Open Access

Advances in Environmental and Engineering Research

LIDSEN Publishing Inc.

Research Article

Initial Validation of a Replicated Field-scale Denitrifying Bioreactor Facility in a Boreal Environment

Lordwin Girish Kumar Jeyakumar [1, ‡], David B. McKenzie [1, *], Laura E. Christianson [2], Evan Derdall [3]

1. St. John's Research and Development Centre, Agriculture and Agri-Food Canada, 204 Brookfield Road, St. John's, NL, Canada; E-Mails: lordwingirish@gmail.com; david.mckenzie@canada.ca
2. University of Illinois, 1102 S. Goodwin Ave, Urbana, IL, USA; E-Mail: lechris@illinois.edu
3. Saskatoon Research and Development Centre, Agriculture and Agri-Food Canada, 107 Science Place, Saskatoon, Saskatchewan, Canada; E-Mail: evan.derdall@canada.ca

‡ Current Affiliation: Nova Scotia Community College, School of Technology and Environment, 80 Mawiomi Place, Dartmouth, Nova Scotia, Canada; E-mail: lordwin.jeyakumar@nscc.ca

* **Correspondence:** David McKenzie; E-Mail: david.mckenzie@canada.ca

Academic Editor: Nicole Mölders

Special Issue: Climate Change and Land

Adv Environ Eng Res
2021, volume 2, issue 2
doi:10.21926/aeer.2102005

Received: December 29, 2020
Accepted: April 05, 2021
Published: April 15, 2021

Abstract

Denitrifying bioreactor technology, where a solid carbon source (woodchips) acts as a reactive medium to intercept agricultural tile drainage water, has been successfully used to convert N (NO_3^-) to di-nitrogen (N_2) gas. Four replicated field-scale (24 m long x 3 m wide x 1 m deep), bioreactors were built and operated at the St. John's Research and Development Centre and were successful at removing a notable amount of nitrate (N) from agricultural subsurface drainage water. The objective of this study was to investigate the internal flow dynamics of one of these field-scale bioreactors as a proxy for the others. The hydraulic conditions in the bioreactor system developed differently than expected; asymmetric flow rates led to long average hydraulic retention time (HRT) and a highly dispersed residence time distribution, which was revealed by a sodium chloride tracer test. To measure the internal flow a known

amount of sodium chloride (salt) was added to water before it entered the bioreactor and samples were collected in 30 minutes intervals. The temperature of water samples taken from the inlet, outlet, and sample ports ranged from 14.5 to 18.4°C With a N removal of 62 to 66% the bioreactor proved at the same time to be very effective under the boreal environment of Newfoundland and Labrador (NL). Mass removal rate (MRR) was calculated to evaluate the performance of woodchip bioreactor. The average MRR was 3.87 $gm^{-3}day^{-1}$ and the highest was 7.19 $gm^{-3}day^{-1}$ respectively. The theoretical retention time was calculated to be approximately 10.64 h based on the active flow volume, the length and depth of the system. In comparison the observed retention was 18.18 h

Keywords
Woodchips; wastewater; bioreactor; tracer; hydraulics; drainage; boreal

1. Introduction

For the past several decades, tile drainage has been one of the largest drivers of the transformation of the agricultural sector. Tile drainage is a widely adopted water management practice in eastern Canada [1] which aims to improve crop yields and reduces surface runoff but contributes to the loss of nutrients from agricultural fields [2]. One mitigation practice that has emerged to limit the impact of nutrient runoff is the development of denitrifying bioreactors. Bioreactors are excavated trenches filled with a carbon (C) source such as woodchips, through which drainage water containing Nitrate (N) passes. Blowes et al. [3] published the first study demonstrating that bioreactors filled with tree bark, woodchips or leaf compost could treat N-laden drainage effluent. Many bioreactor studies have found encouraging results to reduce N loading [4-8]. However, bioreactors are a relatively new management practice and there are still many questions regarding their N removal efficiency, longevity, maintenance requirements, and possible negative effects of their utilization. More importantly, questions have arisen about how internal hydraulic-driven processes work in these engineered treatment systems [9].

Tracer testing is one common method used to investigate the internal hydraulics of complex systems, and such tests in denitrification beds woodchips used to approximate in situ wood media porosity, average HRTs, and pore water velocity [10, 11]. Tracer tests can also be used to determine the in-situ properties of woodchip beds that can be used in their design and modeling [12]. Some of the key performance parameters for denitrification beds include HRT and effective porosity. Effective porosity is the interconnected (active) pore volume that contributes to transmitting water [13, 14], and it is used for estimating the actual HRT in design and modeling of beds [15]. In addition to elucidating flow dynamics, tracer testing can also be a valuable tool for identifying flaws that result in poor denitrification performance. For example, Schipper et al. [16] confirmed that groundwater passed underneath a denitrification wall rather than through it. Cameron and Schipper [17] used tracer testing to investigate the effect of inlet and outlet position upon short-circuiting of flow in denitrification systems.

Most recently, Ghane et al. [12] conducted bromide tracer testing in seven denitrification beds in Willmar, Minnesota, USA, revealing an average bromide recovery of 82 ± 13.3 % (± SD). This study

also estimated the in-situ effective porosity of the field-scale denitrification beds tested was 0.61, which is lower than the value of > 0.65. Hoover et al. [18] used a potassium bromide tracer solution and found an average tracer residence time of 2.3 ± 0.3 h, in close agreement with the estimated HRT value of 2.1 ± 0.3 h. Christianson et al. [19] conducted a series of tracer tests in pilot-scale woodchip denitrification bioreactors treating aquaculture wastewater to help assess the possibility of woodchip clogging over time. A sodium chloride solution was used as a tracer, and sodium N at a concentration of approximately 30-70 mg NO_3 L^{-1} was added to the tracer solution to avoid diluting NO_3^- dynamics during testing. The tests were designed to capture three to four pore volumes and total elution took from 46 to 184 h depending on the retention time treatment. Tracer testing is also an established method in field hydrogeology to obtain information about ground water flow and transport characteristics (e.g. [20-22]) in various fields, including water resource management, contaminant hydrogeology, and geothermal reservoir engineering.

To understand the flow characteristics of bioreactors in St. John's, NL, this study performed tracer testing and well-based monitoring of drainage bioreactors, as there woodchips no studies of hydraulics and efficiency in denitrification systems in St. John's, NL. The objectives of this study were to (1) to design, construct, and evaluate a novel research facility consisting of four full-scale replicated denitrifying bioreactors in a boreal environment (2) compare the theoretical and actual HRT under field conditions for one of the bioreactors. This study elucidates essential information that is required to design efficient denitrification bioreactors situated in cool, boreal environmental conditions.

2. Materials and Methods

2.1 Forage Experimental Set-Up

The forage fields were planted in an incomplete Latin design with three blocks of four treatments. Two cropping systems used in the province of NL were utilized in this experiment: a grass mixture and a 100 % alfalfa stand. The crop treatments received liquid dairy manure applications after first crop harvest either as broadcast manure or as manure spread at ground level). The fields were planted in 2016 at the St. John's Research and Development Centre in St. John's, NL. The field treatments are as follows (the rate of manure application in all cases is 55,000 L ha^{-1} yr^{-1} of liquid dairy manure): Treatment 1: Richmond Timothy (8 kg ha^{-1}), Preval Meadow Fescue (11 kg ha^{-1}), spray manure application; Treatment 2: AC Brador Alfalfa (10 kg ha^{-1}), Richmond Timothy (1 kg ha^{-1}), Yukon Tall Fescue 3.5 kg ha^{-1}, AC Success Bromegrass 8 kg ha^{-1}, banded manure application; Treatment 3: AC Brador Alfalfa 18 kg ha^{-1}, spray manure application; Treatment 4: AC Brador Alfalfa 18 kg ha^{-1}, banded manure application.

2.2 Novel Bioreactors Design

Four replicated field-scale (24 m long x 3 m wide x 1 m deep), bioreactors constructed at the St. John's Research and Development Centre (47°30'48.080" N; 52°47'00.020" W; 110 m above mean sea level), and were successful at removing a significant amount of N from agricultural subsurface drainage water. The field consists of 12 experimental plots in two rows of six. Six plot lines enter on one side of the collection hut and six on the other. The plots themselves are 12 m apart and are separated by buffer lines which are 10 m from the plot lines. All tile used at the site is 0.1 m

diameter. Maximum grades are 2 %. Based on plot discharge curves, drainage coefficients were calculated to be 0.21 – 0.25. Maximum discharge per plot is about 2 L s^{-1} (24 L s^{-1} total). The soil has a gravelly texture, so most flow events occur within 36 hours following precipitation. During the drier parts of the season it usually takes a rainfall of 10 mm or more to initiate flow. Each of the 12 plots is 22 m x 60 m, for a total tile drainage area of 1.6 ha. The four bioreactors were of equal size, with the woodchip beds measuring 24 m long, 3 m wide and 1 m deep (Figure 1). These bioreactors were designed and built that are all the same and can be individually controlled.

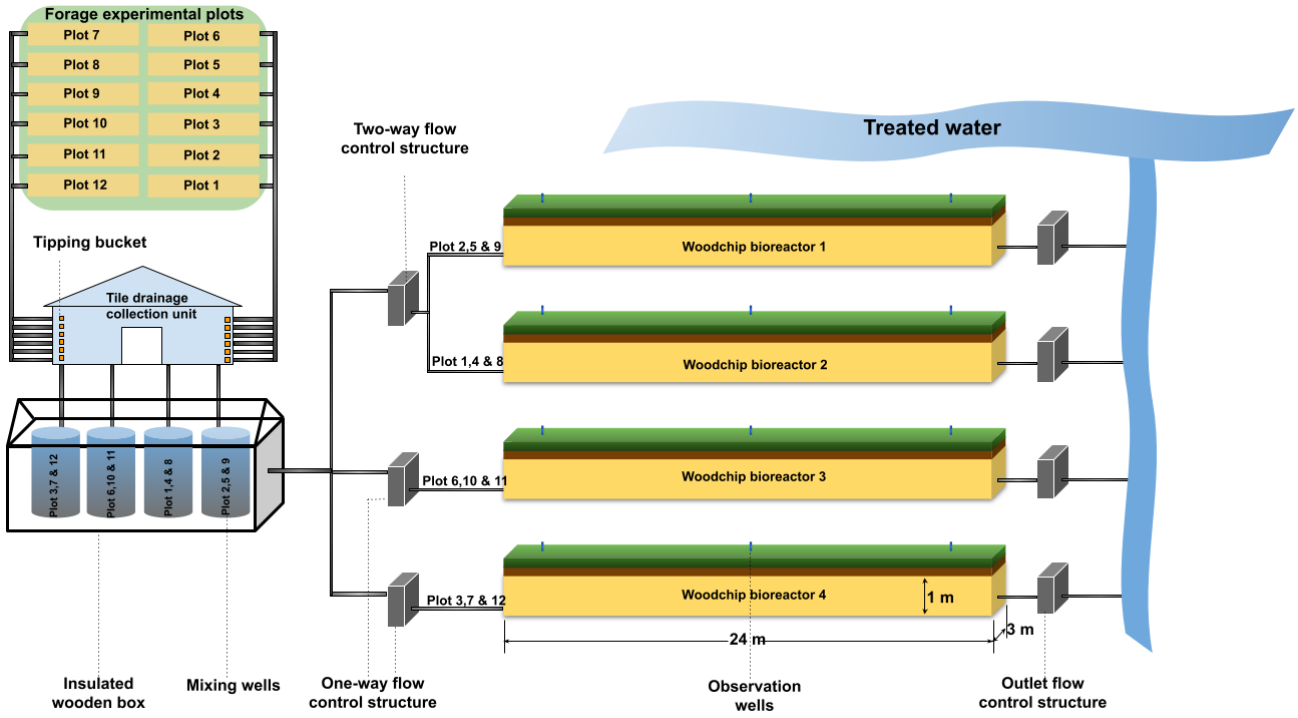

Figure 1 Novel field scale experimental and woodchip bioreactor design set-up at St. John's Research and Development Centre.

Individual drainage plot tile lines are routed into an enclosed tile drainage collection unit, where they can be piped into one of four pump pits. Each pump pit is fitted with a submersible water pump, which pumps the collected drainage water to 1 of 4 dedicated bioreactors. Each pump has an outflow capacity of 1.5 L s^{-1}, which is equal to the treatment capacity of the constructed bioreactors based on an 8 h retention time. Eight flow control structures Agri-Drain, Iowa, United States were installed on both ends of the bioreactor. Three replications of forage plots are combined into one bioreactor for each treatment.

2.3 St. John's Environmental Conditions

The island of Newfoundland has an average summer temperature of 16°C (61°F), while the winter hovers around 0°C (32°F). All regions of NL experiences extreme precipitation events including blizzards and hurricanes, particularly in the winter that leads to intense runoff and drainage events in the spring. The two major contributing factors to these extreme conditions are the proximity of NL to several major storm tracks, and the proximity to the ocean. According to Canadian Climate

Normals station data (1981 to 2010) the precipitation was recorded as 1534.20 mm whereas the snow was noted 335 cm at the St. John's Airport [23].

2.4 Bioreactor Operation

Water was pumped from a given mixing well (PENTAIR MC1033 Submergible pump; range: 1.25 – 1.6 L s^{-1}) to a given flow control structure where it subsequently flowed to the inlet of a given bioreactor. This configuration allowed control of the flow rate for all the bioreactors at approximately 1.26 L. This reactor was designed with a 150 mm PVC by-pass pipe to accommodate heavy excess flow events. Once the water reached the inlet an additional 150 mm pipe equipped with a perforated T-joint connection introduced the drainage water into the bioreactor (#one). The average flow rate through the bioreactor was calculated based on data analysis of in-situ continuous conductivity loggers "HOBO U24-001" (Hoskin Scientific, Canada) placed in the inlet and outlet of the control structures logging conductivity readings every five minutes in conjunction with periodic grab samples from various ports along the length of the reactor. The flow rate of drainage water can also be controlled by the stop logs of the inlet and the outlet control structure; however, for this study the stop logs of the bioreactor remained in place and were not moved to adjust the flow of the system. The theoretical retention time of the bioreactor was estimated to be approximately eight hours based upon the active flow volume, length and depth of the system, as well as the assumed porosity of the woodchip material. The schematic diagram of St. John's woodchip bioreactor is shown in Figure 2.

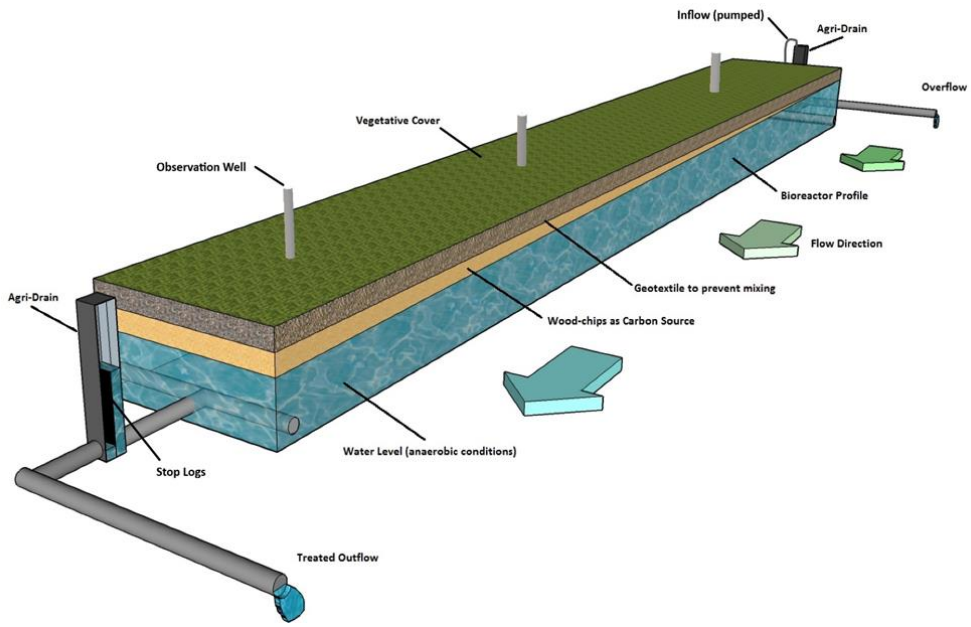

Figure 2 Schematic diagram of one of the four replicated bioreactors at St. John's Research and Development Centre where tracer testing was performed. Arrows indicate the water flow direction and monitoring wells are illustrated along the flow path.

2.5 Porosity Test

Woodchips typically have a total porosity on the order of 0.70 [11]. A benchtop study was conducted based on volumetric method to estimate the porosity of the black spruce woodchips that

were used to fill the bioreactor in this study. Porosity was calculated based on the following equation (vii):

$$Porosity = \frac{V_{final}}{V_{intial}} \times 100\ \% \qquad (vii)$$

Where v_{final} represents the final volume collected (mL) and $v_{initial}$ is the initial volume of water added (1000 mL). Porosity is an important parameter to consider as it will give an estimate of the overall capacity of a reactor's flow rate and level of saturation.

As previously stated, porosity and particle size are important parameters to consider when constructing a bioreactor. Porosity gave an estimate of the overall capacity of a reactor's flow rate and level of saturation. The porosity of any given type of woodchip depends on the ratio of the volume of all pores in comparison to the overall volume of the system. While we were unable to measure the porosity of the overall system, the bench top laboratory study concluded that the softwood Black Spruce woodchip has an average porosity of 71 %. The higher the porosity of the woodchips used in a bioreactor, the higher the flow rate.

2.6 Tracer Testing

The tracer study conducted in September 2017 [24] provided results which allowed for analysis and characterization of the retention time of bioreactor one. Electrical conductivity was used as a proxy for salt concentration during the tracer test; the two were related using a lab-determined relationship shown in Figure 3. The coefficient of determination of the logged values was calculated to be 0.9972 which indicates that the model constructed was an excellent fit to the data collected in the laboratory study. From the curve, the concentrations of associated conductivity observed as seen in Figure 3 were used to determine the trace recovery values for the salt in the bioreactor.

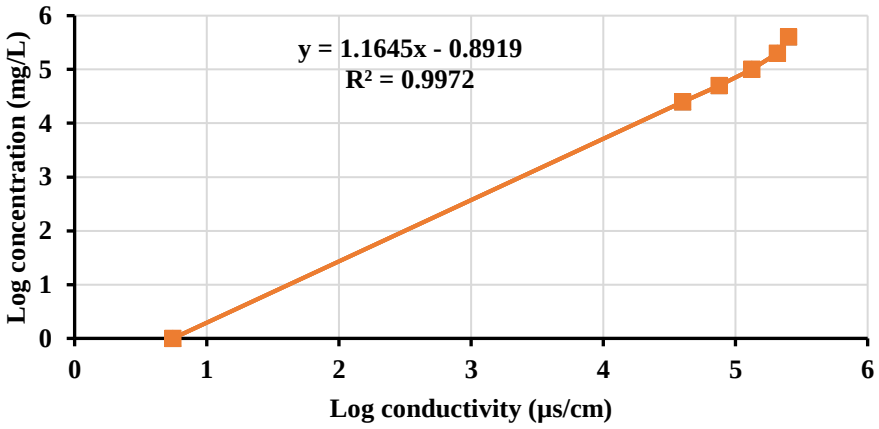

Figure 3 Calibration curve of log conductivity versus log concentration used to calculate associated parameters.

2.7 Tracer Equations

Hydraulic tracer tests are used in bioreactors to evaluate the hydraulic efficiency [9]. Generally, low hydraulic efficiency is largely due to short circuits formed in a basin [25]. According to Thackston

et al. [26], the formation of a dead zone causes short circuits and decreases hydraulic efficiency and he defined the effective volume as the ratio of mean tracer residence time to theoretical HRT. In this study he defined "hydraulic efficiency" as the ratio of mean tracer residence time to theoretical HRT according to equation (i):

$$e = \frac{t}{T} = \frac{t}{\frac{V\rho}{Q}} \qquad (i)$$

where e is the effective volume, t is the mean tracer residence time, T is the theoretical retention time, V is the active flow volume, Q is the flow rate through the reactor, and ρ is the wood media porosity. This is the sum of the incremental time steps (t) times the incremental concentration values (C) divided by the sum of concentration values. Tracer residence time (t) can be evaluated using equation (ii):

$$t \approx \frac{\sum t_i c_i \Delta t_i}{\sum c_i \Delta t_i} \qquad (ii)$$

where t_i and c_i are the time and concentration respectively of the ith sample, and Δt_i is the time increment between measurements [27]. Thackston et al. [26] indicated that a hydraulic efficiency correction factor of 1/e could be used as a design tool to correct for differences in residence and retention times. Persson et al. [28] introduced a simplified equation to evaluate hydraulic efficiency by combining effective volume and a mixing component (iii):

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

where λ is hydraulic efficiency, N is the theoretical number of continuously stirred tank reactors (CSTRs) in series, and t_p is the time the peak tracer concentration eluted.

Kadlec and Knight [29] suggested to use the following equation to calculate the number of CSTRs in series and it was defined based on the difference between the mean retention time and the peak outflow concentration (iv):

$$N = \frac{t}{t - t_p} \qquad (iv)$$

Persson et al. [26] defined "good", "satisfactory", and "poor" hydraulic efficiency as $\lambda > 0.75$, $0.5 < \lambda \leq 0.75$, and $\lambda \leq 0.5$, respectively. Ta and Brignal [30] also developed an equation to describe the extent of short-circuiting (S) based on the time taken for 16% of tracer to exit a system and time for 50% of the tracer to exit a system, i.e. (v):

$$S = \frac{t_{16}}{t_{50}} \qquad (v)$$

A value of S that approaches zero indicates that the reactor may be experiencing short circuiting, whereas ideally performing reactors have S values nearer to one.

The Morrill dispersion index (MDI) is another widely used index to evaluate the amount of diffusion and mixing in the contact system [31] (vi):

$$MDI = \frac{t_{90}}{t_{10}} \quad (vi)$$

where MDI is the Morrill dispersion index, t_{90} is the time at which 90% of the tracer's original concentration is observed at the outlet, and t_{10} when 10% of the original concentration is observed at the outlet [27]. It can be thought of a measure of dispersion occurring in the contact tank [31]. A theoretical ideal plug flow reactor would have an MDI of 1.0 but an MDI less than two is indicative of "effective" plug flow [27].

2.8 Well Sampling and Analysis

In order to monitor and analyze the internal flow rate and hydraulics of the bioreactor, water samples were collected from the inlet and outlet of the bioreactor as well as from three sample wells installed along the length of the bioreactor (14.80 m, 20.80 m and 26.80 m). These values indicate the distance of the well installed from the inlet agri-drain. Samples were collected from the sampling wells as well as the inlet agri-drain, and outlet agri-drain every 30 minutes starting prior to when the tracer was added. This was accomplished by using an EZ field sampler (Hach, Canada) motor equipped with FEP rubbing tubing which was placed in the wells, inlet and outlet to collect samples of water as it passed through reactor. For each sample collection, a minimum of 100 mL of water was taken from each sample site and was analyzed immediately using a HACH field HQD portable meter (Hach, Canada) using the conductivity adaptable probe (Hach, Canada) to measure conductivity as well as temperature.

A sodium chloride salt tracer study was performed in order to determine the retention time of each bioreactor plot constructed; for this study we focused strictly on bioreactor (#one). This was accomplished by rapidly introducing a 0.032 M NaCl conductivity slug (20.89 L) to the inlet control structure of bioreactor (#one) and running the bioreactor at the maximum capacity of the pump (1.26 L s^{-1}). For a better performance, the solution was introduced in less than one minute so that it could move in a plug form flow. This also reduced the dilution factor of the tracer (though it is assumed to be low due the high flow rate produced from the inlet). Samples were manually collected every 30 minutes for a period of approximately 11 h and they were analyzed immediately for conductivity and then verified with HOBO U24-001 loggers. The test was then evaluated for tracer residence time and compared to theoretical retention time based on the resulting calculations of the effective volume metric, the hydraulic efficiency, a short-circuiting metric, and the MDI. The conductivity data was converted into concentration using the linear equation derived from the laboratory test. When the salt concentration was plotted against time for the inlet, outlet, and the three wells, the passage of the salt through the bioreactor could be visualized.

2.9 Pilot-scale woodchip bioreactor tracer testing

Samples were obtained in 30-minute intervals which provided enough data to appropriately represent the entire tracer pathway. The theoretical retention time was calculated based on the active flow volume, length and depth of the system the assumed porosity of the woodchip material and the average flow rate of 1.26 L $s^{-1}$was estimated to be approximately 10.64 h. In order to calculate such parameters as tracer recovery the actual concentration of salt in the tracer solution was required thus a calibration curve was developed relating the salt concentration (mg NaCl L^{-1}) to

the conductivity. This was achieved by preparing a variety of beakers of known salt concentrations (ranging from 0 to 400,000 mg L^{-1}), measuring the conductivity, and plotting the log of the concentration versus the log of conductivity.

3. Results and Discussion

3.1 Tracer Testing

In the field scale bioreactor tracer study (Figure 4), the observed results indicate that the time taken for the tracer (Na Cl salt) to move from the inlet to outlet was approximately 10.64 h. The theoretical retention time was calculated to be approximately 10.64 h based on the active flow volume, the length and depth of the system, the assumed porosity of the woodchip material, and the average flow rate. In comparison, the observed retention time was 18.18 h. The salt did not flow through the bioreactor at a consistent speed: although it moved quickly between Well one to Well two, it took longer to travel from Well three to the outlet despite the fact that these distances were identical (6.0 m). The residence time was found higher as compared with the theoretical HRT given nuances associated with field studies (e.g., inherent, and acceptable error associated with flow monitoring, EC meters, using EC as a proxy for salt concentrations). Thus, the difference between the tracer residence time and theoretical HRT may not have been notably different in practice. Nevertheless, Dougherty [32] reported a bioreactor with baffles similarly had tracer residence times greater than the theoretical HRTs (16, 35, and 22 h versus 13, 20, and 17 h, for three tests, respectively). It may be that the bioreactor studied in the current work had slightly more effective flow routing than expected which would account for the slightly longer than expected tracer residence time. A similar study was conducted in a denitrification bioreactor in Northeast Iowa and it was found that the theoretical retention time was 6.35 h whereas the tracer residence time was found as 3.48 h which is 55 % of the theoretical retention time [9]. During the study period the temperature of water samples taken from the inlet, outlet, and sample ports ranged from 14.5 to 18.4 ˚C (Figure 5). Hoffmann et al. [33] stated that the water temperature and hydraulic residence time control N removal efficiency. Although the effect of temperature on bioreactor performance is compelling there is a need for improving our understanding of the combined effects of temperature and HRT variations in N [34].

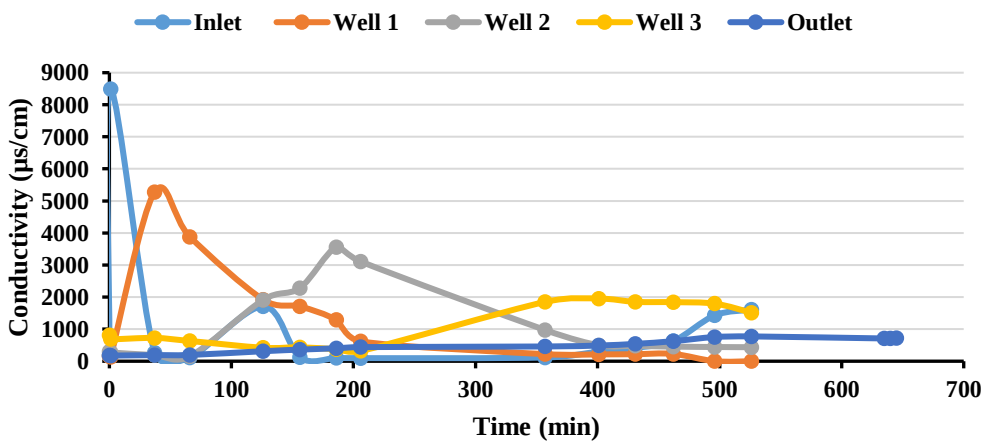

Figure 4 Tracer movement at the bioreactor over the period of time.

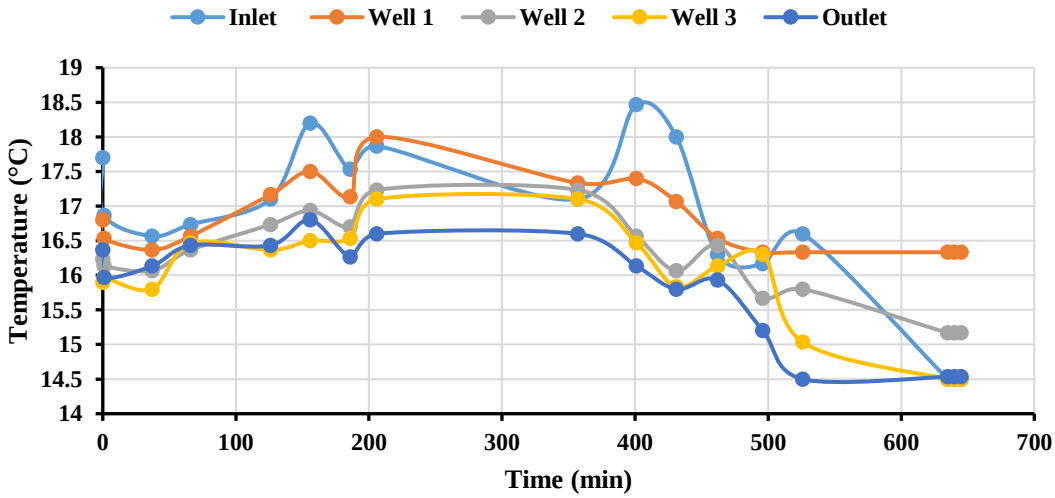

Figure 5 Comparison of change in temperature at each sample location over time.

When a bioreactor is packed with woodchips the water does not flow uniformly through the bioreactor; there may be sections creates little resistance to flow path. On the other hand, the water may pass remain in the bioreactor for an extended period due to internal circulation or a high resistance to flow, which may cause undesirable gases [35, 36] found that methane production happened during the early operation of bioreactors. To understand the bioreactor flow characteristics better, Hoover et al. [34] conducted bromide tracer test and found that the mean residence time (2.25 h) as compared to the theoretical HRT. Greenan et al. [37] found that N removal rates per gram of wood increased with water flow rate and found effective N removal under natural flow rate conditions. An 80 % reduction in N load was achieved with a 40 m3 in-stream bioreactor constructed in London, ON, with a mean flow rate of 24 L min^{-1}. Hassanpour et al. [38] reported that both low temperatures and increased discharge rates caused effluent N concentrations to increase from 0 mg L^{-1} to 8 mg L^{-1}, suggesting that both factors are key to bioreactor efficiency. A study at the North East Research Farm near Nashua, Iowa recorded an average statured hydraulic conductivity of 9.5 cms $^{-1}$ [9]. Furthermore, two tracer tests (with bromide) were conducted at Northeast Iowa indicates that the theoretical retention time (outlet only sampled) was 6.35 h whereas (all wells sampled) was 9.96 h with a lower flow depth as compared to outlet only sampled (0.37m) [9]. Ghane et al. [12] evaluated the hydraulics of seven denitrification beds and found an average bromide recovery of 82 ± 13.3 % (± SD) and this study suggested to use non-sorbing and conservative tracers to investigate the internal hydraulics.

3.2 Practical interpretation of tracer study

Based on the internal hydraulic analysis, cumulative pore volume graphs were generated to represent the entire tracer curve. One of the practical considerations involved in bioreactor design is how to achieve the ideal conditions of hydraulic performance of full-scale reactors. The value of MDI 1.0 indicates ideal plug flow reactor whereas an MDI Value of approximately 22 or above is considered to be a complex-mix reactor [27]. For the bioreactors in St. John's, NL, a tracer study (Table 1) revealed that the MDI values for Well one and Well two were low, but that the outlet and Well three showed higher MDI indicating complex-mix reactor behaviour. However, it might be

possible that the value obtained for Well three was in error because the tracer showed peak in the outlet when we tested with U24 loggers during the study period. The MDI value for Well one (0.0076) indicates an effective plug flow reactor (U.S. EPA 1986). Subsequently, the increase in calculated values may be due to error associated with dilution of the sodium chloride solution at the inlet, inaccuracy associated with the conductivity measurement using Hach HQD potable meter, or errors in the prior laboratory analysis of the chloride solution. Hoover et al. [18] reported MDI values of 2.8 ± 0.3 which is clearly indicates the plug flow characteristics and these values also consistent with previously published value of 3.5 and 4.2 for the field-scale bioreactors [6, 7]. As noted previously, the tracer recovery in some experiments was greater than 100 % [9] due to error in concentrated Br- volume or inaccuracy of flow measurement. A Br leaching experiment indicates that the HYDRUS model [36] can predict various parameters such as λ, θ_m, and ∝ between the modeled and measured output Br concentrations. A recent study conducted by Ghane et al. [12] concluded that the Br tracer is not sorbed by woodchips and can be used as a suitable tracer [15].

Table 1 Tracer testing parameters where ThRT represents theoretical retention time, t is the mean tracer residence time, e is the effective volume, λ is the hydraulic efficiency, S represents the short-circuiting metric and MDI is the Morrill Dispersion Index.

Sample	Distance from Inlet Agri-Drain (m)	Pore volume (m^3)	ThRT (h)	T (h)	e	λ	S	MDI
Well one	14.80	19.30	1.05	1.60	1.53	0.141	0	0.0076
Well two	20.80	28.95	3.14	3.63	1.15	0.485	0.218	4.0000
Well three	26.80	38.60	6.28	5.89	0.94	0.785	0.008	>22.00
Bioreactor Outlet	34.60	48.25	10.64	18.18	1.71	0.824	0.041	22.90

3.3 Hydraulic Characteristics

In order to compare the theoretical retention time to the observed experimental retention time, the hydraulic efficiency, a short-circuiting metric and the MDI were evaluated (Table 1). The inlet of the system showed low hydraulic efficiency (λ = 0.007), as did Well one and Well two (λ = 0.141 and λ = 0.485 respectively), while Well three and the outlet presented high hydraulic efficiency (λ = 0.785 and λ = 0.824 respectively). The short-circuiting index indicated short-circuiting along the entire length of the bioreactor which concurs with the MDI of the system. Observing the trend in normalized concentration is one way to represent the flow of the tracer. In addition, the calculated theoretical retention time in hours was plotted against distance travelled by the tracer. Persson et al. [39] described the concepts of effective volume ratio and dispersion in terms of hydraulic performance and evaluated the poor hydraulic efficiency (λ ≤ 0.50) of the reactor [28]. A hydraulic efficiency more than 0.75 is considered good whereas efficiency lower than 0.50 is considered as poor. On the other hand, hydraulic efficiencies between 0.50 and 0.75 are satisfactory [18]. In this study, hydraulic efficiency was higher in Well three and the outlet and slightly lower in Well two, but Well one was found to have poor hydraulic efficiency. This might be due to several factor such

as woodchip compaction [12], short-circuiting [35], particle size [13] and permeability [12]. N removal efficiency in the bioreactor is mainly based on the proper design, flow rate, bio reactor flow volume and woodchip media porosity [40]. Hydraulic performance of non-ideal plug flow reactors in particular with respect to short-circuiting, untimely flow due to poor design, mixing and also the location of inlet and outlet flow control structure [17]. Stop log adjustment is an important aspect of bioreactor operation [40] and the key design of St. John's bioreactor is based on the historical tipping bucket data and the pumping rate of the flow of water. Thackston et al. [26] suggested that several factors/arguments must be considered while considering equality of hydraulic efficiency and effective volume ratio.

3.4 Theoretical Retention Time Vs Distance

In this study the pore volume ranged between 19.30 to 48.25, with an approximate distance of 34.6 m from the initial point towards outlet. Samples collected at Wells one, two, and three and the outlet provide e values of 1.60, 3.63, 5.89 and 18.18, respectively. Well one's e value (1.60) might be compared with the e value (0.310) from tracer testing conducted in Northeast Iowa [9]. The tracer moved rapidly from the inlet control structure to Well one and exponentially slower from port to port after the initial movement in the system (Figure 5). This observation could be the result of many factors such as a variation in packing density, loss of initial pump pressure, dilution of the tracer itself or seepage vertically through the woodchip pathway. Hoover et al. [18] reported that the average theoretical HRT for nine bioreactors was recorded as 2.6 ± 0.4 and the corresponding estimated HRT was recorded as 2.1 ± 0.3, clearly indicating the variation between the theoretical and estimated time. It was concluded that the longer HRT probably helps additional Br- retention or sorption. In the bromide tracer study Ghane et al. [12] calculated that the theoretical retention time ranged from 12.30 h to 19.81 h for 7 beds based on the porosity assumption of 0.85 whereas the mean tracer residence time was observed between 8.84 h to 13.55 h. This this clearly indicates both over estimation and under estimation of flow in the denitrification beds. A study conducted in northeast Iowa indicated that the theoretical retention time (7.53 to 79.3 h) with an average flow depth of 0.20 to 0.40 had a removal rate between 0.38 to 1.06 g N m^{-3} d^{-1} [9]. According to Freeze and Cherry [41], travel time of solute is possible to estimate through a breakthrough as a point of inflection. Furthermore, by dividing the length of the bioreactor by pore water volume, travel time of solute can be estimated. Lepine et al. [42] studied the HRT in bioreactors and found that the optimal HRT to maximize N removal rate is not the same as removal efficiency in the span of 6.6 h to 55 h.

3.5 Precipitation, Max and Min. Temperature and Snow record

Temperature varies most obviously with season and latitude. The summer season in St. John's is brief and cool along the coast because of cold Labrador Current. Precipitation, maximum and minimum temperature, and snow record is shown in Figure 6. Temperature ranged from -6°C to 8°C and the maximum precipitation recorded was approximately 50 cm whereas the snow cover on the ground ranged between 0 to 10 cm.

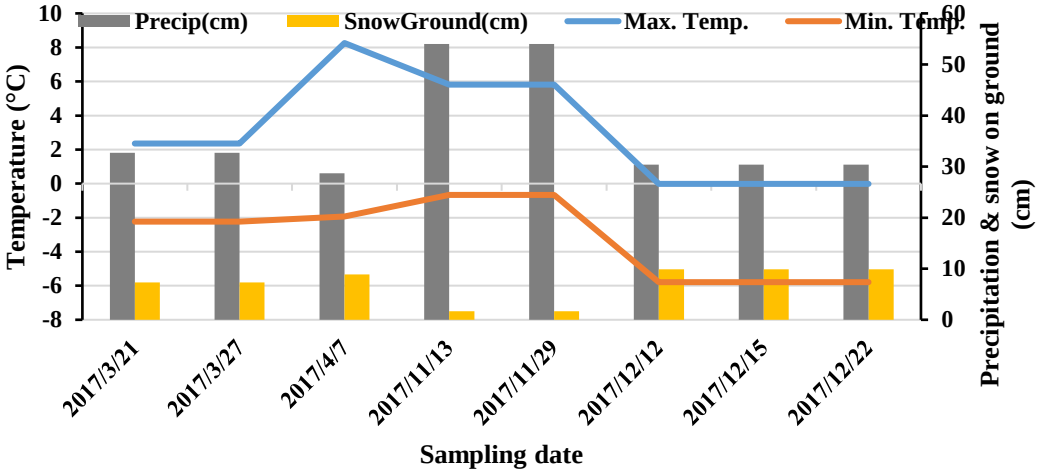

Figure 6 Weather conditions recorded during the time of N analysis.

3.6 N Concentrations

In 2017, water samples were taken from the inflow and outflow of the bioreactors from March 2017 to December 2017. It was found that the minimum inflow concentration was 1.52 mg L^{-1} and the maximum inflow concentration was 4.5 mg L^{-1} whereas the outflow concentration was recorded to be 0.5 mg L^{-1} and 1.7 mg L^{-1} respectively. This study showed good overall performance of the bioreactor under cold conditions although the N concentration was low throughout the year based on the rainfall flow events (Figure 7). One of the novel aspects of this study was the new environmental conditions in which the bioreactor was tested (i.e., cool boreal climate). Denitrifying wood-based bioreactors have proven effective in a variety of locations with cool climates (Denmark: [33]; Lithuania: [43]; Sweden: [44]), thus the results here were encouraging and not unexpected.

N removal rates woodchips reported for a wide range of denitrifying bioreactors. According to Povilaitis and Matikienė [44], the incorporation of activated carbon in denitrifying bioreactors reduced the organic carbon losses while maintaining denitrification. Woodchips achieved the greatest reduction of all the additives, reducing N concentrations by 78 % and it was reported higher removal rates for shorter HRTs are governed by N removal reaction kinetics [40]. Povilaitis and Matikienė [44] reported that the activated carbon amended woodchips showed higher efficiency in terms of N removal. Greenan et al. [37] found that N removal rates per gram of wood increased with increasing flow rates and concluded that bioreactors may be successful at removing significant quantities of N and reducing N concentration from water moving to subsurface drainage at flow rates observed in central Iowa subsoil. In tile drainage water treatment higher N removal was achieved in bioreactors amended with activated C (10% v/v) and biochar (20% v/v) [46]. Research in London, Ontario has shown that an 80 % reduction in N load can be achieved with a 40 m^3 in-stream bioreactor with a mean flow rate of 24 L min^{-1} [47]. Schipper et al. [10] reported an average rate of N removal of 1.4 g N m^{-3} d^{-1} in an environment with an annual average temperature of 12° C. Despite low temperatures, N removal efficiency was found to be consistent in 2017. It is worth mentioning that the influent N-N concentration was low during the time of sampling. According to Hoover et al. [34], N removal showed a stepped increase with temperature. At 21.5°C the N removal was found to be 79 ± 14 % whereas at 10°C it was 18 ± 3 %. A study conducted at East-Central Illinois

woodchip bioreactor demonstrated that the water temperature played a major role in terms of N removal rates [48]. MRR was calculated to evaluate the performance of woodchip bioreactor. It is related to the size of treatment system and treated water volume. In this study, tile drainage outflow was pumped to the bioreactor with a consistent flow rate of 20 US gallon per minute which is equivalent to 130.927 m^3 day^{-1}. The calculated average MRR was 3.87 g m^{-3} day^{-1} with best performance of 7.19 g m^{-3} day^{-1} (Figure 8). During spring, higher inflow resulted in greater MRR when snowmelt happened. In winter, frozen soil and less precipitation caused decrease of inflow as well as MRR.

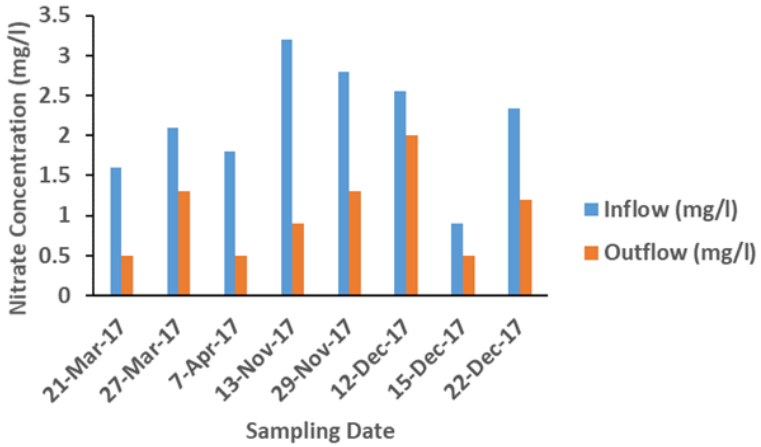

Figure 7 N inflow and outflow concentration of field scale woodchip bioreactor, St. John's, NL.

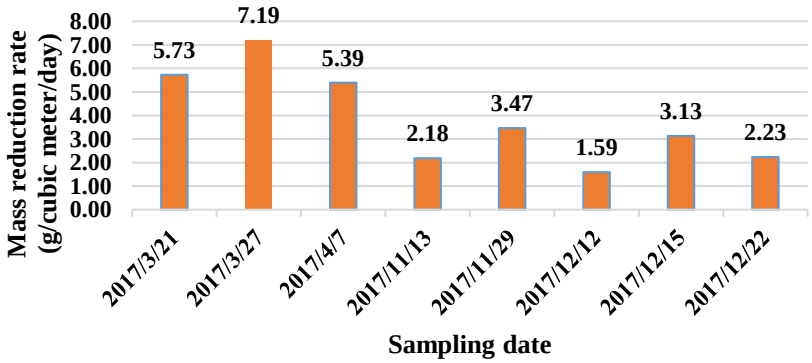

Figure 8 MRR of N removal at bioreactor (#1), St. John's, NL.

4. Conclusions

A new research facility with four field-scale denitrifying bioreactors designed and constructed in a boreal climate showed favorable N removal in at least one of the bioreactors. This presents many opportunities for future studies due to the unique nature of the replication with such large bioreactors. A sodium chloride tracer test was successfully performed to obtain information about the hydraulic properties of the denitrification bioreactor. This packed bioreactor does not flow uniformly, and it was observed that there may be sections in the packed bed that offered little resistance to flow. On the other hand, the internal circulation of flow means that water may spend

a long time in the bioreactor before it reaches the outflow. This shows that the woodchips play an important role in the flow of water to determine the hydraulic properties. This system has provided useful insight regarding the theoretical retention time (10.64 h) in close agreement with the estimated HRT value of 18.18 h, which was calculated using a porosity value of 0.71. Future modifications are possible such as excavation of the existing woodchips and refilling with alternative materials. This bioreactor is designed to receive flow from replicated experimental field plots, which offers flexibility in terms of the capability to change field treatments and to observe the subsequent effects on bioreactor efficiency in terms of flow and N removal capacity. Moreover, the flexible design of the system will help to answer scientific questions related to bioreactor performance and the engineering design.

Acknowledgments

The authors wish to thank Mr. Gary Bishop (Retired Agricultural Engineer) for his initial contribution while designing the woodchip bioreactor and Dr. Shabtai Bittman for including bioreactor research along with the nutrient management project. Special thanks to Dr. Linda Jewell for her suggestions on preparing the manuscript as well as her assistance in editing the manuscript. The authors would also like to thank Ms. Sarah Leonard, Ms. Dena Wiseman and Ms. Karen Compton and Ms. Toni Doody, Mr. Sean Comeau for their assistance in this project.

Author Contributions

Lordwin Jeyakumar and David McKenzie conceived the research plan, developed the detailed methodology, designed the analysis, determined the conclusions, and co-wrote the paper. Evan Derdall assisted the team in constructing the woodchip bioreactors. Laura Christianson performed the analysis and aided in interpreting the results. All authors discussed the results and commented on the manuscript.

Funding

Financial support for this study was provided by a grant from the Agriculture and Agri-Food Canada (J-001403).

Competing Interests

The authors have declared that no competing interests exist.

References

1. Morrison J, Madramootoo CA, Chikhaoui M. Modeling the influence of tile drainage flow and tile spacing on phosphorus losses from two agricultural fields in southern Québec. Water Qual Res J Canada. 2013; 48: 279-293.
2. Skaggs RW, Van Schilfgaarde J. Agricultural drainage. Madison: ASA, CSSA, SSSA; 1999.
3. Blowes DW, Robertson WD, Ptacek CJ, Merkley C. Removal of agricultural N from tile-drainage effluent water using in-line bioreactors. J Contam Hydrol. 1994; 15: 207-221.

4. Zoski ED, Lapen DR, Gottschall N, Murrell RS, Schuba B. Nitrogen, phosphorus, and bacteria removal in laboratory-scale woodchip bioreactors amended with drinking water treatment residuals. Trans ASABE. 2013; 56: 1339-1347.
5. Warneke S, Schipper LA, Bruesewitz DA, Mcdonald I, Cameron S. Rates, controls and potential adverse effects of nitrate removal in a denitrification bed. Ecol Eng. 2011; 37: 511-522.
6. Christianson LE, Bhandari A, Helmers MJ. Pilot-scale evaluation of denitrification drainage bioreactors: Reactor geometry and performance. J Environ Eng. 2011; 137: 213-220.
7. Christianson LE, Hanly JA, Hedley MJ. Optimized denitrification bioreactor treatment through simulated drainage containment. Agric Water Manag. 2011; 99: 85-92.
8. Elgood Z, Robertson WD, Schiff SL, Elgood R. Nitrate removal and greenhouse gas production in a stream-bed denitrifying bioreactor. Ecol Eng. 2010; 36: 1575-1580.
9. Christianson LE, Helmers MJ, Bhandari A, Moorman TB. Internal hydraulics of an agricultural drainage denitrification bioreactor. Ecol Eng. 2013; 52: 298-307.
10. Schipper LA, Barkle GF, Maja VV. Maximum rates of nitrate removal in a denitrification wall. J Environ Qual. 2005; 34: 1270-1276.
11. Van Driel PW, Robertson WD, Merkley LC. Denitrification of agricultural drainage using wood-based reactors. Trans ASABE. 2006; 49: 565-573.
12. Ghane E, Feyereisen GW, Rosen CJ. Efficacy of bromide tracers for evaluating the hydraulics of denitrification beds treating agricultural drainage water. J Hydrol. 2019; 574, 129-137.
13. Fetter CW. Applied Hydrogeology. NJ, USA: Pearson; 2001.
14. Sen Z. Practical and applied hydrogeology. Amsterdam, The Netherlands: Elsevier Inc.; 2015.
15. Kadlec RH, Wallace SD. Treatment wetlands, 2nd ed. Boca Raton, FL, USA: CRC Press; 2009.
16. Schipper LA, Barkle GF, Vojvodic-Vukovic M, Hadfield JC, Burgess CP. Hydraulic constraints on the performance of a groundwater denitrification wall for nitrate removal from shallow groundwater. J Contam Hydrol. 2004; 69: 263-279.
17. Cameron SG, Schipper LA. Evaluation of passive solar heating and alternative flow regimes on nitrate removal in denitrification beds. Ecol Eng. 2011; 36: 1588-1595.
18. Hoover NL, Soupir ML, Vandepol RD, Goode TR, Law JY. Pilot-scale denitrification bioreactors for replicated field research. Appl Eng Agric. 2017; 33: 83-90.
19. Christianson LE, Lepine C, Sharrer KL, Penn C, Summerfelt ST. Denitrifying bioreactor clogging potential during wastewater treatment. Water Res. 2016; 105: 147-156.
20. Cassiani G, Bruno V, Villa A, Fusi N, Binley AM. A saline trace test monitored via time-lapse surface electrical resistivity tomography. J Appl Geophys. 2006; 59: 244-259.
21. Leblanc DR, Garabedian SP, Hess KM, Gelhar LW, Quadri RD, Stollen-werk KG, et al. Large-scale natural gradient tracer test in sand and gravel, cape cod, massachusetts: 1. Experimental design and observed tracer movement. Water Resour Res. 1991; 27: 895-910.
22. Koltermann CE, Gorelick SM. Heterogeneity in sedimentary deposits: A review of structure-imitating, process-imitating, and descriptive approaches. Water Resour Res. 1996; 32: 2617-2658.
23. Weather, Climate and Hazard. Government of Canada. Available from: https://climate.weather.gc.ca/.
24. Vienken T, Huber E, Kreck M, Huggenberger P, Dietrich P. How to chase a tracer-combining conventional salt tracer testing and direct push electrical conductivity profiling for enhanced aqifer characterization. Adv Water Resour. 2017; 99: 60-66.

25. Lloyd BJ, Vorkas CA, Guganesharajah RK. Reducing hydraulic short-circuiting in maturation ponds to maximize pathogen removal using channels and wind breaks. Water Sci Technol. 2003; 48: 153-162.
26. Thackston EL, Shields FD, Schroeder PR. Residence time distributions of shallow basins. J Environ Eng. 1987; 113: 1319-1332.
27. Metcalf, Eddy I. Wastewater engineering: Treatment and Reuse. NY. USA: McGraw-Hill; 2003.
28. Persson J, Somes NL, Wong TH. Hydraulics efficiency of constructed wetlands and ponds. Water Sci Technol. 1999; 40: 291-299.
29. Kadlec RH, Knight RL. Treatment Wetlands. Boca Raton: CRC Press; 1996.
30. Ta CT, Brignal WJ. Application of computational fluid dynamics technique to storage reservoir studies. Water Sci Technol. 1998; 37: 219-226.
31. Teixeira EC, Siqueira RDN. Performance assessment of hydraulic efficiency indexes. J Environ Eng. 2008; 134: 851-859.
32. Dougherty HL. Hydraulic evaluation of a denitrifying bioreactor with baffles. Urbana-Champaign: University of Illinois; 2018.
33. Hoffmann CC, Larsen SE, Kjaergaard C. Nitrogen removal in woodchip-based biofilters of variable designs treating agricultural drainage discharges. J Environ Qual. 2019; 48: 1881-1889.
34. Hoover NL, Bhandari A, Soupir ML, Moorman BT. Woodchip denitrification bioreactors: Impact of temperature and hydraulic retention time on nitrate removal. J Environ Qual. 2015; 45: 803-812.
35. Schipper LA, Robertson WD, Gold AJ, Jaynes DB, Cameron SC. Denitrifying bioreactors-an approach for reducing nitrate loads to receiving waters. Ecol Eng. 2010; 36: 1532-1543.
36. Jaynes DB, Kaspar TC, Moorman TB, Parkin TB. In situ bioreactors and deep drain-pipe installation to reduce nitrate losses in artificially drained fields. J Environ Qual. 2008; 37: 429-436.
37. Greenan CM, Moorman TB, Parkin TB, Kaspar TC, Jaynes DB. Denitrification in wood chip bioreactorsat at different water flows. J Environ Qual. 2009; 38: 1664-1671.
38. Hassanpour B, Giri S, Pluer WT, Steenhuis TS, Geohring LD. Seasonal performance of denitrifying bioreactors in the Northeastern United States: Field trials. J Environ Manag. 2017; 202: 242-253.
39. Persson J, Wittgren HB. How hydrological and hydraulic conditions affect performance of ponds. Ecol Eng. 2003; 21: 259-269.
40. Christianson L, Helmers M, Bhandari A, Kult K, Sutphin T, Wolf R. Performance evaluation of four field-scale agricultural drainage denitrification bioreactors in Iowa. Trans ASABE. 2012; 55: 2163-2174.
41. Freeze RA, Cherry JA. Groundwater. Englewood Cliffs: Prentice-Hall Inc.; 1979.
42. Lepine C, Christianson L, Kata S, Steven S. Optimizing hydraulic retention times in denitrifying woodchip bioreactors treating recirculating aquaculture system wastewater. J Environ Qual. 2015; 45: 813-821.
43. Povilaitis A, Rudzianskaite A, Miseviciene S, Gasiunas V, Miseckaite O, Živatkauskiene I. Efficiency of drainage practices for improving water quality in lithuania. Trans ASABE. 2018; 61: 179-196.
44. Nordström A, Herbert RB. Identification of the temporal control on nitrate removal rate variability in a denitrifying woodchip bioreactor. Ecol Eng. 2019; 127: 88-95.

45. Povilaitis A, Matikienė J. Nitrate removal from tile drainage water: The performance of denitrifying woodchip bioreactors amended with activated carbon and flaxseed cake. Agric Water Manag. 2020; 229: 1-11.
46. Povilaitis A, Jolanta Matikienė J, Vismontienė R. Effects of three types of amendments in woodchip-denitrifying bioreactors for tile drainage water treatment. Ecol Eng. 2020; 158: 1-15.
47. Robertson WD, Merkley LC. In-stream bioreactor for agricultural nitrate treatment. J Environ Qual. 2009; 38: 230-237.
48. David MB, Gentry LE, Cooke RA, Herbstritt SM. Temperature and substrate control woodchip bioreactor performance in reducing tile nitrate loads in East-Central Illinois. J Environ Qual. 2015; 45: 822-829.