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Assessment of Aged Woodchip Bioreactor Physical and Hydraulic Properties

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ASSESSMENT OF AGED WOODCHIP BIOREACTOR PHYSICAL AND HYDRAULIC PROPERTIES

BY

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THESIS ACCEPTANCE PAGE

Shelby Duncan

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This is dedicated to my devoted boyfriend, Casey, and my loving parents, Bryce and Nancy, who have taught me that the only thing holding me back is myself. With your unwavering support, I have learned that I am capable of accomplishing all that I set out to achieve.

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ABBREVIATIONS

BMP	best management practice
USDA	United States Department of Agriculture
MARB	Mississippi/Atchafalaya River Basin
EPA	Environmental Protection Agency
NO_3^-	nitrate
N_2	dinitrogen gas
HRT	hydraulic residence time
MMHg	monomethyl mercury
S	short circuiting
MDI	mass dispersion index
GPS	global positioning system
PVC	polyvinyl chloride
ANOVA	analysis of variance
LSD	least significant difference
KBr	potassium bromide
CSTR	continuously stirred tank reactor

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ABSTRACT

ASSESSMENT OF AGED WOODCHIP BIOREACTOR PHYSICAL AND HYDRAULIC PROPERTIES

SHELBY DUNCAN

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Denitrifying woodchip bioreactors are a critical tool for mitigating nitrate loading to downstream water bodies. The properties of the woodchip are a key factor in the design of the bioreactor which are usually designed to optimize that retention time of the water being treated. Retention time is affected by active flow volume, porosity, and flow rate. As a bioreactor ages, the carbon material will break down and, in some cases, sedimentation will occur within the bioreactor. Both processes will affect the porosity and hydraulic performance of the bioreactor. When flow through the bioreactor is significantly different than the original design, nitrate removal performance will be negatively affected.

A denitrifying woodchip bioreactor was installed in 2014 near Hartford, South Dakota. This bioreactor was monitored since installation and has demonstrated a decline in concentration reduction performance. Since the installation in 2014, the Hartford bioreactor has also been affected by external factors that were not accounted for at the time of installation. Heavy rains and unprotected soil upgradient of the bioreactor led to increased sediment loading and flooding in and around the inflow control structure. In 2021, the bioreactor was excavated, and particles were characterized for particle size distribution, bulk density, drainable porosity, and total porosity at six transects along the length of the bioreactor and three depths within each transect. This study was conducted to characterize woodchip and sediment particles within the bioreactor to assess the likely

causes of failure. Woodchip degradation and sedimentation the two main mechanisms of failure within this system. These mechanisms led to reduced pore sizes in affected areas changing the hydraulic properties within the bioreactor.

A bioreactor was installed in 2012 near Baltic, South Dakota. Weekly inlet and outlet samples have been collected and analyzed for nitrate and *E. coli*. Results from these samples show that treatment performance has diminished, and the bioreactor may be reaching the end of its useful life. Hydraulic performance of the aged bioreactor was assessed with a bromide pulse tracer study in July 2021. The objective of the tracer study is to assess hydraulic performance metrics including time to peak, residence time distribution and the mean residence time of the tracer. These factors will be used to determine the primary flow type, indicate dead zones and short circuiting, and overall hydraulic efficiency. This project will provide guidance for maintenance and recharge methods for denitrifying woodchip bioreactors.

1. Introduction

Water quality in the Midwest has been worsening over the years with much of the decline being associated with runoff and subsurface drainage containing nitrate-nitrogen from agricultural practices. This not only effects the water bodies in this region, but the damages extend to the Gulf of Mexico where much of the Hypoxic Zone there has been attributed to this same cause (Rabalais & Turner, 2019). These issues have led to the creation of nutrient reduction strategies across the Mississippi and Atchafalaya Basins. While contributors of excess nutrients include several sources, including leaking septic systems, urban stormwater outfalls, and agricultural surface and subsurface drainage. For agriculture, nutrient reduction strategies address excess nutrient loading through implementation of best management practices (BPMs) that include in-field management of structural practices and edge-of-field structural or engineering practices.

Denitrifying woodchip bioreactors are an edge-of-field water treatment tool used to reduce nitrate-nitrogen loading from subsurface drainage outflow in agricultural systems. These systems have been researched since the mid-1990s (Blowes et al., 1994) with a significant research activity on nitrate-nitrogen removal performance documented (Christianson & Helmers, 2011; Feyereisen & Christianson, 2015; Christianson et al., 2020). While there is a significant and growing body of research related to woodchip bioreactors, long-term performance and assessment of aged bioreactors is limited. Research that has been performed on aged bioreactors has indicated a reduction in performance due to excess sediment loading and woodchip breakdown (Christianson et al., 2020). One such study has suggested that the true lifespan of a bioreactor is less than

the 10 to 15 year lifespan (USDA, 2015) that was originally estimated for this type of system (Christianson et al., 2020).

The function of a denitrifying bioreactor is dependent on the physical characteristics of the fill media. These characteristics include particle size, porosity, pore size, bulk density, and saturated hydraulic conductivity. Throughout years of use, this media will break down as the bacteria in the system use the carbon and the physical characteristics of this media will change. The bioreactor is designed around these physical characteristics to achieve the optimal hydraulic performance, but as the media deteriorates the physical characteristics of the media change. As the fill media changes, the hydraulic effectiveness of the bioreactor will decrease leading to water that is both over treated and under treated (Christianson et al., 2020).

2. Literature Review

2.1. Gulf of Mexico Hypoxia

The northern waters of the Gulf of Mexico are home to the second largest coastal hypoxic zone in the world. A hypoxic zone is also known as a “dead zone” in which there are low levels of oxygen in the water leading to a habitat which is unsuitable for most life.

The largest contributing factor for the Gulf of Mexico hypoxic zone is from excess nutrient in the water; mainly nitrogen and phosphorus (Rabalais and Turner, 2019). These nutrients reach the coastal waters from their sources and lend themselves as fertilizer for blooms of algae. When algae die and decompose, it is consumed by bacteria that deplete the dissolved oxygen levels in the surrounding waters, leading to the dead zone (Virginia Institute of Marine Science, 2020).

Mississippi/Atchafalaya River Basin (MARB) drains 41% of the land contiguous United States and supplies 90% of the fresh water to the Gulf of Mexico (Mitsch et al., 2001). It is estimated that 71% of the of the nitrogen load attributing to the dead zone is from agricultural practices in this watershed, and 52% is from corn and soybeans practices alone (Ritter and Chitikela, 2020).

The United States Environmental Protection Agency (EPA) created the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force in Fall of 1997. This taskforce was created to understand the effects that hypoxia and eutrophication had on the Gulf of Mexico and create a strategy to reduce the size and scope of the hypoxic zone. Through partnerships with other federal agencies, state governments, and universities, the

EPA started implementing a plan to study strategies to decrease the amount of pollutants being sent downstream and fight eutrophication in the Gulf of Mexico (EPA, 2022).

2.2. Nitrate in Agricultural Drainage

One of the main nutrients being targeted in the strategy to reduce the Gulf of Mexico Hypoxic Zone is nitrate-nitrogen (Hampson, 2018). Nitrate is formed through a biological process in which nitrifying bacterium convert nitrogen from forms that are more stable in the soil to nitrate. Nitrate can be formed from both organic and inorganic sources such as manure, fertilizers, and decaying or dead plants. As nitrifying bacteria transforms other forms of nitrogen to nitrate, the molecule gains oxygen atoms making it more negative (Robertson and Groffman, 2007). Since soil generally has a negative charge as well, nitrate compounds repelled from the soil colloid rather than bonded to it. Therefore, when water flows though the soil, nitrate are attracted to its slight positive charge and is then leached through the soil profile and moved downstream (Fernandez, 2021)

This is a natural process, but the introduction and widespread adoption of nitrogen fertilizers has accelerated downstream nitrogen loading. Due to the increased regulation in the area of water quality and the income loss for farmers, many strategies and products have come to market to help decrease the amount of nitrate being lost downstream (Baligar et al., 2001). These strategies can often be grouped into one of two categories: concentration reduction or flow reduction. Concentration reduction strategies work by reducing the amount of nitrate in the water, while flow reductions strategies reduce the amount of water leaving an area.

2.3. Options for Improving Drainage Water Quality

One of the most well know concentration reduction practices to producers are nitrogen stabilizer additives. These products can be added to commercial fertilizers and manures to inhibit nitrification and other forms of nitrogen volatility. Nitrogen stabilizers often work by inhibiting the growth and effectiveness of nitrifying bacteria. Nitrogen stabilizers were first introduced in the 1960s with new formulations and modes of action being labeled as recently as 2019. This market has been growing in recent years, and with the dip in crop commodities and a hike in nitrogen fertilizer, farmers and producers are more willingly using this product to keep their nitrogen investment in their fields for as long as possible (Abbott, 2022)

While nitrogen stabilizers are very effective when they are applied, they do break down over time. The length of time these products are active is dependent on factors like temperature, sun exposure, and moisture, but some products claim effectiveness up to 12 weeks in soils with a temperature of greater than 52 degrees Fahrenheit (Koch, 2020). Though this suite of products does not have 100% efficiency, it is a good tool to help farmers keep their nitrogen in place through germination and keep their investment in the root zone for a longer period of time (EPA, 2022)

Another practice that farmers are using to save money on their nitrogen investment is split applying their nitrogen fertilizer. Split application is the practice of applying smaller amounts of fertilizer throughout the growing season adding up to the total need of the plant or crop. This allows growers to apply more specific amounts of fertilizer at critical times in a crop's growth cycle, making the use of nitrogen more efficient and less likely to move past the plant's root zone before uptake. One major

downside to this strategy is the extra investment in operation costs and equipment needed to apply fertilizers at several times over several growth stages versus applying all of a crop's fertilizer up front in one pass of the field. Despite that, the agronomy industry has seen an uptick in the adoption of this practice as it lowers the amount of nitrogen input and allows each pound of nitrogen to be used more efficiently.

The next suite of nitrate reduction strategies is collectively known as conservation drainage. Conservation drainage is a term that has been coined to describe practices that allow growers to have more control over the water in their fields using different control structures. Benefits to this can include water storage for between rainfalls, boosted yield, and reduction of nitrate load flowing downstream. Unlike the previous practices, conservation drainage is targeted to reducing nitrate loading after the nitrogen had been applied or broken down in the field rather than before the application.

Within conservation drainage, nitrates and other pollutants are reduced downstream by reducing the amount of pollutant load within the water, or by decreasing the flow volume of the water carrying pollutants.

Practices that reduce flow volume are controlled drainage, and drainage water recycling. Both of these practices reduce downstream loading by holding water at or near the field which prevents anything carried by the water from traveling downstream. Practices that reduce the concentration of pollutants within the drainage water itself include saturated buffers and bioreactors. These practices allow for processes such as denitrification to occur in order to remove nitrates and other pollutants before that water

is fed downstream. Some practices can reduce both concentration and flow volume, such as a constructed wetland.

2.4. Denitrifying Bioreactors

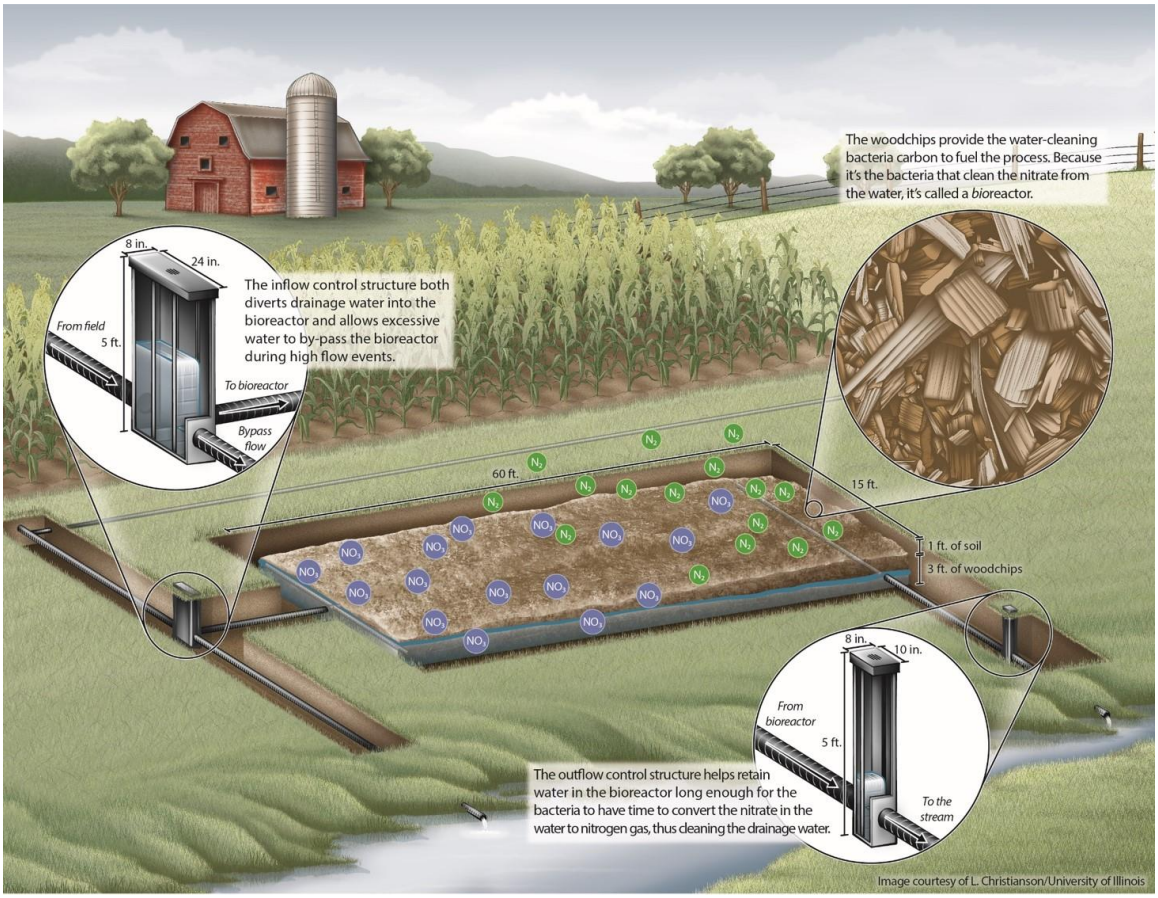

Figure 1: Drawing of denitrifying bioreactor. Image courtesy of L. Christianson/University of Illinois

A bioreactor is an edge of field practice that utilizes denitrifying bacteria to transform nitrate (NO_3^-) into dinitrogen gas (N_2) which prevents it from entering into surface water. A bioreactor is made up of a channel, or a trench, filled with a carbon source, and a drainage control structure that is used to divert field drainage through that carbon source. The bioreactor provides anaerobic conditions and the carbon source needed for denitrifying bacteria to perform the denitrification process which converts NO_3^- into N_2. While effectiveness of various carbon sources is an area of active research,

woodchips are most commonly used as the carbon source for denitrifying woodchip bioreactors (Christianson et al., 2010).

Bioreactors are considered to be a very low maintenance and versatile conservation drainage method. Bioreactors are estimated to last around 10 to 15 years before being recharged with a new carbon source (USDA, 2015). If woodchips are being used as the carbon source, it is recommended that woodchips should range from ¼-inch to 1-inch in size for the best rate of flow. Woodchips should have minimal fine materials including dirt, wood shavings, or gravel as they can reduce the flow of water through the medium (Christianson & Helmers, 2011).

2.5. Hydraulic Residence Time

One of the most important factors relating to bioreactor performance is hydraulic residence time (HRT). HRT is the measure of the average time that it takes for a solution to move completely though the bioreactor. HRT within a woodchip bioreactor has as direct impact on nitrate. In a study done on a bioreactor in Iowa, the HRT was varied to determine the amount of NO_3^- concentration reduction for each HRT. Nitrate removal efficiency increased from 9.0% to 53.8% when the HRT was increase from 2 to 16 hours (Martin et al., 2019).

Although a longer HRT results in improved transform nitrate more effectively, there are potential negative side effects to allowing water to stay in a bioreactor too long. One of these side effects can be production of monomethyl mercury (MMHg) which occurs as sulfate-reducing bacteria and other bacteria methylates ionic and elemental forms of mercury that is in the drainage water or the woodchips (Christianson &

Helmers, 2011). This is potentially hazardous because is increases the risk of human exposure where it acts as a neurotoxin.

To design bioreactors with an optimal hydraulic retention time, several factors have to be taken into account. These include the fill media porosity, bioreactor flow rate, and the bioreactor flow volume. In most edge-of-field applications, bioreactors are designed with an inflow and an outflow control structure that can help manage HRT more precisely. The inflow structure can control the bioreactor inflow volume while also allowing excess high flows to bypass the bioreactor (Chun et al., 2010). Whereas the outflow can help regulate the amount of water that is let out of the bioreactor in order to maintain the desired retention time. The difference in elevation between the inflow and the outflow of a bioreactor can control the hydraulic gradient, which also affects HRT.

2.6. Hydraulic Indexes

Evaluation of hydraulic performance of a bioreactor can be done one of two ways. The first is to directly assess the HRT. Since HRT consists of several factors, it can be difficult to extrapolate which variable, or combination of variables, is responsible for a deviation from the theoretical HRT. In order to determine what factors are responsible for deteriorating performance, hydraulic indexes can be used. Within a bioreactor, there are generally two types of indexes used: short circuit index and mixing index.

Short circuiting is related to the advection of the fluid inside the unit, forcing with part of the fluid to leave the unit earlier than the theoretical retention time. In contrast, mixing related to the random spreading of fluid inside the unit. In this instance mixing

references diffusion via turbulence and phenomena like continuously stirred tank reactor flow. (Teixeira and Siquena, 2008).

In order to use these indexes, a tracer test must be done on the bioreactor. During a tracer study, a slug of a conservative tracer (bromide or chloride) is injected into the inflow of the bioreactor, and the amount of tracer extracted from the bioreactor is measured cumulatively over time.

From the tracer study, one of the most important analyses that can be done is on the hydraulic efficiency:

$$e = \frac{t}{T} \tag{1}$$

where e is the hydraulic efficiency, t is the mean residence time of the tracer, and T is the theoretical hydraulic retention time (Thackston et al., 1987). T is calculated as:

$$T = \frac{V\rho}{Q} \tag{7}$$

where V is active flow volume, ρ is the media porosity, and Q is the flow rate through the bioreactor. The mean tracer residence time is calculated as:

$$t \approx \frac{\sum t_i c_i \Delta t_i}{\sum c_i \Delta t_i} \tag{8}$$

where t_i is the time and c_i is the concentration of the ith sample, and Δt_i is the time between samples (Metcalf and Eddy, 2003).

One of the reasons to test the hydraulic efficiency is due to the short-circuiting mentioned above. When advective forces from the fluid is pulling the fluid through the

reactor, the fluid takes the path of least resistance, so there are parts of the bioreactor that are completely by-passed. As a result, the actual volume of the bioreactor is not indicative of the effective volume, and since the effective volume of the bioreactor is reduced, the theoretical HRT would be larger than the actual HRT (Thackston et al., 1987).

To specifically measure for short circuiting (S), the equation:

$$S = \frac{t_{16}}{t_{50}} \tag{11}$$

where t_{16} andt_{50} are the times at which 16% and 50% of the tracer has passed through the bioreactor, respectively. If S measures near zero, this may be an indicator that there is short circuiting occurring in the bioreactor, and an S value measuring closer to 1.0 may indicate that the bioreactor is performing more ideally (Ta and Brignal, 1998).

Another index that is often used in assessing flow through a porous media is the Morrill Dispersion Index (MDI). The MDI is an indicator of mixing within the system which is calculated:

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

where t_{90} and t_{10} are the time in which 90% and 10% of the tracer has passed through the bioreactor, respectively. An MDI of one is ideal, indicating plug flow through the reactor. If the MDI is greater than two, the system is classified as a continuously stirred tank reactor.

2.7. Breakdown of Woodchip Fill Media

Woodchips used in bioreactors are broken down over time. It is assumed that most available carbon within the woodchips is broken down first, and what is left is the most stable carbon (Feyereisen and Christianson, 2015). This it not only a problem for inefficient nitrate removal, but it can also change the flow inside the bioreactor. As the woodchip fill deteriorates, physical properties such as particle size, porosity, bulk density, and saturated hydraulic conductivity (Christianson, et al., 2020) are altered from the initial installment. These factors all play a large role in the internal hydraulics of the system.

In study conducted on a bioreactor in Iowa, two tracer tests were performed seven years apart. From these tracer tests, they concluded that the drainable porosity decreased from 46% to 33% (Christianson, et al., 2020; Feyereisen and Christianson, 2015). When a decrease in porosity occurs, the theoretical HRT decreases as porosity and theoretical HRT are directly correlated.

Porosity in a bioreactor can affected by the introduction of silt and clay into the media. In agricultural settings, it is common to see small soil particulates leaving fields in the drainage water (Coelho et al., 2010). After a period of time, these soil particles can be deposited inside the bioreactor. This is assumed to cause problems like short circuiting, where the water flowing through the media will take a path of least resistance through the media that does have more pore space. This could cause a drop in the active flow volume, which would again lead to a decrease in the active HRT.

Sedimentation like this can also have an impact on the general porosity of the bioreactor. If sediment is not deposited in a way that would make an area of the bioreactor ineffective, it may be deposited in amounts that would still decrease the porosity of the fill media. In studies of bioreactors with sedimentation, the woodchip drainable porosity was between 32% and 33% (Christianson, et al., 2020) compared to studies with little to no sedimentation that demonstrated a drainable porosity between 37% and 46% (Ghane et al., 2014; Feyereisen and Christianson 2015). This demonstrates that sedimentation can be a large factor in the hydraulic properties of a bioreactor by reducing the effective drainable porosity and decrease pore sizes which in turn will change the HRT of the bioreactor.

Poiseuille's equation can be used to describe the relationship between the flow rate and other factors including pore size. Poiseuille's equation is calculated:

$$Q = \frac{R^4 \rho_w g \Delta H}{8 \eta L} \tag{2}$$

where Q is volumetric flow rate, R is the radius of a water-filled cylinder, ρ_w is the density of water, g is gravity, ΔH is the difference in total head along the cylinder separated by length L, and η is the coefficient of the dynamic water viscosity. This equation is often used to help model steady-state flow through a saturated media. In assuming that a bioreactor operates under steady-state flow, this theory shows that there is a positive correlation between the flow volume allowed through a pore and the radius of the pore. In a bioreactor in which pore size is decreased over time, the flow rate would also decrease which would also correlate with a decreased HRT.

In a study of a bioreactor in Iowa, a comparison of the woodchips at installation and the woodchips after 9.25 years showed a decrease in the average pore size throughout the media (Christianson et al., 2020). This would correlate to a decrease of the pore radius used in Poiseuille's equation, which would throttle the flow rate through the woodchips and increase the HRT of the bioreactor.

Factors that could lead to a deviation from the original HRT of a bioreactor after years of use include the breakdown of the media, settling, and sedimentation. It is still unclear what the most important factors are to watch for, but through future research, more will be uncovered about the true life expectancy of a bioreactor and the efficacy of bioreactors over time.

3. Woodchip Characterization of a Failed Denitrifying Woodchip Bioreactor

3.1. Introduction

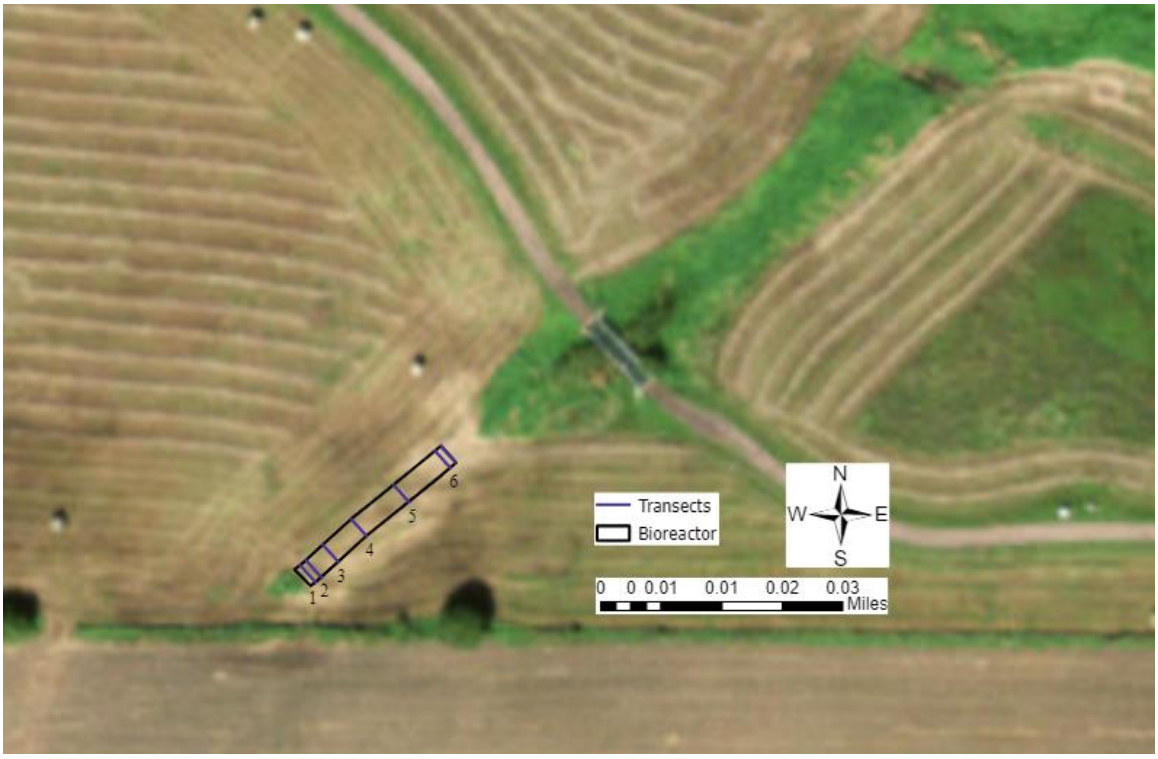

Figure 2: Arial photo of Hartford, SD bioreactor site. Photo retrieved from ERSI and prepared by Kristen Almen

Denitrifying woodchip bioreactors are built using woodchips or wood shreds ranging from 12.0 to 15.1 mm in diameter on average, dependent on source material (Christianson et al., 2020). The material used is a key factor in the design of the bioreactor which are usually designed to optimize that retention time of the water being treated (Christianson & Helmers, 2011). Retention time is affected by active flow volume, porosity, and flow rate. As a bioreactor ages, the carbon material will break down and in some cases, sedimentation will occur within the bioreactor. Both processes will affect the porosity and hydraulic performance of the bioreactor. When flow through the bioreactor is significantly different than the original design, nitrate removal performance will be negatively affected.

A denitrifying woodchip bioreactor was installed in 2014 near Hartford, SD. This bioreactor was monitored since installation (Partheeban, 2014; Thapa, 2017) and has demonstrated a decline in concentration reduction performance. Since the installation in 2014, the Hartford bioreactor has also been affected by external factors that were not accounted for at the time of installation. Heavy rains and unprotected soil upgradient of the bioreactor led to increased sediment loading and flooding in and around the inflow control structure. It is likely that this impacted flow through the bioreactor and resulted in the failure of this bioreactor. This study was conducted to characterize woodchip and sediment particles within the bioreactor to assess the likely causes of failure.

3.2. Material and Methods

3.2.1. Site Characteristics

In November of 2014 a woodchip bioreactor (38.1 m L x 3.0 m W x 1.2 m D) was installed near Hartford, SD in the Minnehaha Conservation District's Dewey C. Gevik Outdoor Learning Center to treat agricultural subsurface drainage. During construction, the sides were lined with plastic, and the top was lined with landscaping fabric. The bottom of the bioreactor was not lined. The bioreactor was designed and constructed using standard methods (USDA, 2015).

The bioreactor was monitored for flow rate and nitrate concentration at the inlet and outlet since installation. Samples were collected approximately weekly throughout the growing season. Primary results were presented in Partheeban (2014) and Thapa (2017) and were summarized in Christianson et al. (2021). A combination of exposed sediment, high rainfall, and significant surface runoff upgradient of the bioreactor site in 2018 and 2019 led to the likely introduction of sediment into the bioreactor through the

inflow control structure. After 2019, there was anecdotal evidence of clogging and a decreased HRT from low flows and a strong hydrogen sulfide smell near the outlet control structure.

3.2.2. Excavation and Sample Collection

Excavation took place August 25, 2021. The bioreactor site was marked with flags to guide excavation with points at 5, 10, 25, 50, 85, and 120 feet from the inlet. Global positioning system (GPS) coordinates were taken at each of these locations. A mini excavator was used to first remove the soil cap and the landscaping fabric that covered the top of the bioreactor. The excavator dug a cross-section of woodchips from the bioreactor one vertical foot at a time. From each vertical foot of woodchips, three subsamples were taken from across the width of the bioreactor. Each subsample was collected separately into a five-gallon bucket that was lined with a trash bag, the trash bag was sealed, and the subsample was bagged a second time and stored in a tote at room temperature until lab experiments began. The process continued until the bottom of each cross-section was reached. From the Hartford bioreactor, 41 individual samples were collected. During excavation, sediment was visible in the sections closest to the inlet and in the lowest cross-sections of the bioreactor.

3.2.3. Porosity

A subsample was taken from each full sample and packed into a 10.16 cm (4 in) inner diameter piece of polyvinyl chloride (PVC) that was cut into a length of five inches. A tamper was created by screwing a piece of acrylic cut to fit inside the PVC pipe to a one-and-a-half-inch diameter, three-foot-long wooden dowel. The PVC pipe was filled with approximately three inches of woodchips, and the tamper was placed on top of the

woodchips. To pack the woodchips, a two-inch diameter, two-foot-long piece of lead pipe with a threaded cap was slipped over the tamper, raised one inch, and dropped. This repeated five times per each layer of woodchips added to the pipe.

Figure 3: Photos of tamping system used to pack woodchip samples

The full pipe was then covered at both ends with cheesecloth and secured with rubber bands and was fully submerged in water for at least 24 hours to fully saturate the core. After saturation, the PVC pipe was capped at both ends and saturated mass was determined.

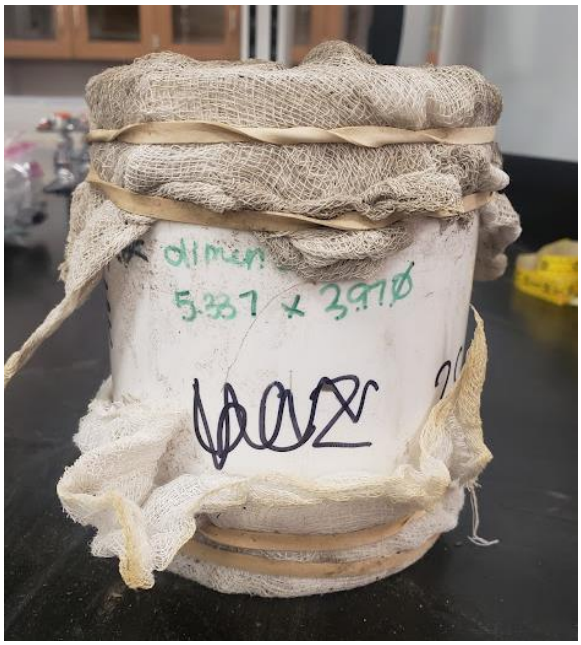

Figure 4: Photo of packed woodchip sample with cheesecloth caps

The caps were then removed, the core was suspended for another 24 hours to freely drain, and field dry mass was determined.

Figure 5: Photos of suspension system used to drain woodchip samples

The sample was removed from the core and transferred into metal oven tins and oven dried at 110°C for 24-48 hours. Oven-dry mass was determined, and the dry media was stored at room temperature in sealed plastic bags.

Figure 6: Photos of oven-dry woodchip sample

Drainable porosity is the volume of water that is able to freely drain by gravity from a unit of media in response to a change in the water table (Marino and Luthin, 1982) In a bioreactor, this is also known as the active pore volume. Drainable porosity was calculated:

$$\phi_d = \frac{(m_s - m_f)}{\rho_w \cdot V} \tag{3}$$

where m_s and m_f are the mass of the saturated and field dry woodchips, respectively, ρ_w is the density of water, and V is the volume of the sample.

The total porosity of a sample is the total amount of pore space in each sample. Total porosity was calculated:

$$\phi_t = \frac{(m_s - m_d)}{\rho_w \cdot V} \tag{4}$$

where m_s and m_d are the mass of the saturated and oven dry woodchips, respectively, ρ_w is the density of water, and V is the volume of the sample.

Bulk density was calculated:

$$\rho_b = \frac{m_d}{V} \quad (5)$$

where m_d is the oven-dry mass and V is the volume of the sample.

3.2.4. Particle Size Distribution

Subsamples of at least 100 g were collected from the oven-dry samples and were sieved using 25, 19, 12.5, 9.5, 8, 6.3, 4.75, 3.35, and 1.18 mm sieves for 10 minutes using a W.S. TYLER® RO-TAP® Electronic Test Sieve Sheker. Similar methods were used by Christianson (2020). The mass in each sieve was determined. This was repeated three times. The masses for the replications of each sample were averaged to determine a representative sample value.

Figure 7: Photo of W.S. TYLER® RO-TAP® Electronic Test Sieve Sheker used to sieve dried woodchip samples. Sieve sizes used were 25, 19, 12.5, 9.5, 8, 6.3, 4.75, 3.35, and 1.18 mm

3.2.5. Statistical Analysis

Statistical analysis was done using both a one-way analysis of variance (ANOVA) (Anscombe, 1948) and the Kruskal-Wallis Test to test for statistical significance between the means and medians of the data (Kruskal & Wallace, 1952). The test used was determined based upon the normality of the data. The Anderson-Darling test was used to test all data for normality using a 95% confidence interval (Anderson & Darling, 1954). If the data failed the test for normality, the Kruskal-Wallis Test was used to determine statistical significance, and all other cases used one-way ANOVA. For cases in which ANOVA was used, the least significant difference (LSD) was also found using the Fisher Pairwise Test (Fisher, 1922). Statistical analysis was performed using Minitab 21 (Minitab LLC, State College, PA).

3.3. Results

To test the physical properties of woodchips, all samples were tested for drainable porosity, total porosity, bulk density, and particle size distribution. Through this series of tests, the mechanisms which have aided in the failure of the Hartford denitrifying woodchip bioreactor have been determined. This is an important process for understanding the upkeep necessary to maintain bioreactors in the future.

3.3.1. Porosity

3.3.1.1. Drainable Porosity

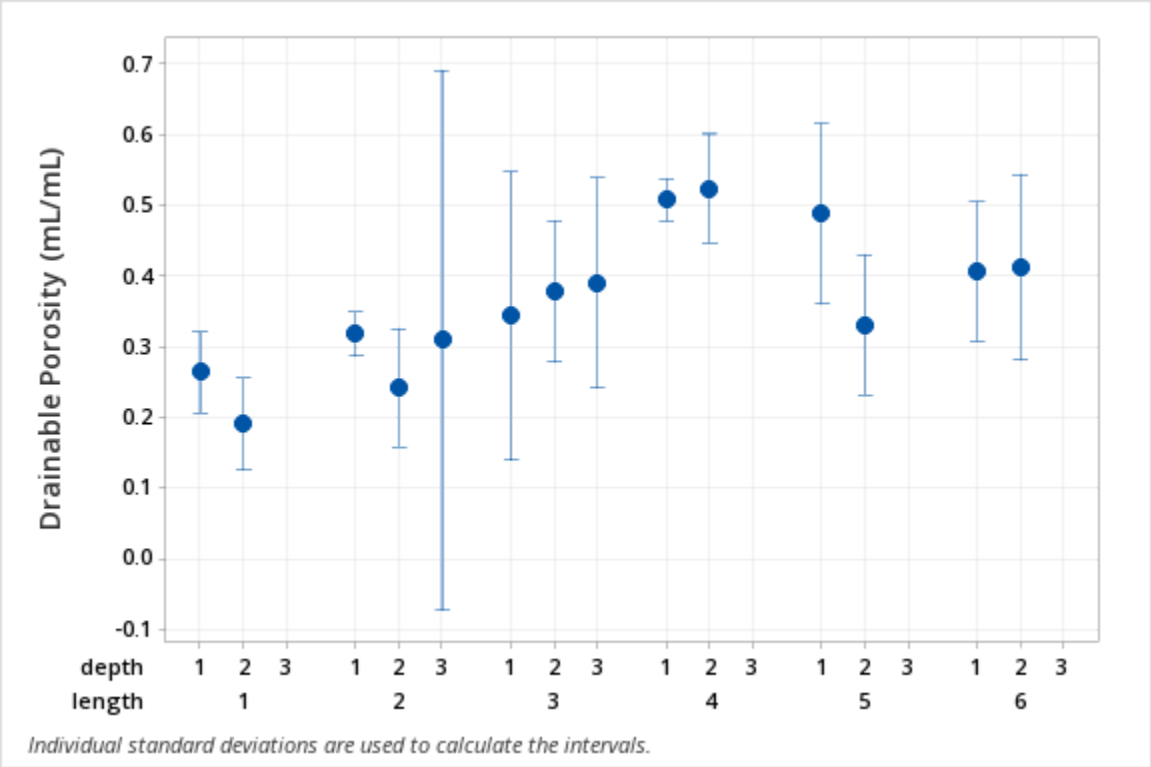

Figure 8: Average drainable porosity of woodchips from Hartford bioreactor by length (from inlet, 1=1.52 m; 2=3.05; 3=7.62; 4=15.24; 5=25.91; 6=36.58) and depth (1=0 to 0.30 m; 2=0.30 to 0.61; 3=0.61 to 0.91)

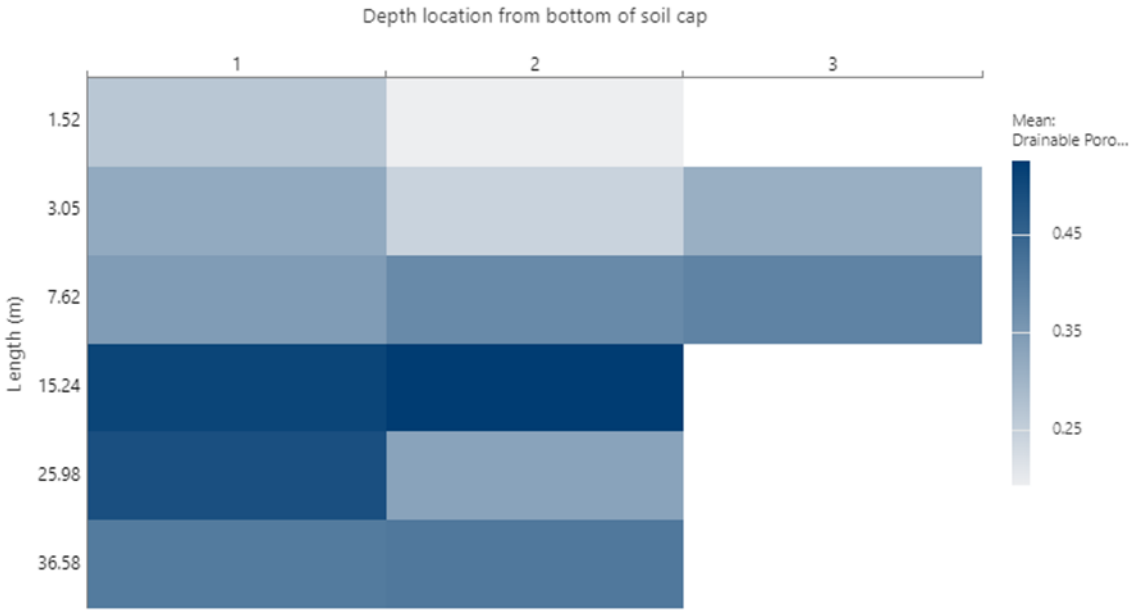

Figure 9: Heat map of drainable porosity by length and depth with light blue indicating low drainable porosity and dark blue indicating high drainable porosity. Each rectangle represents the average drainable porosity from each sample location. Length from inlet is on the vertical axis and depth location from the bottom of the soil cap is on the horizontal axis ((1=0 to 0.30 m; 2=0.30 to 0.61; 3=0.61 to 0.91)

The drainable porosity ratio of the sampled woodchips was 0.37 ± 0.10 (mean ± standard deviation) (Table 3). A One-Way ANOVA test shows that there is a statistical difference at the 95% confidence level across the length (p-value <0.001), but not throughout the depth (p-value of 0.449). Since extreme conditions would have to be met in order for the bioreactor to become completely dry, the total porosity parameter holds little to no meaning in this context regardless of the significance of the data.

3.3.1.2. Total Porosity

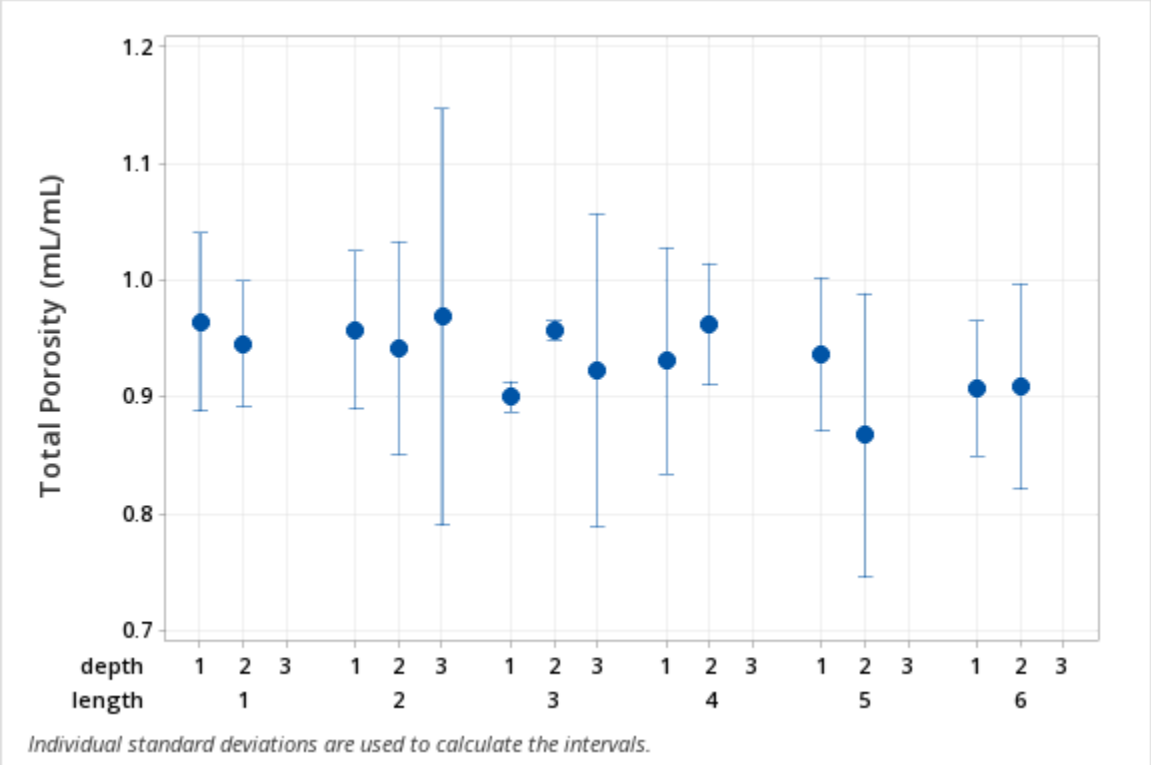

Figure 10: Average total porosity of woodchips from Hartford bioreactor by length (from inlet, 1=1.52 m; 2=3.05; 3=7.62; 4=15.24; 5=25.91; 6=36.58) and depth (1=0 to 0.30 m; 2=0.30 to 0.61; 3=0.61 to 0.91)

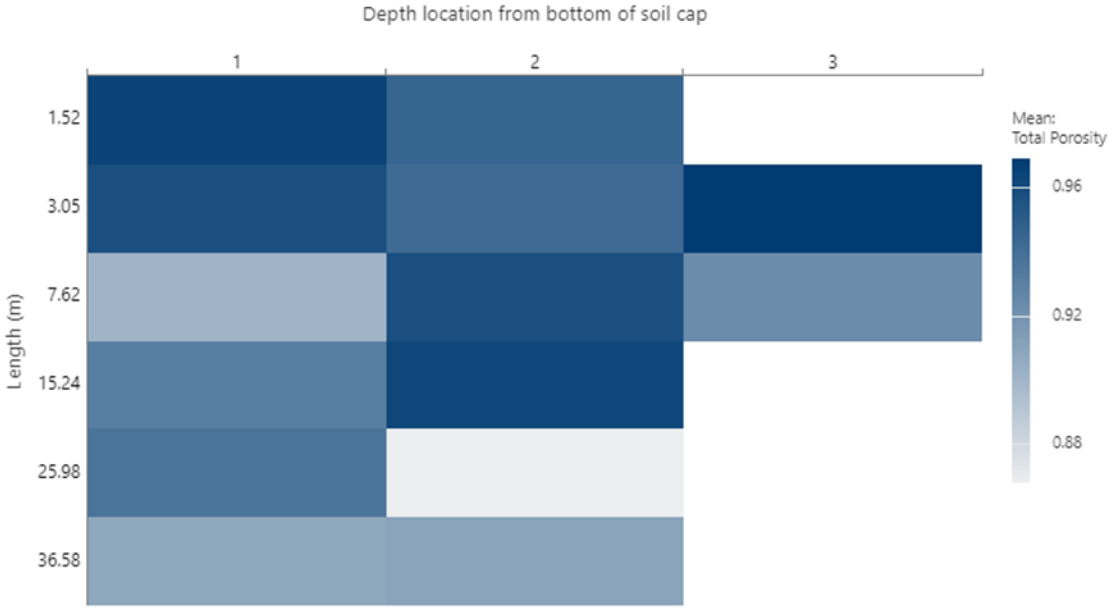

Figure 11: Heatmap of total porosity by length and depth with light blue indicating low total porosity and dark blue indicating high total porosity. Each rectangle represents the average total porosity from each sample

location. Length from inlet is on the vertical axis and depth location from the bottom of the soil cap is on the horizontal axis (1=0 to 0.30 m; 2=0.30 to 0.61; 3=0.61 to 0.91)

The total porosity ratio of the woodchips in the bioreactor was 0.93 ± 0.04. There was a statistical difference in the total porosity ratio by length (p-value of 0.031) but not by depth (p-value of 0.864). Woodchips are a very porous material as noted by the high total porosity ratio. Total porosity changes in relation to the physical structure of a media. Significant differences in the total porosity ratio may indicate sedimentation and woodchip breakdown throughout different areas of the bioreactor.

3.3.1.3. Packed Bulk Density

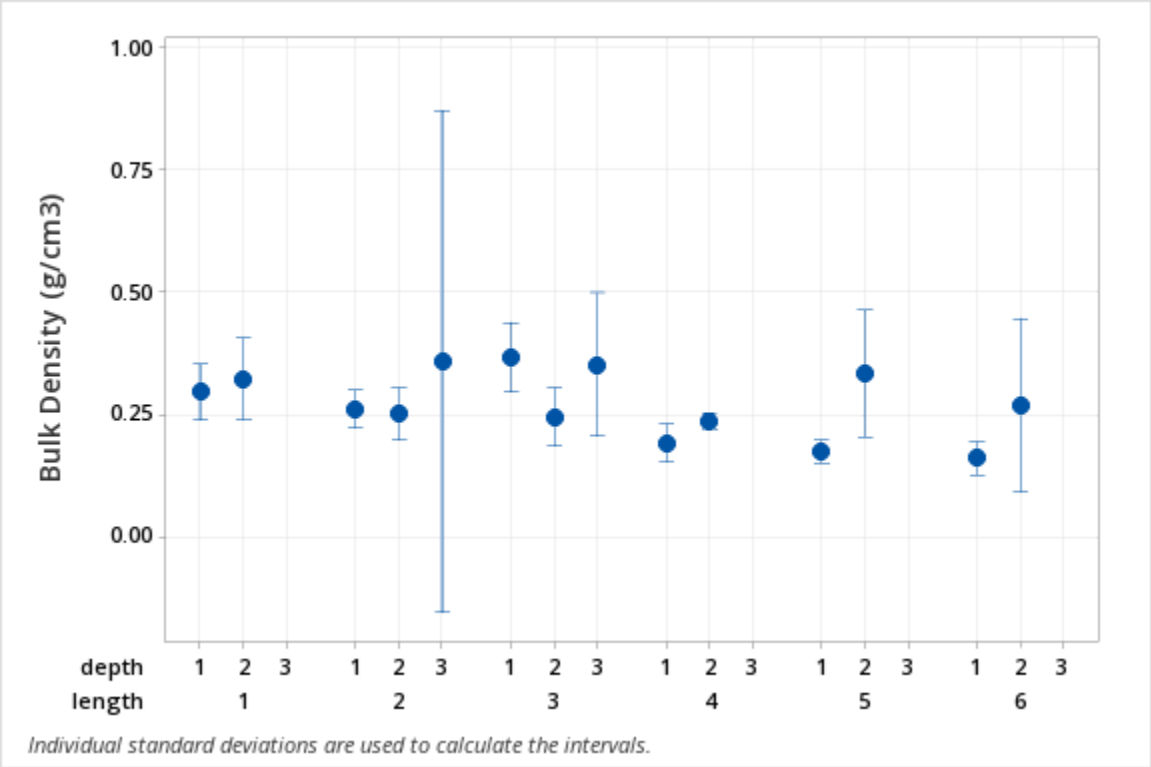

Figure 12: Average packed bulk density of woodchips from Hartford bioreactor by length (from inlet, 1=1.52 m; 2=3.05; 3=7.62; 4=15.24; 5=25.91; 6=36.58) and depth (1=0 to 0.30 m; 2=0.30 to 0.61; 3=0.61 to 0.91)

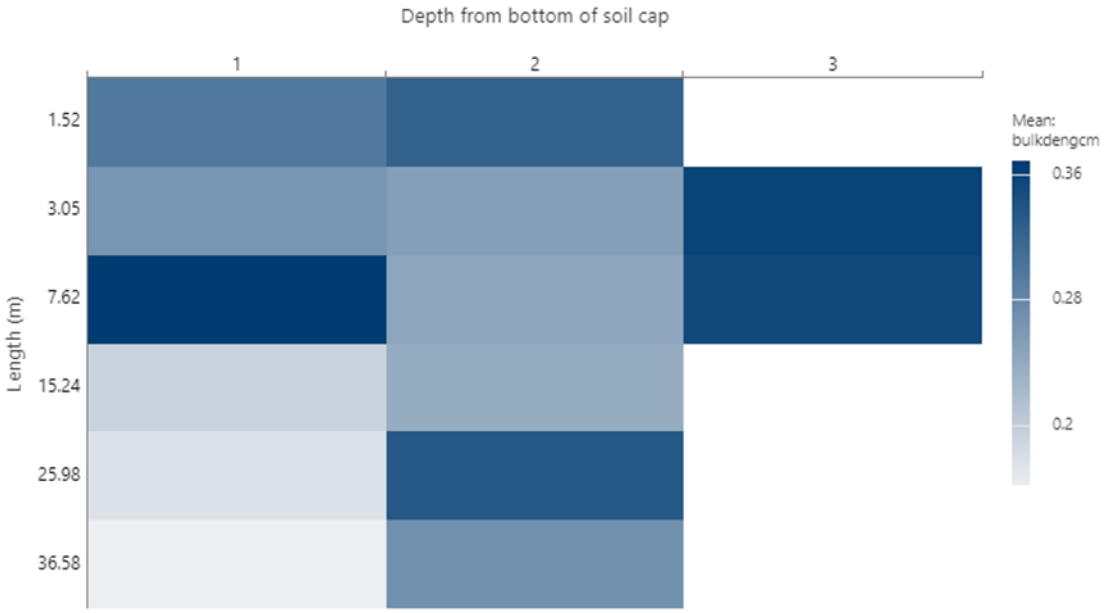

Figure 13: Heatmap of packed bulk density by length and depth with light blue indicating low packed bulk density and dark blue indicating high packed bulk density. Each rectangle represents the average total porosity from each sample location. Length from inlet is on the vertical axis and depth location from the bottom of the soil cap is on the horizontal axis (1=0 to 0.30 m; 2=0.30 to 0.61; 3=0.61 to 0.91)

The bulk density of the packed woodchips was 0.27 ± 0.07 g cm^{-3}. There was a significant difference across the length (p-value of 0.014) and depth (p-value of 0.002) of the bioreactor. The bulk density of the woodchip material was highest closer to the inlet of the bioreactor and lowest towards the middle and the outlet of the bioreactor.

The bulk density of the woodchip material in the bioreactor was higher deeper in the bioreactor and a lower bulk density in the top in the bioreactor. During excavation and testing, it was observed that the samples taken lower in the profile contained more sediment whereas the samples higher in the profile were void of or contained less sedimentation.

Table 1: Average porosity and bulk density of Hartford bioreactor woodchips ranked by length with least significant difference indicator

	Test	Drainable Prosity	Total Porosity	Bulk Density ($g\ cm^{-3}$)
	p-value	0.000	0.031	0.014
Length from inlet	1.52 m	0.23 C	0.96 A	0.31 A
	3.05 m	0.29 C	0.96 A	0.28 AB
	7.62 m	0.38 B	0.93 ABC	0.32 A
	15.24 m	0.52 A	0.95 AB	0.22 B
	25.91 m	0.41 B	0.9 C	0.26 AB
	36.58 m	0.41 B	0.91 BC	0.22 B

Table 2: Average porosity and bulk density of Hartford bioreactor woodchips ranked by depth with least significant difference indicator

	Test	Drainable Prosity	Total Porosity	Bulk Density ($g\ cm^{-3}$)
	p-value	0.449	0.864	0.002
Depth	0.00-0.30 m	0.39 A	0.94 A	0.24 B
	0.30-0.61 m	0.35 A	0.93 A	0.28 B
	0.61-0.91 m	0.36 A	0.94 A	0.36 A

Significant
Not Signficant

3.3.2. Particle Size Distribution

3.3.2.1. Particles less than 1.18mm

The distribution of particles with a diameter of less than 1.18 mm was not significant with length, but it was significant with depth. This means that when sedimentation or major breakdown does occur within the bioreactor, the small particle sizes will settle to the bottom of the bioreactor rather than staying evenly distributed throughout the profile. This may also show that when breakdown does occur, it is more likely to happen at the bottom of the bioreactor rather than in the top.

3.3.2.2. Particles between 1.18 and 6.3 mm

The distribution of particles between 1.18 and 6.3 mm was significant by length but not by depth. This lends the belief that breakdown and infill was dependent on the length of the bioreactor, but it was not dependent on the depth of the bioreactor.
The distribution of particles between 6.3 and 9.5 mm was not significant for either length or depth. This particle size range suggests that there is a point of equilibrium in the breakdown process occurring at this point.

3.3.2.3. Particles between 9.5 and 25 mm

The distribution of particles ranging from 9.5 to 25 mm was significant in terms of length, and 9.5 mm particle size was significant by depth. The significance by the length also points to breakdown being dependent on the length within the bioreactor.

3.3.2.4. Particles greater than 25 mm

The distribution of particles greater 25 mm was not significant for either depth of length. Within the samples, there were very few woodchips that were collected at this size. At 15.24 m, the most particles were at this sieve size collected, but with so few samples containing particles this size, this could not be counted as significant.

Table 3: Average mass of particles collected by sieve ranked by length with least significant difference indicator

Length from inlet	Seive Size	≥ 25mm	≥ 19mm	≥ 12.5mm	≥ 9.5mm	≥ 8mm	≥ 6.3mm	≥ 4.75mm	≥ 3.35mm	≥ 1.18mm	< 1.18mm
	p-value	0.598	0.040	0.008	0.017	0.864	0.113	0.002	0.002	0.000	0.241
1.52 m		0.75	3.8	23.48 AB	19.99 A	10.51 A	11.08 A	7.53	5.3	7.49 BC	10.73
3.05 m		0.28	3.39	23.84 A	20.3 A	11.01 A	11.64 A	8.4	5.35	6.48 C	9.95
7.62 m		0.16	2.46	19.17 BC	16.32 B	11.21 A	11.08 A	8.98	5.97	8.56 B	16.61
15.24 m		2.26	4.74	24.57 A	20.03 A	10.13 A	11.78 A	8.92	5.37	5.15 C	7.69
25.91 m		0.44	4.57	21.01 ABC	17.7 AB	10.43 A	12.44 A	9.44	6.47	7.43 BC	10.54
36.58 m		0.00	1.3	15.95 C	15.45 B	10.87 A	13.19 A	12.65	9.72	11.89 A	9.46

Table 4: Average mass of particles collected by sieve ranked by depth with least significant difference indicator

Depth	Seive Size	≥ 25mm	≥ 19mm	≥ 12.5mm	≥ 9.5mm	≥ 8mm	≥ 6.3mm	≥ 4.75mm	≥ 3.35mm	≥ 1.18mm	< 1.18mm
	p-value	0.807	0.440	0.093	0.004	0.244	0.083	0.313	0.464	0.224	0.001
0.00-0.30 m		0.67	3.69	21.68 AB	18.79 A	11.07 A	12.24 A	9.83	6.73	7.89 A	8.03
0.30-0.61 m		0.56	2.85	22.30 A	19.10 A	10.73 A	11.79 AB	9.00	5.88	7.21 A	11.10
0.61-0.91 m		0.58	3.84	16.83 B	13.73 B	9.64 A	10.47 B	8.22	6.29	9.63 A	21.32

Significant ANOVA
Not Signficant ANOVA

Significant Kruskal-Wallis
Not Signficant Kruskal-Wallis

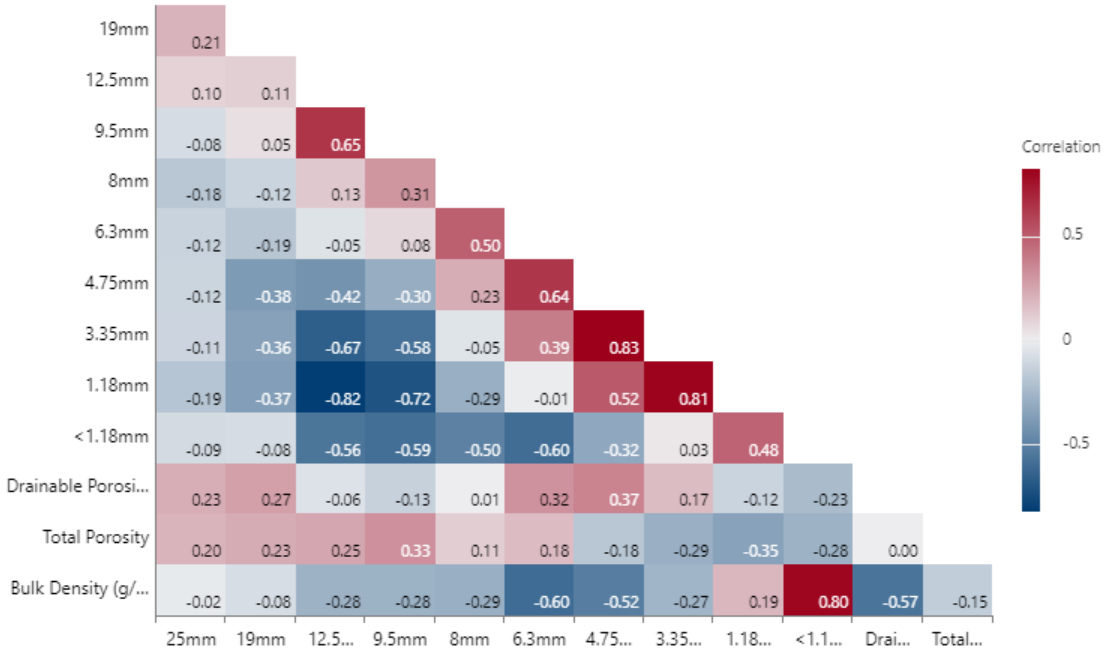

Figure 14: Correlogram depicting correlations between particle sizes, porosity and packed bulk density with red indicating a positive correlation and blue indicating a negative correlation. Strong correlations are depicted in dark shades and weak correlations are depicted in lighter shades

Adjacent particle sizes were positively correlated indicating that particles move from one fraction size to the next and breakdown occurred at a consistent rate in areas where breakdown occurred. There were not significant concentrations of any singular particle size indicating that particle sizes do not break down at differing rates.

There is also a strong correlation between particle sizes less than 1.18 mm and packed bulk density. This indicates that in areas where breakdown occurs, areas with large amounts of small particles and less medium to large particles are not able to retain structure and compaction and settling may occur in these areas.

This also relates to the negative correlation between bulk density and drainable porosity. As areas with small particles compact and settle, large pore spaces will fill. This reduces the amount of active pore space available for water to drain through.

3.4. Discussion

3.4.1. Mechanisms of Failure

Characterization of the woodchips enabled the identification of the mechanisms of failure and reduced performance for Hartford bioreactor and likely of others that have experienced significant sedimentation episodes. In an aged bioreactor in Iowa, Christianson et al. (2020) noted that the median particle size of the woodchips and mixed shreds decreased significantly in the nine years after the bioreactor had been established. This initial woodchip samples were not analyzed for the Hartford bioreactor, but the woodchip analysis suggests a similar trend of woodchip breakdown.

In the same study, in was also determined that there were also small particles of inorganic material, likely derived from soil sediment. The conclusion from that study were that both sedimentation and woodchip breakdown led to the impaired hydraulic performance. This is consistent with indications of woodchip breakdown and sedimentation at the Hartford site, and the likely two mechanisms of failure.

During the sieving process, particles smaller than 1.18 mm were very small woodchip particles, soil particles, or a mixture of both. Since the density of soil particles is higher than that of woodchip particles, areas affected by sedimentation will have a higher bulk density than areas where sedimentation was limited. Using a combination of bulk density and the mass of particles collected in the catch sieve, it can be estimated where the most sedimentation occurred and where the most breakdown occurred throughout the bioreactor.

The as-built depth of the woodchip material in the bioreactor was four feet. At the time of excavation, it was observed that the depth of woodchips in the bioreactor varied

from two to three feet across the length of the bioreactor. This was likely due to the soil deposition of the top of the bioreactor from upgradient erosion. The soil cap was thickest towards the front of bioreactor, and it was less this towards the end of the bioreactor. Deposition of large quantities of sediment on top of the bioreactor is possible to cause compaction to the media below leading to higher densities in areas where more deposition occurred.

3.4.1.1. Sedimentation

When compared along the length, bulk density was highest in the cross-sections closest to the inlet. When compared across depth, the bottom layer had the highest bulk density (Table 2). This is in contrast to portions at the top of the bioreactor that were less dense along with the portions in the middle and nearer to the outlet of the bioreactor, therefore sedimentation affected the front of the bioreactor the most with much of it settling to the bottom of the bioreactor. While the water level near the inlet will be set according to the inflow control structure, the inflow manifold was near the bottom of the bioreactor. This likely partially explains the high amount of sediment present near this location. This also significantly impedes flow into the remainder of the bioreactor.

The portions of the bioreactor near the inlet and outlet both had higher portions of fine particles when compared to the middle of the bioreactor (15.24 m from the inlet). As it has been determined that most of the sediment loading was closer to the inlet of the bioreactor, it stands to reason that the finer particles at the rear of the bioreactor would contain less dense material like fine woodchip particles. That translates into a higher volume of fine particles when the material is less dense than when compared to the same mass of a denser material. As the material in the downstream half of the bioreactor is less

dense, it can be deduced that there was more breakdown of material closer to the outlet. The cross-section closest to the outlet (36.58 m from the inlet) has a higher number of small particles (1.18 to 6.3 mm) and a lower number of large particles (9.5 to 25 mm) with no woodchips greater than 25 mm.

The middle of the bioreactor, length 4 (15.24 m from the inlet), shows the opposite trend of length 6 (36.58 m from the inlet). Length 4 (15.24 m from the inlet) has a much higher mass of particles greater than 25 mm and it has the highest or second highest values in every large particle size category (9.5 to 25 mm). Less particle mass was collected as the sieve sizes decreased with the lowest mass of particles being collected in the two smallest sieves.

3.4.1.2. Effective Flow Volume

Drainable porosity was highest in the middle of the bioreactor and lowest at the upstream end (Table 1). The front and back ends of the bioreactor have the highest fraction of the smallest particle size (bottom pan) which contributes to a low drainable porosity. The bulk density indicates that the upstream end of the bioreactor has more sediment, and the downstream end has less sediment but more small woodchips particles. This indicates that even though the bioreactor likely failed due to sedimentation at the front end of the bioreactor, there are likely still potential issues with clogging at the downstream end of the bioreactor but due to woodchip breakdown instead of sediment. For long-term maintenance implications, the middle of the bioreactor may maintain performance, but the upstream and downstream ends of the bioreactor may be impaired due to sedimentation and woodchip breakdown respectively.

3.5. Conclusion

After approximately nine years, significant changes were observed in the structure and performance of a denitrifying woodchip bioreactor near Hartford, SD. Reduction of performance was assessed through analysis of materials excavated throughout the bioreactor. Woodchip degradation and sedimentation are believed to be the two main mechanisms of failure within this drainage system. These mechanisms can drastically change lead to reduced pore sizes in affected areas changing the hydraulic properties within the bioreactor.

The woodchips in the middle of the Hartford bioreactor are still in relatively intact condition with only a minimal amount of very small particles and could continue to serve as a carbon source and allow adequate flow, but as the performance of the bioreactor has been diminished due to issues on either end of the bioreactor, the middle of the bioreactor is serving little to no function. To reduce recharge costs, a modular system might be used in the future to save areas that in good condition, and only recharge the areas that have declined.

As noted, the Hartford bioreactor received sediment loading from a bare dirt lot upgradient. To protect the integrity of the bioreactor, installing a barrier or buffer could have captured or filtered sediment loading into the control structure of the bioreactor. In addition to the field and tile system characteristics, it is necessary to evaluate the landscape surrounding a bioreactor in order to determine areas of impact, as it can play a large role in the longevity of a bioreactor. This underscores the impact that sediment can have on the performance of bioreactors and should be emphasized in design guidance, installation, and maintenance. If a bioreactor received a significant sediment load, either

through the control structure of through the time from a blowout or surface inlet, the bioreactor can be irreparably damaged and require complete replacement.

4. Study of Internal Hydraulics of an Aged Denitrifying Woodchip Bioreactor

4.1. Introduction and Background

Figure 15: Arial photo of Baltic, SD bioreactor site with tile drainage. Photo courtesy of Cynthuja Partheeban

Bioreactors are an edge-of-field practice used to reduce nitrate-nitrogen loading from tile drainage. Over time, as the woodchip fill media breaks down, the hydraulic properties of the woodchips change, and the hydraulic performance of the bioreactor can be reduced. Tracer studies are a common way to test the internal hydraulics of structures like a bioreactor. By tracking flow through a bioreactor, parameters including average hydraulic retention time, predominant flow type, and hydraulic efficiency can be determined. Understanding the inner workings of a denitrifying woodchip bioreactor can be an effective tool to determine decline in bioreactor performance and better understand how fill media breakdown most affects the system.

Since the installation of the Baltic denitrifying woodchip bioreactor in 2012, the nitrate reduction across the bioreactor has been measured and analyzed with the latest data being from 2020 and initial results being published in thesis and dissertation results

by Partheeban (2014) and Thapa (2017). Performance in 2018 and 2019 were significantly lower than performance in the years following installation. However, the average nitrate concentration reduction performance in 2020 was similar to performance in years prior to 2018. A recent study conducted on the wood fill media of a 9.25-year-old bioreactor showed that after this period of time, the change in the physical and chemical properties of the media was significant enough to impact the performance and operation of the bioreactor. (Christianson et al., 2020).

4.2. Methods and Materials

4.2.1. Site Characteristics

In July 2012, a woodchip bioreactor (35.1 m L x 5.5 m W x 1.2 m D) was installed near Baltic, SD to treat subsurface drainage from 16.2 ha of rotated row cropped (*Zea mays* and *Glycine max*) land (Partheeban, 2014). The bioreactor, including the inlet and outlet control structures, were surrounded by established and mowed grassland on all sides.

The bioreactor was monitored for flow rate and nitrate concentration at the inlet and outlet since installation. Samples were collected approximately weekly throughout the growing season. Preliminary results are presented in Partheeban (2014) and Thapa (2017) and summarized in Christianson et al. (2021). The average concentration reduction from the inlet to the outlet decrease in 2018 and 2019. In 2020, average concentration improved from the prior two years, indicating that performance of the bioreactor may be deteriorating but was not failing.

4.2.2. Conservative Tracer Study

A conservative pulse tracer study was performed at the Baltic bioreactor on 13 July 2021. Potassium bromide (3.2 kg) was diluted with tap water until the potassium bromide (KBr) was completely dissolved. The solution was poured into the inlet of the bioreactor as quickly as possible using a funnel and a section of polyvinyl chloride (PVC) pipe. Due to dry conditions, irrigation water was used during the tracer study. Water was directed into the bioreactor for around 48 hours prior to the experiment to ensure the system had reached steady state conditions prior to the tracer study. Flow rate was kept consistent through the duration of the study. Care was taken to ensure that none of the solution entered the bioreactor bypass. The bucket containing the solution was filled with water, rinsed, and poured through the funnel and PVC pipe immediately after injection to ensure that as much of the KBr was injected as possible. This process was completed in approximately one minute.

Using a Teledyne ISCO Auto-Sampler, 900 ml water samples were collected from the bioreactor outlet every 30 minutes, and flow depth was measured every minute following the injection of the solution using an ISCO 720 Submerged Probe Flow Module. The 900 ml sample was agitated thoroughly by inverting the bottle 3 times, and a 100 ml subsample was taken from each original sample. The samples were stored in a refrigerator and then shipped in a cooler to be analyzed for bromide (Br) using a Lachat Quick-Chem 8000 automated analyzer (Standard Methods, 1998) at the University of Illinois at Urbana-Champaign. Samples were analyzed approximately one month after collection and were refrigerated for the duration between collection and analysis. It is likely that some bromide transformation occurred, but it is expected that this was minimal

since bromide is conservative (less likely to transform) and consistent since all samples were preserved in the same manner (refrigeration) (Christianson et al., 2013; Christianson et al. 2020).

Figure 16: Outlet sampling station for tracer study at the Baltic, SD bioreactor

4.2.3. Bromide Capture

Due to high sample-to-sample variation, the bromide concentration data was transformed, or smoothed, using a moving average technique. The transformed data fit the trend of the raw data with similar time to peak but lower peak concentration and

overall concentration values that were closer to the trend. A time-step of 4.5 hours was used to calculate the moving average.

Flow volume was calculated:

$$Q = 1.7406H^{1.9531} \quad (6)$$

where Q is flow rate (L min^{-1}) and H is the height of water flowing over the V notch (Partheeban, 2014). The flow volume was multiplied by the bromide concentration at that time to determine the total mass of bromide captured in the system. Linear interpolation was used to estimate concentration between each sample time.

4.2.4. Hydraulic Characteristics

Analysis of outflow concentration patterns in a conservative tracer study enables calculation of several key hydraulic characteristics, including theoretical hydraulic retention time, mean tracer residence time, number of tanks in series, Morrill Dispersion Index, and short circuiting.

To determine if the flow through the fill media is as designed, theoretical hydraulic retention time was determined. The theoretical HRT is the time in which it should take water to pass through the bioreactor based upon the known or believed conditions within the bioreactor. The theoretical HRT is calculated:

$$T = \frac{V\rho}{Q} \quad (7)$$

where V is the active flow volume, ρ is the porosity of the fill media and Q is the flow rate through the bioreactor (Thackston et al., 1987). The volume and porosity used in this equation were taken from the parameters used to design the bioreactor. The flow rate used was the average flow rate determine during the tracer study.

The mean tracer residence time is the average time that it takes for tracer to travel through the entirety of the bioreactor. The mean tracer residence time is calculated:

$$t \approx \frac{\sum t_i c_i \Delta t_i}{\sum c_i \Delta t_i} \tag{8}$$

where t_i is the time and c_i is the concentration of the ith sample, and Δt_i is the time between samples (Metcalf and Eddy, 2003).

The number of continuously stirred tank reactors (CSTR) in series is used to characterize flow through a media. This is calculated:

$$n = \frac{\tau^2}{\sigma^2} \tag{9}$$

where τ is the total volume of the bioreactor divided by the flow rate, and σ^2 is the variance of the residence time of the tracer (Fogler, 2016). When the number of CSTRs in series is 1.0, then the fluid in a reactor is completely mixed, but as that number approaches infinity, the flow is considered to be plug flow (Kadlec and Knight, 1996)

The Morrill Dispersion index (MDI) describes the flow type that dominates in a system. This is either plug flow or CSTR flow:

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

where t_{10} and t_{90} are the times at which 10% and 90% of the tracer is eluted. An MDI of 1.0 is indicative of ideal plug slow whereas an MDI greater than 2.0 indicates that the dominant flow type is that of a continuously stirred tank reactor (Metcalf and Eddy, 2003).

Short circuiting occurs when water finds preferential paths through a system. This leads to a lower HRT leaving water under treated. The short circuiting (S) value is calculated:

$$S = \frac{t_{16}}{t_{50}} \quad (11)$$

where t_{16} andt_{50} are the times at which 16% and 50% of the tracer is eluted. An S value equal to 1.0 indicates no short circuiting within a system. Values less than 1.0 indicate that there is short circuiting occurring within the system (Ta and Brignal, 1998).

4.3. Results

4.3.1. Yearly Nitrate Reduction

The average concentration reduction across the bioreactors has been greater than 40% for all years sampled except for 2018 and 2019. The performance data from these years has indicated that the efficacy of the bioreactor is decreasing but not reached complete failure. During the duration of this study, three of the top ten 24-hour precipitation events on record in Sioux Falls, SD occurred; one during 2014 (4.65 in) and two in 2018 (4.40 and 5.07 in) (NOAA, 2020a). The precipitation totals for 2018 and 2019 were over 12 inches higher than the 30-year average (calculated from NOAA, 2020b), or over two standard deviations higher than the average, and 6 inches higher than the next closest precipitation year (2015) (Table 6).

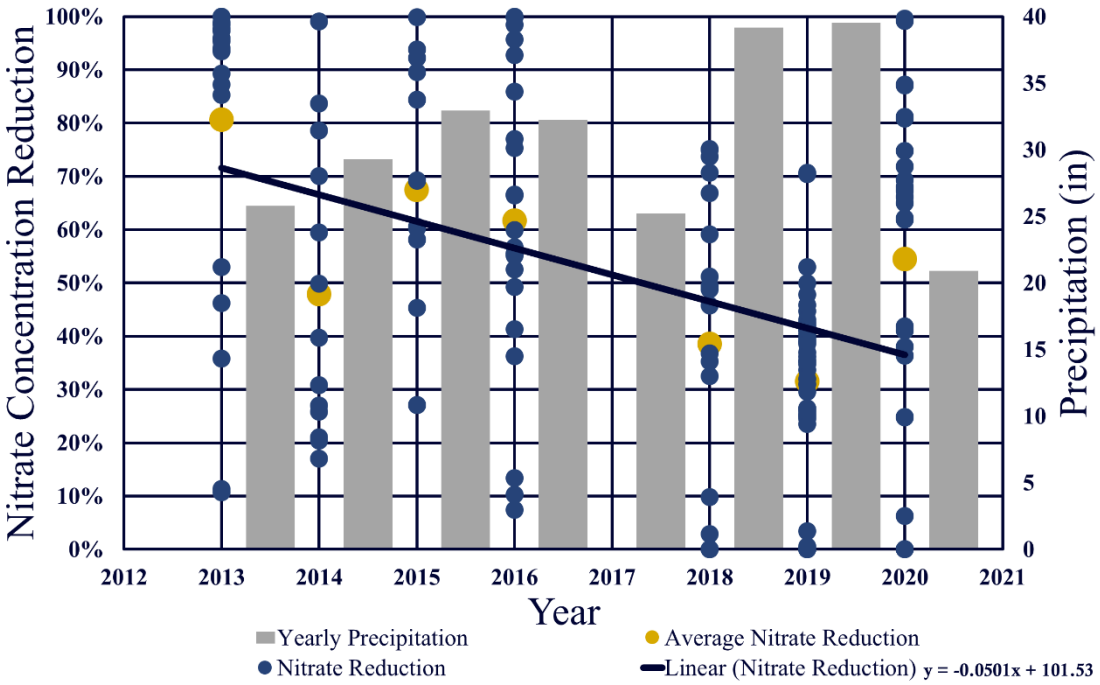

Figure 17: Baltic, SD bioreactor nitrate concentration reduction with yearly total precipitation

Table 5: Yearly rainfall totals in Sioux Falls, SD (NOAA, 2020)

Year	2013	2014	2015	2016	2017	2018	2019	2020	30yr. Avg.
Precipitation (in)	25.79	29.27	32.94	32.23	25.20	39.17	39.54	20.92*	27.90

* At least one day value missing

Over the duration of the tracer study a sufficient number of pore volumes were sampled to capture the tracer curve (greater than 5). The average flow rate during the tracer study was 78.75 ± 6.75 L min^{-1} (mean ± standard deviation) with the mean tracer residence time and the time to peak being 31.60 hours and 34.50 hours, respectively.

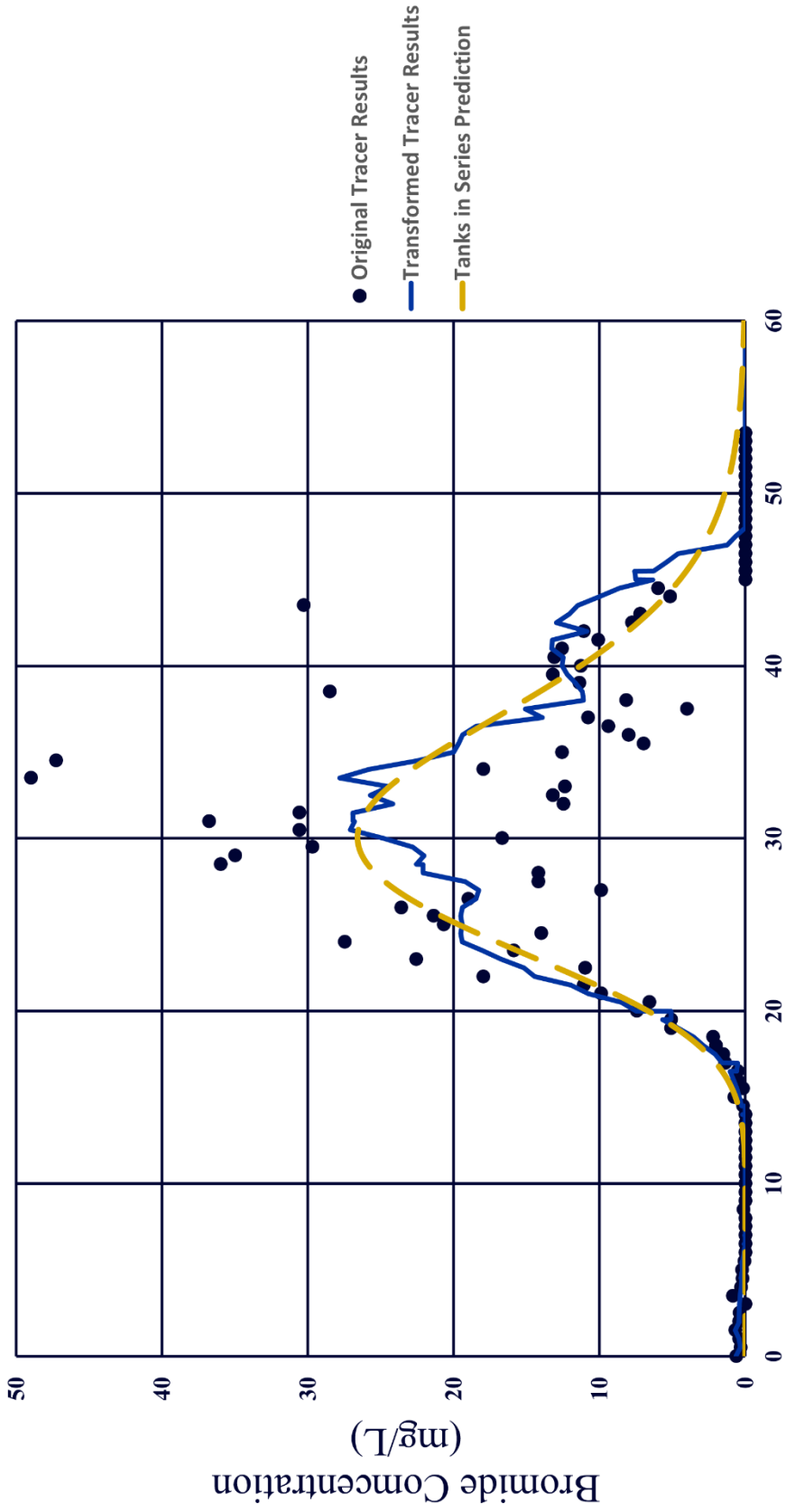

Figure 18: Baltic bioreactor tracer study results

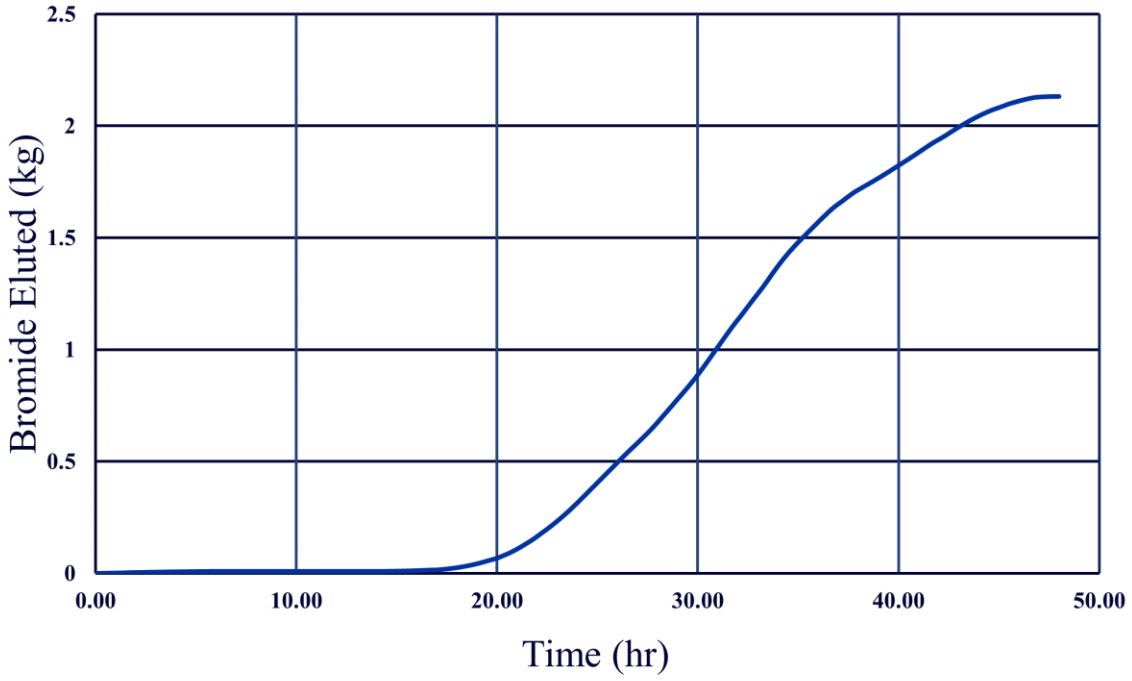

Figure 19: Graph of cumulative bromide eluted from the Baltic bioreactor tracer study

4.3.2. Tanks in Series

The number of tanks in series, *n*, was calculated to be 19.83 (Table 6). When *n* is 1, then the system is completely mixed, but as the number approaches infinity, the flow is classified as plug flow (Kadlec and Knight, 1996). The value calculated for this system is relatively high, which indicates that the system in behaving as plug flow rather than continuously stirred tank reactor (CSTR) flow.

4.3.3. Mass Dispersion Index

The time to 10% and 90% of the tracer eluted was 22.75 and 41.94 hours, respectively. Based upon these collection times, the MDI was 1.84 (Table 6). Since the value is less than 2, this is indicative of a system dominated by “effective” plug flow (Metcalf and Eddy, 2003). This value is very low in comparison to a similarly aged bioreactor where the MDI ranged from 3.2-4.2 (Christianson et al. 2013).

4.3.4. Short Circuiting

The time to 16% and 50% of the tracer was eluted was 24.32 and 31.50 hours, respectively. Based upon these times, the short-circuiting parameter was 0.77 (Table 6). This is near values collected from another bioreactor of a similar age that had S values ranging from 0.55 to 0.76 (Christianson et al. 2013). This value measures less than one which is indicative of a system in which short-circuiting is occurring.

Table 6: Summary of indexes describing the internal hydraulics of the Baltic bioreactor tracer study

Parameter	Value	Rule	Interpretation
Number of Tanks in Series	19.84	If N=1, then CSTR flow If N=∞, the plug flow	Indicates plug flow
MDI	1.84	If less than 2, then effective plug flow	Indicates plug flow
Short Circuiting	0.77	If less than 1, then short circuiting is occurring	Indicates some short circuiting

4.4. Discussion

Results measuring nitrate removal rates from the Baltic bioreactor noted that the bioreactor was decreasing in efficiency and was close to failure. Upon further investigation, the nitrate reduction rates in 2018 and 2019 were greatly impacting the nitrate reduction rate trend. These two years as well as 2014 all had wetter than average years (NOAA, 2020) with three of the highest 24-hour precipitation events occurring in 2014 and 2018 (NOAA, 2020). When the 2020 nitrate removal data are compared to the data from 2016, the average removal is much more similar. Though the trend suggests that the bioreactor is close to failure, the precipitation in a given year, and single event

totals, may be a bigger factor in nitrate removal than the current state of the woodchip media within the bioreactor.

The short-circuiting value of 0.77 derived from this tracer study is high in comparison to what would be expected for a bioreactor with large dead zones or preferential flow. Since the value is less than 1, there is indication of some short-circuiting occurring, but this value in combination with the higher-than-expected mean tracer residence time shows that short circuiting is not a mechanism of failure for this bioreactor.

The MDI for this bioreactor is 1.84. This index is lower than the expected for this system indicating that the flow is “effective” plug flow through the bioreactor. This is not indicative of a failing bioreactor.

Even after all these years, the hydraulic performance of this bioreactor is still sufficient. This is indicated by a relatively low MDI, a higher short circuiting index, and a high number of tanks in series. Past research has indicated that the parameters tested would be different if the bioreactor was closer to failure or had reached failure (Christianson et al., 2013)

4.5. Conclusion

The results from the tracer study completed on a denitrifying woodchip bioreactor in Baltic, SD suggests that this bioreactor is not performing as it was designed to after nine years of use. The tracer study indicates that some short circuiting is occurring, and the mean HRT is higher than it was designed for. These issues can cause both over treatment and undertreatment of the drainage water, which can lead to other problems

downstream. While these issues are not ideal, there is no indication that these issues have led to a complete failure of the bioreactor.

The trend deduced from the nitrate reduction data suggested that this bioreactor was closer to failure than this study suggests, but weather data was not considered to create this trend. The years in which the bioreactor performed the worst was during very wet years. When flow increased, the HRT decreases which could account for the decreased performance in wet years. Rainfall, and therefore flowrate, may have a bigger impact on nitrate reduction than previously understood.

Performance may also be related to the surrounding features of the bioreactor. The bioreactor at this site is surrounded by grass and does not have obvious areas that could be a source of sediment loading, but the surrounding features of the other bioreactor cited are unknown. If the areas surrounding bioreactors had different features, this may cause a bioreactor to fail faster as well.

Further research should be conducted on the Baltic denitrifying woodchip bioreactor to determine the state of the woodchips and see where this bioreactor is beginning to fail. More research like this should also be conducted on bioreactors in varying climates and landscapes to verify if other factors have a greater impact on the long-term performance of these bioreactors.

5. Conclusion

As the hypoxic zone in the Gulf of Mexico remains an area of concern, the United States looks to the corn belt for solutions, like the denitrifying woodchip bioreactor, to reduce the amount of nutrients from reaching the Gulf. The Iowa Nutrient Reduction Strategy cited that at the end of 2018 there were 27 bioreactors installed through cost-share programs with more to be installed as bioreactors are an integral part of the "Iowa Conservation Infrastructure initiative" (Nowatzke et al. 2020).

With more reliance being held on bioreactors, it is important to invest in more research on this tool. The research that has done on bioreactors suggests that sedimentation and breakdown are two factors driving bioreactors to failure, but neither of these factors can be directly tied to age.

Measuring nitrate reduction rates across the length of a bioreactor has led to the discovery of failed bioreactors, but this strategy is not infallible as noted by the research conducted on the Baltic bioreactor. Currently, the only reliable methods to determine the failure of a bioreactor is to conduct a tracer study or excavate and examine the woodchips; both of which require equipment and testing this expensive and time consuming.

Modeling may be the next step in predicting failure of a bioreactor. This could be done by correlating nitrate reduction rates with the theoretical HRT. The theoretical HRT can be determined using flow rate as it is inversely correlated to the HRT. If the HRT can be correlated to decrease in nitrate, a theoretical nitrate reduction rate can be determined. If the true nitrate reduction drifts too far from the theoretical, then it could be assumed

that the porosity or the active flow volume are straying from design, or the woodchips are no longer a viable source of carbon.

This solution would most likely be able to predict failure regardless of the mechanism causing the failure and will normalize the nitrate removal rates in cases of heaving rainfall and high flow. Since flow rate and nitrate reduction rates are much more cost effective than the current options available, this strategy could be used more widely. This would also allow for the bioreactors effectiveness to be tested without destroying the bioreactor.

Woodchip denitrifying bioreactors are an important tool for reducing downstream nitrate loading. While effective for nitrate removal from tile drainage, they do have a limited lifespan. New guidance for bioreactor maintenance is a critical step in ensuring that bioreactors uphold their design quality for longer, and new strategies for testing hydraulic performance need to be developed to allow for more efficient and effective recharge if, and when, needed.

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