practices include in-field practices such as cover cropping and improved nitrogen management and edge of field practices including wetlands and denitrifying bioreactors (Christianson et al., 2016).

Denitrifying 'woodchip' bioreactors are excavated trenches filled with a solid carbon media (typically woodchips) placed at the edge of a field or between fields to encourage the denitrification of drainage water. Denitrification is the natural microbial conversion of NO_3-N into dinitrogen gas (N_2) (Tiedje, 1994). The denitrification process requires four components: NO_3^- or another N oxide, a carbon source, anoxic conditions, and denitrifying bacteria (Korom, 1992). Under suitable anoxic conditions, denitrifying bacteria use the carbon to fuel the denitrification process resulting in N_2, bicarbonate HCO_3-, and carbon dioxide (CO_2) (Equation 1).

$$5C + 4NO_3^- + 2H_20 \rightarrow 2N_2 + 4HCO_3^- + CO_2$$

Equation 1

Bioreactors enhance the natural process of denitrification by diverting NO_3-N laden drainage water through a readily available carbon source and using control structures to manage the water to create anoxic conditions. Early versions of this concept were first studied in New Zealand and Canada in the 1990s (Blowes et al., 1994; Schipper and Vojvodić-Vuković, 1998).

The amount of NO_3-N removed by a denitrifying bioreactor is influenced by factors including water temperature (Feyereisen et al., 2016; Schipper et al., 2010), woodchip age (Addy et al., 2016), and the amount of time the water spends in the bioreactor (hydraulic retention time; Christianson et al., 2012b;). The Iowa and Illinois Nutrient Reduction Strategies reported bioreactors reduce annual NO_3-N loss by 43 and 25%, respectively (IDALS, 2014; IEPA and IDOA, 2015). However, this can vary depending on the site and year with bioreactors in Iowa, Illinois, New York, Maryland, and Canada removing between 9-62% of the annual NO_3-N load (Christianson et al., 2012a; Husk et al., 2017; Rosen & Christianson, 2017). Another way to assess bioreactor effectiveness is to evaluate the N removal rate which is calculated as g N removed per m^3 of the bioreactor per day (g N m^{-3} d^{-1}). In a past review, Schipper et al. (2010) reported denitrification beds (i.e., bioreactors) had an average N removal rate of 3.96 g N m^{-3} d^{-1} which compared reasonably well with a more recent meta-analysis by Addy et al. (2016) who reported a mean N removal rate of 4.7 g N m^{-3} d^{-1} for denitrification beds.

While denitrifying bioreactors are designed for NO_3-N removal, some bioreactor studies have observed phosphorus (P) removal as well. As woodchips are known to contain P, which can leach, there is much discussion within the scientific community as to whether bioreactors are a source or a sink for dissolved phosphorus in drainage water. Sharrer et al. (2016) found that when a bioreactor was first operational the woodchips were a source of phosphorus, but later observed dissolved reactive phosphorus (DRP) removal at low flow rates with a maximum DRP removal efficiency of 54%. Husk et al. (2018) also reported initial woodchip P leaching but additionally found that the potential for P removal over a longer period time depended on P species. A woodchip bioreactor study conducted on a commercial fish farm in Denmark also observed orthophosphate leaching at the time of start-up, but this declined by 98% within three days, and by week 15, there was no net release of TP or orthophosphate (von Ahnen et al., 2016). These findings support evidence of a bioreactor P-leaching phase followed by neutral or positive TP removal. The bioreactor meta-analysis by Addy et al. (2016) concluded a second meta-analysis should be conducted exclusively for P when additional data become available.

Subsurface drainage bioreactors are currently designed on an individual basis due to a variety of field-specific factors (e.g., flow rate, effective porosity of available chips). The United States Department Agriculture Natural Resources Conservation Service (USDA NRCS) Conservation Practice Standard 605 for denitrifying bioreactors, which was influenced by the design methods proposed in Christianson et al. (2011) and Cooke & Bell (2014), is currently the guiding design standard for this practice (USDA NRCS, 2017). This practice standard advises that bioreactors be designed to treat at least one of the following: 15% of the drainage system's peak flow rate, 60% of the long-term average annual flow volume, or the peak flow from a 10-year, 24-hour drainage event (USDA NRCS, 2017). The NRCS standard also requires bioreactors be designed for a minimum hydraulic retention time of 3 h at the peak flow capacity (USDA NRCS, 2017). Hydraulic retention time (Equation 2), or the theoretical amount of time it takes for water to travel through the bioreactor, is defined as:

$$T = \frac{\rho V}{Q}$$

Equation 2

Where T was theoretical hydraulic retention time (h), ρ was the woodchip porosity (ratio of woodchip pore volume to total volume, as a fraction), V was the bioreactor saturated volume (m^3), and Q was the average flow rate (m^3/h) (Fenton et al., 2016; Feyereisen et al., 2016; Hoover et al., 2017). If the retention time is too short, it may not allow dissolved oxygen to be consumed to sufficiently low concentrations to create the anoxic conditions needed for denitrification. Higher retention times usually correlate with greater percent N reductions (N removal efficiencies) up to 100%, but also lower N removal rates as hydraulic loading is reduced (Lepine et al., 2016).

Bioreactors treating tile drainage are designed to allow bypass flow during high flow events to prevent significant reduction of drainage capacity in the field. This practical need for a bypass pipe results in a portion of the annual flow volume being untreated, thus reducing the overall NO_3-N load reduction potential. Bioreactors across literature have treated 13-99% of the total annual drainage volume. Christianson et al. (2012a) reported treatment of 51-100% (83±17%; mean ± standard deviation) of the annual drainage flow across 14 bioreactor site-years in Iowa and Hassanpour et al. (2017) reported similar values of 63-100% flow treated (n = 3 site-years, 81±20%). A study in Maryland reported a slightly lower average of 48±34% (n = 5 site-years, 13-98%; Rosen & Christianson, 2017).

One potential solution to maximize the volume of water treated would be to over-design bioreactors, although this would potentially remove land from production and be less desirable to landowners. Another option would be to maintain a consistent surface footprint and design bioreactors wider at the expense of length. Currently, narrow bioreactors may be restricting the inflow water volume due to the relatively narrow width which has been recommended to maintain a length to width ratio of at least 4:1 to achieve plug flow conditions (Persson et al., 1999). Maintaining a consistent surface area footprint with a wider bioreactor would sacrifice bioreactor length which is critical for achieving adequate treatment retention times. An engineering solution for this could be to add baffles which are a feature that is used to regulate or direct the flow path (Tchobanoglous et al., 2003; David, 2014). Technically, the addition of baffles in a reactor does not change the hydraulic retention time, as can be seen from Equation 2; that is, baffles do not change the actual volume used in the equation. Rather, baffles are an approach to elongate the flow path and force a more effective reactor volume utilization. Taken together, a wider bioreactor with baffles may help achieve a higher percentage of the flow treated while not sacrificing sufficient treatment.

The aim of this study was to evaluate a new wider full-sized bioreactor design which included flow-routing baffles. These baffles were intended to elongate the flow path of the water through the bioreactor and to increase the bioreactor's effective volume. The specific objectives were to (1) evaluate the hydraulic performance of this novel bioreactor design compared to existing "conventional" bioreactors using tracer testing, and (2) assess the NO_3-N and dissolved phosphorus (PO_4-P) removal performance of this bioreactor.

2. METHODS

2.1 Site Descriptions

2.1.1 Advanced Bioreactor with Baffles

A denitrifying woodchip bioreactor (16.8 x 10.7 x 0.91 m) was installed with two plastic flow-routing baffles at the University of Illinois Dudley Smith Research Farm (Christian County, Illinois) in October 2016 (Figure 1; Table 1). The bioreactor was located in the northeast corner of a 42.9 ha field cropped to continuous corn (*Zea mays* L.) during the study period. The bioreactor received subsurface drainage from an estimated 14.2 ha of drainage research plots (9 x 0.81 ha plots plus border tiles; 9.5 mm/d drainage coefficient; 25.4 cm diameter main tile). Two 4.9 m baffles made from plastic anti-seep sheets (6 mm thick high-density polyethylene; Springfield Plastics, Auburn, IL, USA) were installed 5.8 m from the inflow and 5.5 m from the outflow. A plastic liner minimized interaction with groundwater (20 MIL thickness; Midwest Construction Products Corp., Ft. Myers, FL, USA), and the woodchips were covered with geofabric to separate them from the soil cover (GeoForce brand; Midwest Construction Products Corp., Ft. Myers, FL, USA).

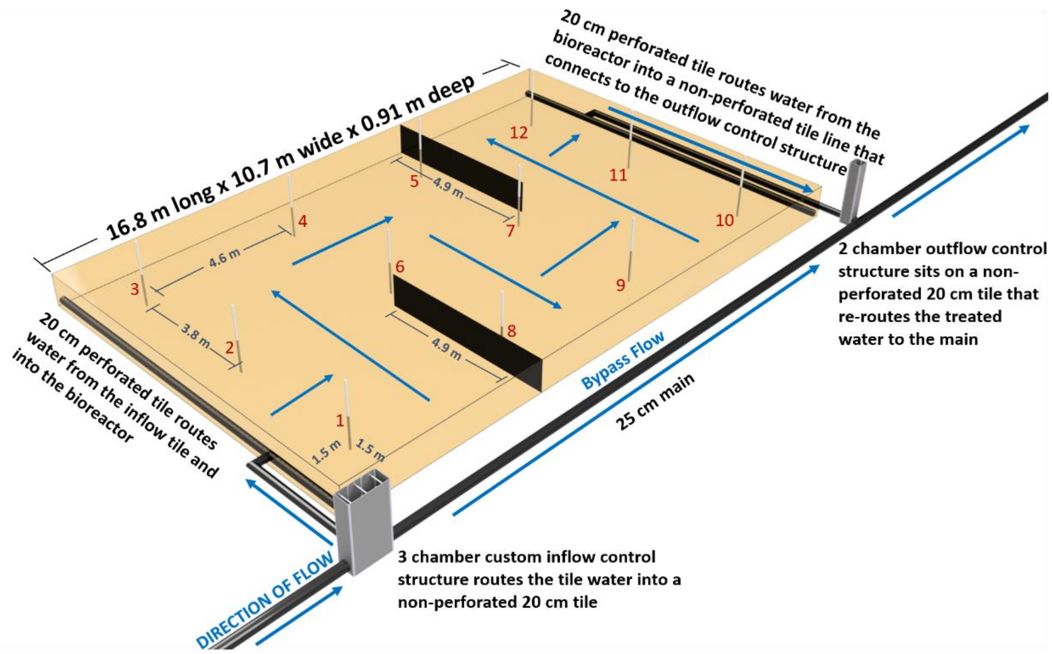

Figure 1. Diagram of the Advanced Bioreactor with baffles and monitoring wells (numbered in red) installed in Christian Co., Illinois in October 2016. Generalized flow direction noted with blue arrows.

Table 1. Four tile drainage denitrifying bioreactors in Iowa and Illinois evaluated with tracer tests.

Bioreactor	Location	Installation date	Drainage treatment area ha	Tile main diameter cm	Length x Width x Depth m	Volume m^3	Tracer Testing Date(s) MM/DD/YY
"Advanced Bioreactor" Univ. of IL Dudley Smith Farm	South Central Illinois	October 2016	14.2	25.4	16.8 x 10.7 x 0.91	164	04/09/18, 04/23/18, 06/17/18,
Iowa State Univ. Northeastern Research Farm Bioreactor	Northeast Iowa	April 2009	14.2	15.2	36.6 x 4.6 top x 2.4 bottom x 1.0	128	04/01/18
IL Farm Bureau Henry Co. Bioreactor	Northwest Illinois	September 2017	2.8	15.2	9.8 x 1.8 x 0.91	16	06/05/18
Mercer Co. Bioreactor	Northwest Illinois	August 2017	20.2	15.2	13.4 x 3.4 x 0.91	41	06/13/18

One control structure was placed on the 25 cm main to divert water into the bioreactor, and a second structure was placed to control bioreactor saturation level through the use of movable stop logs. The bioreactor was designed to achieve a 3 h hydraulic retention time at a design flow rate of 6.9 L s^{-1}, which was estimated to be 75% of the peak tile flow rate. Consistent with the design conditions, the inflow and outflow control structure stop log heights were set to 76 and 31 cm, respectively, except for when the outflow structure stop logs were removed during summer low flow conditions.

2.1.2 "Conventional" Bioreactor Comparison Sites

Hydraulic performance of the Advanced Bioreactor was compared with three relatively conventionally designed bioreactors (Table 1). Two of the three sites were designed consistently with the USDA NRCS Denitrifying Bioreactor Conservation Practice Standard 605 and were installed in Illinois in the summer of 2017 (USDA NRCS, 2017). The exception was the Iowa State University Northeastern Research Farm bioreactor (NERF) which was designed by Iowa

State University researchers, installed in 2009, and has been previously described by Christianson et al. (2012a, 2013). The comparison bioreactors each received subsurface drainage from 2.8 to 20.2 ha which were under conventional US Midwestern cropping systems (i.e., generally, a corn and soybean [*Glycine max*] rotation). Another key difference between the four comparison sites was that the woodchips at the Mercer County bioreactor were chipped municipal storm debris obtained free of charge, which exhibited unique physical and chemical properties compared to the other woodchips.

2.1.3 Woodchip Analyses

Woodchips from the Advanced Bioreactor and two of the conventional bioreactors were analyzed at the University of Illinois at Urbana-Champaign for moisture content, porosity, bulk density, and particle size (Table 2). Woodchip characteristics were previously reported for the NERF bioreactor (Christianson et al., 2010). However, these characteristics have likely changed over time due to biological processes. Porosity and bulk density were estimated in triplicate for each woodchip type by packing 1 L glass jars (Ball Corporation, Broomfield, CO, USA) in four tamped layers, filling with water, and allowing to equilibrate overnight. They were calculated as (Equation 3 and Equation 4):

$$\rho = \frac{Volume\ of\ voids}{Total\ volume} \times 100\%$$

Equation 3

Where ρ was the total porosity (in percent), the volume of voids was the mass of the water (g) in the woodchip-filled jar divided by the density of water (g/mL), and the total volume was the total volume of the empty jar (mL).

$$\rho_b = \frac{Oven\ dried\ weight}{bottle\ volume}$$

Equation 4

Where ρ_b was bulk density (g/cm^3) consisting of oven dried weight of woodchips (g) and bottle volume (cm^3). Moisture content was estimated in triplicate on the day of porosity testing by drying a subset of woodchips at 70˚C until a constant weight was achieved. Particle size analysis was performed in triplicate using standard methods (ANSI/ASABE, 2007; 38.1, 25.4, 19.1, 12.7, 6.4, 3.2, and 1.7 cm sieves for all but the Mercer Co. chips which also required a 102 cm sieve; Shaker Table Model Rx-812 WSTyler, Mentor, OH, USA). These data were used to calculate the D_{10}, D_{50}, D_{90} and uniformity coefficient (UC) of each type of chip. The D values refer to the interpolated size (or, particle diameter) below which the subscript value (10, 50, 90) percentage by mass are smaller; in other words, a D_{10} of 5.0 mm indicates 10% of the media, by mass, were smaller than 5.0 mm. The UC represents the sample uniformity by dividing the D_{60} by the D_{10}. Woodchip carbon (C), N, and phosphorus (P) analyses were performed on a combustion analyzer (C and N) or using a digestion method (P) (Brookside Laboratories Inc., New Bremen, OH, USA; Elementar EL Cube; Thermo Fisher Scientific 6500 Duo ICP, Ronkonkoma, NY, USA). Prior to nutrient analyses, woodchips were dried at 60˚C for 48 h and then ground using a Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA) with a 1.0 mm screen.

Table 2. Woodchip characteristics for the Advanced Bioreactor and two of the conventional bioreactors. The Mercer Co. bioreactor woodchips were not to USDA NRCS specification but were sourced for free. UC, C, N, and P represent uniformity coefficient, carbon, nitrogen, and phosphorus content, respectively.

	-- Particle size analysis --						------- Nutrient Content -------			
	D_{10}	D_{50}	D_{90}	UC	Bulk Density	Porosity	C	N	P	C:N Ratio
	-------- mm --------			---	kg m^{-3}	%	-------------%-----------			---
Advanced Bioreactor	7.8	15	25	2.0	214	74	48.3	0.16	0.013	299
IL FB Henry Co.	9.3	16	25	1.9	199	72	48.3	0.23	0.022	235
Mercer Co.	3.9	17	271	6.6	125	82	47.3	0.79	0.092	60

2.2 Bioreactor Monitoring

2.2.1 Tracer testing (All Bioreactors)

Conservative tracer tests are a simple and effective approach used to evaluate reactor hydraulic performance and retention time characteristics (Tchobanoglous., et al., 2003). These tests help identify non-ideal reactor flow regimes such as dead zones, where water becomes trapped and short-circuiting, where an unexpected portion of the flow exits the bioreactor sooner than expected. Additionally, tracer tests can be used to compare the theoretical retention time with the mean tracer residence time to evaluate if the bioreactor is functioning as intended. Denitrifying bioreactor tracer tests commonly use chloride or bromide as a conservative tracer, so called because these molecules do not significantly absorb to or react with woodchip surfaces and these molecules behave similarly to nitrate (Ghane et al., 2015; Hoover et al., 2017).

Three conservative tracer tests were performed at the Advanced Bioreactor ("treatment") and three tests were performed at the more conventionally-designed bioreactors ("controls") between April and June 2018 (Table 1). Each test began by pouring a concentrated potassium bromide (KBr) solution (Table 3) into the inlet control structure in under one minute at a steady pace when no bypass flow was occurring. Bioreactor outlet samples were collected using two auto-samplers (Teledyne ISCO model 3700, Lincoln, NE, USA), with hand grab sampling performed as a backup method. The sample timing was staggered to ensure sufficient capture of eluted KBr given the estimated flow rate and was based on capturing multiple pore volumes based on the theoretical hydraulic retention time (Kadlec and Wallace, 2009). The mass of KBr required for each tracer was calculated based on the estimated bioreactor pore volume, the solubility of KBr, and analytical bromide-detection limit (Lachat Quickchem method Bromide 18-135-21-2-B, Loveland, CO, USA). Flow rates during the tracer tests were calculated based on a series of hand-measured flow depths in the outflow control structure and using the appropriate weir equation for each bioreactor.

Table 3. Start time and tracer solution details for six potassium bromide (KBr) conservative tracer tests performed at four bioreactors in 2018.

Tracer test	Tracer start date/time MM/DD/YY 00:00	Mass of KBr Kg	Solution volume L	Initial bromide concentration g Br L^{-1}
NERF	04/01/18 10:30am	4.1	18.9	140
Advanced Bio 1	04/09/18 11:45am	3.5	18.9	113
Advanced Bio 2	04/23/18 11:32am	3.5	18.9	120
IL FB Henry Co.	05/06/18 11:45am	0.1	8.0	76.9
Mercer Co.	05/13/18 11:50am	1.5	7.0	139
Advanced Bio 3	06/17/18 11:50am	3.5	18.9	111

Tracer testing allows evaluation of several metrics, or tracer testing statistics, which were calculated for all tests. The mean tracer residence time (*t*, Equation 5) is the average amount of time it takes for the tracer slug to move through the reactor:

$$t \approx \frac{\Sigma t_i c_i \Delta t_i}{\Sigma c_i \Delta t_i}$$

Equation 5

Where *t* was mean tracer residence time, t_i was time at the i^{th} measurement, c_i was the concentration at time *i*, and Δt_i was change in time (Tchobanoglous et al., 2003). Using the same variables, the variance of the mean tracer residence time (σ, Equation 6) is used to shows the variation in the time it takes for the tracer slug to move through the reactor (Tchobanoglous et al., 2003).

$$\sigma_\Delta \approx \frac{\Sigma t_i c_i \Delta t_i}{\Sigma c_i \Delta t_i} - (t^2)$$

Equation 6

Tracer residence time, the measure of in-situ retention of the tracer can be compared against the theoretical retention time (Equation 2) to assess reactor volume utilization, that is, the reactor's effective volume (*e*, Equation 7).

$$e = \frac{t}{T}$$

Equation 7

If the tracer residence time is longer than the theoretical hydraulic retention time, the effective volume is greater than 1.0, which indicates the reactor is operating more effectively than its dimensions and that specific flow rate would indicate. On the other hand, if the mean tracer residence time is shorter than the theoretical hydraulic retention time, the effective volume will be less than 1.0 meaning the reactor volume is possibly being underutilized. These conditions indicate possible occurrence of a dead zone and associated short-circuiting around the dead zone causing the tracer to exit earlier than expected (i.e., $t < T$). In this case, the reactor is not using the entire volume, and the resulting *e* is less than 1.0 (Thackston et al., 1987).

The Morrill Dispersion Index (MDI; Equation 8) is an indicator of dispersion of the tracer throughout the reactor (Tchobanoglous et al., 2003).

$$MDI = \frac{t_{90}}{t_{10}}$$

Equation 8

Where t_{10} and t_{90} were the time in which 10 and 90% of the tracer passed through the reactor, respectively. A high MDI indicates the tracer spread out within the reactor chamber and the resulting tracer curve will be wide rather than sharply peaked. The MDI would be 1.0 for a theoretically ideally operating reactor, and an MDI of 2.0 or less is considered to represent effective plug flow through the reactor (USEPA, 1986).

Hydraulic efficiency (λ, Equation 9) is the ratio between the time to the tracer peak and the theoretical hydraulic retention time:

$$\lambda = \frac{t_p}{T}$$

Equation 9

Where t_p was the time at which the peak concentration of the tracer test was observed (h). A theoretically ideal reactor would have a tracer peak elute when exactly one pore volume had been eluted, which would equate to one hydraulic retention time, and thus λ=1.0. Hydraulic efficiency can be defined as “good”, “satisfactory”, or “poor” with $\lambda > 0.75$, $0.5 < \lambda \leq 0.75$, or $\lambda \leq 0.5$, respectively (Persson et al., 1999).

Short-circuiting is considered a non-ideal flow regime because a portion of the water flows through the reactor with a relatively lower treatment time than intended. Tchobanoglous et al. (2003) suggested that the location of inlets and outlets, poor mixing, and inadequate design were potential causes of this phenomena. A Short-circuiting Index (*S*; Equation 10) provides a relative comparison of this effect between reactors (Ta and Brignal, 1998).

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

Equation 10

With t_{16} and t_{50} being the time at which 16 and 50% of the tracer passed through the reactor, respectively. An S nearer to zero indicates the reactor may be experiencing short-circuiting (i.e., t_{16} is much lower than t_{50}), and S values nearer to 1.0 reflect a more ideally performing reactor (Ta and Brignal, 1998).

As the sample sizes for this study were small (n = 3) for both the control (conventional bioreactors) and treatment (Advanced Bioreactor) groups, and the tests at the Advanced Bioreactor were technically a repeated measures procedure, traditional statistical analysis was not applied. However, in large-scale applications such as this, the tracer testing metrics themselves can be treated as “statistics” for comparison. While the flow rates and bioreactor dimensions each differed, the tracer tests were comparable because the theoretical hydraulic retention times, which can be used to normalize such differences in flow rates and dimensions, were similar across all tests (ranging from 13-23 h).

2.2.2 Nutrient Removal Performance (Advanced Bioreactor Only)

Inflow and outflow water quality monitoring was initiated in February 2017 (five months after bioreactor installation) using automated samplers and pressure transducers for continuous flow monitoring (Teledyne ISCO model 6712 with 720 submerged probe modules, Lincoln, NE, USA). One daily 800 L composite sample (200 mL collected 4 times per day, composited into one bottle) was obtained from both sampling locations. Samples were collected from the site weekly and brought on ice to the lab at the University of Illinois at Urbana-Champaign where they were filtered (0.45 µm disposable membrane filters) then frozen until analysis (within 28 days) for NO_3-N and PO_4-P (Lachat Quickchem, 10-107-04-1-A, and 10-115-01-1-A, Loveland, CO, USA).

The flow depth in both the inflow and outflow control structures was logged every fifteen minutes and later compiled into average daily water depths. The pressure transducer in the inflow structure allowed for the calculation of bypass flow during periods of overflow through the v-notch weir stop log, whereas the pressure transducer in the outlet structure allowed calculation of how much water exited the bioreactor (i.e., treated flow) assuming no water was lost from the lined bioreactor. The summation of flow volumes calculated using the inflow (bypass flow) and outflow (bioreactor flow) pressure transducers allowed for estimation of total flow from the field. Custom 45˚ rounded bottom v-notch weir stop logs (Agri-Drain, Adair, IA, USA) were placed in the control structures to facilitate flow rate calculations, particularly at low flow rates. Manufacturer supplied flow equations (Equation 11, Equation 12; supplied in Imperial units only) were used after correcting the logged water depths by the logged barometric pressure and the measured stop log height in each control structure. Control structure water depths were also recorded by hand for on-site validation starting fall 2017 (Kolor Kut Products Co, LTD, Houston, TX, USA).

$$If\ H \leq 6.56, Q = (2.5866H)^{2.0464}$$

Equation 11

$$If\ H > 6.56, Q = (2.5866H)^{2.0464} + \mathrm{Q}_{flat\ weir}$$

Equation 12

Where H was the height of water above the bottom of the v-notch (inches), W was the width of the weir (inches), Q was the flow rate of water over the weir (gpm), and $Q_{\text{flat weir}}$ is also a manufacturer supplied equation depending on the size of the control structure. Post-processing of flow data included setting maximum governors for the bypass flow rate based on the 25 cm tile pipe (14.5 L s^{-1} assuming full pipe flow and 0.1% site grade) and for the bioreactor flow rate based on Darcy's Law and the hydraulic gradient across the bioreactor bottom (saturated hydraulic conductivity of 4.5 cm s^{-1}; Feyereisen et al., 2016).

Nitrate-N and PO_4-P mass loads entering, exiting, and bypassing the bioreactor were calculated by multiplying the incremental flow volume prior to a sampling event by that sampling event's nutrient concentration, and then summing those incremental loads over the monitoring period.

The overall load from the field and the overall load sent downstream were calculated as the load entering the bioreactor + bypass load and the load exiting the bioreactor + bypass load, respectively. The N removal efficiency (i.e., percent N load reduction) was calculated for both water treated in the bioreactor ("Bioreactor removal efficiency") and across the entire system ("Overall removal efficiency"; including untreated bypass flow) by subtracting the outgoing load from the entering load and dividing by the entering load. Nutrient removal rates were calculated by dividing the cumulative mass of the nutrient removed over the monitoring period by the volume of the bioreactor (164 m^3) and by the count of days in the period (including days of no flow).

Twelve 2.13 m tall, 5 cm diameter PVC sampling wells (screened 31 cm from the bioreactor bottom) were placed in a grid pattern (Figure 1) following the assumed bioreactor flow path. Water samples were collected approximately monthly during flow periods in each well after measuring the depth to water (Solinst water level meter Model 102M, Sacramento, CA, USA), purging at least 3.8 L (i.e., approximately three times the well volume), and re-measuring the depth to verify the wells had re-filled (100 mL sample; Whale Pump mini 50 WP4012, Bangor, County Down, Northern Ireland). Samples were transported, filtered, and analyzed following previously mentioned methods. Following well sample collection, dissolved oxygen and oxygen reduction potential (ORP) (YSI Professional Plus 1020 capable ORP/DO probe, Yellow Springs, OH, USA) were measured. Potential maximum and minimum flow path lengths inside the bioreactor were estimated based on bioreactor dimensions and were averaged to show well sampling values along the flow path.

3. RESULTS AND DISCUSSION

3.1 Tracer Testing

Tracer tests at the Advanced Bioreactor showed this bioreactor with baffles had a greater calculated effective volume, ranging from 1.26-1.73, compared to the conventionally designed bioreactors which ranged from 0.17-1.06 (Table 4). This evidence supported the design hypothesis that the baffles in the Advanced Bioreactor would create conditions for better reactor volume utilization. The advanced and conventional design's theoretical hydraulic retention times during the test (13-20 vs. 18-23 h; Table 4) and tracer residence times (16-35 vs. 3-25 h; Table 4) generally overlapped, which indicated the resulting metrics were comparable across all tests. These tests were performed within the range of theoretical retention times reported for bioreactors in previous studies (i.e., minutes to days; Christianson et al., 2012b).

The advanced design also resulted in significantly lower dispersion and less short-circuiting compared to the conventional designs. For example, the Morrill Dispersion Index ranged from 2.29-2.98 versus 3.15-3.59 and the short-circuiting index ranged from 0.65-0.69 versus 0.53-0.64 (Table 4) for the two types of designs, respectively. While all the dispersion indices were relatively high (e.g., 2.0 is considered representative of effective plug flow; USEPA, 1986), the lower Morrill Dispersion Indices from the advanced design meant there was relatively less dispersion of the tracer within that bioreactor. Woodchip bioreactors in previous studies (conventional designs) have had Morrill Dispersion Indices ranging from 2.8-4.2 (Christianson et al., 2013; Hoover et al., 2017), relatively consistent with the values here. A higher short-circuiting index associated with the advanced design (i.e., closer to 1.0, meaning the t_{16} and t_{50} were relatively more similar per Equation 10) indicated a lower likelihood of short-circuiting or preferential flow within the reactor.

Table 4. Bioreactor tracer metrics (Equations 2 and 5-10) from three tracer tests performed at the Advanced Bioreactor with baffles and one tracer test each performed at three conventionally-designed bioreactors in Iowa and Illinois.

Tracer test	One pore volume during test	Cumulative pore volumes for entire test	Average test flow rate	Theoretical hydraulic retention time (HRT), T	Mean tracer residence time ± Variance, $t \pm \sigma$	Effective volume, e	Time to peak	Morrill Dispersion Index, *MDI*	Short-circuiting index, S	Hydraulic efficiency, λ	Tracer Recovery
	m^3	---	$L\ s^{-1}$	h	h	---	h	---	---	---	%
Advanced Bioreactor 1	51.9	3.39	1.15	13	16±7.3	1.26	10	2.98	0.68	0.82	90
Advanced Bioreactor 2	49.6	3.38	0.67	20	35±12	1.73	31	2.29	0.69	1.52	78
Advanced Bioreactor 3	50.2	4.39	0.84	17	22±11	1.34	18	2.81	0.65	1.10	94
NERF	56.5	2.51	0.67	23	25±10	1.06	19	3.23	0.53	0.81	158
IL FB Henry Co.	7.92	3.57	0.11	20	20±10	0.99	16	3.59	0.60	0.81	44
Mercer Co.	12.4	1.10	0.19	18	3.1±1.6	0.17	2.2	3.15	0.64	0.12	15

The Advanced Bioreactor's *e*, MDI, *S* were all closer to the ideal values and indicated the advanced design was performing more efficiently than the conventional bioreactors, and in fact, the Advanced Bioreactor design did exhibit greater hydraulic efficiencies (λ) compared to the conventional designs (Table 4; Advanced: 0.82-1.52; conventional: 0.12-0.81). A theoretically ideal reactor would have a hydraulic efficiency of 1.0, and Persson et al. (1999) stated values greater than 0.75 indicate "good" hydraulic performance. All the hydraulic efficiency values except the Mercer Co. test fell within the "good" category, with the Advanced Bioreactor having two tests that exceeded the ideal λ =1.0 (Table 4). The Advanced Bioreactor tended to have the tracer peak elute later than the conventional designs, generally at greater than 1.0 cumulative pore volumes (Figure 2). This may serve as an indication of an elongated flow path relative to the dimensions of the Advanced Bioreactor, as the theoretical retention time used in the hydraulic efficiency calculation is based upon the physical dimensions of the reactor.

There were some other general nuances of these tracer tests which could have been related to specific features of each bioreactor. For example, the NERF bioreactor was the oldest bioreactor tested (9 versus 1-2 y; Table 1), and this tracer test had the lowest short-circuiting metric (0.53) indicating relatively greater potential for short-circuiting at this site. It is possible that some preferential flow paths developed over time as the woodchip properties changed. Christianson et al. (2013) performed a tracer test at this bioreactor in May 2011 and reported an effective volume of 0.55, hydraulic efficiency of 0.40, a short-circuiting value of 0.76, and a MDI of 3.2. Since that time, there has been an improvement in the effective volume (1.06) and hydraulic efficiency (0.81), no notable change in dispersion (3.23), and increased likelihood of short-circuiting occurring (0.53) (Table 4). These changes indicate the NERF bioreactor may now be using its internal volume more effectively, with a reduction in dead zones as suspected in the earlier work, although with increased potential for preferential flow paths. Importantly, comparison of these two tests indicates that bioreactor hydraulic properties can change over time.

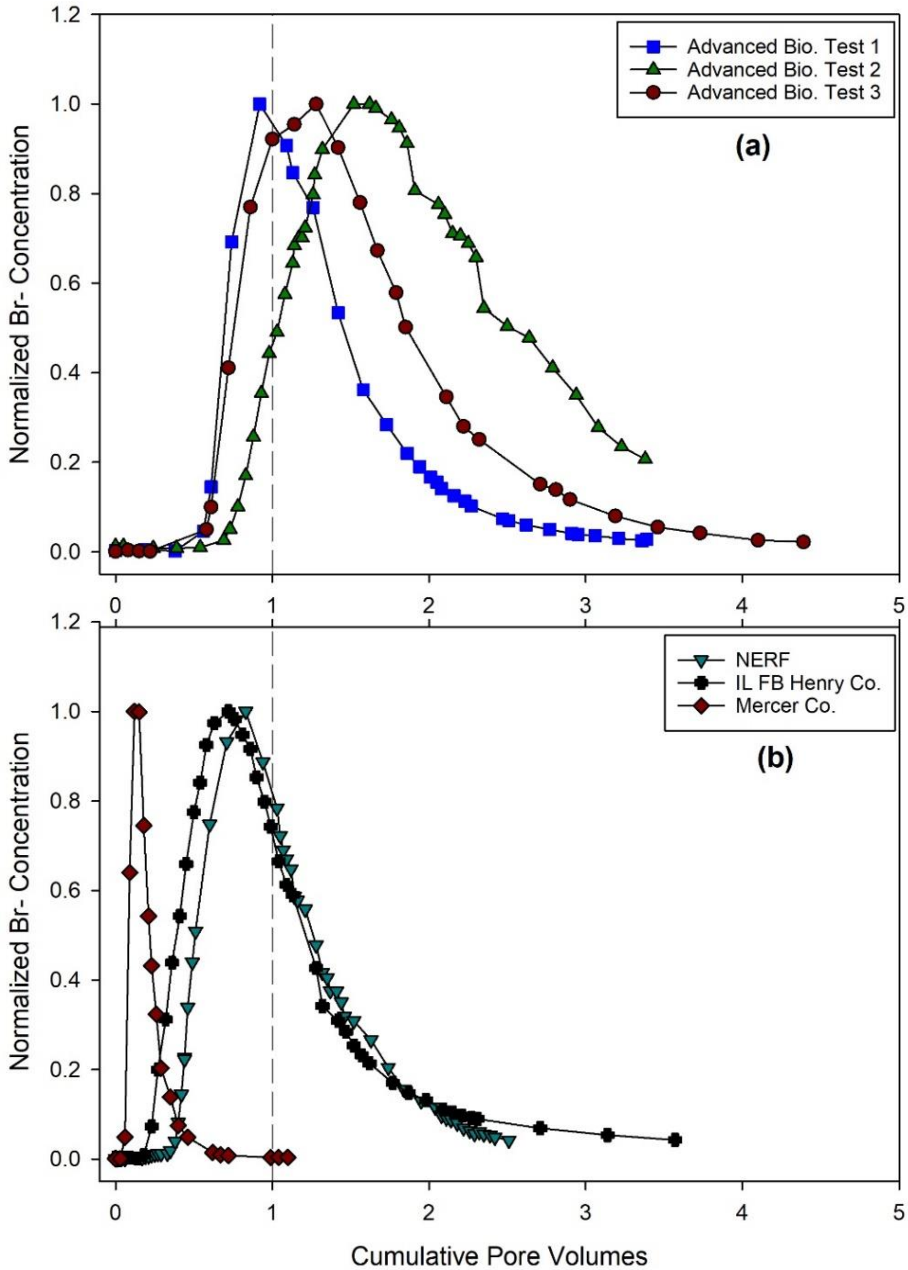

Figure 2. Treatment tracer testing curves (a: Advanced Bioreactor tests 1, 2, 3) versus control curves (b: NERF, IL Farm Bureau Henry Co., Mercer Co.) with concentrations normalized to the highest outflow bromide concentration for each test. The dashed vertical line indicates 1.0 cumulative pore volume when a theoretically ideal tracer test would peak.

The NERF and Henry Co. bioreactor tracer tests were remarkably similar (Figure 2b), despite large differences in bioreactor volume (Table 1), pore volume (Table 4), and age. The Henry Co.

tracer test resulted in slightly higher dispersion and lower potential for short-circuiting compared to the NERF tracer, but in general, both designs resulted in effective plug flow (that is, no internal mixing within the reactor; Kadlec and Wallace, 2009). These two bioreactors had the highest length to width ratio (> 5.0; Table 1), which is known to be important for achieving plug flow (Persson et al., 1999).

The Mercer Co. bioreactor was installed with chipped storm debris obtained for free which was notably different than the woodchips used in the other bioreactors (e.g., uniformity coefficient, bulk density, porosity; Table 2). It is possible this bioreactor's different bulk density and porosity, in particular, may have resulted in the extremely early peak and very low effective volume and hydraulic efficiency (0.17 and 0.12, respectively; Table 4). Further tracer testing here will be important to establish if this was the case, as the cost of this bioreactor's installation was very low (≈$4,000) due in part to the free fill media.

3.2 Advanced Bioreactor Nutrient Removal Performance

3.2.1 Nitrate-N Removal

The Advanced Bioreactor design resulted in 23 and 24% overall N load reduction in Years 1 and 2 (3.19 and 3.98 kg N ha^{-1} removed, respectively), considering only 40 and 41% of the flow from the field was routed into the bioreactor during the two years, respectively (Table 5; Figure 3c). Rainfall during these two periods was 506 and 970 mm, with approximately 24 and 20% of this occurring as drainage from the field (some of which was treated, some of which bypassed). The water routed into the bioreactor had 64 and 62% of the N load removed, equating with N removal rates of 1.30 and 1.25 g N m^{-3} d^{-1} for the two periods (Table 5). Bioreactor influent nitrate-N concentrations ranged from 0.01-22 mg N L^{-1} (Figure 3a) with the highest values corresponding with flow events following freezing and/or dry periods (e.g., February 2017 and 2018) and following pre-plant and side-dress fertilizer applications (May and June 2017; May and June 2018). Regardless, influent nitrate concentrations were often below the U.S. EPA maximum contaminant level of 10 mg L^{-1} NO_3-N (USEPA, 2018), and the bioreactor effluent concentrations only exceeded this level three times (28 April 2017 and 20-21 February 2018; n = 311 effluent NO_3-N samples).

Table 5. Nitrate-N and dissolved phosphorus removal at the Advanced Bioreactor during the first two years of operation (07 February 2017 through 31 July 2018; assessed by water year). Bioreactor and Overall N removal efficiency (%) reflected the percentage of nitrate removed from water that was treated and from total water from the field (treated + bypass), respectively. Removal rates were based on the total bioreactor volume and the total number of days monitored (including days of no flow).

Water year	Flow treated	N mass load removed	Bioreactor N removal efficiency	Overall N removal efficiency	N removal rate	P mass load removed	Bioreactor P removal efficiency	Overall P removal efficiency	P removal rate
	%	kg N ha^{-1}	%	%	g N m^{-3} d^{-1}	g P ha^{-1}	%	%	g P m^{-3} d^{-1}
2017	40	3.19	64	23	1.30	26.0	72	24	0.011
2018	41	3.98	62	24	1.25	246	74	23	0.077

While the tracer testing indicated the Advanced Bioreactor was potentially a more effective design hydraulically, this did not necessarily result in increased nitrate removal performance compared to other bioreactors in literature. For example, the Illinois Nutrient Loss Reduction Strategy assigned bioreactors a 25% NO_3-N load reduction (IEPA and IDOA, 2015), and the performance of the Advanced Bioreactor was close to this literature review-based value (23 and 24%; Table 5). While other full-size bioreactors range in effectiveness from 9-62% N load reduction at the edge of the field, many of the published values average around approximately 30% N removal (Christianson et al., 2012a; Husk et al., 2017; Rosen & Christianson, 2017)

The Advanced Bioreactor N removal rates (1.30-1.25 g N m^{-3} d^{-1}, Table 4) were lower than the mean removal rate of 4.70 g N m^{-3} d^{-1} for denitrifying beds reported in the recent bioreactor meta-analysis, although this published mean may have been skewed slightly higher due to the inclusion of several wastewater studies (Addy et al., 2016). The rates here were very consistent with the reported ranges of other tile drainage bioreactors. Christianson et al. (2012a) reported annual N removal rates ranging from 0.38 – 7.76 g N m^{-3} d^{-1} from four bioreactors across Iowa, and Rosen and Christianson (2017) reported removal rates of 0.21-5.36 g N m^{-3} d^{-1} for three tile drainage bioreactors in Maryland.

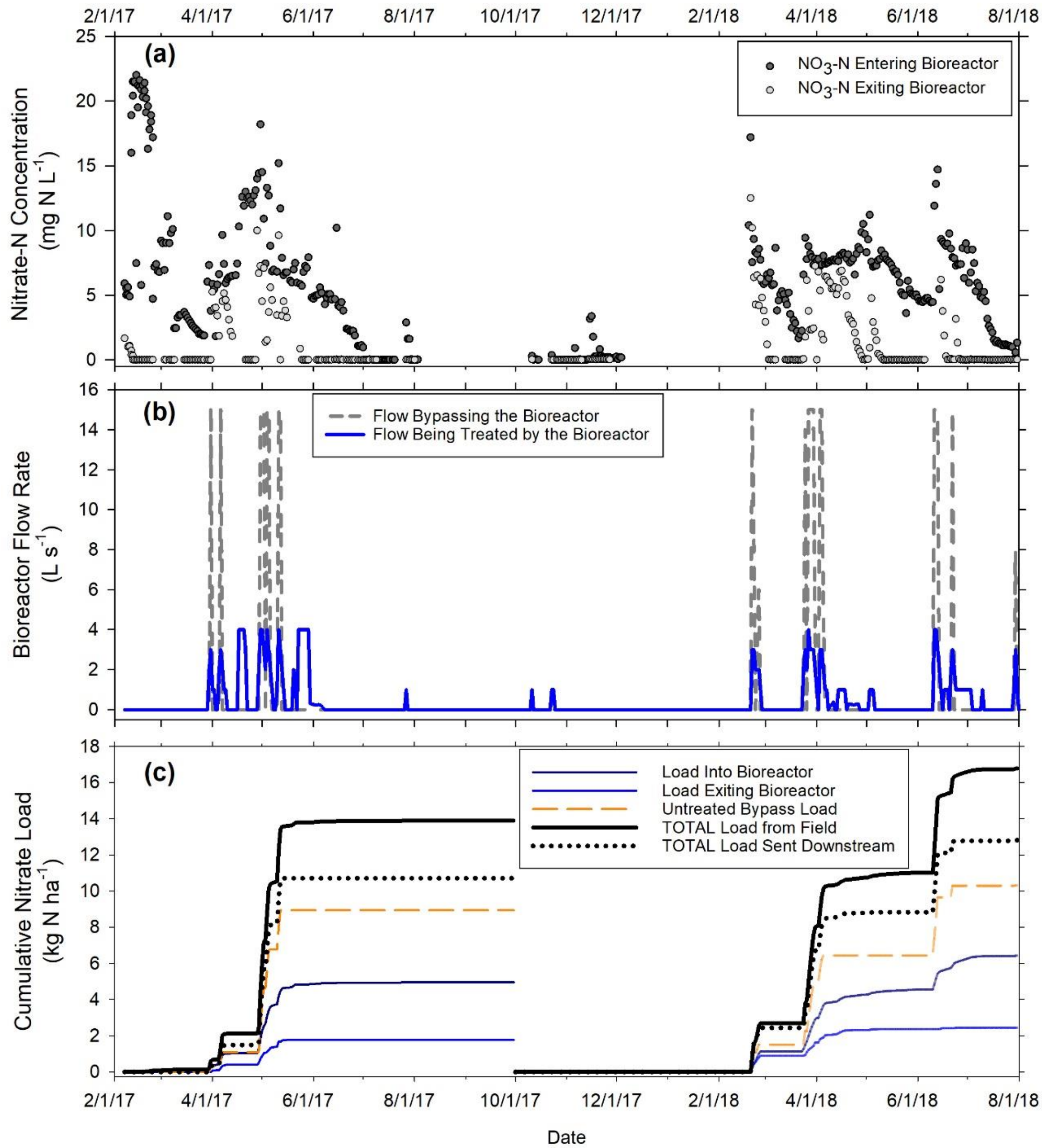

Figure 3. Advanced bioreactor influent and effluent nitrate-N concentrations (a), bioreactor and bypass flow rate (b), and cumulative nitrate-N loads (c) for nearly two years of monitoring.

An important design objective was to maximize the amount of flow treated while minimizing the bypass flow. The Advanced Bioreactor's treatment of 40 and 41% of the total annual drainage water (Table 5) was less than across reported literature where many values are between 60-95% (Christianson et al., 2012a; Hassanpour et al., 2017; Husk et al., 2017; Rosen & Christianson, 2017; Verma et al., 2010). This further confirmed that while the Advanced Bioreactor was well-functioning, it was not improving performance beyond previous observations. The drainage flow at this research site in particular appeared relatively flashy (Figure 3b) which might have at least partially accounted for the relatively lower percentages of drainage volumes treated. Due to the nature of full-size bioreactor trials, there can be no true "control" against which to compare this design. It is possible that a more conventionally designed bioreactor in place of the Advanced Bioreactor would have treated even less water, as a conventional design would likely have been narrower (i.e., the inflow manifold length might have restricted flow in a conventional design).

3.2.1.1 Advanced Bioreactor Well Monitoring

Tracer testing provides an indication of internal hydraulic performance but does not allow the assessment of internal reactor water chemistries since well samples were not collected during the tracer tests to conserve the tracer volume. To evaluate such internal water chemistries along the flow path, water samples from the twelve monitoring wells were collected during a variety of flow conditions. The collected water samples confirmed NO_3-N concentrations decreased along the flow path (Figure 4a). The inlet NO_3-N concentration was reduced to the detection limit by approximately half of the flow path length (or, approximately 13 m) for most sampling dates. Dissolved oxygen and ORP measured in the wells during a subset of events provided supporting evidence nitrate removal was due to denitrification. Anoxic conditions (< 0.5 mg DO L^{-1}, Tchobanoglous et al., 2003) were generally achieved within the bioreactor, especially considering the likely occurrence of anoxic microsites on the woodchips as compared to the bulk solution which was measured in the monitoring wells (Figure 4b). Denitrification occurs between -50 to +50 mV ORP (YSI, 2008), and those conditions were met within the bioreactor at different distances along the flow path depending upon the sampling date and water temperature.

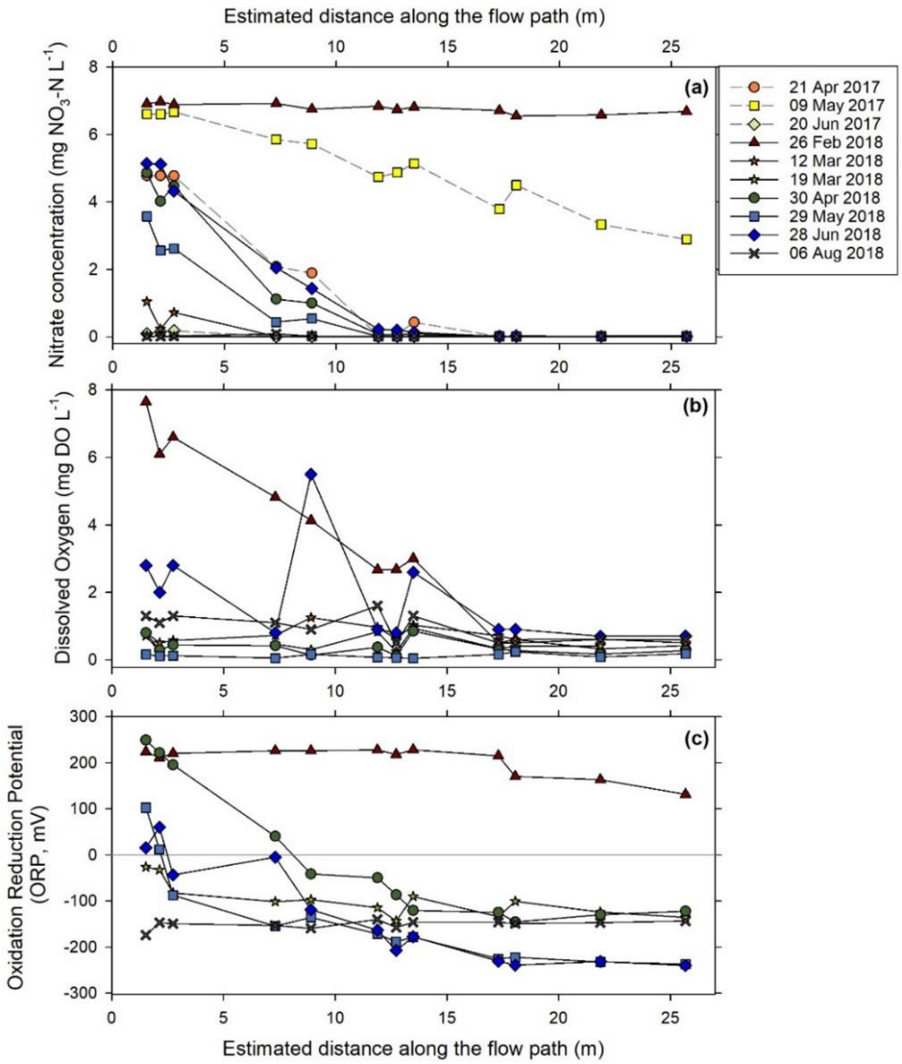

Figure 4. Nitrate-N concentrations (mg NO_3-N L^{-1}) (a), dissolved oxygen (mg DO L^{-1}) (b), and oxidation-reduction potential (mV) (c) observed in the 12 monitoring wells at the Advanced Bioreactor shown along the length of the estimated flow path.

Nitrate-N removal along the flow path during the first sampling event (21 April 2017; orange circles, Figure 4a) was consistent with many other sampling events indicating that conditions suitable for denitrification had been achieved, especially in the early portions of the bioreactor. The subsequent sampling event on 09 May 2017 (yellow squares, Figure 4a) occurred after a total of 174 mm of rain during the preceding two weeks and an in-field pre-plant nitrogen fertilizer application on 25 April. The relatively higher inflow NO_3-N concentration and potentially precipitation-induced flow fluctuation may account for the relatively lower N removal along the flow path on this date. The most notable deviation from most sampling events was February 2018 when the estimated hydraulic retention time was 13 h and the corresponding DO, ORP, and nitrate data showed little evidence of conditions suitable for denitrification (Figure 4). This was the first flow event of 2018 and it is likely that low water temperatures were a confounding factor.

3.2.2 Dissolved P Removal

Although denitrifying bioreactors are an edge of field practice meant to reduce NO_3-N loss, the Advanced Bioreactor also showed promising PO_4-P removal. Of the water that passed through the bioreactor, 72 and 74% of the PO_4-P load was removed per year, equating to P removal rates of 0.011 and 0.077 g P m^{-3} d^{-1} for the two periods, respectively (Table 5). When considering bypass flow, PO_4-P loads were reduced by 24 and 23% in years 1 and 2, respectively, at the edge of the field (26.0 and 246 g P ha^{-1} removed, respectively; Table 5, Figure 5).

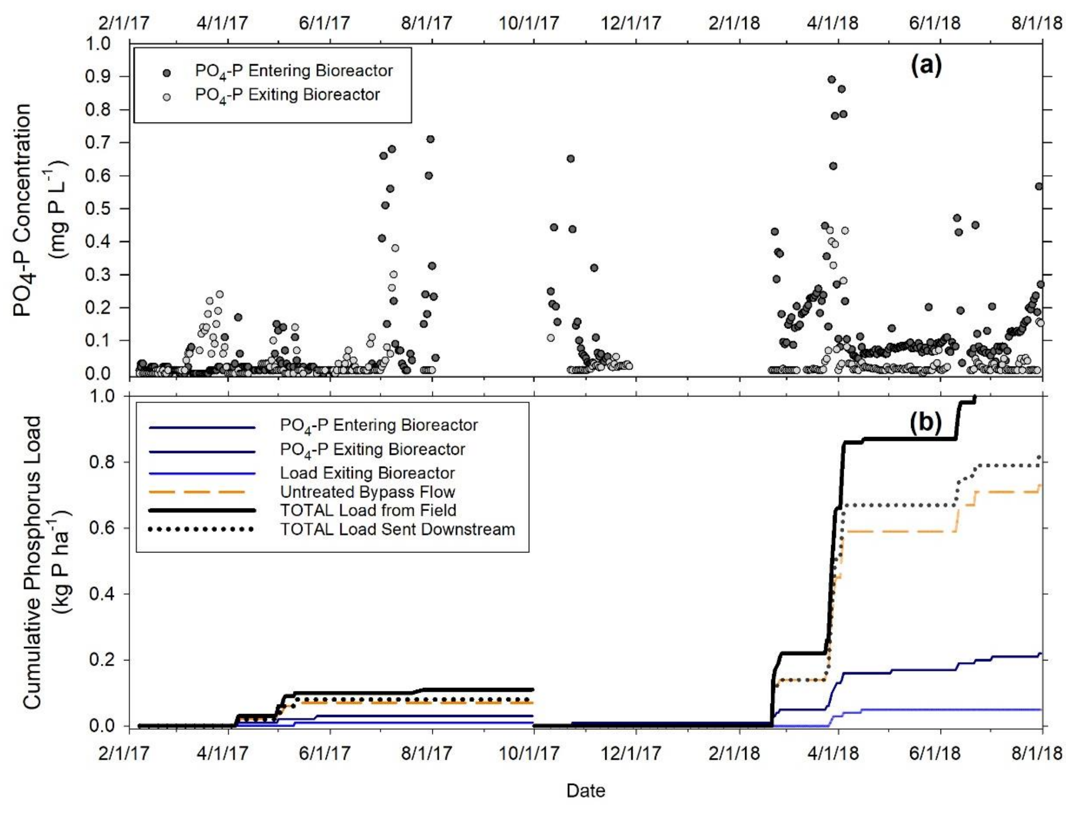

Figure 5. Advanced Bioreactor influent and effluent PO_4-P concentrations (mg P L^{-1}) (a) and cumulative PO_4-P loads (kg P ha^{-1}) (b) for nearly two water years of monitoring.

Bioreactor influent PO_4-P concentrations generally ranged from 0.01-0.75 mg P L^{-1} (Figure 5) with the highest values corresponding with high flow events (end of March 2018), startup of flow after a dry period (mid-February 2018), and potentially higher water temperatures (e.g., inflow PO_4-P concentrations reached greater than 0.50 several days during July 2017). A multi-year P fertilizer application was applied in November 2017 (≈ 335 kg ha^{-1} triple superphosphate, 45% analysis P_2O_5 = 66 kg P ha^{-1}). Elevated bioreactor inflow PO_4-P concentrations were observed that fall and again in the spring when flow initiated (Figure 5a). During the no-flow period between those two periods, PO_4-P concentrations were extremely high in standing water in the inflow control structure (10-102 mg PO_4-P L^{-1}; data not shown), although this did not translate into an elevated load during this time due to no flow. Promisingly, effluent P concentrations have never been elevated above 0.44 mg PO_4-P L^{-1}, even after this fertilizer application. While 170 of 384 inflow samples (44%) exceeded the recommended U.S. EPA concentration of 0.0763 mg P L^{-1} for streams and rivers in eco-region 6 (USEPA, 2007), only 29 of 315 outflow samples (9%) exceeded this critical value. Moreover, 11 of these 29 sample events showed a reduction in PO_4-P concentration across the bioreactor. The most notable exception to this was in March 2017 where elevated bioreactor outflow P concentrations may have been related to woodchip P leaching as the bioreactor was within its first several months of flow.

Several previous bioreactor studies indicate woodchip bioreactors are initially a source of P, with potential for P removal over longer periods. Sharrer et al. (2016) found that following a P leaching period, DRP was removed at low flow rates (P removal: 28-35%). Husk et al. (2018) also reported initial woodchip P leaching, but later documented a soluble reactive P removal rate of 0.018 g m^{-3} d^{-1}, similar to the observed rates here. A bioreactor study at a commercial fish farm in Denmark observed high PO_4-P leaching during bioreactor start-up, but by week 15, there was no net release of total phosphorus or PO_4-P (von Ahnen et al., 2016). Mechanisms of P removal in woodchip bioreactors potentially include enhanced biological P removal with the help of polyphosphate accumulating organisms and P sorption (Sathasivan, 2009; Sims et al., 1998). Despite a small initial P leaching event, the Advanced Bioreactor has consistently been a P sink, but further investigation into the longevity of and mechanisms causing this unexpected removal are necessary (Figure 5).

4. CONCLUSIONS

The Advanced Bioreactor design had greater effective volume and hydraulic efficiency, and lower dispersion and short-circuiting metrics compared to conventionally designed bioreactors. The tracer testing data indicated that this novel bioreactor with baffles facilitated more effective reactor volume utilization, but this did not necessarily translate into improved NO_3-N removal. The overall performance of 23-24% N removal at the edge of the field was similar to many other published studies. Additionally, while this bioreactor was relatively wide to maximize the percentage of flow treated, only 40-41% of the annual flow volume was treated which is lower than many other studies. It is possible that a more conventionally-designed bioreactor in place of this novel design would have treated even less water, but this cannot be tested at the field scale due to the nature of full-size bioreactor field studies. The drainage system at this new research facility may have been inherently flashy which may have partially accounted for the lower than expected percentage of annual drainage volume treated and overall N load reduction. Regardless, tracer testing at this field-scale study of a denitrifying woodchip bioreactor with baffles indicated the idea of baffles is worth investigating at additional sites to improve the hydraulic performance of bioreactors treating tile drainage.

The Advanced Bioreactor also provided an unexpected benefit of PO_4-P removal. Further investigation into the mechanisms of this P removal and the ultimate fate of the removed P are important next steps. Further conservative tracer testing at additional denitrifying woodchip bioreactors is also suggested as these tests at the conventional bioreactors highlighted important nuances. For example, hydraulic properties can change over time (NERF bioreactor) and woodchip physical properties play an important role in bioreactor functioning (Mercer Co. bioreactor). Such further testing can help better inform bioreactor design models which are heavily based on expected hydraulic performance.

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APPENDIX A. – Dudley Smith Farm

Figure 6.The northwest half of the drainage plots at the University of Illinois Dudley Smith Research Farm (green; 14.2 ha) drain to the Advanced Bioreactor (red).

Figure 7. Aerial image of the Advanced Bioreactor detailing the well and baffle placement before the geofabric and soil cap was placed during construction.

APPENDIX B. – Tracer Test

Table 6. Listing of all potassium bromide (KBr) conservative tracer tests performed during this master's project with the location, date, solution details, and explanation for unsuccessful tests. DSF is the Dudley Smith Farm with the Advanced Bioreactor at Pana, Illinois; NERF is Iowa State University Northeastern Research Farm at Nashua, Iowa.

Tracer test	**Tracer date** MM/DD/YY	**Mass of KBr** kg	**Solution volume** L	**Explanation for unsuccessful tests**
Advanced Bioreactor, IL	02/24/17	2.5	18.9	Autosampler timing was insufficient to capture the full tracer curve
Advanced Bioreactor, IL	03/10/17	3.5	18.9	Autosampler timing was adjusted but still insufficient to capture the full tracer curve
Advanced Bioreactor, IL	04/14/17	3.5	18.9	Autosampler timing was adjusted but still insufficient to capture the full tracer curve
Advanced Bioreactor, IL	05/17/17	3.5	18.9	Autosampler programming error resulting in multiple samples in a given bottle
Advanced Bioreactor, IL	05/30/17	4.5	18.9	Successful in-field test procedure, but unexplained spikes in the tracer curve
NERF, IA	06/11/17	4.1	18.9	Flow data were not sufficiently recorded/verified in the field
Advanced Bioreactor, IL	03/07/18	3.5	18.9	Autosampler tubing failure resulting in insufficient samples collected
IL FB Henry Co., IL	03/13/18	1.0	8.0	Unexplained autosampler error *** Following this test, grab sampling by hand was made mandatory for every test. ***
Advanced Bioreactor, IL	03/20/18	3.5	18.9	Autosampler tubing failure resulted in insufficient data despite additional hand sampling

Table 6. (cont.)

NERF, IA	04/01/18	4.1	18.9	Successful tracer curve; Autosampling plus hand samples
Advanced Bioreactor, IL	04/09/18	3.5	18.9	Successful tracer curve; Autosampling plus hand samples
Advanced Bioreactor, IL	04/23/18	3.5	18.9	Successful tracer curve; Autosampling plus hand samples
IL FB Henry Co., IL	05/10/18	1.0	8.0	Unexplained autosampler error
IL FB Henry Co., IL	06/05/18	1.0	8.0	Successful tracer curve; Autosampling plus hand samples
Mercer Co., IL	06/13/18	1.5	7	Successful tracer curve; Autosampling plus hand samples
Advanced Bioreactor, IL	06/17/18	3.5	18.9	Successful tracer curve; Autosampling plus hand samples
Advanced Bioreactor, IL	07/05/18	3.5	18.9	Autosampler timing was insufficient to capture the full tracer curve
Advanced Bioreactor, IL	07/17/18	3.5	18.9	Unexpected rainfall flooded the site during the tracer test

INSTRUCTIONS			**Created by L Christianson and H Dougherty, Univ. of Illinois; September 2017								
Input numbers in these cells						Tracer Metrics:			Interpolate Morrill Dispersion Index:		
Values solved for						Average flow rate during test	1.1480	L/s	10	36940	Cumulative L
Ignore (intermediate calcs)			Tracer Solution			Active pore volume	51898.07	L	90	110169	Cumulative L
These equations must be adjusted for 10/90% based on the given data			Br per K Br	0.6723	Chemistry	Theroetical RT:	45209	sec	MDI	2.98	unitless
These equations must be adjusted for 16/50% based on the given data			g of KBr added to solution	3500	g KBr	Theoretical RT:	12.56	hr			
			Volume of solution added	18.9	L water	Sum of C X T	283795		Time to peak eluted	4/9/18 22:00	set = to time of peak Br conc
Bioreactor Dimensions (m):			total mg of Br added	2352956	mg Br	Sum of t^2 x C	326102194		Time to peak	0.43	d
L	16.76	m	Theoretical solution concentration	124495	mg Br/L	Q5/Summed Conc	948.42		Time to peak	10.25	hr
D	0.39	m, flow depth, NOT bio. Depth	Observed sample of tracer solution (lab analysis)	113000	mg Br/L	Tracer residence time (mean)	15.81	hr		0.816	CPV
W	10.67	m	% difference	9.23	Desire w/in 10%		436.243		Hydraulic Efficiency	0.82	<- λ = tp/T
			Mass of Br injected	2135700	mg Br	Tracer res. time (variance)	7.27	hr			
Active (saturated) volume:	70.13	m3									
Woodchip porostiy:	0.74					Effective Volume (e):	1.26	<- e=t/T	16	512.35	Cumulative min
			Summed Concentration	299					50	749.44	Cumulative min
Pore volume	51.90	m3	Max	41	mg Br/L	Sum of L* Conc	1920740	mg Br	Short Circuiting Index	0.68	unitless
Pore volume	51898.07	L				Tracer Recovery:	90	Should be <100%			

Figure 8. Example screenshot of tracer testing metrics calculations performed for each tracer test based on the raw tracer and flow data (see below Figures 9.-14.).

Sample #	4/9/2018 11:45 Sample Time	------ Flow rate (L/s)	Incremental volume (L)	Cumulative volume (L)	Cumulative pore volumes	Br- Conc	Change in minutes	Cumulative Time (min)	C/C0	Cumulative Conc.	Cumulative % Conc	C x t	t^2 x C	Normalized Conc.	mg L* conc
2 hr 1	4/9/18 12:00	1.417	0	0.00	0.00	0.12		0	0.00000107	0.121	0	0	0	0.003	0
2 hr 2	4/9/18 14:00	1.386	9979	9978.96	0.19	0.19	120	120	0.00000165	0.307	0.10	22.32	2678	0.005	1856
2 hr 3	4/9/18 16:00	1.355	9756	19734.49	0.38	0.10	120	240	0.00000090	0.409	0.14	24.48	5875	0.002	995
2 hr 4	4/9/18 18:00	1.324	9532	29266.58	0.56	1.89	120	360	0.00001673	2.299	0.77	680.4	244944	0.046	18016
6hr 2	4/9/18 18:30	1.316	2369	31635.63	0.61	5.97	30	390	0.00005283	8.269	2.76	2328.3	908037	0.145	14143
2 hr 5	4/9/18 20:00	1.293	6981	38617.12	0.74	28.50	90	480	0.00025221	36.769	12.29	13680	6566400	0.692	198972
2hr 6	4/9/18 22:00	1.262	9085	47702.33	0.92	41.20	120	600	0.00036460	77.969	26.06	24720	14832000	1.000	374311
2hr 7	4/10/18 0:00	1.231	8862	56564.11	1.09	37.40	120	720	0.00033097	115.369	38.56	26928	19388160	0.908	331430
6hr 3	4/10/2018 0:30	1.223	2201	58765.59	1.13	34.90	30	750	0.00030885	150.269	50.22	26175	19631250	0.847	76832
2 hr 8	4/10/18 2:00	1.200	6479	65244.34	1.26	31.70	90	840	0.00028053	181.969	60.81	26628	22367520	0.769	205376
2 hr 9	4/10/18 4:00	1.169	8415	73659.24	1.42	22.00	120	960	0.00019469	203.969	68.16	21120	20275200	0.534	185128
2 hr 10	4/10/18 6:00	1.138	8191	81850.71	1.58	14.90	120	1080	0.00013186	218.869	73.14	16092	17379360	0.362	122053
2 hr 11	4/10/18 8:00	1.107	7968	89818.73	1.73	11.70	120	1200	0.00010354	230.569	77.05	14040	16848000	0.284	93226
HS 1	4/10/18 9:45	1.080	6801	96619.69	1.86	9.05	105	1305	0.00008009	239.619	80.08	11810	15412376	0.220	61549
HS 3	4/10/18 10:45	1.064	3830	100450.09	1.94	7.81	60	1365	0.00006912	247.429	82.69	10661	14551787	0.190	29915
HS 5	4/10/18 11:45	1.064	3830	104280.49	2.01	6.87	60	1425	0.00006080	254.299	84.98	9789.8	13950394	0.167	26315
HS 6	4/10/18 12:15	1.064	1915	106195.69	2.05	6.43	30	1455	0.00005690	260.729	87.13	9355.6	13612471	0.156	12315
HS 7	4/10/18 12:45	1.064	1915	108110.89	2.08	5.81	30	1485	0.00005142	266.539	89.08	8627.9	12812357	0.141	11127
HS 9	4/10/18 13:45	1.064	3830	111941.29	2.16	5.15	60	1545	0.00004558	271.689	90.80	7956.7	12293179	0.125	19727
HS 11	4/10/18 14:45	1.064	3830	115771.69	2.23	4.65	60	1605	0.00004115	276.339	92.35	7463.3	11978516	0.113	17811
HS 12	4/10/18 15:15	1.064	1915	117686.89	2.27	4.22	30	1635	0.00003735	280.559	93.76	6899.7	11281009	0.102	8082
2 hr 16	4/10/18 18:00	1.064	10534	128220.49	2.47	3.04	165	1800	0.00002690	283.599	94.78	5472	9849600	0.074	32022
6hr 6	4/10/2018 18:30	1.064	1915	130135.69	2.51	2.89	30	1830	0.00002558	286.489	95.74	5288.7	9678321	0.070	5535
2 hr 17	4/10/18 20:00	1.064	5746	135881.29	2.62	2.46	90	1920	0.00002177	288.949	96.56	4723.2	9068544	0.060	14134
2 hr 18	4/10/18 22:00	1.064	7661	143542.09	2.77	2.04	120	2040	0.00001805	290.989	97.25	4161.6	8489664	0.050	15628
2 hr 19	4/11/18 0:00	1.064	7661	151202.89	2.91	1.70	120	2160	0.00001504	292.689	97.81	3672	7931520	0.041	13023
6hr 7	4/11/2018 0:30	1.064	1915	153118.09	2.95	1.62	30	2190	0.00001434	294.309	98.36	3547.8	7769682	0.039	3103
2 hr 20	4/11/18 2:00	1.064	5746	158863.69	3.06	1.49	90	2280	0.00001319	295.799	98.85	3397.2	7745616	0.036	8561
2 hr 21	4/11/18 4:00	1.064	7661	166524.49	3.21	1.24	120	2400	0.00001097	297.039	99.27	2976	7142400	0.030	9499
2 hr 22	4/11/18 6:00	1.064	7661	174185.29	3.36	1.02	120	2520	0.00000903	298.059	99.61	2570.4	6477408	0.025	7814
6hr 8	4/11/2018 6:30	1.064	1915	176100.49	3.39	1.17	30	2550	0.00001035	299.229	100.00	2983.5	7607925	0.028	2241

Figure 9. Raw tracer and flow data for the Advanced Bioreactor Tracer Test #1 (04/09/18). The green and blue highlighting refer to the calculation of Morrill Dispersion Index and the Short-circuiting Index, respectively (See Figure 6. above).

	4/23/2018 11:32		Incremental	Cumulative	Cumulative		Change in	Cumulative		Cumulative	Cumulative			Normalized	mg
Sample #	Sample Time	Flow rate (L/s)	volume (L)	volume (L)	pore volumes	Br- Conc	minutes	Time (min)	C/CO	Conc.	% Conc	C x t	t^2 x C	Conc.	L^ conc
1HR_1	4/23/18 11:30	0.674	0	0.00	0.00	0.31		0	0.00000256	0.307	0	0	0	0.013	0
1HR_2	4/23/18 12:30	0.674	2426	2426.40	0.05	0.30	60	60	0.00000252	0.609	0.12	18.12	1087	0.013	733
1HR_6	4/23/18 16:30	0.674	9706	12132.00	0.24	0.18	240	300	0.00000149	0.788	0.15	53.7	16110	0.008	1737
1HR_9	4/23/2018 19:30	0.674	7279	19411.20	0.39	0.18	180	480	0.00000151	0.969	0.19	86.88	41702	0.008	1318
1HR_12	4/23/18 22:30	0.674	7279	26690.40	0.54	0.24	180	660	0.00000198	1.206	0.24	156.42	103237	0.010	1725
1HR_15	4/24/18 1:30	0.674	7279	33969.60	0.69	0.59	180	840	0.00000488	1.791	0.35	491.4	412776	0.026	4258
1HR_16	4/24/18 2:30	0.674	2426	36396.00	0.73	1.16	60	900	0.00000967	2.951	0.58	1044	939600	0.051	2815
1HR_17	4/24/18 3:30	0.674	2426	38822.40	0.78	2.31	60	960	0.00001925	5.261	1.03	2217.6	2128896	0.101	5605
1HR_18	4/24/18 4:30	0.674	2426	41248.80	0.83	3.88	60	1020	0.00003233	9.141	1.79	3957.6	4036752	0.170	9414
1HR_19	4/24/18 5:30	0.674	2426	43675.20	0.88	5.85	60	1080	0.00004875	14.991	2.93	6318	6823440	0.257	14194
1HR_20	4/24/18 6:30	0.674	2426	46101.60	0.93	8.08	60	1140	0.00006733	23.071	4.51	9211.2	10500768	0.354	19605
1HR_21	4/24/18 7:30	0.674	2426	48528.00	0.98	10.10	60	1200	0.00008417	33.171	6.48	12120	14544000	0.443	24507
1HR_22	4/24/18 8:30	0.674	2426	50954.40	1.03	11.20	60	1260	0.00009333	44.371	8.67	14112	17781120	0.491	27176
1HR_23	4/24/2018 9:30	0.674	2426	53380.80	1.08	13.10	60	1320	0.00010917	57.471	11.23	17292	22825440	0.575	31786
1HR_24	4/24/18 10:30	0.674	2426	55807.20	1.13	14.70	60	1380	0.00012250	72.171	14.11	20286	27994680	0.645	35668
HS 1	4/24/18 10:45	0.674	607	56413.80	1.14	15.60	15	1395	0.00013000	87.771	17.15	21762	30357990	0.684	9463
1HR_25	4/24/18 11:30	0.674	1820	58233.60	1.17	16.00	45	1440	0.00013333	103.771	20.28	23040	33177600	0.702	29117
HS 3	4/24/18 11:45	0.674	607	58840.20	1.19	16.00	15	1455	0.00013333	119.771	23.41	23280	33872400	0.702	9706
HS 4	4/24/18 12:15	0.674	1213	60053.40	1.21	16.50	30	1485	0.00013750	136.271	26.63	24502.5	36386213	0.724	20018
HS 6	4/24/18 13:15	0.674	2426	62479.80	1.26	18.20	60	1545	0.00015167	154.471	30.19	28119	43443855	0.798	44160
1HR_27	4/24/2018 13:30	0.674	607	63086.40	1.27	19.20	15	1560	0.00016000	173.671	33.94	29952	46725120	0.842	11647
1HR_28	4/24/18 14:30	0.674	2426	65512.80	1.32	20.50	60	1620	0.00017083	194.171	37.95	33210	53800200	0.899	49741
1HR_32	4/24/18 18:30	0.674	9706	75218.40	1.52	22.80	240	1860	0.00019000	216.971	42.41	42408	78878880	1.000	221288
1HR_34	4/24/18 20:30	0.674	4853	80071.20	1.62	22.80	120	1980	0.00019000	239.771	46.86	45144	89385120	1.000	110644
1HR_35	4/24/18 21:30	0.674	2426	82497.60	1.66	22.60	60	2040	0.00018833	262.371	51.28	46104	94052160	0.991	54837
1HR_37	4/24/18 23:30	0.674	4853	87350.40	1.76	22.00	120	2160	0.00018333	284.371	55.58	47520	102643200	0.965	106762
1HR_38	4/25/18 0:30	0.674	2426	89776.80	1.81	21.60	60	2220	0.00018000	305.971	59.80	47952	106453440	0.947	52410
1HR_39	4/25/18 1:30	0.674	2426	92203.20	1.86	20.80	60	2280	0.00017333	326.771	63.87	47424	108126720	0.912	50469
1HR_40	4/25/18 2:30	0.674	2426	94629.60	1.91	18.40	60	2340	0.00015333	345.171	67.46	43056	100751040	0.807	44646
1HR_43	4/25/2018 5:30	0.674	7279	101908.80	2.06	17.7	180	2520	0.00014750	362.871	70.92	44604	112402080	0.776	128842
1HR_44	4/25/18 6:30	0.674	2426	104335.20	2.10	17.2	60	2580	0.00014333	380.071	74.28	44376	114490080	0.754	41734
1HR_45	4/25/18 7:30	0.674	2426	106761.60	2.15	16.2	60	2640	0.00013500	396.271	77.45	42768	112907520	0.711	39308
1HR_46	4/25/18 8:30	0.674	2426	109188.00	2.20	16.1	60	2700	0.00013417	412.371	80.60	43470	117369000	0.706	39065
1HR_47	4/25/18 9:30	0.674	2426	111614.40	2.25	15.7	60	2760	0.00013083	428.071	83.67	43332	119596320	0.689	38094
1HR_48	4/25/18 10:30	0.674	2426	114040.80	2.30	15	60	2820	0.00012500	443.071	86.60	42300	119286000	0.658	36396
3 hr_17	4/25/18 11:30	0.674	2426	116467.20	2.35	12.4	60	2880	0.00010333	455.471	89.02	35712	102850560	0.544	30087
3 hr_18	4/25/18 14:30	0.674	7279	123746.40	2.50	11.5	180	3060	0.00009583	466.971	91.27	35190	107681400	0.504	83711
3 hr_19	4/25/18 17:30	0.674	7279	131025.60	2.64	10.9	180	3240	0.00009083	477.871	93.40	35316	114423840	0.478	79343
3 hr_20	4/25/18 20:30	0.674	7279	138304.80	2.79	9.37	180	3420	0.00007808	487.241	95.23	32045.4	109595268	0.411	68206
3 hr_21	4/25/18 23:30	0.674	7279	145584.00	2.94	7.99	180	3600	0.00006658	495.231	96.79	28764	103550400	0.350	58161
3 hr_22	4/26/18 2:30	0.674	7279	152863.20	3.08	6.34	180	3780	0.00005283	501.571	98.03	23965.2	90588456	0.278	46150
3 hr_23	4/26/18 5:30	0.674	7279	160142.40	3.23	5.36	180	3960	0.00004467	506.931	99.08	21225.6	84053376	0.235	39017
3 hr_8	4/26/18 8:30	0.674	7279	167421.60	3.38	4.71	180	4140	0.00003925	511.641	100.00	19499.4	80727516	0.207	34285

Figure 10. Raw tracer and flow data for the Advanced Bioreactor Tracer Test #2 (04/23/18). The green and blue highlighting refer to the calculation of Morrill Dispersion Index and the Short-circuiting Index, respectively (See Figure 6. above).

Sample #	Sample Time	Flow rate (L/s)	Incremental volume (L)	Cumulative volume (L)	Cumulative pore volumes	Br- Conc	Change in minutes	Cumulative Time (min)	C/C0	Cumulative Conc.	Cumulative % Conc	C x t	t^2 x C	Normalized Conc.	mg L- conc
	6/17/18 11:50	---													
DSF_2 hr_1	6/17/18 12:00	1.064	0	0.00	0.00	0.04		0	0.00000035	0.0384	0	0	0	0.001	0
DSF_HS_1	6/17/18 13:00	1.064	3831	3831.28	0.08	0.14	60	60	0.00000124	0.1764	0.06	8.28	497	0.004	529
DSF_2 hr_2	6/17/18 14:00	1.011	3638	7469.11	0.15	0.05	60	120	0.00000044	0.2251	0.08	5.844	701	0.002	177
DSF_HS_2	6/17/18 15:00	1.011	3638	11106.94	0.22	0.02	60	180	0.00000021	0.2479	0.09	4.104	739	0.001	83
DSF_2 hr_5	6/17/18 20:00	0.997	17941	29048.31	0.58	1.55	300	480	0.00001396	1.7979	0.64	744	357120	0.050	27809
DSF_8hr_2	6/17/18 20:30	0.995	1792	30839.97	0.61	3.08	30	510	0.00002775	4.8779	1.72	1571	801108	0.100	5518
DSF_2 hr_6$Diluted	6/17/18 22:00	0.991	5353	36192.64	0.72	12.70	90	600	0.00011441	17.5779	6.21	7620	4572000	0.411	67979
DSF_2 hr_7$Diluted	6/18/18 0:00	0.986	7097	43289.89	0.86	23.80	120	720	0.00021441	41.3779	14.62	17136	12337920	0.770	168915
DSF_2 hr_8$Diluted	6/18/18 2:00	0.980	7058	50347.50	1.00	28.50	120	840	0.00025676	69.8779	24.68	23940	20109600	0.922	201142
DSF_2 hr_9$Diluted	6/18/2018 4:00	0.975	7018	57365.46	1.14	29.50	120	960	0.00026577	99.3779	35.10	28320	27187200	0.955	207030
DSF_2 hr_10$Diluted	6/18/18 6:00	0.969	6978	64343.77	1.28	30.90	120	1080	0.00027838	130.2779	46.02	33372	36041760	1.000	215630
DSF_2 hr_11$Diluted	6/18/18 8:00	0.964	6939	71282.43	1.42	27.90	120	1200	0.00025135	158.1779	55.87	33480	40176000	0.903	193589
DSF_2 hr_12$Diluted	6/18/18 10:00	0.958	6899	78181.45	1.56	24.10	120	1320	0.00021712	182.2779	64.39	31812	41991840	0.780	166266
DSF_2 hr_13$Diluted	6/18/2018 12:00	0.810	5830	84011.86	1.67	20.80	120	1440	0.00018739	203.0779	71.74	29952	43130880	0.673	121272
DSF_2 hr_14$Diluted	6/18/18 14:00	0.810	5830	89842.26	1.79	17.90	120	1560	0.00016126	220.9779	78.06	27924	43561440	0.579	104364
DSF_HS_5$Diluted	6/18/18 15:00	0.763	2747	92589.57	1.85	15.50	60	1620	0.00013964	236.4779	83.53	25110	40678200	0.502	42583
2 hr Reset 3	6/18/18 20:00	0.740	13315	105904.31	2.11	10.70	300	1920	0.00009640	247.1779	87.31	20544	39444480	0.346	142468
2 hr Reset 4	6/18/18 22:00	0.730	5258	111162.73	2.22	8.64	120	2040	0.00007784	255.8179	90.37	17626	35956224	0.280	45433
2 hr Reset 5	6/19/18 0:00	0.721	5191	116353.66	2.32	7.75	120	2160	0.00006982	263.5679	93.10	16740	36158400	0.251	40230
2 hr Reset 9	6/19/18 8:00	0.683	19684	136037.68	2.71	4.66	480	2640	0.00004198	268.2279	94.75	12302	32478336	0.151	91728
2 hr Reset 10	6/19/18 10:00	0.674	4854	140891.20	2.81	4.30	120	2760	0.00003874	272.5279	96.27	11868	32755680	0.139	20870
2 hr Reset 11	6/19/18 12:00	0.674	4854	145744.72	2.90	3.61	120	2880	0.00003252	276.1379	97.54	10397	29942784	0.117	17521
2 hr Reset 14	6/19/18 18:00	0.664	14349	160093.92	3.19	2.46	360	3240	0.00002216	278.5979	98.41	7970	25824096	0.080	35299
2 hr Reset 17	6/20/18 0:00	0.632	13645	173738.55	3.46	1.70	360	3600	0.00001532	280.2979	99.01	6120	22032000	0.055	23196
2 hr Reset 20	6/20/18 6:00	0.632	13645	187383.19	3.73	1.31	360	3960	0.00001180	281.6079	99.48	5188	20542896	0.042	17874
2 hr Reset 24	6/20/2018 14:00	0.632	18193	205576.03	4.10	0.80	480	4440	0.00000724	282.4119	99.76	3570	15849734	0.026	14627
DSF_Br_8 hr_11	6/20/2018 20:30	0.632	14782	220357.72	4.39	0.68	390	4830	0.00000614	283.0939	100.00	3294	15910310	0.022	10081

Figure 11. Raw tracer and flow data for the Advanced Bioreactor Tracer Test #3 (06/17/18). The green and blue highlighting refer to the calculation of Morrill Dispersion Index and the Short-circuiting Index, respectively (See Figure 6. above).

ISCO Samples	4/1/2018 10:30 Sample Time	------- Flow rate (L/s)	Incremental volume (L)	Cumulative volume (L)	Cumulative pore volumes	Br- Conc	Change in minutes	Cumulative Time (min)	C/C0	Cumulative Conc.	Cumulative % Conc	C x t	t^2 x C	Normalized Conc.	mg L^{-} conc
10:45:00 AM	4/1/18 10:45	0.658	0	0.00	0.00	0.09		0	0.00000066	0.0925	0	0	0	0.001	0
11:00:00 AM	4/1/18 11:00	0.659	593	592.95	0.01	0.11	15	15	0.00000080	0.20	0.02	1.68	25	0.001	66
11:15:00 AM	4/1/18 11:15	0.660	594	1186.66	0.02	0.10	15	30	0.00000070	0.30	0.02	2.955	89	0.001	58
11:45:00 AM	4/1/18 11:45	0.661	1190	2377.07	0.04	0.14	30	60	0.00000096	0.44	0.03	8.1	486	0.002	161
12:15:00 PM	4/1/18 12:15	0.663	1193	3570.50	0.06	0.08	30	90	0.00000056	0.52	0.04	7.011	631	0.001	93
2:45:00 PM	4/1/18 14:45	0.671	6042	9612.85	0.17	0.28	150	240	0.00000199	0.79	0.06	66.96	16070	0.003	1686
3:15:00 PM	4/1/18 15:15	0.673	1211	10824.33	0.19	0.51	30	270	0.00000362	1.30	0.10	136.89	36960	0.006	614
3:45:00 PM	4/1/18 15:45	0.675	1214	12038.81	0.21	0.60	30	300	0.00000431	1.91	0.14	181.2	54360	0.007	734
4:02:00 PM	4/1/18 16:02	0.676	689	12727.99	0.23	0.88	17	317	0.00000628	2.78	0.21	278.643	88330	0.010	606
4:30:00 PM	4/1/18 16:30	0.677	1138	13865.72	0.25	0.95	28	345	0.00000675	3.73	0.28	326.025	112479	0.011	1075
5:00:00 PM	4/1/18 17:00	0.679	1222	15087.73	0.27	1.00	30	375	0.00000714	4.73	0.35	375	140625	0.012	1222
5:30:00 PM	4/1/18 17:30	0.681	1225	16312.75	0.29	1.04	30	405	0.00000743	5.77	0.43	421.2	170586	0.012	1274
6:30:00 PM	4/1/18 18:30	0.684	2462	18774.82	0.33	1.15	60	465	0.00000821	6.92	0.51	534.75	248659	0.013	2831
7:00:00 PM	4/1/18 19:00	0.686	1234	20008.86	0.35	1.64	30	495	0.00001171	8.56	0.63	811.8	401841	0.019	2024
7:30:00 PM	4/1/18 19:30	0.687	1237	21245.91	0.38	3.43	30	525	0.00002450	11.99	0.89	1800.75	945394	0.040	4243
8:00:00 PM	4/1/18 20:00	0.689	1240	22485.97	0.40	7.11	30	555	0.00005079	19.10	1.42	3946.05	2190058	0.082	8817
8:30:00 PM	4/1/18 20:30	0.691	1243	23729.04	0.42	12.50	30	585	0.00008929	31.60	2.34	7312.5	4277813	0.145	15538
9:00:00 PM	4/1/18 21:00	0.692	1246	24975.12	0.44	19.60	30	615	0.00014000	51.20	3.79	12054	7413210	0.227	24423
9:02:00 PM	4/1/18 21:02	0.692	83	25058.20	0.44	19.30	2	617	0.00013786	70.50	5.22	11908.1	7347298	0.223	1604
9:30:00 PM	4/1/18 21:30	0.694	1166	26224.02	0.46	29.30	28	645	0.00020929	99.80	7.39	18898.5	12189533	0.339	34158
10:00:00 PM	4/1/18 22:00	0.696	1252	27476.11	0.49	38.00	30	675	0.00027143	137.80	10.21	25650	17313750	0.440	47580
10:30:00 PM	4/1/18 22:30	0.697	1255	28731.22	0.51	44.00	30	705	0.00031429	181.80	13.47	31020	21869100	0.509	55225
12:30:00 AM	4/2/18 0:30	0.704	5069	33799.77	0.60	64.60	120	825	0.00046143	246.40	18.26	53295	43968375	0.748	327429
3:00:00 AM	4/2/18 3:00	0.712	6411	40210.68	0.71	80.50	150	975	0.00057500	326.90	24.22	78487.5	76525313	0.932	516078
5:30:00 AM	4/2/18 5:30	0.721	6486	46696.81	0.83	86.40	150	1125	0.00061714	413.30	30.62	97200	109350000	1.000	560401
8:00:00 AM	4/2/18 8:00	0.729	6561	53258.16	0.94	76.60	150	1275	0.00054714	489.90	36.30	97665	124522875	0.887	502599
9:47:00 AM	4/2/18 9:47	0.735	4719	57976.86	1.03	67.70	107	1382	0.00048357	557.60	41.32	93561.4	129301855	0.784	319456
10:15:00 AM	4/2/18 10:15	0.734	1232	59209.19	1.05	62.40	28	1410	0.00044571	620.00	45.94	87984	124057440	0.722	76898
10:45:00 AM	4/2/18 10:45	0.732	1318	60526.72	1.07	59.70	30	1440	0.00042643	679.70	50.36	85968	123793920	0.691	78656
11:15:00 AM	4/2/18 11:15	0.730	1315	61841.42	1.09	57.90	30	1470	0.00041357	737.60	54.65	85113	125116110	0.670	76121
11:45:00 AM	4/2/18 11:45	0.729	1312	63153.29	1.12	56.00	30	1500	0.00040000	793.60	58.80	84000	126000000	0.648	73465
12:15:00 PM	4/2/18 12:15	0.727	1309	64462.33	1.14	50.70	30	1530	0.00036214	844.30	62.56	77571	118683630	0.587	66368
12:45:00 PM	4/2/18 12:45	0.726	1306	65768.54	1.16	49.90	30	1560	0.00035643	894.20	66.26	77844	121436640	0.578	65180
1:45:00 PM	4/2/18 13:45	0.723	2601	68369.64	1.21	48.20	60	1620	0.00034429	942.40	69.83	78084	126496080	0.558	125373
3:15:00 PM	4/2/18 15:15	0.718	3876	72245.82	1.28	41.30	90	1710	0.00029500	983.70	72.89	70623	120765330	0.478	160086
4:15:00 PM	4/2/18 16:15	0.715	2573	74818.62	1.32	36.00	60	1770	0.00025714	1019.70	75.56	63720	112784400	0.417	92621
4:45:00 PM	4/2/18 16:45	0.713	1284	76102.19	1.35	35.00	30	1800	0.00025000	1054.70	78.15	63000	113400000	0.405	44925
5:15:00 PM	4/2/18 17:15	0.712	1281	77382.93	1.37	32.50	30	1830	0.00023214	1087.20	80.56	59475	108839250	0.376	41624
6:15:00 PM	4/2/18 18:15	0.708	2550	79933.09	1.41	32.40	60	1890	0.00023143	1119.60	82.96	61236	115736040	0.375	82625
6:45:00 PM	4/2/18 18:45	0.707	1272	81205.34	1.44	30.30	30	1920	0.00021643	1149.90	85.20	58176	111697920	0.351	38549
7:15:00 PM	4/2/18 19:15	0.705	1269	82474.76	1.46	27.60	30	1950	0.00019714	1177.50	87.25	53820	104949000	0.319	35036
8:30:00 PM	4/2/18 20:30	0.701	3156	85630.63	1.52	26.70	75	2025	0.00019071	1204.20	89.23	54067.5	109486688	0.309	84262
11:00:00 PM	4/2/18 23:00	0.693	6241	91871.62	1.63	23.00	150	2175	0.00016429	1227.20	90.93	50025	108804375	0.266	143543
1:30:00 AM	4/3/18 1:30	0.686	6170	98041.86	1.74	17.70	150	2325	0.00012643	1244.90	92.24	41152.5	95679563	0.205	109213
4:00:00 AM	4/3/18 4:00	0.678	6099	104141.35	1.84	13.50	150	2475	0.00009643	1258.40	93.24	33412.5	82695938	0.156	82343
6:30:00 AM	4/3/18 6:30	0.670	6029	110170.10	1.95	11.20	150	2625	0.00008000	1269.60	94.07	29400	77175000	0.130	67522
9:00:00 AM	4/3/18 9:00	0.585	5265	115435.10	2.04	9.99	150	2775	0.00007136	1279.59	94.81	27722.3	76929244	0.116	52597
10:00:00 AM	4/3/18 10:00	0.585	2106	117541.10	2.08	8.45	60	2835	0.00006036	1288.04	95.44	23955.8	67914551	0.098	17796
10:45:00 AM	4/3/18 10:45	0.585	1580	119120.60	2.11	7.98	45	2880	0.00005700	1296.02	96.03	22982.4	66189312	0.092	12604
11:30:00 AM	4/3/18 11:30	0.585	1580	120700.10	2.14	7.57	45	2925	0.00005407	1303.59	96.59	22142.3	64766081	0.088	11957
12:45:00 PM	4/3/18 12:45	0.585	2633	123332.60	2.18	6.93	75	3000	0.00004950	1310.52	97.11	20790	62370000	0.080	18243
1:45:00 PM	4/3/18 13:45	0.585	2106	125438.60	2.22	6.01	60	3060	0.00004293	1316.53	97.55	18390.6	56275236	0.070	12657
2:45:00 PM	4/3/18 14:45	0.585	2106	127544.60	2.26	5.57	60	3120	0.00003979	1322.10	97.96	17378.4	54220608	0.064	11730
3:45:00 PM	4/3/18 15:45	0.585	2106	129650.60	2.29	4.89	60	3180	0.00003493	1326.99	98.33	15550.2	49449636	0.057	10298
4:30:00 PM	4/3/18 16:30	0.585	1580	131230.10	2.32	5.24	45	3225	0.00003743	1332.23	98.72	16899	54499275	0.061	8277
5:15:00 PM	4/3/18 17:15	0.585	1580	132809.60	2.35	4.81	45	3270	0.00003436	1337.04	99.07	15728.7	51432849	0.056	7597
6:15:00 PM	4/3/18 18:15	0.585	2106	134915.60	2.39	4.64	60	3330	0.00003314	1341.68	99.42	15451.2	51452496	0.054	9772
7:00:00 PM	4/3/18 19:00	0.585	1580	136495.10	2.42	4.23	45	3375	0.00003021	1345.91	99.73	14276.3	48182344	0.049	6681
9:30:00 PM	4/3/18 21:30	0.585	5265	141760.10	2.51	3.66	150	3525	0.00002614	1349.57	100.00	12901.5	45477788	0.042	19270

Figure 12. Raw tracer and flow data for the Iowa State University North Eastern Research Farm bioreactor tracer test (04/01/18). The green and blue highlighting refer to the calculation of Morrill Dispersion Index and the Short-circuiting Index, respectively (See Figure 6. above).

Sample #	6/5/2018 11:45 Sample Time	Flow rate (L/s)	Incremental volume (L)	Cumulative volume (L)	Cumulative pore volumes	Br- Conc	Change in minutes	Cumulative Time (min)	C/C0	Cumulative Conc.	Cumulative % Conc	C x t	t^2 x C	Normalized Conc.	mg L^{-} conc
20180608_VF_1Hr_1	6/5/18 12:00	0.102	0	0.00	0.00	0.12		0	0.00000150	0.115	0	0	0	0.003	0
20180608_VF_1Hr_2	6/5/18 13:30	0.101	547	546.63	0.07	0.15	90	90	0.00000191	0.262	0.04	13.23	1191	0.004	80
20180608_VF_1Hr_3	6/5/18 14:00	0.101	182	728.45	0.09	0.14	30	120	0.00000176	0.397	0.07	16.2	1944	0.004	25
20180608_VF_1Hr_4	6/5/18 15:00	0.101	362	1090.56	0.14	0.06	60	180	0.00000079	0.4581	0.08	10.998	1980	0.002	22
VF_1hr_5	6/5/18 16:00	0.100	361	1451.13	0.18	0.32	60	240	0.00000414	0.7761	0.13	76.32	18317	0.009	115
VF_1hr_6	6/5/18 17:00	0.100	359	1810.16	0.23	2.52	60	300	0.00003277	3.2961	0.56	756	226800	0.073	905
VF_1hr_7	6/5/18 18:00	0.099	357	2167.65	0.27	6.92	60	360	0.00008999	10.2161	1.73	2491.2	896832	0.200	2474
20180608_VF_1Hr_8$Diluted	6/5/18 19:00	0.099	356	2523.61	0.32	10.80	60	420	0.00014044	21.0161	3.56	4536	1905120	0.312	3844
20180608_VF_1Hr_9$Diluted	6/5/18 20:00	0.098	354	2878.02	0.36	15.20	60	480	0.00019766	36.2161	6.14	7296	3502080	0.439	5387
20180608_VF_1Hr_10$Diluted	6/5/18 21:00	0.098	353	3230.89	0.41	18.80	60	540	0.00024447	55.0161	9.33	10152	5482080	0.543	6634
20180608_VF_1Hr_11$Diluted	6/5/18 22:00	0.098	351	3582.23	0.45	22.80	60	600	0.00029649	77.8161	13.19	13680	8208000	0.659	8010
20180608_VF_1Hr_12$Diluted	6/5/18 23:00	0.097	350	3932.02	0.50	26.80	60	660	0.00034850	104.6161	17.74	17688	11674080	0.775	9375
20180608_VF_1Hr_13$Diluted_R	6/6/18 0:00	0.097	348	4280.28	0.54	29.10	60	720	0.00037841	133.7161	22.67	20952	15085440	0.841	10134
20180608_VF_1Hr_14$Diluted	6/6/18 1:00	0.097	350	4630.38	0.58	32.00	60	780	0.00041612	165.7161	28.10	24960	19468800	0.925	11203
20180608_VF_1Hr_15$Diluted	6/6/18 2:00	0.098	352	4982.31	0.63	33.70	60	840	0.00043823	199.4161	33.81	28308	23778720	0.974	11860
20180608_VF_1Hr_17$Diluted	6/6/18 4:00	0.099	711	5693.54	0.72	34.60	120	960	0.00044993	234.0161	39.67	33216	31887360	1.000	24609
20180608_VF_1Hr_18$Diluted	6/6/18 5:00	0.099	357	6051.00	0.76	34.00	60	1020	0.00044213	268.0161	45.44	34680	35373600	0.983	12153
20180608_VF_1Hr_19$Diluted	6/6/18 6:00	0.100	359	6410.29	0.81	32.80	60	1080	0.00042653	300.8161	51.00	35424	38257920	0.948	11785
20180608_VF_1Hr_20$Diluted	6/6/18 7:00	0.100	361	6771.42	0.86	31.70	60	1140	0.00041222	332.5161	56.37	36138	41197320	0.916	11448
20180608_VF_1Hr_21$Diluted	6/6/18 8:00	0.101	363	7134.40	0.90	29.50	60	1200	0.00038362	362.0161	61.38	35400	42480000	0.853	10708
20180608_VF_1Hr_22$Diluted	6/6/18 9:00	0.101	365	7499.21	0.95	27.60	60	1260	0.00035891	389.6161	66.05	34776	43817760	0.798	10069
20180608_VF_1Hr_23$Diluted	6/6/18 10:00	0.102	367	7865.86	0.99	25.70	60	1320	0.00033420	415.3161	70.41	33924	44779680	0.743	9423
20180608_VF_1Hr_24$Diluted	6/6/18 11:00	0.102	368	8234.35	1.04	23.00	60	1380	0.00029909	438.3161	74.31	31740	43801200	0.665	8475
20180608_VF_1Hr_25$Diluted	6/6/18 12:00	0.103	370	8604.69	1.09	21.20	60	1440	0.00027568	459.5161	77.91	30528	43960320	0.613	7851
20180608_VF_1Hr_26$Diluted	6/6/18 13:00	0.103	372	8976.86	1.13	20.40	60	1500	0.00026528	479.9161	81.36	30600	45900000	0.590	7592
VF_1hr_29$Diluted	6/6/18 16:00	0.105	1133	10109.93	1.28	14.78	180	1680	0.00019220	494.6961	83.87	24830.4	41715072	0.427	16747
VF_1hr_30$Diluted	6/6/18 17:00	0.105	380	10489.46	1.32	11.84	60	1740	0.00015397	506.5361	85.88	20601.6	35846784	0.342	4494
VF_1hr_32	6/6/18 19:00	0.106	766	11255.88	1.42	10.70	120	1860	0.00013914	517.2361	87.69	19902	37017720	0.309	8201
VF_1hr_33	6/6/18 20:00	0.107	385	11640.93	1.47	9.86	60	1920	0.00012822	527.0961	89.36	18931.2	36347904	0.285	3797
20180608_VF_1Hr_34$Diluted	6/6/18 21:00	0.107	387	12027.81	1.52	8.80	60	1980	0.00011443	535.8961	90.86	17424	34499520	0.254	3405
20180608_VF_1Hr_35	6/6/18 22:00	0.108	389	12416.54	1.57	8.04	60	2040	0.00010455	543.9361	92.22	16401.6	33459264	0.232	3125
20180608_VF_1Hr_36	6/6/18 23:00	0.108	391	12807.11	1.62	7.42	60	2100	0.00009649	551.3561	93.48	15582	32722200	0.214	2898
VF_1hr_39	6/7/18 2:00	0.110	1188	13995.37	1.77	5.89	180	2280	0.00007659	557.2461	94.47	13429.2	30618576	0.170	6999
VF_1hr_41	6/7/18 4:00	0.114	824	14819.60	1.87	5.13	120	2400	0.00006671	562.3761	95.34	12312	29548800	0.148	4228
VF_1hr_43	6/7/18 6:00	0.119	856	15675.90	1.98	4.56	120	2520	0.00005930	566.9361	96.12	11491.2	28957824	0.132	3905
20180608_VF_1Hr_45	6/7/18 8:00	0.123	888	16564.26	2.09	3.85	120	2640	0.00005007	570.7861	96.77	10164	26832960	0.111	3420
20180608_VF_1Hr_46	6/7/18 9:00	0.126	452	17016.45	2.15	3.61	60	2700	0.00004694	574.3961	97.38	9747	26316900	0.104	1632
20180608_VF_1Hr_47	6/7/18 10:00	0.128	460	17476.66	2.21	3.36	60	2760	0.00004369	577.7561	97.95	9273.6	25595136	0.097	1546
20180608_VF_1Hr_48	6/7/18 11:00	0.130	468	17944.89	2.27	3.20	60	2820	0.00004161	580.9561	98.49	9024	25447680	0.092	1498
VF_3hr_17	6/7/18 11:45	0.132	356	18300.57	2.31	3.12	45	2865	0.00004057	584.0761	99.02	8938.8	25609662	0.090	1110
VF_3hr_19	6/7/18 17:45	0.145	3134	21434.54	2.71	2.38	360	3225	0.00003095	586.4561	99.43	7675.5	24753488	0.069	7459
VF_3hr_21	6/7/18 23:45	0.158	3423	24857.07	3.14	1.88	360	3585	0.00002445	588.3361	99.75	6739.8	24162183	0.054	6434
VF_3hr_23	6/8/18 5:45	0.158	3423	28279.60	3.57	1.50	360	3945	0.00001951	589.8361	100.00	5917.5	23344538	0.043	5134

Figure 13. Raw tracer and flow data for the Henry Co. bioreactor tracer test (06/05/18). The green and blue highlighting refer to the calculation of Morrill Dispersion Index and the Short-circuiting Index, respectively (See Figure 6. above).

Sample #	6/13/18 11:50 Sample Time	Flow rate (L/s)	Incremental volume (L)	Cumulative volume (L)	Cumulative pore volumes	Br- Conc	Change in minutes	Cumulative Time (min)	C/C0	Cumulative Conc.	Cumulative % Conc	C x t	t^2 x C	Normalized Conc.	mg L⁻ conc
Kirwan_2 hr_1	6/13/18 12:00	0.208	0	0.00	0.00	0.15		0	0.00000108	0.151	0	0	0	0.002	0
Kirwan_HS_1	6/13/18 12:00	0.208	0	0.00	0.00	0.06	0	0	0.00000042	0.2089	0.06	0	0	0.001	0
Kirwan_HS_2	6/13/18 12:30	0.208	374	373.81	0.03	0.08	30	30	0.00000059	0.2912	0.08	2.469	74	0.001	31
Kirwan_HS_3	6/13/18 13:00	0.208	374	747.61	0.06	3.48	30	60	0.00002496	3.7712	1.01	208.8	12528	0.049	1301
Kirwan_HS_4$Diluted	6/13/18 13:30	0.208	374	1121.42	0.09	45.40	30	90	0.00032568	49.1712	13.22	4086	367740	0.640	16971
Kirwan_2 hr_2$Diluted	6/13/18 14:00	0.208	374	1495.53	0.12	70.90	30	120	0.00050861	120.0712	32.28	8508	1020960	1.000	26524
Kirwan_HS_5$Diluted	6/13/18 14:30	0.208	374	1869.93	0.15	70.80	30	150	0.00050789	190.8712	51.32	10620	1593000	0.999	26508
Kirwan_HS_6$Diluted	6/13/18 15:00	0.185	333	2202.47	0.18	52.80	30	180	0.00037877	243.6712	65.51	9504	1710720	0.745	17558
Kirwan_HS_7$Diluted	6/13/18 15:30	0.208	374	2576.28	0.21	38.50	30	210	0.00027618	282.1712	75.87	8085	1697850	0.543	14392
Kirwan_2 hr_3$Diluted	6/13/18 16:00	0.185	333	2908.82	0.23	30.60	30	240	0.00021951	312.7712	84.09	7344	1762560	0.432	10176
Kirwan_HS_8$Diluted	6/13/18 16:30	0.185	333	3241.36	0.26	23.00	30	270	0.00016499	335.7712	90.28	6210	1676700	0.324	7649
Kirwan_HS_9$Diluted	6/13/18 17:00	0.185	333	3574.36	0.29	14.40	30	300	0.00010330	350.1712	94.15	4320	1296000	0.203	4795
Kirwan_2 hr_4	6/13/18 18:00	0.208	748	4321.98	0.35	9.85	60	360	0.00007066	360.0212	96.80	3546	1276560	0.139	7364
Kirwan_HS_12	6/13/18 19:00	0.185	665	4987.07	0.40	5.30	60	420	0.00003802	365.3212	98.22	2226	934920	0.075	3525
Kirwan_2 hr_5	6/13/18 20:00	0.185	665	5652.15	0.46	3.50	60	480	0.00002511	368.8212	99.16	1680	806400	0.049	2328
Kirwan_30 min_8	6/13/18 23:00	0.185	1995	7647.42	0.62	1.03	180	660	0.00000739	369.8512	99.44	679.8	448668	0.015	2055
Kirwan_30 min_10	6/14/18 0:00	0.185	665	8312.50	0.67	0.72	60	720	0.00000517	370.5722	99.63	519.1	373766	0.010	480
Kirwan_30 min_12	6/14/18 1:00	0.185	665	8977.59	0.72	0.57	60	780	0.00000408	371.1412	99.79	443.8	346180	0.008	378
Kirwan_2 hr_10	6/14/18 6:00	0.185	3325	12303.03	0.99	0.25	300	1080	0.00000179	371.3902	99.85	268.9	290434	0.004	828
Kirwan_30 min_24	6/14/18 7:00	0.185	665	12968.11	1.04	0.30	60	1140	0.00000212	371.6852	99.93	336.3	383382	0.004	196
Kirwan_2 hr_11	6/14/18 8:00	0.185	665	13633.20	1.10	0.25	60	1200	0.00000179	371.9352	100.00	300	360000	0.004	166

Figure 14. Raw tracer and flow data for the Mercer Co. bioreactor tracer test (06/13/18). The green and blue highlighting refer to the calculation of Morrill Dispersion Index and the Short-circuiting Index, respectively (See Figure 6. above).

APPENDIX C. – Advanced Bioreactor Well Sampling (Raw Data)

Table 7. Advanced Bioreactor dissolved oxygen (DO) well values recorded in mg/L. The (---) indicate no samples were collected.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12
2/26/2018	7.65	6.10	6.60	4.82	2.67	4.13	3.0	2.68	0.50	0.32	0.60	0.42
3/12/2018	0.81	0.50	0.57	0.72	0.96	1.25	1.03	0.62	0.71	0.61	0.60	0.50
3/19/2018	0.71	0.24	---	0.47	0.83	0.30	0.94	0.24	0.33	0.41	0.40	---
4/30/2018	0.80	0.29	0.44	0.42	0.37	0.14	0.85	0.12	0.32	0.17	0.27	0.27
5/29/2018	0.16	0.11	0.12	0.05	0.07	0.16	0.04	0.06	0.16	0.08	0.24	0.18
6/28/2018	2.80	2.0	2.80	0.80	0.90	5.50	2.60	0.80	0.90	0.70	0.90	0.70
8/6/2018	1.30	1.10	1.30	1.10	1.60	0.90	1.30	0.50	0.50	0.60	0.50	0.60

Table 8. Advanced Bioreactor oxidation-reduction potential (ORP) well values recorded in mV.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12
2/26/2018	225	211	220	226	228	226	228	218	215	163	170	132
3/19/2018	-26.2	32.4	-82.3	-101	-114	-97.1	-90.3	-143	-134	-124	-101	-136
4/30/2018	249	222	196	40.4	-49.5	-41.1	-120	-86.4	-125	-130	-146	-122
5/29/2018	103	122	-87.3	-155	-172	-136	-178	-188	-225	-232	-222	-237
6/28/2018	15.6	60.1	-43.2	-4.9	-163	-119	-178	-208	-230	-231	-239	-240
8/6/2018	-174	-147	-149	-153	-140	-159	-146	-157	-146	-147	-149	-143

Table 9. Advanced Bioreactor NO_3-N well values recorded in mg N/L. Values at 0.01 mg N/L are at or below the analytical detection limit. The (---) indicate no samples were collected.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12
4/14/2017	5.73	---	---	---	2.69	---	---	3.01	---	---	2.02	---
4/21/2017	4.78	4.78	4.77	2.08	0.03	1.89	0.43	0.08	0.01	0.01		0.01
5/9/2017	6.61	6.60	6.67	5.85	4.74	5.72	5.14	4.87	3.79	3.33	4.50	2.89
6/20/2017	0.09	0.15	0.18	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2/26/2018	6.91	6.97	6.89	6.92	6.84	6.75	6.81	6.74	6.71	6.58	6.55	6.68
3/8/2018	1.04	0.23	0.72	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
3/19/2018	0.03	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.02
4/30/2018	4.86	4.02	4.47	1.12	0.07	1.00	0.09	0.06	0.02	0.01	0.01	0.01
5/29/2018	3.57	2.56	2.62	0.44	0.01	0.54	0.01	0.01	0.01	0.01	0.01	0.01
6/27/2018	5.14	5.12	4.32	2.05	0.22	1.43	0.13	0.20	0.01	0.01	0.03	0.01
8/6/2018	0.01	0.01	0.02	0.09	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.02

Table 10. Advanced Bioreactor PO_4-P well values recorded in mg P/L. The (---) indicate no samples were collected.

	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12
4/14/2017	0.010	---	---	---	0.010	---	---	0.010	---	---	0.010	---
4/21/2017	0.010	0.012	0.016	0.010	0.011	0.010	0.010	0.010	0.036	0.032	0.044	0.044
5/9/2017	0.017	0.020	0.021	0.010	0.010	0.011	0.010	0.010	0.010	0.010	0.010	0.010
6/20/2017	0.136	0.177	0.133	0.121	0.109	0.187	0.166	0.103	0.072	0.066	0.119	0.137
2/26/2018	0.156	0.140	0.194	0.089	0.023	0.071	0.029	0.061	0.011	0.010	0.010	0.010
3/8/2018	0.112	0.159	0.106	0.106	0.019	0.100	0.034	0.562	0.045	0.010	0.010	0.010
3/19/2018	0.341	0.879	0.404	0.428	0.032	0.253	0.094	0.797	0.205	0.014	0.015	0.015
4/30/2018	0.093	0.076	0.063	0.029	0.020	0.028	0.032	0.033	0.036	0.028	0.030	0.018
5/29/2018	0.070	0.063	0.065	0.040	0.041	0.045	0.054	0.035	0.031	0.026	0.036	0.035
6/27/2018	0.076	0.073	0.069	0.041	0.019	0.037	0.023	0.025	0.019	0.016	0.020	0.022
8/6/2018	0.375	0.281	0.269	0.310	0.146	0.306	0.185	0.267	0.121	0.061	0.067	0.036