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Project Title

Nutrient Removal and Recovery from Stormwater Using Water Treatment Residual Coated Woodchips

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Research Needs

Stormwater runoff is generated from rain and snowmelt events that flow over land or impervious surfaces. Stormwater discharge from transportation, municipal and agricultural sources may contain various pollutants including suspended solids, nutrients, heavy metals, hydrocarbons and microbial pathogens, which can deteriorate water quality of receiving water bodies and threaten public health. Nitrate and phosphate are two main nutrients identified in stormwater runoff. Elevated nutrient levels in surface waters can lead to a number of negative water quality impacts including harmful algal blooms, hypoxic zones in the ocean, and contamination of drinking water supplies (Anderson et al., 2002; Rabalais et al., 2002; Schilling, 2005). Harmful algal blooms have been frequently reported in aquatic ecosystems in the United States. South Dakota Department of Environment and Natural Resources (SDDENR) assessed 171 of the 575 lakes and reservoirs assigned recreation and/or fish life beneficial uses from 2012 to 2017 (SDDENR 2018). An estimated 84.3% of the assessed lake acreage did not support all assigned beneficial uses. One major cause is excessive algae growth due to nutrient enrichment from watershed scale nonpoint sources. As urban land continues to expand, stormwater runoff from various sources may lead to increased nutrient loading to surface waters in the future. Thus, treatment technologies are critically needed to reduce nitrate and phosphate levels in stormwater runoff to protect natural water resources.

Woodchip bioreactors have been developed as a water management tool to reduce nitrate concentrations in stormwater runoff (Schipper et al., 2010; Peterson et al., 2015; Lepine et al., 2016; Rambags et al., 2016; Lopez-Ponnada et al., 2017; Abdi et al., 2020). Woodchips are used as an organic carbon source in bioreactors to support the growth of denitrifying bacteria which can convert nitrate to inert nitrogen gas. Woodchips are relatively inexpensive materials that are widely available. Woodchips can also serve as a long-persistent organic carbon source for the denitrification process. The large particle sizes and physical stability of woodchips allow high flow rates in woodchip bioreactors (Christianson et al., 2010). Due to these practical advantages, woodchip bioreactors have been increasingly used for nitrate removal in agricultural drainage, urban stormwater, and wastewaters. Long-term field experiences indicate that woodchip bioreactors can provide consistent nitrate removal for 5 to15 years with little maintenance required (Robertson et al., 2000; Schipper et al., 2010). Although woodchip bioreactors have been demonstrated to be an effective tool for nitrate removal in stormwater runoff, these reactors do not substantially remove phosphate (Jaynes et al., 2008). Phosphorus is usually considered the limiting nutrient in aquatic ecosystems. New woodchip bioreactor treatment systems with phosphate removal capacity should be developed to remove nitrate and phosphate simultaneously in stormwater runoff.

Emerging phosphate removal technologies are being developed to reduce phosphorus pollution using low-cost adsorption materials, A variety of materials have been evaluated for phosphate adsorption from aqueous solutions, including natural minerals (e.g., calcite, limestone, and zeolite), industrial byproducts (e.g., steel slag, fly ash, and drinking water treatment residuals), and commercial synthetic products (Drizo et al., 2002; Chardon et al., 2012; Grace et al., 2015; Lalley et al., 2016; Soleimanifar et al., 2016). The phosphorus adsorbents typically provide metal cations (iron, aluminum, or calcium) to bind with dissolved phosphorus to form insoluble compounds (Weng et al., 2012; Lyngsie et al., 2014). Water treatment residuals (WTR) are sludge produced during coagulation and flocculation processes during drinking water treatment. Aluminum and ferric salts are the most commonly used coagulants for water treatment. The resulting WTRs typically contain large amounts of aluminum, iron, or calcium compounds with high phosphate adsorption capacity. The use of WTRs for phosphate removal is an inexpensive stormwater management practice. In addition, reuse of WTRs can also reduce of the cost of sludge disposal for water treatment plants. Laboratory adsorption experiments have shown that WTRs can significantly reduce phosphate concentrations from surface water and wastewater (Razali et al., 2007; Wendling et al., 2013). WTRs have also been used to amend woodchip bioreactors for nitrate and phosphate removal. Zoski et al. (2013) showed >99% removal of phosphate from simulated agricultural runoff using laboratory woodchip bioreactors amended with WTR. Gottschall et al. (2016) observed that removal efficiencies of woodchips with 10-20% WTR by volume were significantly greater than woodchip only bioreactor for nitrate and phosphate. These studies suggest that WTRs can be potentially used as a low-cost phosphate sorption material to amend woodchip bioreactors to remove nitrate and phosphate from stormwater runoff.

Although WTRs could be used to enhance phosphate removal in woodchip bioreactors, they could also greatly lower hydraulic conductivity and restrict the flow rate due to their fine particle sizes (Zoski et al., 2013). Ament et al. (2020) showed that the solid WTR layer incorporated into a lab bioretention reactor restricted water flow and exhibited incomplete phosphate removal. Therefore, special consideration must be given for flow-through properties of WTRs for phosphate removal from stormwater runoff. Soleimanifar et al. (2016) developed a new technology using WTR coated wood mulch for phosphate removal from stormwater runoff. The results showed that wood mulch coated with WTR at a mass ratio of 3 was able to remove 97% phosphate from simulated stormwater during batch adsorption experiments. The use of WTR coated woodchips could help improve the flow through properties of bioreactors while maintaining effective phosphate removal performance. However, the impact of WTR coating on nitrate removal has not being carefully studied. More research is needed to evaluate the effectiveness of WTR coated woodchips on nitrate removal such that this technology can be used to remove both nitrate and phosphate from stormwater runoff.

Unlike nitrate, phosphate is a non-renewable natural resource that cannot be substituted with other nutrient sources. Therefore, it is important to develop technologies that could remove and recover phosphate from stormwater runoff. Phosphorus recovery and reapplication would reduce the impact of runoff on the environment and make fertilizing a more sustainable process. Sellner et al. (2019) showed that the use of 0.2 M sodium hydroxide solution was able to desorb 80% of the phosphate adsorbed onto steel chips. It is possible that alkaline solutions can also be used to desorb phosphate adsorbed onto WTRs. The desorbed phosphate can then be further processed to produce fertilizer. Phosphate removal and recovery using WTRs is a promising low-cost technology for sustainable phosphorus control in stormwater runoff.

Research Objectives

In this study, we will conduct laboratory experiments to investigate the performance of WTR coated woodchips for nitrate and phosphate removal from stormwater runoff and evaluate the recovery potential of phosphate adsorbed by WTRs using alkaline solutions. Alum and ferric salt based WTRs will be collected from drinking water treatment plants in South Dakota. Woodchips will be collected from a local playground woodchip supplier. WTR coated woodchips will be produced in the lab to evaluate nitrate and phosphate removal efficiencies. In addition, woodchips will also be directly coated with water treatment coagulants in the laboratory. The nutrient removal performance of coagulant coated woodchips will be compared with WTR coated woodchips.

The objectives of this study are to:

1. Provide a state-of-the-art review of phosphate removal from stormwater using WTRs.
2. Determine the impact of different WTRs, coating methods, and woodchip sizes on the phosphate adsorption capacity of WTR coated woodchips.
3. Determine nitrate and phosphate removal efficiencies of WTR coated woodchips using flow through column reactors.
4. Evaluate phosphate desorption potential of WTR coated woodchips using alkaline solutions.
5. Provide recommendations on the application of WTR coated woodchips for nitrate removal and phosphate recovery from stormwater runoff.

Research Methods

This research will be conducted through a literature review, laboratory batch experiments, and laboratory column experiments to achieve the project objectives. A comprehensive literature review will be conducted to summarize the latest developments in using low-cost filtration materials for phosphate removal from stormwater runoff. This review will include different filter materials for phosphate adsorption, and factors that may affect phosphate removal by stormwater filtration. A focus of this review will be on WTR based materials for phosphate adsorption. The results of this review will help the design of the laboratory batch adsorption and flow-through column experiments for phosphate removal using WTR coated woodchips.

We will collect woodchips made from cottonwood trees from a supplier in Sioux Falls, SD. The same type of woodchips has been used in bioreactors for nitrate removal in agricultural subsurface drainage in South Dakota. WTRs will be collected from two surface water treatment plants in South Dakota using alum and ferric chloride as coagulants, respectively. Woodchips will be coated with WTRs in the lab. Laboratory batch adsorption experiments will be conducted to determine phosphate adsorption isotherms and kinetics of WTR coated woodchips. The impact of different WTRs, woodchip particle sizes, and coating methods on phosphate adsorption will be determined through batch experiments. After the completion of the batch experiments, column reactors will be built and filled with different WTR coated woodchips. Simulated stormwater runoff with nitrate and phosphate will be pumped to the column reactors. The column reactors will be operated for 12 months under continuous flow conditions to evaluate the long-term nitrate and phosphate removal performance. After the flow-through column experiments, WTR coated woodchips will be packed into several smaller column reactors, alkaline solutions with different strength will be pumped to each reactor to determine phosphate desorption potential of WTR coated woodchips. The results of the batch and column experimental results will be analyzed to provide recommendation on full scale application of WTR coated woodchips for nitrate and phosphate removal from stormwater runoff.

Expected Outcomes

This research will evaluate the use WTR coated woodchips to remove nitrate and recover phosphate from stormwater runoff. This new water management tool has great potential to remove nitrate and phosphate simultaneously from stormwater. The adsorbed phosphate onto WTRs could be desorbed and used as a fertilizer source. The development of low-cost filtration technology using WTR coated woodchips has significant implications in surface water quality improvement and public health protection. The expected outcomes of this project include:

1. A new filtration technology using WTR coated woodchips to remove nitrate and phosphate from stormwater runoff.
2. An understanding of the long-term performance of lab-scale WTR coated woodchip reactors.
3. An understanding the desorption potential of phosphate adsorbed onto WTR coated woodchips.
4. Recommended full scale application conditions of WTR coated woodchips.

Relevance to Strategic Goals

The proposed project and its expected outcomes are directly related to the strategic goals of Environmental Sustainability, and Livable Communities. This research aims to develop a WTR coated woodchip filtration best management practice to reduce the concentrations of nitrate and phosphate in the runoff from various sources. This new nutrient control management tool can be used to reduce the environmental impact of transportation and urban and rural development to protect natural water resources.

Educational Benefits

One PhD student and one undergraduate student will work on this project under the direction of the PIs and receive training on water treatment, experimental design, and analytical skills. This study involves stormwater management, batch and column experiments, and water quality analyses, which provide great training opportunities for the student. The students will learn about developing an innovative engineered solution for an important water quality issue, which will improve their critical thinking and problem solving ability. The students will present the results at regional and national conferences, and prepare manuscripts for peer-reviewed journals. These opportunities will improve students' skills in written and oral communication.

Technology Transfer

The findings of this project will be transferred to other researchers, professionals and practitioners through conferences, meeting presentations, and publications.

1. We will present the result of study at regional and national conferences including the South Dakota Association of Rural Water System Annual Technical Conference, Eastern South Dakota Water Conference and WEFTEC.
2. A PhD dissertation will be developed based on the results of this project. This dissertation will be available to the public through Open Prairie, the South Dakota State University public access institutional repository.
3. We will submit manuscripts to peer-reviewed journals based on the results of this project.
4. The undergraduate researcher will be present a poster at SDSU's Undergraduate Research, Scholarship and Creative Activities Day.

Work Plan

Task 1 Literature Review on Phosphate Removal by WTRs

A comprehensive literature review will be conducted to summarize the latest developments in using WTRs and other low-cost adsorbents for phosphate removal from stormwater runoff. This review will cover physical and chemical properties of WTRs, phosphate adsorption capacity of WTRs, and factors affecting WTR applications in stormwater treatment.

Task 2 Evaluate Different Methods for WTR Coating onto Woodchips

We will use different coating methods to attach WTR particles onto woodchips.

1. Dry Coating Method. Alum and ferric chloride based WTRs will be collected from drinking water treatment plants. The collected WTRs will be air-dried and sieved to remove large particles (e.g. > 2 mm). Woodchips made from cottonwood will be collected from a playground woodchip supplier. The collected woodchips will be cleaned with distilled water and air-dried. After that, woodchip surface will first be coated with an environmental friendly woodchip glue. Then, WTRs fine particles will be added and mixed with the woodchips. The coated woodchips will be dried before use.

2. Wet Coating Method. Alum and ferric chloride based WTRs will be collected as wet sludge. Distilled water will be used as needed to maintain water content of the wet sludge. The collected woodchips will be cleaned with distilled water. Then, woodchips will be mixed with wet sludge to attach WTRs onto woodchip surface. The coated woodchips will be dried before use.
3. Direct Coating of Coagulants. Alum and ferric chloride coagulants will be collected from drinking water treatment plants. Woodchips will be soaked with the two coagulants to coat woodchip surface with aluminum and iron species. The coagulant coated woodchips will be dried before use.

The mass ratio of WTR or coagulant to woodchips will be determined based on the mass difference of woodchips before and after coating experiments. Scanning electron microscopy images will be taken for selected coated woodchip samples to evaluate the WTR particle attachment.

Task 3 Batch Phosphate Adsorption Experiments Using WTR Coated Woodchips

The WTR coated woodchips will be manually separated into different size groups (e.g., 1-2, 2-4, and 4-6 cm). Batch adsorption experiments will be conducted on different woodchips to determine phosphate adsorption isotherm and kinetics at a fixed temperature of 20 ºC. Initial phosphate concentrations will be varied during the batch adsorption experiments. Additional batch adsorption experiments will be conducted at different temperatures (5-30 ºC) and initial pH values (6-9) to cover a wide range of stormwater runoff conditions.

Task 4 Long-Term Column Experiments Using WTR Coated Woodchips

Clear acrylic pipes with an inside diameter of 8.85 cm and a length of 1.2 m will be used to build column reactors for the long-term column experiments. WTR and coagulant from one drinking water treatment plant will be selected based on the batch adsorption experiments. Four column reactors filled with dry WTR coated woodchips, wet WTR coated woodchips, coagulant coated woodchips, and raw woodchips, will be operated under continuously flow conditions for 6-12 months. Simulated stormwater runoff will be used during the column experiments. Daily samples will be collected to evaluate nitrate and phosphate removal efficiencies of the four reactors.

After the long-term column experiments, WTR and coagulant coated woodchips in the columns will be packed into four smaller column reactors. Distilled water with various sodium hydroxide concentrations (0-0.2 M) will be pumped to these small reactors to desorb phosphate from coated woodchips. The total desorbed phosphate mass will be compared with the total adsorbed phosphate mass from long-term column experiment to determine the phosphate desorption and reuse potentials.

Task 5 Project Reporting

The PIs will write and submit the final report. The reports will summarize the experimental results and recommendations for the application of WTR coated woodchips for nitrate and phosphate removal from stormwater runoff.

Table 1 presents the proposed project schedule.

Tasks	Months								
	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-26	26-29
1. Literature Review	■	■							
2. WTR Coating		■	■	■					
3. Batch Experiments			■	■	■	■			
4. Column Experiments				■	■	■	■		
5. Project Reporting								■	■

Project Cost

Total Project Costs:	$195,439
MPC Funds Requested:	$ 97,673
Matching Funds:	$ 97,766
Source of Matching Funds:	South Dakota Association of Rural Water Systems ($10,000; cash match), SDSU Water and Environmental Engineering Research Center ($10,000; cash match), and SDSU ($77,766; faculty time in-kind match)

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