MOUNTAIN-PLAINS CONSORTIUM

MPC 25-578 | G. Hua, A. Debnath, S. Ebrahimzadeh, and C. Schmit

PILOT SCALE EVALUATION OF ESCHERICHIA COLI REMOVAL FROM STORMWATER RUNOFF USING STEEL BYPRODUCT FILTRATION

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
MPC-690		

4. Title and Subtitle	5. Report Date
Pilot Scale Evaluation of Escherichia Coli Removal from Stormwater Runoff Using Steel Byproduct Filtration	April 2025
	6. Performing Organization Code
7. Author(s) Guanghui Hua Ankur Debnath Siavash Ebrahimzadeh Christopher Schmit	8. Performing Organization Report No. MPC 25-578
9. Performing Organization Name and Address Dept. of Civil and Environmental Engineering South Dakota State University SCEH 301, Box 2219 Brookings, SD 57007-0495	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address Mountain-Plains Consortium North Dakota State University PO Box 6050, Fargo, ND 58108	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Supported by a grant from the US DOT, University Transportation Centers Program

16. Abstract

Escherichia coli (E. coli) in stormwater is a significant environmental concern as it indicates potential contamination from fecal matter, raising risks for both human and aquatic health. Conventional stormwater best management practices are generally not effective at removing E. coli from stormwater runoff. Recycled steel byproducts, including steel chips and steel slag, have shown high capacity for E. coli removal from stormwater in laboratory and field scale studies. The objective of this study was to design and construct a pilot scale filter structure using steel byproduct media at a stormwater site in Sioux Falls, SD, and evaluate the filter performance for E. coli and phosphate removal under real stormwater treatment conditions. Five sampling events were conducted for the pilot scale filter from June to August 2024. The results showed that the pilot filter removed an average of 44.2% of the E. coli and an average of 53.8% of the phosphate in the stormwater. The results of this pilot study demonstrate that filtration using steel slag and steel chips media is an effective technology for removing E. coli and phosphate under real stormwater treatment conditions. This technology can be used as a cost-effective best management practice to control bacteria and phosphate contamination in urban stormwater systems.

17. Key Word	18. Distribution Statement
bacteria, contaminants, filtration, recycled materials, runoff, sewage treatment, steel, waste products (materials)	Public distribution

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	43	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Acknowledgements

This study was funded by the US Department of Transportation (USDOT) through the Mountain Plains Consortium (MPC) - University Transportation Center (UTC), East Dakota Water Development District, City of Sioux Falls, and South Dakota State University. For technical support, we thank the City of Sioux Falls, SD, on the pilot scale stormwater treatment study.

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ABSTRACT

Escherichia coli (E. coli) in stormwater is a significant environmental concern as it indicates potential contamination from fecal matter, raising risks for both human and aquatic health. Conventional stormwater best management practices are generally not effective at removing E. coli from stormwater runoff. Recycled steel byproducts, including steel chips and steel slag, have shown high capacity for E. coli removal from stormwater in laboratory and field scale studies. The objective of this study was to design and construct a pilot scale filter structure using steel byproduct media at a stormwater site in Sioux Falls, SD, and evaluate the filter performance for E. coli and phosphate removal under real stormwater treatment conditions. Five sampling events were conducted for the pilot scale filter from June to August 2024. The results showed that the pilot filter removed an average of 44.2% of the E. coli and an average of 53.8% of the phosphate in the stormwater. The results of this pilot study demonstrate that filtration using steel slag and steel chips media is an effective technology for removing E. coli and phosphate under real stormwater treatment conditions. This technology can be used as a cost-effective best management practice to control bacteria and phosphate contamination in urban stormwater systems.

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1. EXECUTIVE SUMMARY

1.1 Introduction

Stormwater contamination has become an increasingly environmental concern as global populations and industrialization continue to rise. Typical stormwater contaminants include particles, nutrients, toxic organic compounds, heavy metals, and microorganisms. Among different types of microorganisms in stormwater, Escherichia coli (E. coli) is often used as an indicator organism to quantify the microbial safety of natural water resources. E. coli in stormwater is a significant environmental concern as it indicates potential contamination from fecal matter, raising risks for both human and aquatic health. Therefore, effective treatment technologies are needed to control E. coli in stormwater systems.

To manage stormwater and protect aquatic ecosystems, there are several stormwater best management practices (BMPs) frequently used, such as detention and retention ponds, infiltration basins, and wetlands. Although these conventional practices can remove some common water contaminants such as suspended particles, they are not effective at removing E. coli and other pathogenic microorganisms. A new filtration technology using steel byproducts, including steel chips and steel slag, has been developed to remove E. coli from stormwater. Laboratory and field scale studies have shown that filtration using steel chips and steel slag media is effective at removing E. coli. However, large pilot-scale filtration studies are needed to verify the performance of steel byproduct filters for stormwater treatment and promote the full-scale applications of this technology for E. coli management in stormwater.

1.2 Pilot Scale Study

The objective of this study was to design and construct a pilot scale filter structure at a stormwater site in Sioux Falls, SD, and evaluate the filter performance for E. coli and phosphate removal under real stormwater treatment conditions. The stormwater BMP site at 3103 S Sycamore Avenue was selected for this study. The City of Sioux Falls constructed the filter structure, which included two filtration sections with each section containing filter media 20 ft long, 6 ft wide, and 1.5 ft high. The filter media consisted of 70% steel slag and 30% steel chips.

The SDSU project team conducted five sampling events to evaluate the filter performance; each event had 12 sampling points for both filter influent and effluent. The average flow rate of the five sampling events was 0.67 cubic feet per second (cfs), which is well above the design flow of 0.26 cfs. The filter average influent E. coli concentration was 1,120 MPN/100 mL and the filter average effluent E. coli concentration was 625 MPN/100 mL. The pilot filter removed an average of 44.2% of the E. coli in the stormwater. The filter also effectively removed phosphate. The average filter influent phosphate concentration was 0.13 mg/L and the average filter effluent phosphate concentration was 0.06 mg/L. The pilot filter removed an average of 53.8% of the phosphate in the stormwater. An average increase of 0.03 mg/L of iron concentration was observed after filtration. All the filter influent and effluent iron concentrations were well below the EPA secondary drinking water standard of 0.3 mg/L.

1.3 Recommendations

The results of this pilot study demonstrate that filtration using steel slag and steel chips media is an effective technology for removing E. coli and phosphate under real stormwater treatment conditions. This technology can be used as a cost-effective BMP to control bacteria and phosphate contamination in urban stormwater systems. Full-scale applications of this filtration technology are recommended to reduce the E. coli and phosphate contamination from stormwater runoff and protect natural water resources. Regular filter media maintenance is also recommended if the filter is subject to particles and algae accumulation.

2. INTRODUCTION

2.1 Stormwater Runoff and Contaminants

Stormwater runoff, generated from precipitation events such as rainfall or melting snow, frequently leads to flooding, erosion, and pollution. The issue of runoff is increasingly pressing due to the rapid pace of urbanization. As urban areas expand, the prevalence of impervious surfaces, such as roads, parking lots, and rooftops, also increases. This expansion occurs at the expense of pervious areas like forests, wetlands, and prairies. Consequently, there is an increase in runoff volumes because the diminished pervious surfaces reduce soil infiltration and baseflow. This surge in runoff has several negative environmental impacts, including a decline in water quality. The reduced ability of natural habitats to filter out pollutants highlights the environmental challenges posed by increased stormwater runoff (Brabec et al., 2002; Tafuri and Field, 2012).

The pollution associated with stormwater can be categorized into point source pollution and nonpoint source (NPS) pollution. Following the enactment of the Federal Water Pollution Control Act in 1972, and subsequent amendments to the Clean Water Act (CWA) in 1977 and 1983, there has been a significant reduction in point source pollution (Keiser and Shapiro, 2019). Consequently, nonpoint source pollution has emerged as the predominant contributor to stormwater contamination. NPS pollution, unlike pollution from industrial and wastewater treatment plants, arises from multiple diffuse sources. As rainfall, snowmelt, or irrigation water percolates through the ground, it transports pollutants into rivers, lakes, wetlands, coastal waters, and groundwater, thereby compromising water quality. The prevalent NPS pollutants include salts from irrigation practices and acidic wastewater from abandoned mine drainage; surplus fertilizers, herbicides, and insecticides from agricultural and residential areas; oil, grease, and toxic chemical compounds from urban and industrial runoff; as well as bacteria and nutrients from livestock, manure, and malfunctioning septic systems (Baker, 1992). Major contributors to stormwater pollution are agriculture and urbanization (Pitt et al., 1995). Agriculture in the United States is renowned for its high productivity, quality, and efficiency, with over 330 million acres dedicated to cropland (Alston et al., 2009). However, when stormwater traverses agricultural areas, it can transport substantial quantities of salts, nutrients such as phosphorus and nitrogen, heavy metals, herbicides, pesticides, and soil particles into rivers and lakes. The National Water Quality Assessment (NAWQA) identifies agriculture as the principal source of pollution in rivers, streams, surveyed estuaries, and groundwater, and as the third-largest source of lake pollution (Carpenter et al., 1998). This pollution predominantly occurs in poorly managed areas lacking conservation plans, characterized by inappropriate animal feeding operations, inadequate manure treatment, overgrazing, excessive plowing, and improper timing and application of fertilizers.

Urbanization profoundly impacts landscapes and water quality. The increased impervious surfaces hinder water from penetrating the ground, elevating runoff levels from about 10% in undisturbed environments to roughly 55% in fully urbanized areas. This escalation leads to more frequent flooding and severe stream bank erosion (Paul and Meyer, 2001). Additionally, urbanization introduces a variety of organic and inorganic pollutants into the environment, significantly impairing water quality and posing human health risks. According to the Department of Economic and Social Affairs, the global urban population is projected to reach 6.3 billion by 2050, with the rapid pace of urbanization expected to worsen stormwater pollution issues (UNDESA, 2018). Consequently, comprehending the sources and pathways of contaminants in urban settings is essential for planning effective management strategies to enhance urban stormwater quality. Stormwater can transport a variety of organic and inorganic pollutants, including nutrients, total suspended solids, floating litter, pathogens, organic chemicals, heavy metals, and oil and grease into rivers and lakes. Elevated phosphorus and nitrogen levels contributes to harmful algal blooms in surface waters, which can clog waterways, block sunlight, inhibit photosynthesis in aquatic plants and lead to low dissolved oxygen levels. This can result in the death of fish and other aquatic organisms, significantly disrupting ecosystems (Conley et al., 2009). The primary sources of phosphorus and nitrogen in stormwater are fertilizers, animal excrement, and detergents. Suspended solids are frequently transported through the physical erosion of soils during storm events. As rain falls and runs off impermeable surfaces, it often picks up sediment and fine particles, which are then carried into stormwater runoff. While small amounts of these particles are typically harmless to ecosystems, elevated levels of suspended solids can obstruct sunlight and create sediment build-ups. These conditions can harm ecosystems by altering the natural balance of organisms due to reduced sunlight and accumulated sediment.

Millions of tons of anthropogenic solid litter enter surface waters annually. The toxic chemicals, non-degradable plastics, and bacteria in this litter can cause water pollution, resulting in the death of aquatic animals and birds. Commonly observed floating litter includes cigarette filters, plastic bags, food wrappers, beverage bottles and caps, and straws, with plastics constituting 60% to 80% of this waste (Rios et al., 2007). According to statistics from the United Nations Environment Assembly and previous studies, from 4.8 to 12.7 million tons of plastic waste enter the world's oceans each year (Jambeck et al., 2015). This floating debris is often ingested by aquatic animals and birds, leading to the absorption of highly concentrated toxic chemicals into their bloodstream and causing gastrointestinal blockages. Moreover, floating litter can have significant habitat, chemical, and biological impacts on animals, which can ultimately affect humans as well.

Microorganisms, including bacteria, viruses, and parasites, can cause gastrointestinal diseases when water contaminated with these pathogens is consumed by humans. Common sources of microbial pollution include human and animal wastes, sewer leakage, underground storage tanks, and septic tank seepage (Jamieson et al., 2004). Organic matter, both natural and synthetic, can be carried into surface water by stormwater runoff. Biodegradable organic matter such as proteins, amino acids, carbohydrates, and fatty acids can be oxidized by bacteria under aerobic conditions, potentially depleting dissolved oxygen in surface waters and threatening aquatic life. These substances can also cause problems related to color, taste, and odor. Non-biodegradable organic matter, including tannic and lignin acids, cellulose, and phenols, can be toxic to aquatic animals and microorganisms when discharged into water (Volk et al., 2000). Many of these substances are cumulative toxins that can bioaccumulate and eventually transfer up the food chain, posing risks to human health.

Heavy metals present in water, such as cadmium, copper, lead, mercury, nickel, chromium, and arsenic, can be toxic to aquatic life and other animals, thereby directly or indirectly threatening human health (Mulligan et al., 2001). Heavy metals do not degrade naturally in the environment; instead, they accumulate in fish or plants and eventually enter the human food chain. These pollutants often originate from various human activities, including mining, vehicle emissions, tire wear, and motor oil factories (Wackernagel and Rees, 1998). Oil and grease are also toxic to aquatic life. Exposure to oil and grease can cause fish to experience abnormal skin lesions, decreases in lymphocyte and smooth muscle cell counts, cardiotoxicity, repressed growth, and impaired swimming performance (Hajji and Lucas, 2024). The primary sources of oil and grease in storm drains include automotive leaks and spills and the improper disposal of used oil and automotive products.

2.2 Stormwater Management Practices

Detention ponds, wet retention ponds, infiltration basins, and porous pavement are among the most common BMPs for infiltration systems. Detention ponds are used to temporarily store stormwater during rainfalls, which allow pollutants to settle at the bottom, thereby reducing flooding and pollution issues. Detention and/or infiltration treatment systems are practical methods for NPS pollution control. Wet retention ponds, similar to detention ponds, serve as storage for stormwater, with their permanent pools retaining runoff and enhancing pollutant removal through sedimentation and biodegradation. Infiltration basins operate differently, storing stormwater which then infiltrates into sand and soil, effectively removing fine particle pollutants. However, they may become clogged by coarse particles in stormwater. Porous pavement promotes stormwater infiltration into the soil, aiding in the removal of fine particles. Water quality inlets, or trapping catch basins, are designed to reduce sediments, oils, and greases from runoff generated in parking lots before discharge to storm drains or infiltration basins. In addition to these conventional stormwater BMPs, media filtration has gained increased attention in stormwater quality control. Filtration systems consist of two major components: sedimentation chambers and filter media. Sedimentation chambers are designed to remove total suspended solids to prevent clogging, while filter media target dissolved pollutant removal. The performance of filtration systems is influenced by water quality, flow rate, and the physical and chemical characteristics of the media. Various materials, including sand, coated sand, iron filings, zeolite, limestone, wood chips, and biochar, have been studied as filter media for treating different pollutants in stormwater.

The advantages and disadvantages of BMPs must be evaluated against physical site constraints, management objectives (flow control and/or water quality control), and costs. Due to limitations in permeable surfaces and concerns over groundwater pollution, infiltration systems may not be suitable for urban areas. Compared with infiltration systems, media filtration systems have fewer physical requirements, such as soil characteristics, pollutant characteristics, loading rate, land use, and groundwater levels. Stormwater filters can be designed for different sizes of drainage areas. Therefore, media filtration is increasingly applied in urban stormwater management systems.

2.3 E. Coli Occurrence and Control in Stormwater Management

2.3.1 E. coli Health Risks and Sources

Escherichia coli (E. coli) is a species of bacterium commonly found in the environment, foods, and the intestines of humans and animals (Sondi and Salopek-Sondi, 2004). E. coli comprises a large and diverse group of bacteria, most of which are harmless or cause only mild diarrhea. However, certain pathogenic strains can cause diseases such as nausea, gastrointestinal issues, and diarrhea. Although severe side effects are less common, vulnerable populations such as children and the elderly may develop kidney failure, which can be fatal (WHO, 2021). Each year, approximately 1.3 million children under the age of five die due to diarrheal diseases, with contaminated water being one of the primary transmission routes (Mokomane et al., 2018). The presence of E. coli in water samples is considered a reliable indicator of potential fecal contamination. The U.S. Environmental Protection Agency (EPA) designates E. coli as an indicator of fecal contamination and regulates E. coli concentration in freshwater at 126 colony-forming units (CFU)/100 mL [or 126 most probable number (MPN)/100 mL].

Contaminated food and water sources are prevalent vectors for E. coli outbreaks. Water sources frequently become contaminated through exposure to high concentrations of fecal matter, originating from sources such as polluted wastewater, stormwater, or agricultural runoff. These pollutants infiltrate rivers, lakes, streams, ponds, and groundwater supplies, thereby degrading water quality. A 2017 study investigating the impact of combined sewer overflow found that a wastewater plant discharging 4.3% of its untreated wastewater into a local river resulted in an increase in E. coli concentrations from 3 MPN/100mL to 2.8 x 10^3 MPN/100mL (Mascher et al., 2021). Another study examined the effect of treatment lagoons on local groundwater wells, revealing that E. coli and total coliform levels exceeded drinking water limits in most wells (Barakat et al., 2019).

2.3.2 E. coli Removal from Stormwater

(1) Disinfection

In recent decades, various methods have been developed for controlling E. coli. Among these, chlorine disinfection is one of the most prevalent techniques. This method involves introducing chlorine gas, hypochlorite solutions, or other chlorine compounds in solid or liquid forms to oxidize cellular materials and eliminate the target organisms. Chlorine disinfection has been utilized for drinking water disinfection for over a century (EPA, 2000). Over the years, it has evolved into a well-established and widely adopted technology. Chlorine disinfection is cost-effective and reliable, effectively treating a wide range of pathogenic microorganisms. Additionally, the residual chlorine remaining in the water can extend the disinfection effect. However, there are notable disadvantages to chlorine disinfection. Chlorine residuals are toxic to aquatic life, often necessitating dechlorination before discharge into surface waters. The handling, storage, and transportation of chlorine are subject to stringent safety regulations due to its highly corrosive and toxic properties. Furthermore, chlorine's strong oxidizing nature can lead to reactions with natural organic matter (NOM), producing harmful disinfection byproducts (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs), which are known carcinogens (Krasner et al., 2006; Richardson et al., 2007). These limitations restrict the use of chlorine disinfection in stormwater applications.

Ultraviolet (UV) light is a widely utilized disinfection method, with costs and efficacy similar to those of chlorine. UV radiation from mercury arc lamps penetrates the cell walls of microorganisms, inhibiting their reproductive capabilities. The effectiveness of UV disinfection depends on the water's characteristics. Water with elevated levels of suspended solids or turbidity may show reduced efficacy in eliminating target organisms. Unlike chemical treatments, UV disinfection is a physical process, thus avoiding the need for handling and storing hazardous chemicals like chlorine and preventing the formation of DBPs. However, UV lamps require regular maintenance and replacement to ensure treatment efficiencies.

Ozone is another powerful oxidant used in water and wastewater treatment to inactivate viruses and bacteria. Ozone treatment involves the direct oxidation of the cell walls of microorganisms, leading to their destruction. Despite its effectiveness, ozone is less commonly used in treatment facilities due to its higher operational costs. The technology required for ozonation is complex, and ozone must be generated on-site due to its instability. Additionally, the operation of ozone equipment demands significant energy and maintenance.

(2) Retention Ponds

Retention ponds have consistently demonstrated high efficacy in removing significant percentages of bacteria. The efficiency of bacterial inactivation in retention ponds is influenced by various factors, including temperature, pond depth, environmental conditions, dissolved oxygen levels, turbidity, and pH. Properly designed retention ponds often achieve coliform removal rates exceeding 90% (Struck et al., 2006). While multiple factors affect the overall removal efficiency, the primary mechanism is believed to be sunlight-mediated disinfection (Passos, Dias, and Sperling, 2020). Sunlight serves as the disinfectant, and turbidity can hinder this process by limiting light penetration. Consequently, the E. coli removal efficiencies can be significantly reduced for stormwater with high turbidity.

(3) Wetlands

Wetlands are unique ecosystems characterized by saturated land, either seasonally or year-round. They are often classified into various types, including marshes, swamps, bogs, and fens. Constructed wetlands are designed to mimic these natural ecosystems and are utilized as stormwater management practices. Determining the exact efficiency of wetlands in removing bacteria is challenging due to their complexity and biodiversity. Many studies have reported high removal rates, often exceeding 90% for E. coli (Karim et al., 2008; Abunaser and Arwa, 2020; Zurita and Carreon-Alvarez, 2015). However, other studies have shown significantly lower removal efficiency. One such study observed only a 6.7% removal rate of E. coli (Lamori et al., 2019). The variability in removal rates across studies is likely attributed to the differing characteristics of each wetland, including variations in plant, soil, and animal life.

(4) Biofiltration

Biofiltration involves using a bioreactor containing living organisms to remove pollutants from water. This method is commonly applied in water and wastewater treatment, utilizing microorganisms to eliminate target pollutants. Biofiltration is not limited to microorganisms and can also employ larger organisms. Recent studies have explored the use of plant and aquatic life for effective E. coli removal in small-scale experiments. A 2018 study investigating the biofiltration capabilities of Corbicula fluminea demonstrated high removal efficiencies for E. coli, heavy metals, and other common stormwater contaminants. Plant species have also shown potential in reducing E. coli concentrations in water. A 2017 study evaluated the biofiltration capabilities of 17 native Australian plant species, with nine of them significantly reducing E. coli populations and inhibiting growth. Additionally, each plant reduced nitrogen and other nutrient concentrations in the water (Shirdashtzadeh et al., 2017). These plants could be integrated with specialized green wall materials to further decrease E. coli levels. Hydraulically slow media such as coir, rockwool, and Fytofoam achieved up to 80% E. coli removal, while fast media like perlite, vermiculite, growstone, expanded clay, or river sand showed up to 20% removal (Prodanovic et al., 2017). Properly utilized, biofilters offer an environmentally friendly approach to reducing E. coli concentrations in stormwater.

(5) Biochar

Biochar is a charcoal-like material produced from organic biomass through pyrolysis at high temperatures. It possesses high porosity, surface area, and water holding capacity, making it an effective adsorbent for various constituents. Biochar is relatively inexpensive to produce and is often incorporated into soils or containers to enhance adsorption capacity. Recent research has explored its efficacy in removing E. coli. A 2014 study found that amending sand filters with 5% biochar by weight improved E. coli removal rates. Although the introduction of influent with high concentrations of natural organic matter (NOM) reduced removal efficiency, the biochar-amended filter still outperformed the sand filter alone (Mohanty et al., 2014). Biofilms naturally form on biochar-amended filters during the filtration process, which can either enhance or impair the filter's removal potential. Similar to the effects of high NOM concentrations, biofilms often decrease the performance of biochar-amended filters, yet they still achieve higher removal rates than sand filtration alone (Mohanty et al., 2014; Afrooz and Boehm, 2016). Over time, biochar-amended filtration systems exhibit minimal physical degradation but may experience a decline in removal capacity. Intermittent rain events are believed to alter the biofilm within the filter, leading to long-term reductions in capacity (Mohanty et al., 2014; Kranner et al., 2019). Although the long-term use of biochar-amended filters is limited, they demonstrate significant potential for E. coli removal under optimal conditions.

(6) Iron Enhanced Sand Filter

Iron enhanced sand filters (IESFs) represent an advanced filtration technology that integrates the use of iron-coated sand to improve the removal efficiency of various contaminants from stormwater and wastewater. These systems rely on the adsorptive properties of iron oxides, which can remove phosphorus, heavy metals, and pathogenic microorganisms like E. coli. The operational principle of IESFs involves the addition of iron compounds to conventional sand filter media, resulting in iron coating on the surface of sand. As water passes through the iron-enhanced medium, contaminants are removed through a combination of adsorption, co-precipitation, and microbial degradation processes. Iron oxides facilitate the formation of complexes with phosphorus, significantly reducing its mobility and bioavailability in the treated effluent (Erickson et al., 2012). Several studies have demonstrated the efficacy of IESFs in various environmental settings. For instance, a field study conducted by Erickson et al. (2012) reported that an IESF achieved an average phosphorus removal efficiency of 85% from urban stormwater runoff. Similarly, research by Li et al. (2016) indicated that IESFs could achieve up to 90% removal of dissolved phosphorus from agricultural runoff, underscoring their potential application in non-urban environments. Moreover, IESFs have shown promise in pathogen removal. A study by Park and Kim (2009) demonstrated that iron-enhanced sand media could significantly reduce E. coli concentrations in stormwater. This is attributed to the antimicrobial properties of iron oxides, which disrupt bacterial cell membranes and generate reactive oxygen species that inactivate pathogens (Diao and Yao, 2009). Despite their advantages, the performance of IESFs can be influenced by several factors, including the initial concentration of contaminants, hydraulic loading rates, and the physical and chemical properties of the influent water. Additionally, long-term maintenance and periodic replacement of the iron-coated sand media are essential to sustain the filter's effectiveness (Erickson et al., 2012).

(7) Steel Byproducts

Two common byproducts from steel production, steel chips and steel slag, are readily available and cost-effective materials. Recent research has investigated their applications for removing E. coli from water. Studies have demonstrated that steel chips and steel slag exhibit varying efficiencies for E. coli removal. A 2017 bench-scale adsorption study reported that steel chips achieved a 94% removal rate of E. coli within two hours at initial concentrations of 10^4 MPN/mL, whereas steel slag removed only 28.5% under the same conditions (Hooshyari, 2017). Subsequent column studies in 2019 confirmed high E. coli removal rates by steel chips, with the largest chips (4–9 mm in diameter) removing 60% and the smallest chips (0.5–1 mm in diameter) nearly 100% at an initial concentration of 10^6 MPN/mL (Dai, 2019). In 2019, a pilot study utilizing a field filter composed of a mixture of steel slag and steel chips evaluated the real-world application of these byproducts for stormwater treatment. The study found that the filter consistently removed 50% of E. coli across multiple runoff events. However, the field filter also resulted in an increase of 0.5 mg/L in dissolved iron content post-filtration (Neville, 2019). Overall, steel byproducts show promise as low-cost media for the removal of E. coli from water.

2.4 Flow-through Filters

A flow-through filter is a type of filtration system engineered to purify water by channeling it through a filter medium, which extracts contaminants via physical, chemical, and biological mechanisms. These filters are extensively employed in water and wastewater treatment processes to enhance water quality by eliminating suspended solids, pathogens, nutrients, and other pollutants. The operation of flow-through filters involves guiding influent water through a filter bed composed of various materials such as sand, gravel, activated carbon, or specialized media like biochar or iron-coated sands. Contaminants are removed as water traverses the filter media through processes including adsorption, sedimentation, biological degradation, and chemical reactions.

Flow-through filters offer multiple benefits, including high removal efficiencies for a broad spectrum of contaminants, relatively low operational costs, and ease of maintenance. However, their performance can be affected by factors such as the characteristics of the filter media, flow rate, influent water quality, and operational conditions. Research has validated the efficacy of flow-through filters in diverse applications. For instance, Rambags et al. (2016) assessed a woodchip filter for nutrient and pathogen removal from a septic tank effluent. The study revealed that the filter significantly decreased concentrations of nitrogen and E. coli, illustrating the potential of flow-through filters to treat septic wastewater. Similarly, Vymazal (2011) reviewed the application of constructed wetlands as flow-through filters for wastewater treatment. The review underscored the capability of these systems to efficiently remove organic matter, nutrients, and pathogens from wastewater, highlighting their suitability for decentralized treatment scenarios.

A field-scale filter was installed in a stormwater detention pond in Brookings, SD, in 2018 to evaluate the on-field performance of the mixed media of steel slag and steel chips to remove E. coli and phosphate from stormwater (Neville, 2019). The filter was engineered with dimensions of 5 ft wide, 6 ft long, and 8 inches high. Both the inlet and outlet plates were perforated with 1-inch diameter holes to facilitate the passage of runoff through the filter, thereby ensuring a free-flowing system. Figure 2.1 shows a photo of the filter after a storm event. The filter media composition was specifically selected, comprising 25% large steel slag, 12.5% small steel slag, 50% large steel chips, and 12.5% small steel chips. These ratios were changed to 30% steel chips and 70% steel slag in 2021 (Olevson, 2021). These proportions were determined based on batch test results and material properties. Given the tendency of steel chips to agglomerate over time, which could potentially clog the filter and diminish its efficacy in treating runoff, a higher percentage of large steel slag and large steel chips was incorporated to mitigate this effect and enhance the media's longevity. The filter was packed with 6 inches of mixed media, allowing for a 2-inch freeboard. The three-year field stormwater treatment study showed that the mixed media filter removed an average of 50% of the E. coli and the phosphate in the stormwater. These results demonstrate that steel slag and steel chips are promising filter media that could be applied to remove E. coli from stormwater. Larger scale field studies would be needed to verify the performance of steel byproduct filters under various stormwater conditions.

Figure 2.1 Field mixed media filter for stormwater treatment in Brookings, SD

2.5 Project Objectives

The objective of this project was to establish a pilot scale flow-through stormwater filtration system to evaluate the performance of steel byproduct media to remove E. coli. A stormwater drainage basin located in Sioux Falls, SD, was selected as the pilot scale stormwater study site. The City of Sioux Falls and SDSU worked closely to evaluate the physical conditions of the selected drainage basin and design the pilot scale E. coli filtration system. The City of Sioux Falls constructed the filter structure and installed the filter media using recycled steel chips and steel slag. The SDSU project team collected filter influent and effluent samples for multiple sampling events from June to August 2024. Samples collected from the pilot filter site were analyzed for E. coli concentrations to determine the removal efficiency. In addition, the ability of the filter to removal phosphate removal was also evaluated. Overall, this study can lead to full-scale implementation of steel byproduct filtration systems for E. coli and phosphate management in stormwater.

3. MATERIALS AND METHODS

3.1 Stormwater Filtration Pilot Study Site Selection

The first step of this pilot scale stormwater filtration study was to select a study site. The City of Sioux Falls and SDSU project team identified the following five potential stormwater sites for this pilot filtration study.

Site 1:2304 S Wheatland Avenue
Site 2: 5404 S Southwind Avenue
Site 3: 3201 S Bahnson Avenue
Site 4: 3103 S Sycamore Avenue
Site 5: 1201 N Sycamore Avenue

The SDSU project team conducted a site visit on June 22, 2022. Figures 3.1 through 3.5 presents photos of the five stormwater sites.

Figure 3.1 Stormwater site 2304 S Wheatland Avenue

Figure 3.2 Stormwater site 5404 S Southwind Avenue

Figure 3.3 Stormwater site 3201 S Bahnson Avenue

Figure 3.4 Stormwater site 3103 S Sycamore Avenue

Figure 3.5 Stormwater site 1201 N Sycamore Avenue

Flow tests were conducted for the downstream channels of the five stormwater sites using a floating object. In each test, the width, depth, and flow length of the drainage channel were measured. Flow time was recorded for the time needed for the floating material to travel the flow length. Flow rates were calculated based on the flow test data. Table 3.1 summarizes flow test results for each stormwater site. The physical conditions of each site were also evaluated. Table 3.2 presents the comparison of the physical conditions of the five sites.

Table 3.1 Stormwater site downstream flow tests

Location	Width (ft)	Depth (ft)	Flow Length (ft)	Flow Time (s)	Water Velocity (ft/s)	Flow Rate (ft^3/s)
Site 1: 2304 S Wheatland Avenue	7	0.17	3	2	1.5	1.75
Site 2: 5404 S Southwind Avenue	3.5	0.46	60	76	0.79	1.27
Site 3: 3201 S Bahnson Avenue	4	0.42	11	34	0.32	0.75
Site 4: 3103 S Sycamore Avenue	3	0.38	2.5	11	0.23	0.26
Site 5: 1201 n Sycamore Avenue	No open area for test					

Table 3.2 Comparison of stormwater sites

Location	Pros	Cons
2304 S Wheatland Avenue	Good base flow, easy access	Multiple outlets, no clear flow channel, flow split, large amount of vegetation
5404 S Southwind Avenue	Good base flow, easy access, clear downstream flow channel	Proximity to neighbors, narrow access to channel beyond a fence
3201 S Bahnson Avenue	Good base flow, easy access	Steep downstream channel with rocks
3103 S Sycamore Avenue	Good base flow, easy access, clear and flat downstream flow channel	Large amount of vegetation
1201 N Sycamore Avenue	Easy access	No base flow, steep downstream channel with rocks

The City of Sioux Falls and the SDSU project team evaluated the results of the site visit of the five stormwater sites; the BMP site at 3103 S Sycamore Avenue was selected for this pilot scale E. coli filtration study. Figure 3.6 presents the retention pond outlet structure of this site. Figures 3.7 and 3.8 present the discharge channel and its inlet structure of the selected stormwater BMP site.


Figure 3.6 The selected stormwater BMP site retention pond outlet structure


Figure 3.7 The discharge channel of the selected stormwater BMP site

Figure 3.8 The discharge channel inlet structure

Table 3.3 presents the physical conditions of the discharge channel of the BMP site at 3103 S Sycamore Avenue observed on June 22, 2022.

Table 3.3 Physical conditions of the discharge channel of the selected stormwater site

Downstream channel	4 ft width, 2 ft depth
Downstream water stream	3 ft flow width, 4.5 inch depth
Water flow rate	0.26 cubic feet/sec (cfs), base flow

3.2 Design of the Stormwater Filter Structure

The goal of the stormwater filter design for this pilot study is to provide sufficient contact time between filter media and the stormwater for E. coli removal and to allow good hydraulic permeability to minimize its impact on the stormwater discharge hydraulics. The SDSU project team proposed a design hydraulic residence time (HRT) of 3.5 minutes for the filter under the 0.26 cfs base flow condition and the use of coarse media for the pilot study. The City of Sioux Falls completed the final design based on the proposed design conditions.

3.2.1 Size of the Filter Structure

Two filter sections were designed to meet the design HRT. The dimension of each filter structure section is 20 ft long, 6 ft wide, and 1.5 ft high. The filter structure is 40 ft long. The two filter sections are separated by a 6-ft-long intermediate section. A 6-ft inlet section and a 6-ft outlet section were also designed to direct the stormwater flows. The total effective length of the filter is 58 ft. Reinforced concrete was used to construct the filter structure. Both the inlet and outlet have ripraps for structural stability and for separating incoming large debris from the inlet side. Four stainless steel weirs were designed to keep the filter media within the filter structure and evenly distribute the flow to the filter media. Each weir is 1 ft high and 6 ft long and has 18 circular openings (diameter = 4 inches) in two rows. Type B drainage fabric was designed to cover the bottom of the ripraps to eradicate the chance of infiltration. The design height of filter media is 6 inches. The design filtration HRT is 3.85 minutes assuming 50% porosity of the media. Figures 3.9 and 3.10 present the plan view and section view of the filter structure design. Figures 3.11 and 3.12 show the section view of the filter weir and the performed weir plate design. The existing stormwater discharge channel was expanded to 6 ft to construct the proposed filter structure.

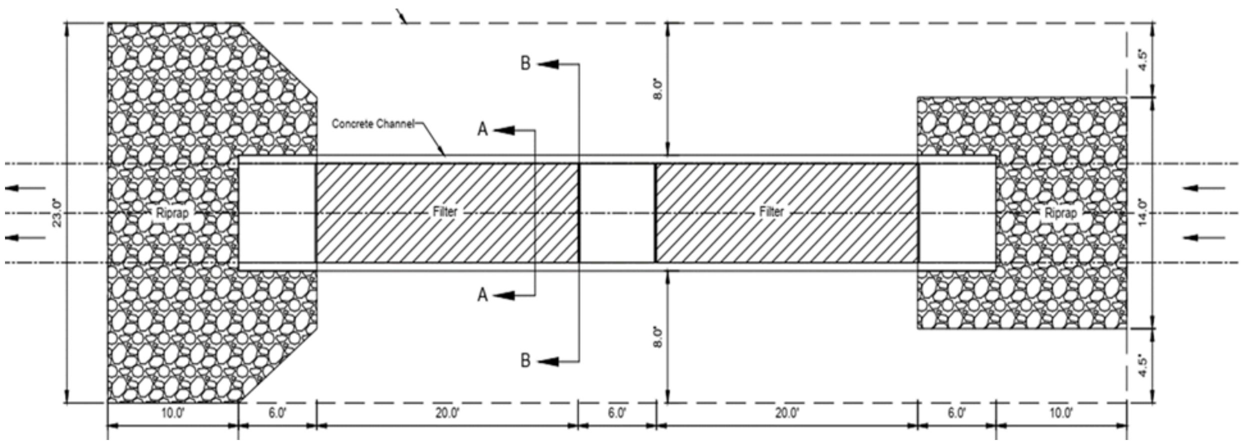

Figure 3.9 Plan view of the filter structure

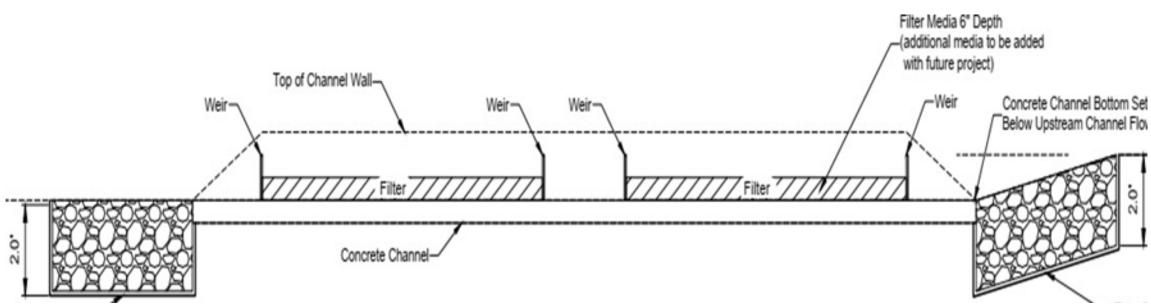

Figure 3.10 Section view of the filter structure

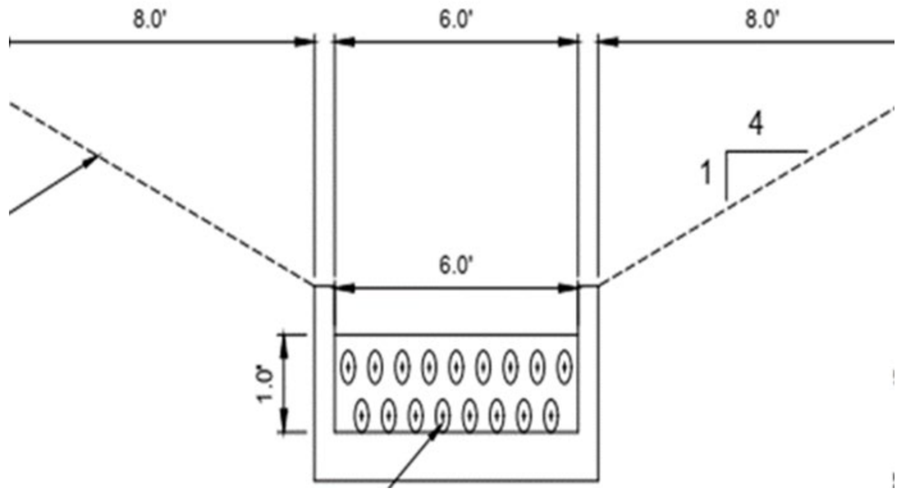

Figure 3.11 Section view of the filter weir

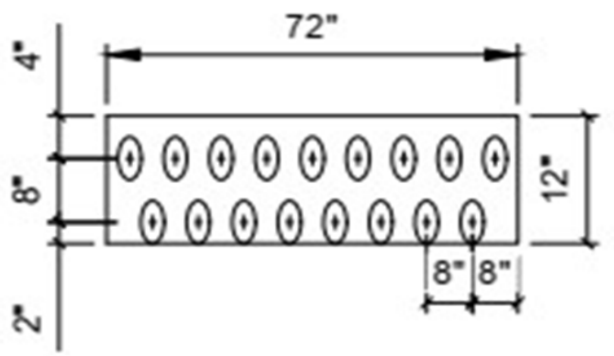

Figure 3.12 Perforated steel plate for the filter weir

Table 3.4 presents a summary of the design conditions of the stormwater filter structure.

Table 3.4 Summary of the design of filter structure

Design Elements	Description
Number of filter sections	2
Size of each filter section	20 ft (length) × 6 ft (width) × 1.5 ft (height)
Inlet section	6 ft (length) × 6 ft (width) × 1.5 ft (height)
Intermediate section	6 ft (length) × 6 ft (width) × 1.5 ft (height)
Outlet section	6 ft (length) × 6 ft (width) × 1.5 ft (height)
Total length of the filter	58 ft, reinforced concrete
Stainless steel weirs	Total of 4 plates, each 6 ft width, 1 ft height
Weir perforation	18 circular openings, 4-in. diameter

3.2.2 Filter media

The filter media for this pilot study included recycled steel slag and steel chips. Steel chips are generated as waste materials from steel machining, cutting, and grinding processes. Steel slag is a steel-making byproduct that is typically rich in aluminum, calcium, and iron. Both materials have been evaluated at SDSU in previous studies and showed good E. coli removal capacities. The selection of the filter media sizes and the composition of the two materials requires a balance between treatment efficiencies and hydraulic properties. Table 3.5 presents the filter media properties selected for the pilot study.

Table 3.5 Media properties for the pilot filtration study

Design Elements	Description
Steel chips	Steel chips made from carbon steel
Steel slag	Electric arc furnace steel slag
Filter media size	¼ inch – ½ inch (6.35 – 12.7 mm)
Filer media height	6 inches
Volume ratio of the filter media	Steel slag=70%, steel chips=30%
Volume of steel slag	70% of (40 ft × 6 ft × 0.5ft) = 84 cubic feet
Volume of steel chips	30% of (40 ft × 6 ft × 0.5ft) = 36 cubic feet

Table 3.6 shows information regarding steel slag and steel chips suppliers for this project. The steel slag size is in the range of 0 to 1 inch, and the size of the steel chips varies. The steel slag and steel chips were processed to the design media size range.

Table 3.6 Steel slag and steel chips suppliers

Filter medium	Material supplier	Product information
Steel slag	Tube City Ims, LLC, Norfolk, NE	Steel slag size = 0–1inch Price = $14/ton
Steel chips	TJN Enterprises, Inc, Sioux Falls, SD	Steel chips size = vary Steel chips price = 9 cents/lb

3.3 Filter Construction, Maintenance and Sampling Schedule

3.3.1 Filter construction and maintenance

The City of Sioux Falls completed the filter structure construction and placed the filter media in April 2024. Figure 3.13 presents an overview of the installed filter structure. Figures 3.14 and 3.15 show the inlet and outlet of the filter structure.

Figure 3.13 Overview of the stormwater filter structure

Figure 3.14 Filter structure inlet


Figure 3.15 Filter structure outlet

The SDSU project team visited the filter structure on May 13, 2024, after it was put into operation. It was observed that the filter weirs were partially clogged by debris and algae. A large amount of sand also blocked the inlet weir openings. These sand particles were carried from the upstream detention pond to the filter structure during the prior storm events. Bulk sand also accumulated in the filter media and created blockage in the porous space among materials. These blockages caused the water to flow over the media and weirs. The SDSU project team cleaned the filter structure and media before taking samples from the filter. The SDSU project members manually cleaned the filter using shovels, pick axes, and other tools. Figure 3.16 shows the filter structure before filter maintenance and 3.17 shows the filter structure after the maintenance. It was determined that the filter structure requires periodic maintenance to keep good flow-through properties during this pilot scale filtration study.

Figure 3.16 Filter structure before and during filter maintenance

Figure 3.17 Filter structure after filter maintenance

3.3.2 Filtration Pilot Study Sampling Schedule

Table 3.7 presents the filter maintenance and sampling schedule for this study. Five sampling events were performed from June to August 2024, and two filter maintenances were performed to clean the filter. During each sampling event, grab samples of filter influent and effluent were collected simultaneously every 20 minutes. Twelve sets of samples were collected for each event. During the sampling process, samples were stored in a cool container and immediately transported to the Environmental Laboratory at SDSU after the completion of all samples. Flow rates were also measured using a floating method. A floating object was placed at the beginning of the intermediate filter section. The time it took the floating object to travel to the end of the intermediate filter section was recorded. The flow rate was calculated using the formula $Q=A\times v$ (where Q is flow rate, A is cross-sectional area, and v is velocity).

Table 3.7 Filter maintenance and sampling schedule

Date	**Field Study Activities**
April 2024	Filter construction and installation by the City of Sioux Falls
May 13, 2024	SDSU filter site visit
June 13, 2024	Filter maintenance
June 14, 2024	First sampling event
July 15, 2024	Filter maintenance
July 16, 2024	Second sampling event
August 3, 2024	Third sampling event
August 13, 2024	Fourth sampling event
August 26, 2024	Fifth sampling event

3.3.3 Water Quality Analysis

All collected samples were measured for E. coli, phosphate, and iron. E. coli concentrations were determined using the Colilert 18 method, which provides results in MPN (most probable number) per milliliter. Samples were diluted to achieve concentrations within the expected range of 100 to 2,000 MPN per 100 mL. These dilutions were then transferred into 100 mL containers supplied by IDEXX, and one packet of Colilert reagent was added to each container. The containers were sealed and rotated to ensure complete dissolution of the reagent in the diluted sample. The entire content was subsequently transferred to a Quanti-Tray2000 and sealed using an IDEXX Quanti-Tray sealer. The prepared Quanti-Trays were incubated in an oven set at 35 ± 0.5°C for 24 hours. Following incubation, the trays were analyzed under blacklight in a dark room, and results were calculated according to IDEXX instructions.

Dissolved iron and orthophosphate were measured using colorimetric methods with a DR/6000U Spectrometer (Hach Company, Loveland, CO). Stormwater samples were filtered using a 0.45 µm filter before analysis to remove constituents that might interfere with the colorimetric results. The dissolved iron concentration was determined using the FerroVer® method. Orthophosphate levels were measured with the PhosVer3® (Ascorbic Acid) method.

4. RESULTS AND DISCUSSION

4.1 Filter Flow Rates

Figure 4.1 presents the filter flow rates during the five sampling events. The flow rates varied from 0.31 cfs (08/26/24) to 1.05 cfs (06/14/24), with an average of 0.67 cfs. These flows allowed the filter performance evaluation under different flow conditions. Note that these flows are all above the design flow of 0.26 cfs.

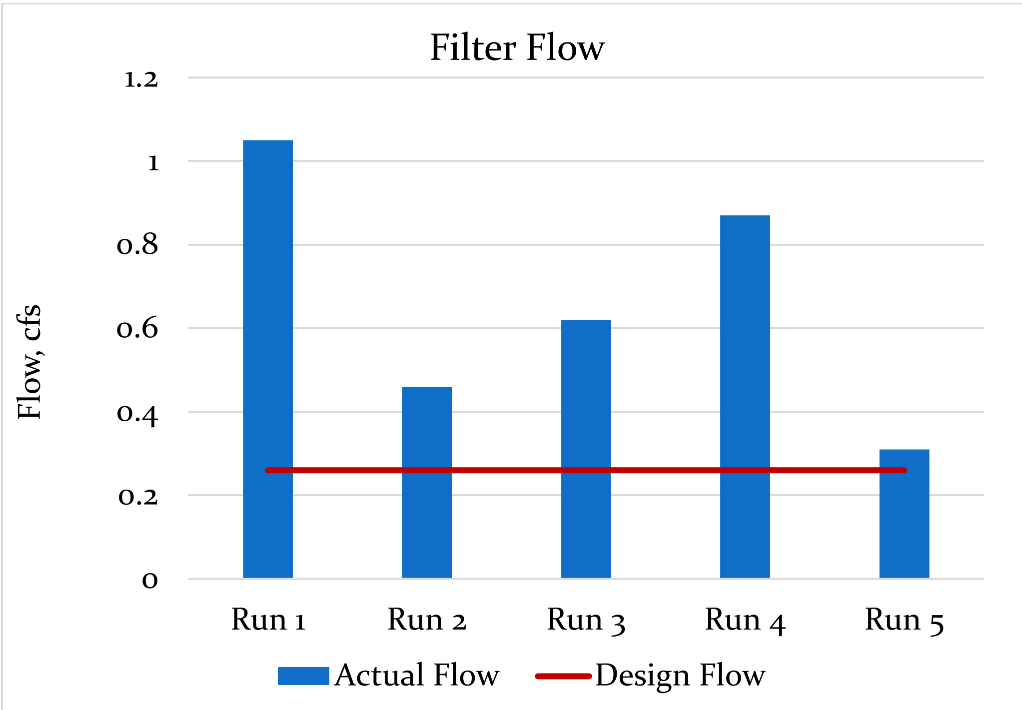

Figure 4.1 Pilot study filter flow rates during five sampling events

4.2 E. Coli Removal by the Filter

Figures 4.2 through 4.6 show the E. coli removals by the filter during the five sampling events. It was observed that the filter influent E. coli levels varied substantially during the 12 samples points for each event. The E. coli influent concentration ranges were 1,414–2671, 215–1,120, 727–1,553, 202–425, and 1,120–1,450 MPN/100 ml, respectively, for the five sampling events. The corresponding filter effluent E. coli ranges were 981–1,703, 121–621, 329–682, 113–301, and 545–1,519 MPN/100 ml, respectively. The resulting average E. coli removal efficiencies were 35.7%, 46.7%, 51.0%, 43.9%, and 49.1%, respectively, for the five sampling events.

Figure 4.7 shows the overall E. coli removal efficiencies of the filter during the pilot study. The average filter influent E. coli concentration was 1,121 MPN/100 mL and the average filter effluent E. coli concentration was 625 MPN/100 mL. The average E. coli removal of the filter was 44.2%. This demonstrates that filtration using steel slag and steel chips media is an effective treatment technology to remove E. coli under real stormwater treatment conditions.

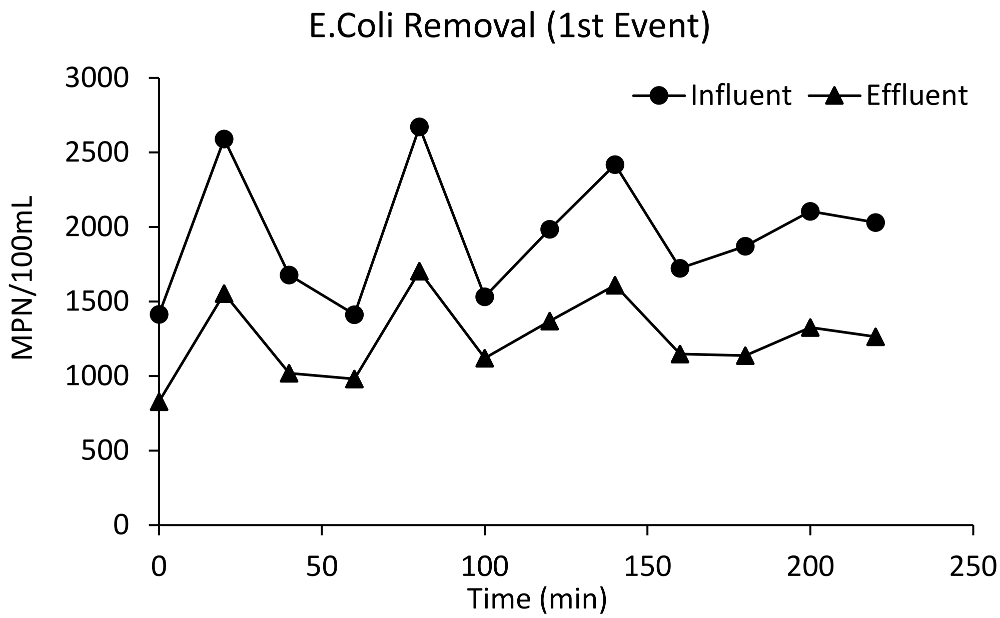

Figure 4.2 E. coli removal (06/14/24)

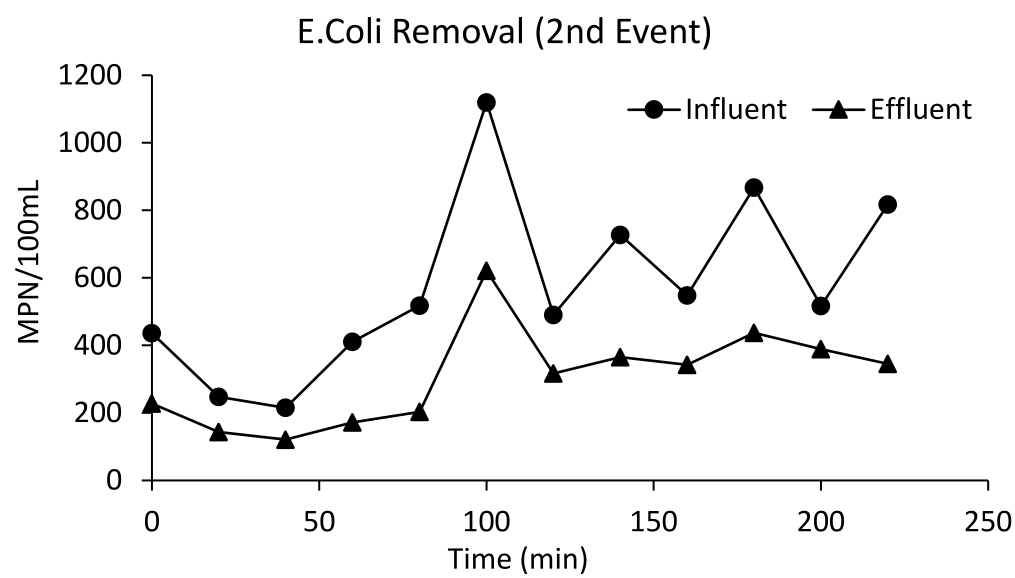

Figure 4.3 E. coli removal (07/16/24)

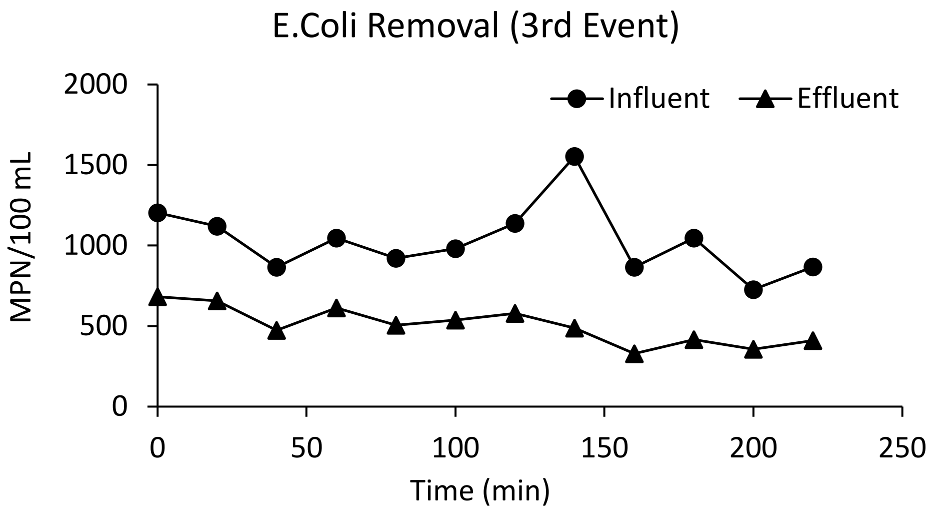

Figure 4.4 E. coli removal (08/03/24)

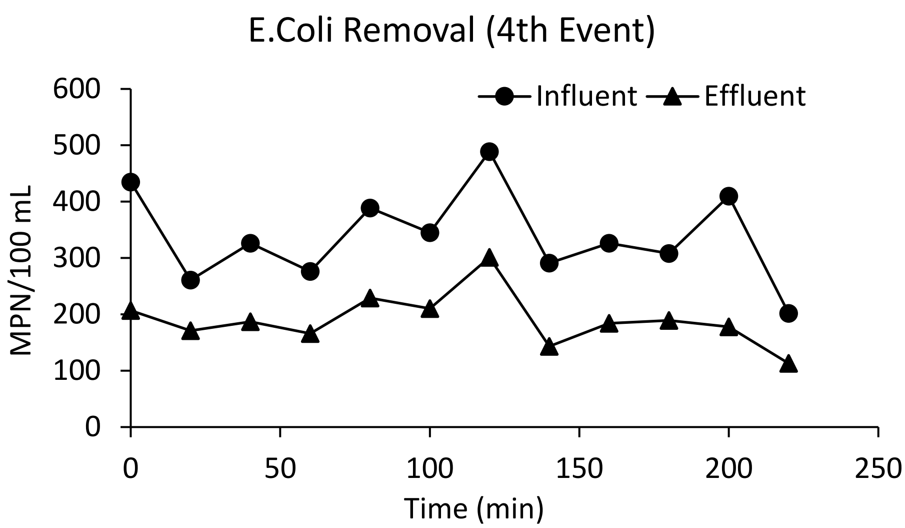

Figure 4.5 E. coli removal (08/13/24)

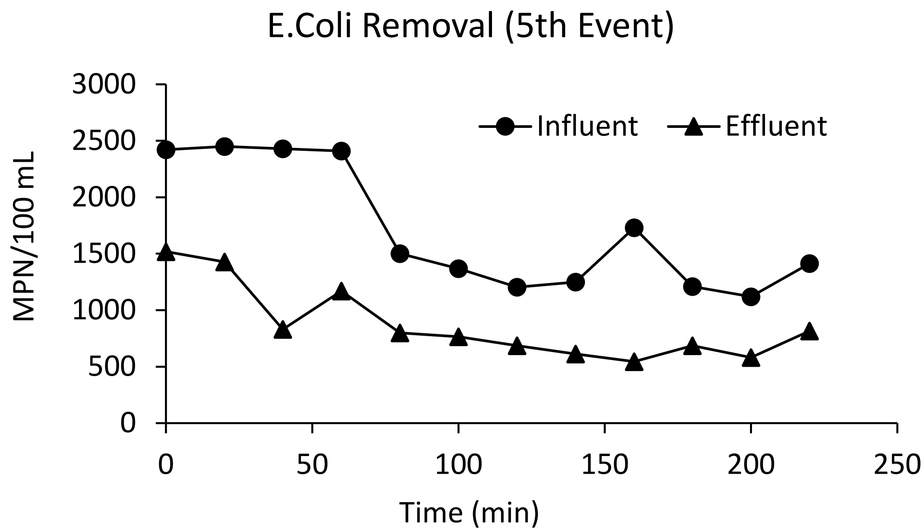

Figure 4.6 E. coli removal (08/26/24)

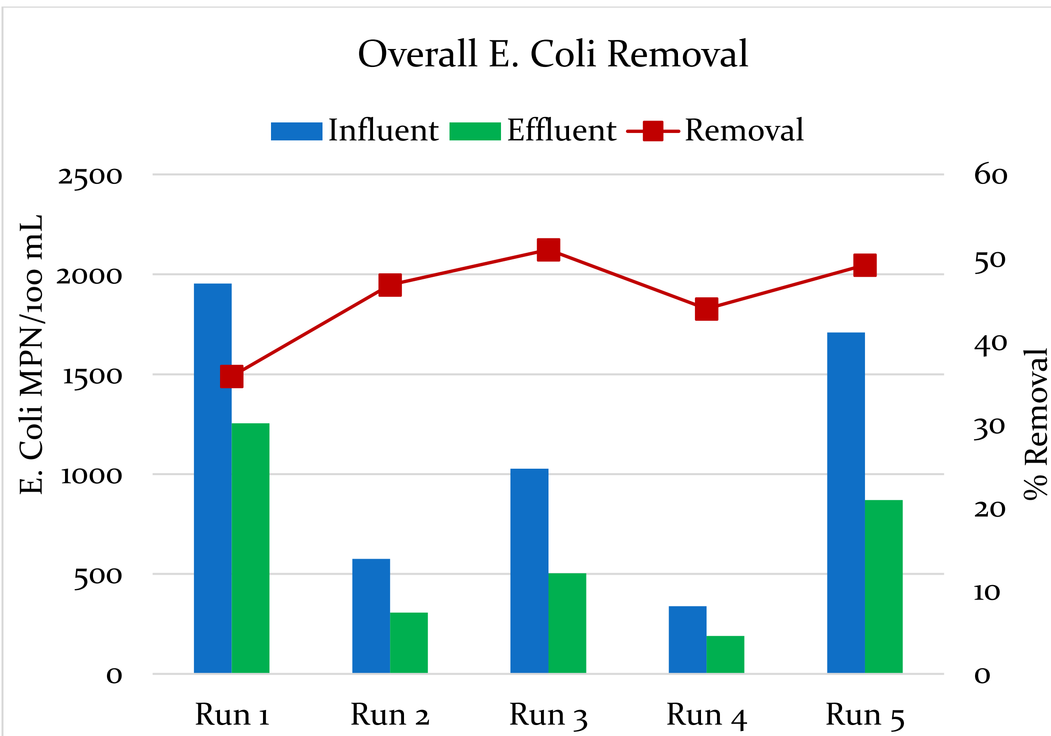

Figure 4.7 Overall E. coli filtration removal during the pilot study

4.3 Phosphate Removal by the Filter

Figures 4.8 through 4.12 show the phosphate removals by the filter during the five sampling events. The filter influent phosphate levels also varied substantially among different sampling events and during the 12 samples points for each event. The influent phosphate concentration ranges were 0.17–0.25, 0.02–0.16, 0.05–1.00, 0.05–0.22, and 0.06–0.13 mg/L, respectively, for the five sampling events. The corresponding filter effluent phosphate concentration ranges were 0.09–0.15, 0.02–0.05, 0.02–0.05, 0.02–0.07, and 0.02–

0.06 mg/L, respectively. The resulting average phosphate removal efficiencies were 37.6%, 20.9%, 59.9%, 76.4%, and 34.4%, respectively, for the five sampling events.

Figure 4.13 shows the overall phosphate removal efficiencies of the filter during the pilot study. The average filter influent phosphate concentration was 0.13 mg/L, and the average filter effluent phosphate concentration was 0.06 mg/L. The average phosphate removal by the filter was 53.8%. This demonstrates that filtration using steel slag and steel chips media was also effective at phosphate removal. Therefore, recycled steel byproducts filtration media can be used to remove both bacteria and phosphate from stormwater.

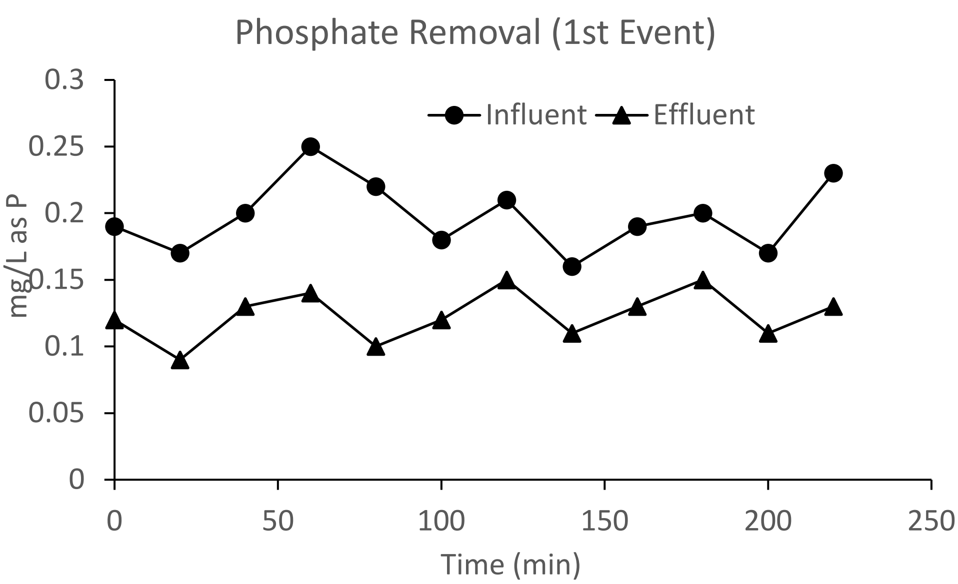

Figure 4.8 Phosphate removal (06/14/24)

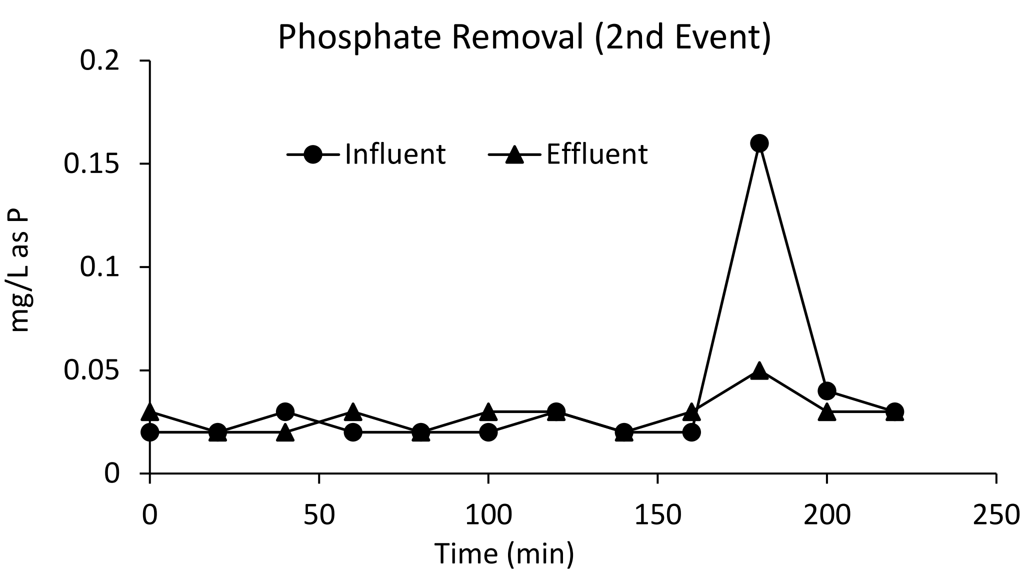

Figure 4.9 Phosphate removal (07/16/24)

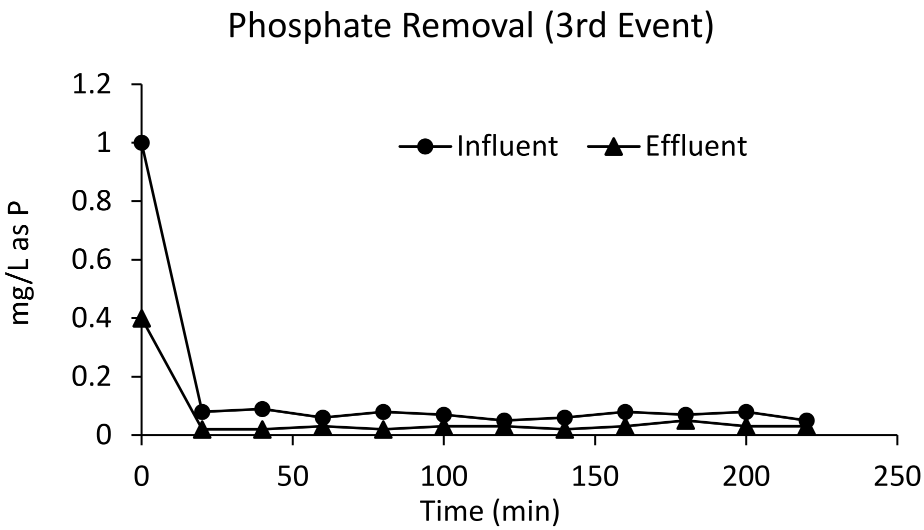

Figure 4.10 Phosphate removal (08/03/24)

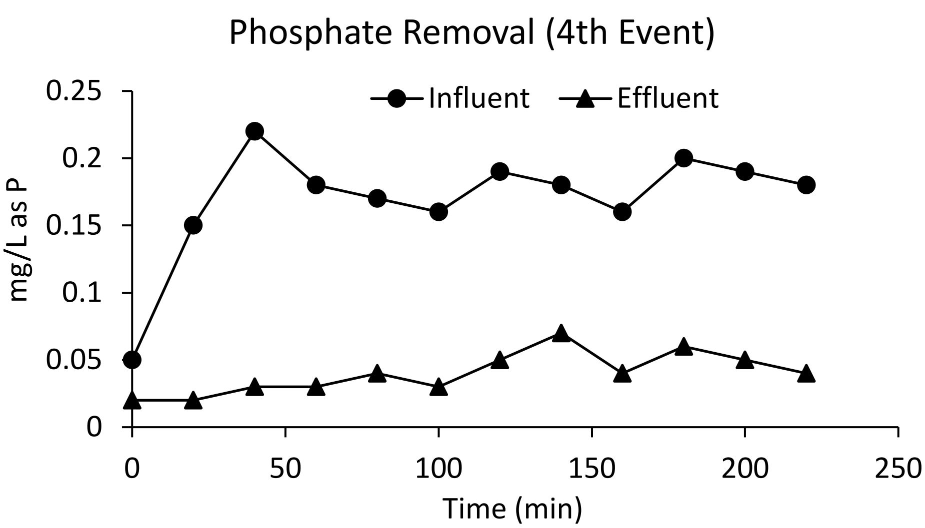

Figure 4.11 Phosphate removal (08/13/24)

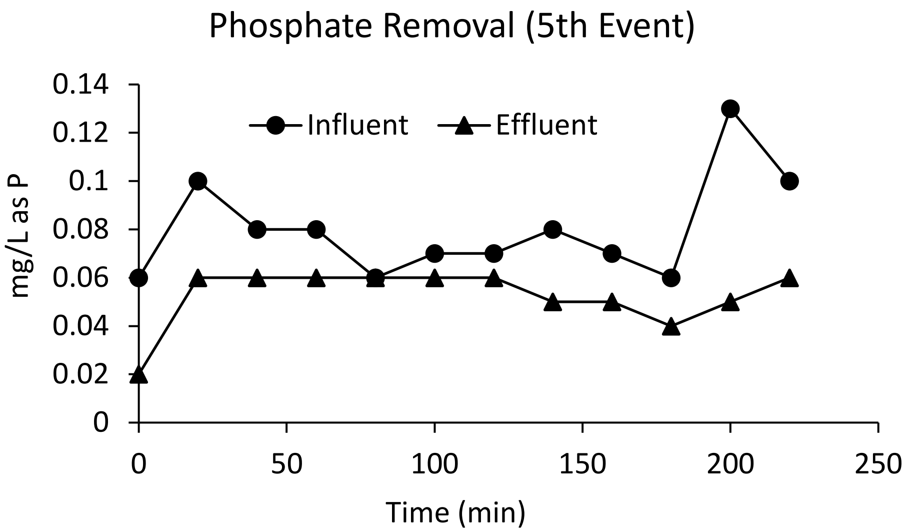

Figure 4.12 Phosphate removal (08/26/24)

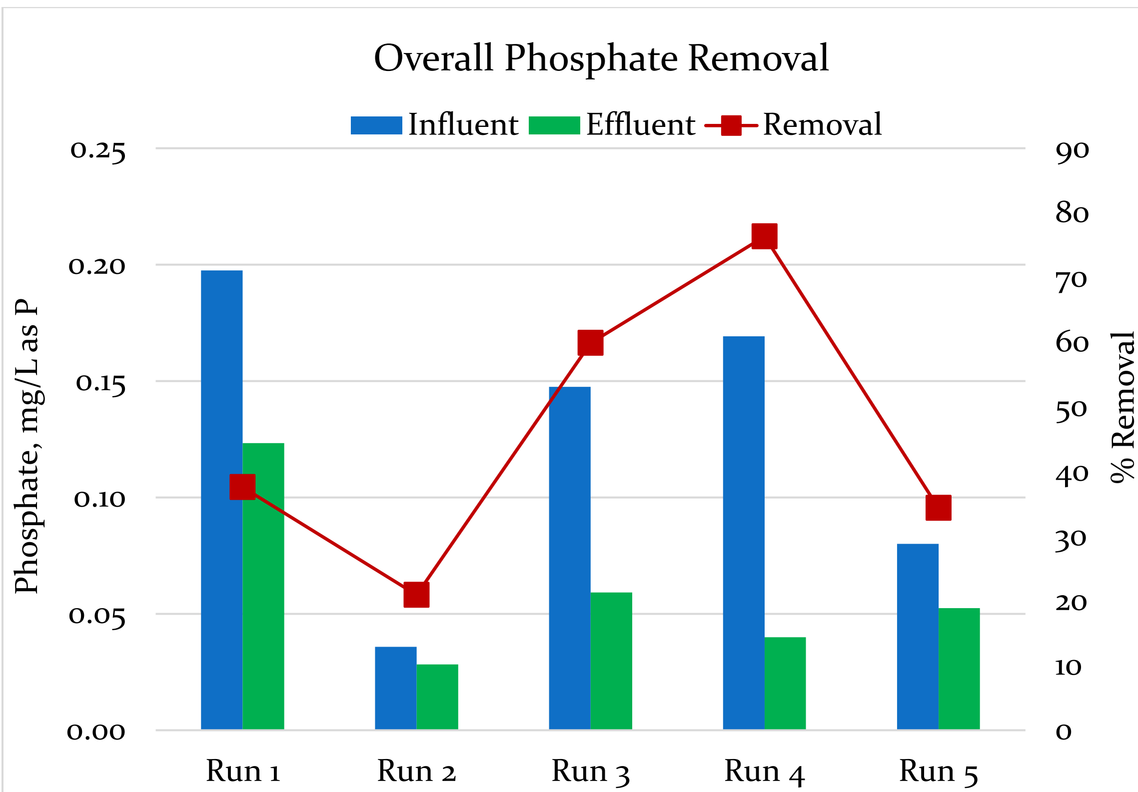

Figure 4.13 Overall phosphate filtration removal during the pilot study

4.4 Iron Leaching by the Filter

The filter media used for this study consisted of 70% of steel slag and 30% steel chips. The use of steel chips in the filter may lead to increased iron concentrations in the effluent. The iron concentrations in the influent and effluent of the filter were monitored during this pilot study. Figures 4.14 through 4.18 show the iron concentrations during the five sampling events. The influent iron concentration ranges were 0.13–0.21, 0.13–0.20, 0.03–0.06, 0.02–0.12, and 0.05–0.10 mg/L, respectively, for the five sampling events. The corresponding filter effluent phosphate concentration ranges were 0.18–0.24, 0.18–0.24, 0.06–0.10, 0.05–0.16, and 0.10–0.17 mg/L, respectively. These results suggest that the filter media released some iron during the filtration, which led to increases in iron concentration in the filter effluent. The average increases in iron concentrations were 0.04, 0.04, 0.04, 0.02, and 0.04 mg/L, respectively, for the five sampling events. Therefore, the increases in iron concentrations by the filter media were very small during the pilot study. All the filter influent and effluent iron concentrations were well below the EPA secondary drinking water standard of 0.3 mg/L.

Figure 4.19 shows the overall iron release by the filter during the pilot study. The average filter influent iron concentration was 0.11 mg/L, and the average filter effluent iron concentration was 0.14 mg/L. An average increase of 0.03 mg/L of iron concentration was observed after filtration. This demonstrates that filtration using steel slag and steel chips media did not cause significant increases in iron concentration under the conditions of this pilot study.

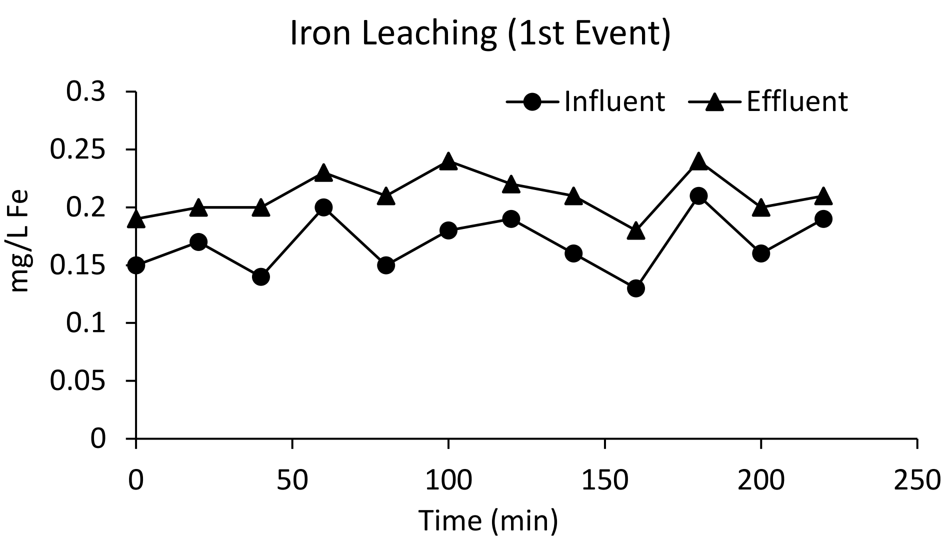

Figure 4.14 Iron release from the filter (06/14/24)

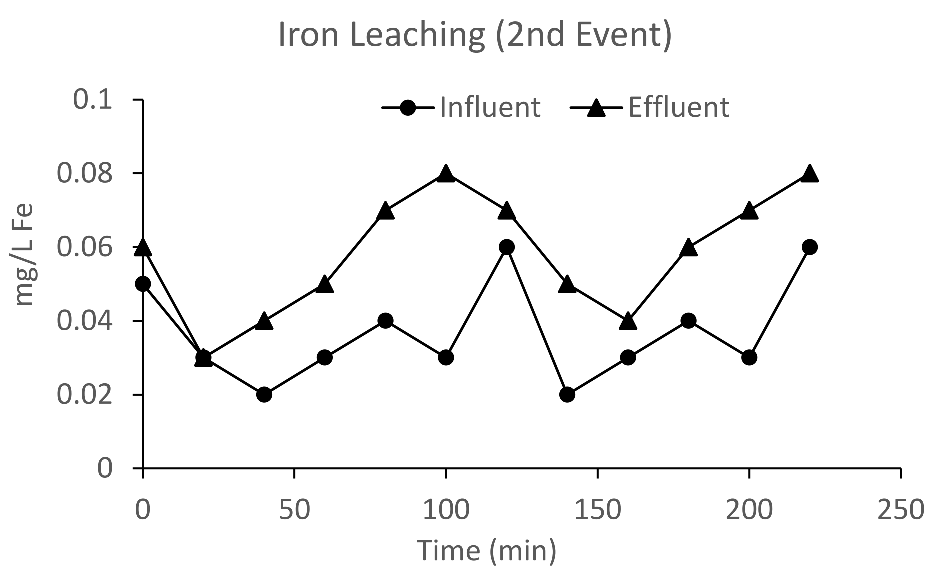

Figure 4.15 Iron release from the filter (07/16/24)

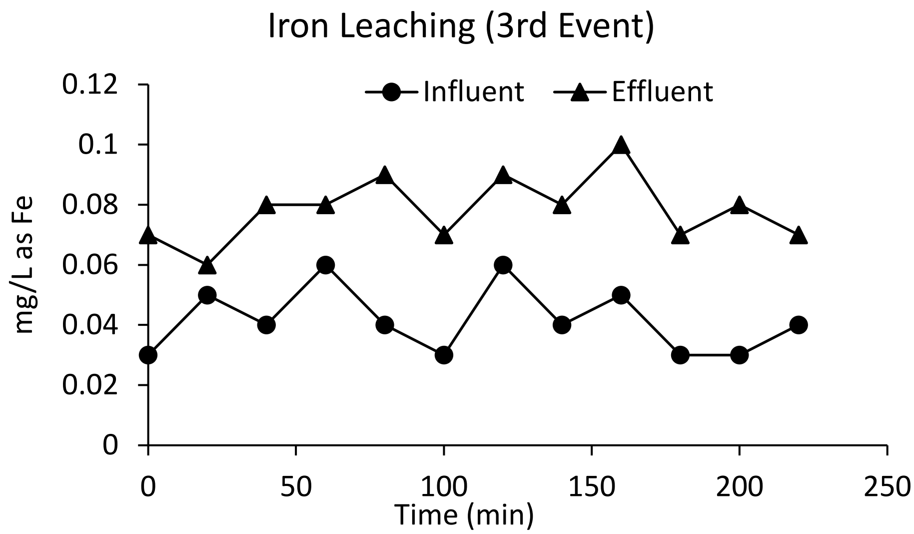

Figure 4.16 Iron release from the filter (08/03/24)

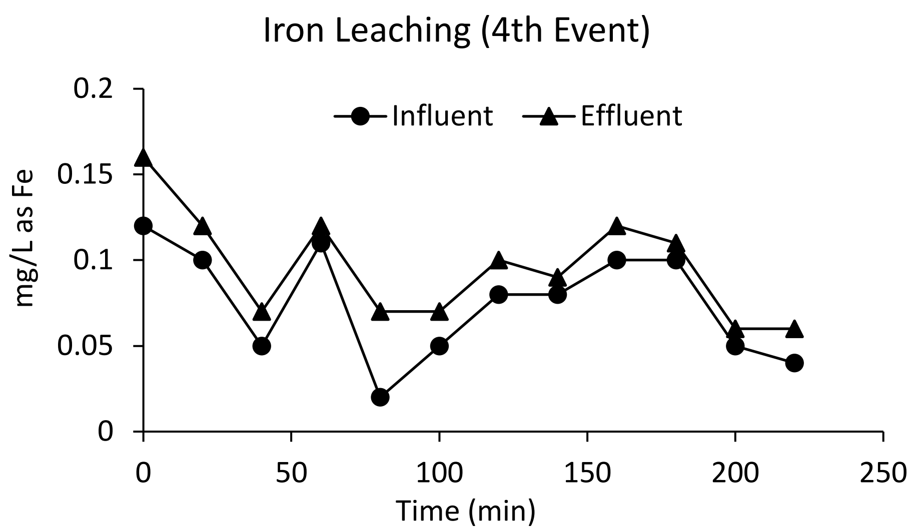

Figure 4.17 Iron release from the filter (08/13/24)

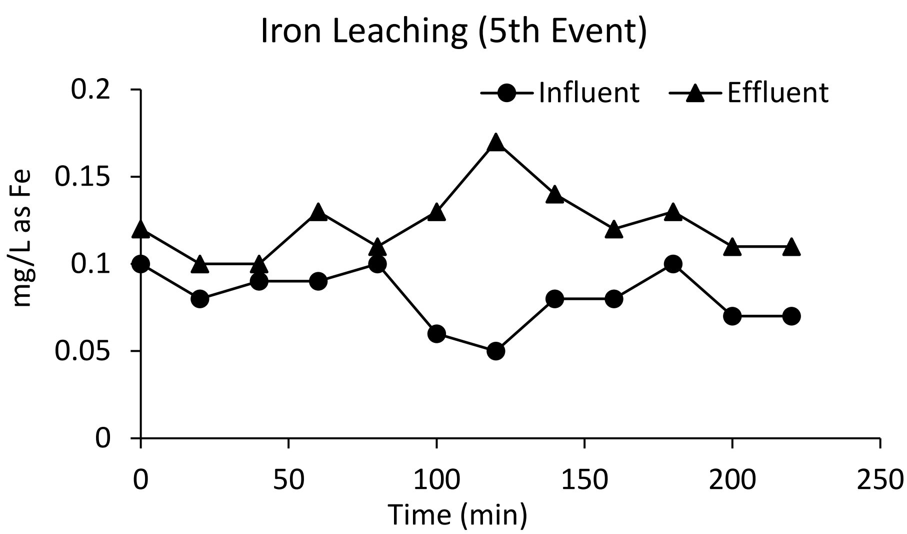

Figure 4.18 Iron release from the filter (08/26/24)

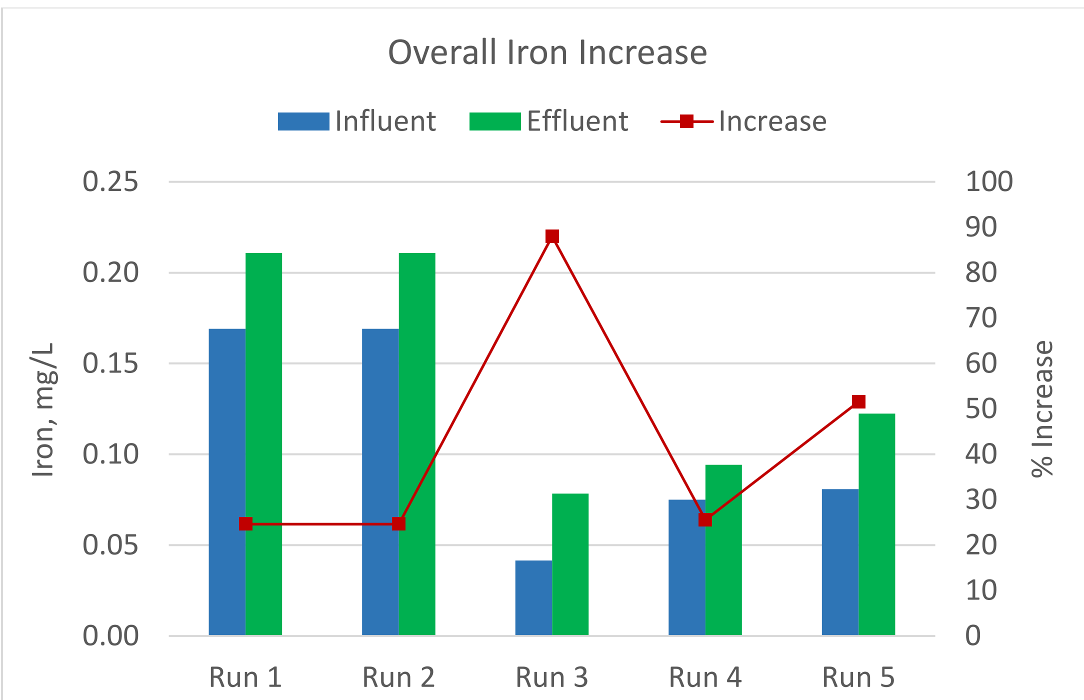

Figure 4.19 Overall iron release from the filter during the pilot study

5. CONLUSIONS AND RECOMMENDATIONS

The objective of this study was to design and construct a pilot scale filter structure in a stormwater site at Sioux Falls, SD, and evaluate the filter performance for E. coli and phosphate removal under real stormwater treatment conditions. The stormwater BMP site at 3103 S Sycamore Avenue was selected for this study. The City of Sioux Falls constructed the filter structure, which included two filtration sections with each section containing a filter media 20 ft long, 6 ft wide, and 1.5 ft high. The filter media consisted of 70% steel slag and 30% steel chips.

The SDSU project team conducted five sampling events to evaluate the filter performance; each event had 12 sampling points for both filter influent and effluent. The average flow rate of the five sampling events was 0.67 cfs, which is well above the design flow of 0.26 cfs. The filter average influent E. coli concentration was 1,120 MPN/100 mL, and the filter average effluent E. coli concentration was 625 MPN/100 mL. The pilot filter removed an average of 44.2% of the E. coli in the stormwater. The filter also demonstrated an effective removal capacity for phosphate. The average filter influent phosphate concentration was 0.13 mg/L, and the average filter effluent phosphate concentration was 0.06 mg/L. The pilot filter removed an average of 53.8% of the phosphate in the stormwater. An average increase of 0.03 mg/L of iron concentration was observed after filtration. All the filter influent and effluent iron concentrations were well below the EPA secondary drinking water standard of 0.3 mg/L.

In summary, the results of this pilot study demonstrate that filtration using steel slag and steel chips media is an effective technology for removing E. coli and phosphate under real stormwater treatment conditions. This technology can be used as a cost-effective BMP to control bacteria and phosphate contamination in urban stormwater systems. Full-scale applications of this filtration technology are recommended to reduce the E. coli and phosphate contamination from stormwater runoff and protect natural water resources. Regular filter media maintenance is also recommended if the filter is subject to particles and algae accumulation.

REFERENCES

Abunaser, S., Abdelhay, A. 2020. “Performance of a novel vertical flow constructed wetland for greywater treatment in rural areas in Jordan.” *Environmental Technology* 1–11.

Afrooz, A., Boehm, A., 2016. “Escherichia coli Removal in Biochar-Modified Biofilters: Effects of Biofilm.” *PLoS ONE* 11(12): e0167489.

Alston, J., Beddow, J., Pardey, P., 2009. “Agricultural research, productivity, and food prices in the long run.” *Science*. 325 (5945):1209-1210.

Baker, L., 1992. “Introduction to nonpoint source pollution in the United States and prospects for wetland use.” *Ecological Engineering* 1(2), 1-26.

Barakat, A., Hilali, A., Baghdadi, M. E., Touhami, F., 2019. “Assessment of shallow groundwater quality and its suitability for drinking purpose near the Béni-Mellal wastewater treatment lagoon (Morocco).” *Human and Ecological Risk Assessment: An International Journal*, 26(6), 1476–1495.

Brabec, E., Schulte, S., Richards, P., 2002. “Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning.” *Journal of Planning Literature*. 16(4), 499-514.

Carpenter, S., Caraco, N., Correll, D., Howarth, R., Sharpley, A., Smith, V., 1998. “Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen.” *Ecological Applications* 8(3), 559-568.

Conley, D., Paerl, H., Howarth, R., Boesch, D., Seitzinger, S., Havens, K., Lancelot, C., Likens, G., 2009. “Controlling eutrophication: nitrogen and phosphorus.” *Science*, 323, 1014-1015.

Dai, P., 2019. “Escherichia coli removal from stormwater using steel chips filter.” Master’s thesis, South Dakota State University.

Diao, M., Yao, M., 2009. “Use of Zero-Valent Iron Nanoparticles in Inactivating Microbes.” *Water Research* 43, 5243-5251.

Erickson, A., Gulliver, J., Weiss, P., 2012. “Capturing phosphates with iron enhanced sand filtration.” *Water Research* 46(9), 3032-3042.

Hajji, A., Lucas, K., 2024. “Anthropogenic stressors and the marine environment: From sources and impacts to solutions and mitigation.” *Marine Pollution Bulletin* 205, 116557.

Hooshyari, G., 2017. “Evaluating filter materials for E. coli removal from Stormwater.” Master’s thesis, South Dakota State University.

Jambeck, J., Geyer, R., Wilcox, C., Siegler, T., Perryman, M., Andrady, A., Narayan, R., Law K., 2015. “Plastic waste inputs from land into the ocean.” *Science* 347,768-771.

Jamieson, R., Gordon, R., Joy, D., Lee, H., 2004. “Assessing microbial pollution of rural surface waters: A review of current watershed scale modeling approaches.” *Agricultural Water Management* 70 (1), 1-17.

Karim, M., Glenn, E., Gerba, C., 2008. “The effect of wetland vegetation on the survival of Escherichia coli, Salmonella typhimurium, bacteriophage MS-2 and polio virus.” *Journal of Water and Health* 6(2), 167-75.

Keiser, D., Shapiro, J., 2019. “Consequences of the Clean Water Act and the Demand for Water Quality.” *The Quarterly Journal of Economics*, 134 (1), 349–396.

Kranner, B., Afrooz, A., Fitzgerald, N., Boehm, A., 2019. “Fecal indicator bacteria and virus removal in stormwater biofilters: Effects of biochar, media saturation, and field conditioning.” *PLoS ONE* 14(9): e0222719.

Krasner, S., Weinberg, H., Richardson, S., Pastor, S., Chinn, R., Sclimenti, M., Onstad, G., Thruston, A. Jr., 2006. “Occurrence of a new generation of disinfection byproducts.” *Environmental Science & Technology*. 40(23), 7175-85. doi: 10.1021/es060353j. PMID: 17180964.

Lamori, J., Xue, J., Rachmadi, A., Lopez, G., Kitajima, M., Pepper, I., Brooks, J., Sherchan, S., 2019. “Removal of fecal indicator bacteria and antibiotic resistant genes in constructed wetlands.” *Environmental Science and Pollution Research* 26, 10188–10197.

Li, J., Davis, A., 2016. “A unified look at phosphorus treatment using bioretention.” *Water Research* 90, 141-155.

Mascher, F., Mascher, W., Pichler-Semmelrock, F., Reinthaler, F., Zarfel G., Kittinger, C., 2017. “Impact of Combined Sewer Overflow on Wastewater Treatment and Microbiological Quality of Rivers for Recreation.” *Water* 9 (11), 906.

Mohanty, S., Cantrell, K., Nelson, K., Boehm, A., 2014. “Efficacy of biochar to remove Escherichia coli from stormwater under steady and intermittent flow.” *Water Research* 61, 288-296.

Mokomane, M., Kasvosve, I., de Melo, E., Pernica, J., Goldfarb, D., 2018. “The global problem of childhood diarrhoeal diseases: emerging strategies in prevention and management.” *Ther Adv Infect Dis.* 5(1), 29-43.

Mulligan, C., Yong, R., Gibbs, B., 2001. “Heavy metal removal from sediments by biosurfactants.” *Journal of Hazardous Materials* 85 (1-2), 111-125.

Neville, J., 2019. “Pilot Scale Evaluation of E. Coli Filtration Removal From Stormwater Using Recycled Steel.” Master’s thesis, South Dakota State University.

Olevson, B. 2021. “Long Term Evaluation of E. coli Removal from Stormwater Using Recycled Steel Byproducts.” Master’s thesis, South Dakota State University.

Park, S., Kim, S., 2009. “Adhesion of Escherichia coli to iron-coated sand in the presence of humic acid: a column experiment.” *Water Environ Res*. 81(2), 125-30.

Passos, R., Dias, D., von Sperling, M., 2020. “Simple mid-depth transverse baffles to improve bacterial disinfection in a shallow maturation pond – performance evaluation and CFD simulation.” *Environmental Technology* 43(10), 1437–1445.

Paul, M., Meyer, J., 2008. “Streams in the Urban Landscape.” *Annual Review of Ecology and Systematics*. 32(1), 207-231.

Pitt, R., Field, R., Lalor, M., Brown, M., 1995. “Urban stormwater toxic pollutants: assessment, sources, and treatability.” *Water Environment Research* 67(3) 260-275.

Prodanovic, V., Hatt, B., McCarthy, D., Zhang, K., Deletic, A., 2017. “Green walls for greywater reuse: Understanding the role of media on pollutant removal.” *Ecological Engineering* 102: 625-635.

Rambags, F., Tanner, C., Stott, R., Schipper, L., 2016. “Fecal Bacteria, Bacteriophage, and Nutrient Reductions in a Full-Scale Denitrifying Woodchip Bioreactor.” *Journal of Environmental Quality* 45(3), 847-854

Richardson, S., Plewa, M., Wagner, E., Schoeny, R., Demarini, D., 2007. “Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: a review and roadmap for research.” *Mutation Research/Reviews in Mutation Research*, 636(1-3), 178-242.

Rios, L., Moore, C., Jones, P., 2007. “Persistent Organic pollutants carried by synthetic polymers in the ocean environment.” *Marine Pollution Bulletin* 54(8), 1230-7.

Shirdashtzadeh, M., Chandrasena, G., Henry, R., McCarthy, D., 2017. “Plants that can kill; improving E. coli removal in stormwater treatment systems using Australian plants with antibacterial activity.” *Ecological Engineering* 107: 120-125.

Sondi, I., Salopek-Sondi, B., 2004. “Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for Gram-negative bacteria.” *Journal of Colloid and Interface Science*, 275(1),177-82.

Struck, S., Selvakumar, A., Borst, M. 2006. “Performance of stormwater retention ponds and constructed wetlands in reducing microbial concentrations.” U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Office of Research and Development. EPA/600/R-06/102.

Tafuri, A., Field, R., 2012. “Treatability aspects of urban stormwater stressors.” *Environ. Sci. Eng*. 6(5): 631–637.

UN DESA. 2018. “World urbanisation prospects.” UN Department of Economic and Social Affairs: Population Dynamics.

USEPA. 2000. “The History of Drinking Water Treatment,” EPA-816-F-00-006.

Volk, C., Bell, K., Ibrahim, E., Verges, D., Amy, G., LeChevallier, M., 2000. “Impact of enhanced and optimized coagulation on removal of organic matter and its biodegradable fraction in drinking water.” *Water Research* 34(12), 3247-3257.

Vymazal, J., 2011. “Constructed Wetlands for Wastewater Treatment: Five Decades of Experience.” *Environmental Science & Technology* 45(1), 61-69.

Wackernagel, M., Rees, W., 1998. *Our Ecological Footprint: Reducing Human Impact on the Earth (Vol. 9)*. Gabriola: New Society Publishers.

World Health Organization. 2021. E. Coli. https://www.who.int/news- room/factsheets/detail/e-coli.

Zurita, F., Carreón-Álvarez, A., 2015. “Performance of three pilotscale hybrid constructed wetlands for total coliforms and Escherichia coli removal from primary effluent – a 2-year study in a subtropical climate.” *Journal of Water and Health* 13(2), 446-458.