Core ideas:

1. A subsurface drainage fed bioreactor was retrofitted with a supplemental surface water pumping system.
2. Design criteria of the pumping system is presented along with challenges and future recommendations.
3. Pumped bioreactor systems show promise for treatment of alternative nitrate-laden sources of water.
4. Pumped bioreactors have the potential to remove nitrate beyond the typical drainage season.

Modification of a dual-chamber denitrification bioreactor with a surface water pumping system

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Abbreviations: DNR, Department of Natural Resources; ISU, Iowa State University; NO_x–N. nitrate-nitrogen + nitrite-nitrogen; NRCS, Natural Resources Conservation Service.

ABSTRACT

Denitrification bioreactors are an edge-of-field conservation practice being implemented to reduce nonpoint nitrogen pollution to downstream waterbodies. In the Midwestern region of

the United States, these bioreactors are commonly used for the treatment of nitrate-laden subsurface drainage systems. Innovative strategies will be needed to reach the nutrient reduction goals established; here, a typical denitrification bioreactor was retrofitted with a supplemental surface water pumping system to enhance the bioreactor use and performance. Potential benefits of the pumped bioreactor system include extended treatment beyond the typical drainage season, increased nitrate mass removal, extended bioreactor lifespan, and extended applications of the bioreactor such as treatment of surface waters. Current challenges associated with pumped bioreactors exist with the timing of the pumping and water source identification. Considerations include the water availability and the potential need to obtain a permit for the water extraction, and nitrate concentration, temperature, and carbon content of the source to be pumped from. Conditions that would promote complete nitrate removal should be avoided. Additional potential applications for these pumped bioreactors have been identified and include, but are not limited to, treatment of additional surface water sources, irrigation waters, drainage ditches, and groundwater.

INTRODUCTION

Globally, over 400 hypoxic zones have been identified (Diaz & Rosenberg, 2008), with the second largest hypoxic zone in the world forming seasonally in the Gulf of Mexico each year (Rabalais & Turner, 2019). Nitrogen, especially in the form of nitrate, is one of the main nutrients of concern in the formation of these hypoxic zones (Jones et al., 2018; Rabotyagov et al., 2010). Besides the impact of excess nitrate on the environment, there are concerns for human health. A drinking water standard of 10 mg N L^{-1} has been established in the United States (E.P.A, 2021) largely due to the link between high nitrate levels and infant methemoglobinemia, commonly referred to as blue baby syndrome (Knobeloch et al., 2000). More recently, nitrate has been linked to several types of cancer (Ward et al., 2018; Ward, 2009). Excess nitrate levels have been observed in surface waters receiving subsurface drainage, requiring nitrate reduction to be in accordance with current safe drinking water standards (White, 1996).

Edge-of-field technologies and in-field management strategies are all being adopted to reduce nutrient loads and the size of the hypoxic zone in the Gulf of Mexico (Illinois E.P.A, 2015; Iowa Department of Agriculture and Land Stewardship, 2017; Minnesota Pollution Control Agency, 2014). Denitrification bioreactors are becoming an increasingly popular edge-of-field treatment technology to reduce nonpoint source nitrate-nitrogen loading to downstream surface waters (Christianson et al., 2021) as they require minimal amounts of agricultural land to be taken out of production and can be integrated into flat landscapes, aiding in the adoption of the practice by producers (Liu et al., 2018). Other edge-of-field treatment technologies for nonpoint source nitrogen pollution include saturated buffers and constructed wetlands (Groh et al., 2015; Iowa Department of Agriculture and Land Stewardship, 2017; Jaynes & Isenhart, 2014).

The bioreactor at its core consists of a trench of woodchips which receive nitrate-laden water (Schipper et al., 2010). The woodchips (or other carbon source) within the bioreactor act as an electron donor to promote microbial denitrification (Greenan et al., 2009; Healy et al., 2011; Schipper et al., 2010). The trench of woodchips is often covered with soil which can be seeded in a pollinator habitat to provide additional ecological benefits (NRCS, 2020). Bioreactors are being used globally to reduce nitrate-nitrogen with median percent reductions of 46% being observed and median mass removal rates of 5.1 g N m^{-3} d^{-1} (Christianson et al., 2021).

Bioreactors are commonly used to treat subsurface tile drainage, but they have been modified to include treatment of additional nitrate-laden sources such as spring water effected by legacy nitrogen and brine from groundwater desalination facilities (Díaz-García et al., 2021; Easton et al., 2019). Due to the adaptability of the design of denitrifying bioreactors and the need for reductions to nitrate loading for both ecological and human health concerns, additional uses of bioreactor systems warrant study to allow for treatment of further sources of water. The subsurface drainage flow is often seasonal in the Midwestern region of the United States, with flow subsiding in the summer when the crop water demand is greatest (Helmers et al., 2022; Helmers et al., 2005). This period of low or no flow conditions presents an opportunity for unique bioreactor designs to be implemented. During these periods, bioreactors have the potential to be retrofitted to treat nitrate-laden surface waters or irrigation water to allow for additional nitrate reduction and enhance the bioreactor use.

We monitored a retrofitted dual-chamber bioreactor (two bioreactors connected in parallel) which received lower than anticipated flow rates. The site was retrofitted with a pumping system to supplement the flow rate entering the bioreactor and to explore the potential for additional uses of denitrifying bioreactors. We had the goals of (i) documenting the design and installation of a retrofitted pumping system to augment flow to a dual-chamber bioreactor, (ii) exploring the potential of additional pumped bioreactor systems, and (iii) evaluating the challenges of this system to provide future recommendations for pumped bioreactor systems.

MATERIALS AND METHODS

Dual-Chamber Bioreactor Site Description

This study was conducted at Iowa State University's (ISU's) Uthe dual-chamber bioreactor site (Boone Co., Section 9 – T82N-R25W, Garden Township), located at a Committee for Agricultural Development farm. The dual-chamber bioreactor was installed in summer 2018 and received tile drainage from a 35.56 cm diameter main tile line. This site was designed using the USDA Natural Resource Conservation Service (NRCS) conservation practice standard 605 to allow for treatment of about 17% of the peak flow from the tile drainage system (NRCS, 2015). This corresponded to an approximate combined flow rate for the two chambers of ~10.5 L s^{-1}. This design resulted in the two bioreactor chambers each having dimensions of 36.58 m × 10.36 m × 1.1 m, connected in parallel. Extensive monitoring occurred at this site in 2019–2021. From this monitoring, it was determined that the design flow rate was never achieved due to a smaller diameter main tile line upstream and smaller than expected drainage area (Sarah Anderson, USDA–NRCS, personal communication, September 2, 2022), creating undesirable conditions in the bioreactor. Briefly, these conditions included low flow rates, near complete removal of nitrate on most sampling dates, and byproduct formation including methane gas (Hartfiel et al., 2023). As a result of the monitoring at this site, the Iowa USDA–NRCS approved two modifications to this system (Christian Osborn, USDA–NRCS, personal communication, July 28, 2020). The first modification was to add a nearby 40.64 cm diameter main tile line that drained a grassed waterway into the system which was completed in April 2021. The second modification that was approved at this site was the addition of a pumping system which is described in detail in the subsequent sections.

Design of the Pumping System for the Dual-Chamber Bioreactor

Prior to designing the pumping system, the nearby creek that the bioreactor outlets to (Big Creek) was monitored for its nitrate concentration via grab samples to identify if this surface water source was reasonable for a retrofitted pumping system to a bioreactor. The nitrate-nitrogen + nitrite-nitrogen concentrations (NO_x–N), referred to as the nitrate concentrations hereafter, were measured at ISU's Water Quality Research Laboratory using a Seal Analytical

AQ2 Discrete Autoanalyzer (AQ2 method EPA-114-A Rev. 11, a cadmium reduction method). The nitrate concentrations were often observed to be similar to the incoming subsurface drainage to the bioreactor (Figure 1). With the pumping water source identified, the rest of the design moved forward. The pumping system was designed based off the initial design flowrate from the USDA–NRCS of ~10.5 L s^{-1}. This flowrate was used as the maximum amount of possible flow through the pumping system. A water use permit was obtained from the Iowa Department of Natural Resources (DNR) to pump water from the nearby Big Creek at a maximum rate of the design flow rate for the bioreactor system or a total water volume of 162,773 m^3 from April 1st to September 30th each year. The water use permit is valid until June 2031 (Iowa Water Use Permit Number 10,369; Iowa DNR, 2021).

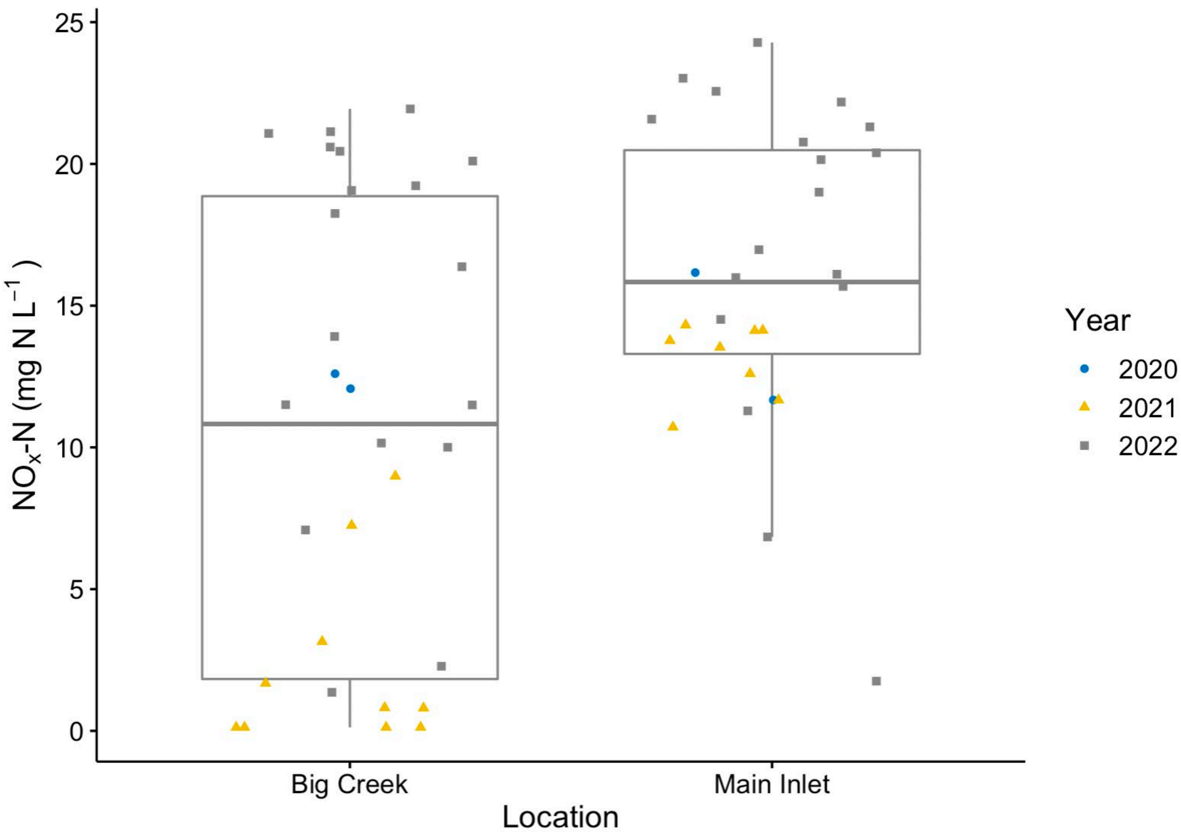

Figure 1. Boxplot of nitrate-nitrogen + nitrite-nitrogen (NO_x–N) within Big Creek at the research site. Concentrations are represented for 2020 (blue circles), 2021 (yellow triangles), and 2022

(gray squares). Concentrations in Big Creek were generally lower in 2021 due to on-going drought conditions.

With approval to treat water from Big Creek from both the Iowa USDA–NRCS and the Iowa DNR, the remainder of the pumping system was designed. Since the pumping system is a new application to tile drainage bioreactor systems and would be seasonal in nature, this design was created with flexibility in mind to be able to tear down and easily re-install the system as needed. The main components of the system included a pump, meters, valves to control the flow, and an intake filter to reduce debris entering the pumping system. A fine filter was not included in this system due to concern for frequent clogging and subsequent strain on the pump. Using the maximum flowrate of 10.5 L s^{-1}, the size of the pump and flexible hose was determined, accounting for the anticipated head loss to the system. Since this site featured two bioreactor chambers, a main component to consider in the head loss for the system was a wye to divide the flow from the creek into the two bioreactor chambers. A factor of safety was added into the design to ensure the target flow rate of 10.5 L s^{-1} would be achievable. Therefore, in the design, we ensured a flowrate of 14.2 L s^{-1} could be achieved. With these key components, the diameter of the flexible hose (7.62 cm in diameter) and expected head loss were determined.

A pump (AMT pump company, Self-Priming Circulation Pump, 7.5 hp) was then sized, ensuring the design flowrate could be achieved at the expected head loss of 14.1 m. With the size of the hose and pump determined, the flow meters (Banjo 2" Full Port Manifold Flow Meter), valves (Banjo 3" Full Port Ball Valve), and course filter (EasyPro High Volume Centrifugal Pump Intake Filter) were selected, ensuring their performance range included the design flowrate of 10.5 L s^{-1}. With the main components of the system determined, the remaining parts for the pumping system were selected, including the necessary fittings, adapters, and clamps to connect the main components to the flexible hose. A large, heavy-duty steel chest was purchased with a lock to store the pump and meters in to protect it from the environment and other disturbances. Lastly, electrical service had to be installed at the site which included a wooden stand for the electrical panel, meter, and single phase 240V electrical power with a three phase to single phase converter. The electrical service was installed through a collaborative effort between the local power company and local electricians. The configuration of the pumping system design is illustrated in Figure 2, highlighting the main components of the system.

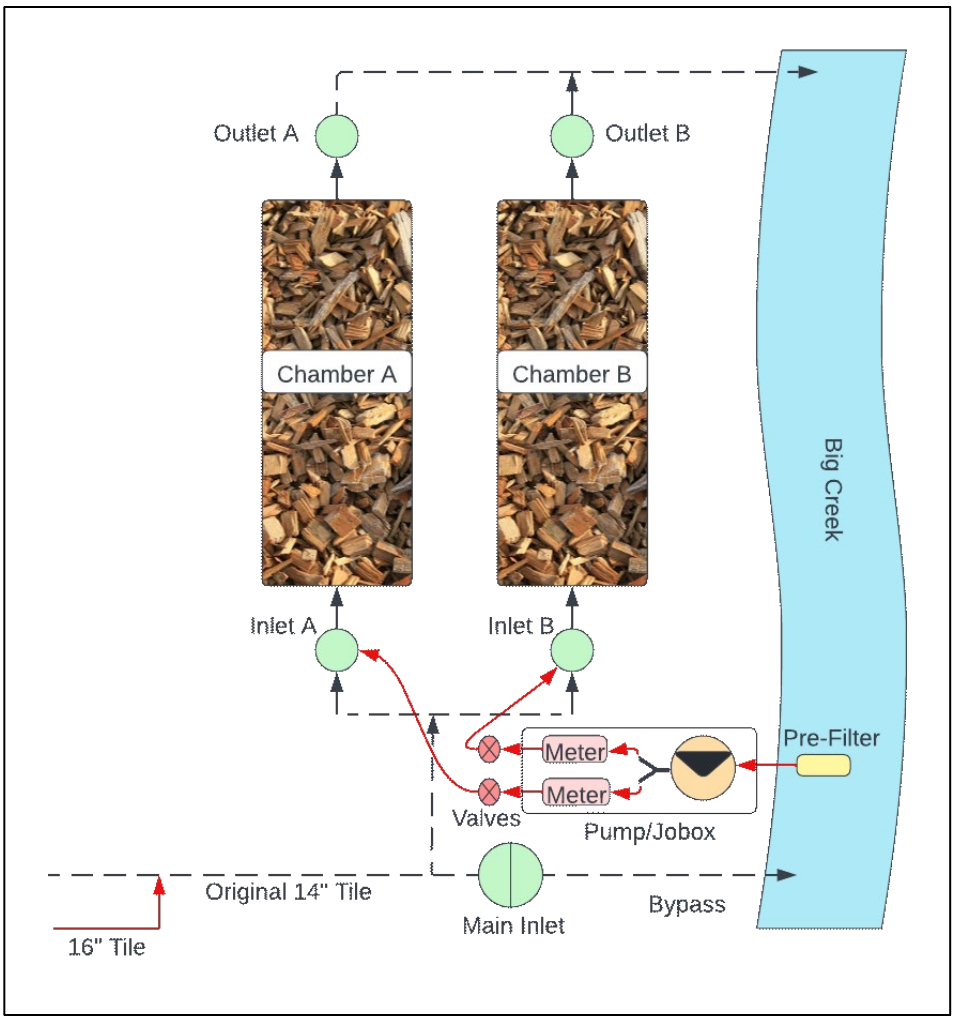

Figure 2. Illustration of the design of the pumping system with respect to the existing bioreactor infrastructure (black dashed lines). The flexible hose for the pumping system is denoted by the curved red solid lines.

Pumping System Installation

The installation of the pumping system was completed in the spring of 2022, beginning with the installation of electrical service at the research site. Upon completion of the electrical service installation, a wooden platform was constructed to place the steel chest with the pump and meters on (Figure 3). This was a necessary feature for this pumping system as the site of the bioreactor is located within the floodplain of the creek and has previously been completely flooded.

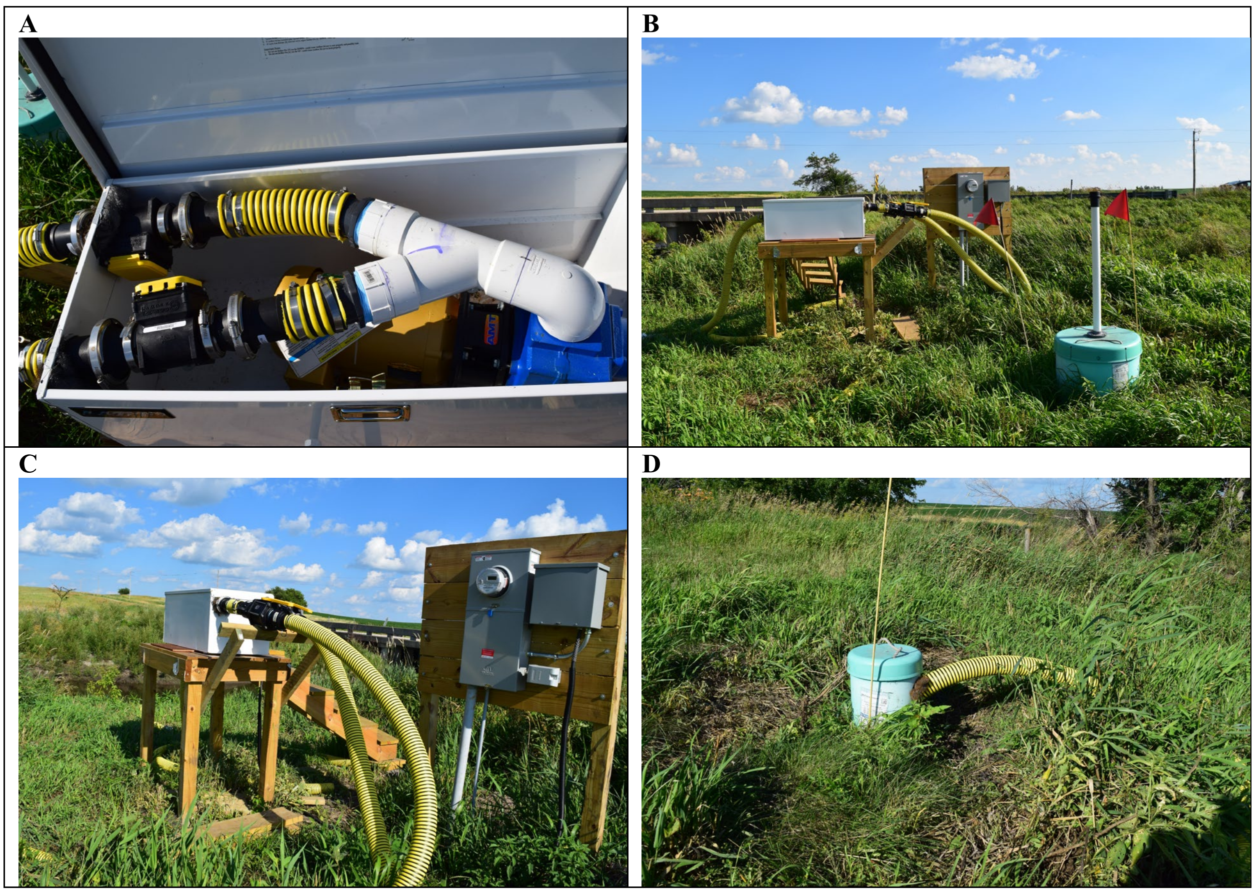

Figure 3. Demonstration of components of the pumping system during installation. (A) shows the pump, wye, and flow meters located within the steel chest, (B) shows the flexible hose entering the steel chest and valves/flexible hose leaving the chest, (C) shows a closer view of the valves and flexible hose leaving the pump/chest and the electrical service, and (D) shows the flexible hose entering one of the inlet water control structures.

As the pump and meters were to be stored in the steel chest, holes were cut in the box to allow the flexible hose to enter and leave the pump and meters. Once this was completed, the pump was placed within the box and the wye and meters were connected to the pump (Figure 3). The remaining components were then attached (valves, intake filter, and remaining flexible hose to the pump and to the water control structures). Lastly, holes were made in the two inlets water control structures (inlet A and inlet B in Figure 2) to allow for the flexible hose to be placed in the structures (Figure 3).

Upon completion of the installation, the pumping system could be started as needed to supplement the flow into the bioreactor. The flow rate from the system was controlled and monitored with the flow meters and valves. Flow leaving the bioreactor system were also monitored using vented pressure transducers (Solinst Model 3250 LevelVent; Solinst, Ontario, Canada) and V-notch weirs (Agri Drain Corporation, Adair, IA).

RESULTS AND DISCUSSION

Flow Rates Achieved

Prior to 2022, the bioreactor site experienced lower than expected flow rates furthered by drought conditions in 2020 and 2021. More specifically, the bioreactor received an estimated 940, 665, and 717 mm of precipitation in 2019, 2020, and 2021 respectively with 935 mm representing the average annual precipitation in Ames, Iowa (30-year average from 1981-2010) (Daigh et al., 2015). In 2022, it became evident that while the bioreactor was designed for a flow rate of 10.5 L s^{-1}, this flow rate was not actually achievable. This is believed to be a result of a poor slope or gradient within the bioreactor in combination with suspected woodchip degradation near the inlets restricting the inflow. The bioreactor was installed against the natural gradient at the site due to the location of the incoming subsurface drainage. Through a survey at the site, the inlet of chamber B was identified as the lowest point in the entire bioreactor system. In 2022, the addition of the second 40.64 cm diameter tile line in combination with greater precipitation contributed to increased flow rates, limiting the need for the pumping system. In July and early August 2022, the pumping system was used to supplement the flow to the bioreactor system as the subsurface drainage flow subsided.

When using the pumping system, the flow rate through the bioreactor was between 1.06 L s^{-1} and 2.17 L s^{-1}, for each bioreactor chamber. The bioreactor could not handle all of the flow being pumped, and an average of 41% of the flow being pumped was bypassed back to the stream, going untreated. These were the total flow rates at the outlet of the bioreactor or bypassing the bioreactor, which were monitored with the vented pressure transducers described previously. We suspect the lower flow rates are a result of woodchip degradation near the inlet manifolds restricting the inflow. The flow rates from the pumping system (Banjo flow meters described previously) still require validation in the field.

Challenges and Future Recommendations

As the supplemental pumping system is a new concept, challenges have been experienced, creating the opportunity for recommendations for future systems. Unexpected challenges with this system occurred in the sizing of the pump and subsequent other components due to the discrepancies between the observed maximum flow rates and the actual design flow rate, with the observed maximum flow rate being approximately 55% (5.66 L s^{-1}) of the design flow rate. As a result, the pump capacity is higher than necessary, resulting in greater restriction of the flow than expected. Knowing the actual bioreactor system capacity, rather than the design capacity, will allow for more proper design and sizing of these pumping systems.

An additional consideration in the installation of these pumping systems is the timing of the application. When treating surface waters in the summer months, the temperature of the water being pumped can be much warmer than the subsurface drainage. We observed as much as a 10°C increase in the temperature of the supplemental surface waters pumped versus the incoming subsurface tile drainage. As the denitrification process in these systems is microbially driven, a large increase in temperature can lead to more rapid denitrification (Ghane et al., 2015; Hoover et al., 2016; Warneke et al., 2011). Therefore, it is important to consider both the temperature of the pumping source and its nitrate concentration, to ensure that harmful pollution swapping will not occur as a result of complete denitrification (Davis et al., 2019; Hartfiel et al., 2022; Healy et al., 2011). Lastly, the total or dissolved organic carbon levels within the pumping system is another consideration. As surface waters contain sediment, the pumping of surface waters can add carbon from the sediment to the bioreactor system. Carbon is necessary for microbial denitrification, acting as an electron donor or food source for the denitrifying bacteria (Schipper et al., 2010); the addition of potentially readily available carbon from the pumped water can stimulate enhanced denitrification (Cameron & Schipper, 2010; Feyereisen et al., 2016; Warneke et al., 2011). The creek typically contained total organic carbon concentrations ~1.5 times greater than the incoming subsurface drainage, although the creek total organic carbon concentrations were relatively low being at or below 4.2 mg C L^{-1} during the monitoring period in 2022. The potential addition of carbon from pumping is likely due to increased sediment loads to the bioreactor which is an area of caution; previous research has demonstrated that in aquaculture wastewater systems treated by bioreactors that elevated total suspended solids creates a potential for clogging to occur especially near the bioreactor inlet (Christianson et al., 2016). While the pumping source has the potential to add additional carbon into the bioreactor system, there is preliminary evidence that the higher temperature water contributed to quicker release of the total organic carbon from the woodchips as well. This was evidenced by increasing total organic carbon concentrations from the inlet to the outlet of the bioreactor; however, these total organic carbon samples were only collected on one pumping date and are therefore limited.

Considering both the increased temperatures and potential for increased carbon entering the bioreactor for pumped surface water systems, it is important to consider the timing of the pumping application and the nitrate concentrations in the pumping source. By pumping from these warmer surface water systems during the spring or fall where cooler temperatures may be present, especially in the subsurface drainage, enhanced microbial denitrification conditions may be promoted (Addy et al., 2016; Christianson et al., 2012; Hoover et al., 2016), potentially contributing to improved bioreactor performance in cooler months.

Potential for Additional Pumped Bioreactor Systems

The pumping source at this site, Big Creek, does have high nitrate concentrations while the creek is flowing (Figure 1). However, this site has experienced extremes in the amount of flow with both stagnant conditions and out-of-bank flooding being observed in a one-year period (Supplemental Figure S1). The application of these pumped bioreactor systems would therefore be better fit for less flashy surface water systems or alternative nitrate-laden sources of water. Here, the pumping system was used to extend the use of bioreactor by three weeks by allowing for treatment of the pumped surface waters. During this time, the bioreactor was monitored weekly for water quality but was checked every day to two days while pumping to ensure uniform pumping and bioreactor flow conditions were occurring. Due to the increased temperatures, the system was nitrate limited during two of the three weeks of monitoring, where nitrate was completely removed prior to the water reaching the outlet of the bioreactor. In the first week of the pumping system and monitoring when the system was not nitrate limited, the bioreactor was able to achieve a combined average daily removal rate of 6.58 g N m^{-3} d^{-1} per bioreactor chamber (range of 5.77 – 7.39 g N m^{-3} d^{-1}) compared to a combined daily average removal rate of 3.62 g N m^{-3} d^{-1} per bioreactor chamber (range of 3.42 – 3.82 g N m^{-3} d^{-1}) the previous week without pumping.

While our system was nitrate limited during much of its use as the flow in the creek diminished, there are other surface waters where more consistent flow conditions and nitrate concentrations could be encountered, making these systems more ideal for a pumping system. For demonstration purposes, the potential of these pumped bioreactor systems will be made using our observations during the period where the system was not nitrate limited (with a combined average removal rate of 6.58 g N m^{-3} d^{-1} for the system). If these rates were able to consistently be achieved, on a daily basis, the bioreactor could remove 5,513 g N d^{-1} (average of 2,756 g N d^{-1} per chamber). Extended over a one-month period, the bioreactor could remove 165 kg N (average of 83 kg N per month per chamber).

In the upper Midwest region of the United States, the application of bioreactor systems has been primarily for treatment of subsurface drainage (Christianson et al., 2021). With the nutrient reduction goals set as part of the Gulf Hypoxia Action Plan (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008), more widespread adoption of conservation practices will be needed (Iowa Department of Agriculture and Land Stewardship, 2017), which presents the opportunity for unique bioreactor designs to be explored, such as pumped bioreactor systems, that could treat nitrate-laden sources of water that are otherwise going untreated. Potential applications of these pumped bioreactor systems could include treatment of additional nitrate-laden surface waters, irrigation waters, drainage ditches, pumped cistern systems for stored subsurface drainage, or potentially groundwater.

Lastly, there is potential for these pumped bioreactor systems to prolong the bioreactor life. Research is showing more rapid decomposition of the carbon source, typically woodchips, near the inlet of the system (Christianson et al., 2020; Schaefer et al., 2021). The carbon source located near the inlet can be subjected to aerobic conditions (with higher dissolved oxygen levels) where greater decomposition can occur (Moorman et al., 2010; Schaefer et al., 2021). The inlet of the bioreactor can also experience larger fluctuations in the water level, experiencing periods of drying and rewetting that have also been hypothesized as accelerating woodchip decomposition (Ghane et al., 2018; Maxwell et al., 2019). As most bioreactors in the Midwest region of the United States receive subsurface drainage, there can be periods of no or low flow conditions as the drainage often subsides with crop development (Helmers et al., 2022; Helmers et al., 2005). With the use of a pumping system, the bioreactor could potentially experience more uniform, consistent flow rates with less variation in the saturation level of the bioreactor, potentially extending the life of the bioreactor.

The cost of a pumped bioreactor system is a consideration for future installations of these systems. Due to the short period of monitoring in this study, we have not provided an estimate of electricity use or cost per kg N removed. A scenario-based cost assessment of three pumped bioreactor systems has been conducted in another study. That study identified that pumped bioreactor systems tended to have a slightly higher unit cost of nitrate removal ($ kg N removed^{-1}) than a traditional, subsurface drainage-fed bioreactor due to greater material and installation costs (Hartfiel, 2022). However, for larger scale pumped bioreactor systems (e.g., 300+ m^3) the unit costs were comparable to those of a traditional bioreactor ranging from about $8 to $28 kg N removed^{-1} for most of the scenarios evaluated. The potential for higher mass removal rate, extended lifespan of the bioreactor, and extended operating period allowed for the unit costs to decrease (Hartfiel, 2022).

CONCLUSIONS

There is a need for reductions to the nutrient loading from the upper Midwest region of the United States to the Gulf of Mexico. To reach the nutrient reduction goals established, innovative solutions are needed. A new concept is the use of pumped bioreactor systems to allow for treatment beyond temporary subsurface drainage. Potential applications of these pumped systems briefly include treatment of nitrate-laden surface waters, irrigation waters, drainage ditches, or groundwater. When determining a source to be pumped, a few considerations are the source water nitrate concentrations, temperature, and carbon content. The timing of the pumping application should factor in these parameters to optimize the bioreactor system's performance. Pumping during periods of high temperatures and/or carbon levels with lower nitrate concentrations should be avoided as these conditions can promote enhanced microbial denitrification leading to complete nitrate reduction and potential pollution swapping opportunities.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPLEMENTAL MATERIAL

The supplemental materials include a figure to demonstrate the fluctuations in water level (stagnant conditions and out-of-bank flooding) that can be observed within a one-year period at the site we were pumping from.

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