THESIS

WASTE TO RESOURCE - BENEFICIAL USE OF WATER TREATMENT RESIDUALS AS A STORMWATER CONTROL MEASURE AMENDMENT FOR PHOSPHORUS REMOVAL

Submitted by

Omar Shehab

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2020

Master's Committee:

Advisor: Neil Grigg

Sybil Sharvelle
Dana Hoag

ABSTRACT

WASTE TO RESOURCE - BENEFICIAL USE OF WATER TREATMENT RESIDUALS AS A STORMWATER CONTROL MEASURE AMENDMENT FOR PHOSPHORUS REMOVAL

The increase in nutrient pollution is an alarming issue, and innovative and cost-effective measures need to be taken. This study addressed two issues: removing dissolved phosphorus introduced through stormwater runoff using water treatment residuals (WTRs) and the economic value of diverting this waste material from landfills to be used as an amendment in stormwater best management practices for treating stormwater runoff.

The City of Fort Collins has monitored a bioretention rain garden located at a municipal facility for several years and has consistently seen a slight decrease and, at times, even an increase in the total mass of phosphorous in stormwater effluent leaving these facilities. The increase in mass was primarily due to higher dissolved phosphorous concentrations in the rain garden’s effluent. Based on prior research at Colorado State University, the use of water treatment residuals (WTRs) was selected for laboratory-scale analysis and field-scale evaluation. This research aimed to evaluate whether this waste material generated during drinking water treatment operations could be diverted from landfills and instead, used as an amendment in stormwater best management practices (BMPs) for treating stormwater runoff. Simultaneously, it is hoped that this waste product's beneficial use can result in a safe and significant reduction in dissolved phosphorous input into water bodies.

WTRs from the local water treatment plant were evaluated and found to have a very high adsorptive capacity for phosphorus with a phosphorus sorption capacity (PSC) of 21.56 lbs.

dissolved phosphorus per ton WTRs, making it a strong candidate as an amendment to current BMPs. A column test was conducted to demonstrate a proof of concept for how WTRs can reduce phosphorus loads leaving BMPs. Column tests revealed that exposure time and application location (top, mixed, or bottom) of WTRs within the BMP media were the critical factors of phosphorus removal. A study was also conducted to determine how much phosphorus load could be reduced if WTRs were applied to BMPs throughout Fort Collins. The citywide analysis displayed a significant reduction, if not an elimination, of the need to send this current waste product to local landfill facilities, thereby reducing disposal costs and increasing the useful life of local landfill operations.

The current operation by the City of Fort Collins disposes WTRs into the county's landfill. This study estimated the cost of current operations, the cost of using WTRs in stormwater BMPs, and an additional potential scenario in where the landfill was moved twice as far. Transportation, tipping/application, and staff time were the main cost components and were estimated for the different scenarios. It was found that using WTRs as an amendment in stormwater BMPs would save the City around $5,000 annually compared to the current operation and $13,000 compared to the disposing of WTRs to the new landfill. The outcome of such an approach was shown to be not only economical, but it also provided environmental and social benefits as it would reduce dissolved phosphorus significantly from stormwater runoff, which results in improved water quality and elimination of a current product.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to Dr. Neil Grigg for his guidance and continuous support that he has provided me throughout the past two years. I would also like to thank Dr. Mazdak Arabi for his help and assistance. Additionally, I would like to thank Dr. Sybil Sharvelle and Dr. Dana Hoag for their guidance throughout this project.

I cannot begin to express my thanks to Tyler Dell for his mentorship and insight; this project would not have been possible without his support and nurturing. Also, I would like to thank C.J. Sheiman and the Colorado Stormwater Center research group. And a special thanks to my family and friends for their support and encouragement throughout the past two years. And finally, I would like to show my ultimate gratitude to Silvia Guerra, she kept me going on, and this work would not have been possible without her support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Chapter 1: Introduction

Urban stormwater contributions to nutrient pollution are increasing with urban development, and the costs of traditional treatment methods push researchers towards exploring efficient and cost-effective measures to deal with this issue. This research aims to evaluate whether water treatment residuals (WTRs) can be diverted from landfills and instead, used as an amendment in best management practices (BMPs) for phosphorus removal from stormwater runoff. The study is based on WTRs and BMPs data from Fort Collins, Colorado. Simultaneously, it is hoped that WTRs' beneficial use could result in a safe, significant, and cost-effective reduction in phosphorous input into water bodies, wherever this occurs.

1.1 Study Objectives

Objectives of the study are:

- Identify the amount of phosphorus introduced through stormwater runoff in Fort Collins.
- Calculate how much phosphorus can be removed by WTRs produced by the treatment plant of Fort Collins.
- Estimate the minimum and the ideal amounts of WTRs needed to remove the phosphorus introduced to the stormwater system in Fort Collins.
- Estimate the cost of using Al-WTRs as an amendment in stormwater BMPs in Fort Collins for phosphorus removal.

1.2 Background

The environmental cost of increased urban development is evident in various fields, one of which is stormwater. The increase in the amount of impervious land covers and the climatic profile changes have all led to drastic alterations to the stormwater runoff characteristics (Walsh et al., 2005). Alterations of runoff characteristics include increased volumes and peak flow rates of stormwater runoff, frequency and intensity of rain events that disturb the ecosystems around it (Booth, 2005), and the elevated levels of different polluting nutrients concentrations in runoff effluents (Dietz & Clausen, 2008; Hatt et al., 2004; Pyke et al., 2011). Post-development runoff values increased by more than 100 percent than pre-development for 2-year storm events (**Figure 1**). In addition, stormwater events with the expected occurrence of 25 years in the pre-development stage are expected to happen at twice the frequency in the post-development stage (Booth & Jackson, 1997; X. Wang et al., 2010)

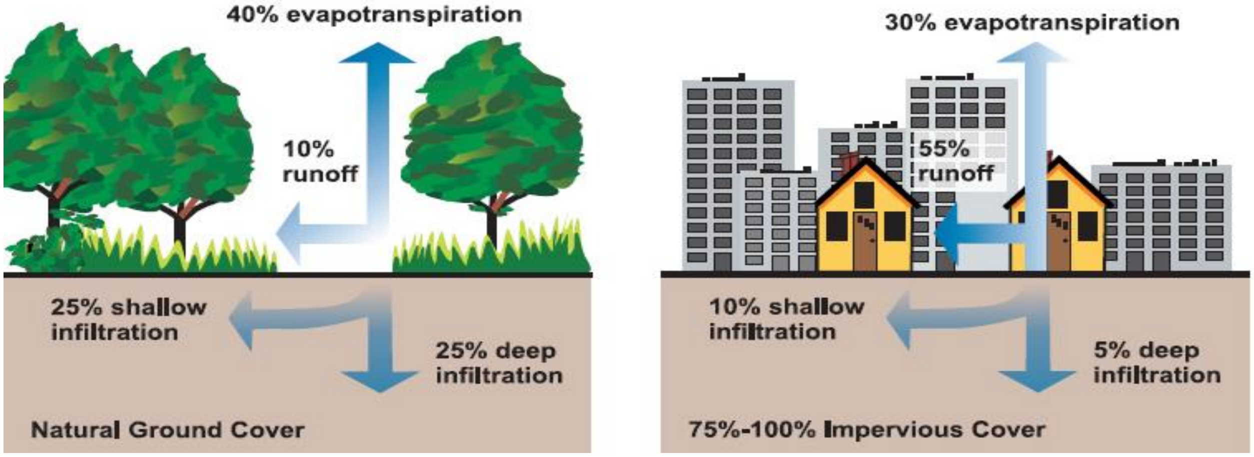

Figure 1: Example of Pre and Post Development Effects on Stormwater

Increased impervious land cover also means that runoff will flow across longer routes until it reaches its outfall, and most of these routes are on hard surfaces with minimal contact with soil and vegetation. The minimal contact leads to less interaction with any filtering media, which means that it will be carrying more pollutants like heavy metals, organic matter, and dissolved nutrients. Those pollutants will be discharged directly into lakes, streams, and rivers. In the United States, more than 10,000 water bodies were severely damaged because of excess nutrients (Shapiro, 2013). Because of phosphorus and nitrogen, 46% of river and stream miles are in poor biological condition (USEPA, 2017).

Among those pollutants, phosphorus and nitrogen are of most concern to researchers and scientists. Nutrients essential in vital processes and food production for humans and aquatic ecosystems (Smil, 2000). However, high levels of these nutrients in water bodies can lead to numerous issues like eutrophication, acidification, water quality degradation, drinking water pollution, and intrusion to the balance of ecosystems (Hsieh et al., 2007; Oliver et al., 2011). Eutrophication can be defined as the extreme growth of algae and plants in water bodies due to excessive levels of nutrients, and it can lead to blooms of cyanobacteria, drinking water pollution, and deterioration of water bodies used for recreation (Chislock et al., 2013). In the United States, damage caused by eutrophication is estimated to cost more than $2 billion annually (Carpenter et al., 1998; Dodds et al., 2009; Schindler, 2006). The decomposition of the excess organic matter resulting from eutrophication lowers oxygen levels and produces large amounts of carbon dioxide, decreasing the pH levels in water bodies, which is known as acidification (Cai et al., 2011; Wallace et al., 2014).

Many sources have been identified for excess nutrient disposal in water bodies, and they include atmospheric deposition, agriculture and irrigation, wastewater treatment plants, and stormwater runoff (USEPA 2020). Although contributions from atmospheric deposition and agriculture are larger than other sources, contributions from wastewater and stormwater are concerning and cannot be ignored (Badruzzaman et al., 2012; Puckett, 1995). It is crucial to study each source to be able to solve the problem of excess nutrients correctly and in a cost-effective manner. This study will focus on stormwater as a source and the urban stormwater practices as mechanisms of phosphorus removal.

1.3 Regulation

Stormwater has always been identified as a significant contributor to water pollution. However, the first serious step to tackle this issue by federal regulation started to take place in 1972 by expanding the Clean Water Act (CWA), which is implemented by the U.S. Environmental Protection Agency (EPA). CWA was aimed then at industrial and municipal discharges, with a long-term purpose to eradicate the disposal of pollutants in water bodies by 1985. That goal was not achieved due to the late arrival of the regulation, which by that time was hard to implement in already developed cities. In 1987, Section 402(p) was introduced to CWA by the congress directing the EPA to include stormwater under the National Pollutant Discharge Elimination System (NPDES), a program that was controlling the discharges from industrial and municipal sources. The EPA implemented Section 402(p) through two phases; Phase I in 1990 and Phase II in 1999, in which NPDES permits were required for municipal separate storm sewer systems (MS4s). According to the EPA regulations, permittees are required to present a stormwater management plan that shows the control measures used to prevent stormwater from polluting neighboring water bodies. Those control measures are referred to as Stormwater Control Measures (SCM), Best Management Practices (BMP), or Low Impact Development (LID). Those terms are used to describe similar concepts in different parts of the world inspired by local cultures or political contexts of those regions (Fletcher et al., 2015). The term of choice in this study will be Best Management Practices (BMP).

1.4 Best Management Practices (BMPs)

Best Management Practices (BMPs) is a term used to describe natural-based technologies employed near the source to restore the pre-development hydrologic conditions in the post-development phase while reducing the amounts of pollutants discharged in receiving water bodies through different techniques including infiltration and detention (De Paola et al., 2018; Joksimovic & Alam, 2014). The primary function of stormwater management in the 1970s and 1980s was to reduce flooding and mitigate its damages; however, that purpose was expanded to include pollutant removal during the 1990s (Fletcher et al., 2015; Prince George's County, 1999). Conventional stormwater drainage systems aim to collect water and convey it to a discharge point, provide low to zero treatment, and require high capital and operating cost. Meanwhile, BMPs collect water near the source, decrease pollutant loading, and are cheaper and more flexible to construct than conventional stormwater systems (USEPA, 2009). BMPs have proved to reduce peak flows, control runoff volume effectively, and reduce pollutant loading in stormwater, while typically costing considerably less than conventional stormwater treatment practices (Bedan & Clausen, 2009; Dietz & Clausen, 2008; Houle et al., 2013).

The bioretention cell (or rain garden) is an infiltration-based technology that reduces peak flow effectively and improves water quality; and is the most implemented BMP in the United States (A. P. Davis et al., 2009). The design of a bioretention cell generally consists of permeable soil and a source of organic matter to maximize infiltration, adsorption, and plant growth and usually is topped with a layer of mulch (Roy-Poirier et al., 2010). Sand is a crucial component in bioretention media because of its role in ensuring high hydraulic conductivity, which corresponds to high infiltration rates (Hsieh & Davis, 2005; Palmer et al., 2013). Topsoil, clays, and other types of finer particulates are also necessary to detain water and nutrients which are used to promote vegetation (UDFCD, 2010). Organic matter sources like compost are commonly used to improve soil quality, increase water infiltration, and promote vegetation (Iqbal et al., 2015; Prince George's County, 2007). Vegetation is essential as it detains runoff, decreases erosion, promotes evapotranspiration and biological activity, preserves porosity, absorbs pollutants, enhances air quality, and improves the bioretention cell aesthetics (A. Davis, 2008; Muerdter et al., 2018).

Figure 2: Example of a Rain Garden.

Bioretention systems have been studied extensively over the past 20 years for their performance in runoff reduction and pollutant removal. A study by (Hunt et al., 2006) of three different bioretention sites found that significant runoff volume reduction achieved 40% removal of total nitrogen, 98%, 99%, and 81% for zinc, copper, and lead, respectively. Jiang et al. (2017) investigated the performance of bioretention from 2014 to 2017 and found that anti-seepage rain gardens can retain inflow volumes by 54.1% and remove pollutants by 54.3% on average with an estimated annual pollutant removal of 75.5%. Shrestha et al. (2018) evaluated eight bioretention cells under various treatments and found significant average reductions of runoff volumes of 91%. They also found that TSS concentrations were considerably reduced by 94% on average irrespective of treatments, storm characteristics, and seasonality. F. Yang et al. (2020) found that bioretention was able to achieve removal rates of 86% for COD, 71.8% for total nitrogen, and 68% for total phosphorus.

Bioretention filter media efficiency in runoff volume reduction and pollutant removal comes with a major concern, nutrient leaching. The use of compost in bioretention is beneficial for its role in promoting vegetation by providing organic matter and increasing the availability of essential nutrients such as phosphorus and nitrogen (Hurley et al., 2017). However, the availability of phosphorus and nitrogen in compost can lead to these nutrients being leached in bioretention effluents (Mullane et al., 2015). Djodjic et al. (2004) found that when sand is mixed with compost, it leads to a significant increase in leaching due to nutrients bypassing sorption capacity, especially during large rain events. Brown et al. (2015) found that compost mixed with soil was a source of dissolved phosphorus when Phosphorus Saturation Index (PSI) was above 0.1.

Because of the biochemical and physicochemical processes needed to remove dissolved nutrients, special arrangements of soil media and retention times have to be considered (Shrestha et al., 2018). To address that, additives or alternative materials have been researched to fix nutrient leaching and improve the function of bioretention systems, including mulch and other natural materials, water treatment residuals, and biochar. The role of these additives is enhancing vegetation growth, increasing water infiltration, and decrease pollutants loading, with some additives targeting specific pollutants than others. This study will focus on phosphorus and the additives that accomplish this process efficiently.

Saeed & Sun (2011) used organic wood mulch and gravel in vertical flow and horizontal flow wetland reactors, while the removal rate of phosphorus by wood mulch in the vertical flow reactor reached 60.3%, gravel alone was better in horizontal flow as wood mulch resulted in net increases in phosphorus. (Peterson et al., 2015) studied the effects of using different sizes of woodchips as an organic carbon source, the results showed leaching of total phosphorus with the leaching decreases when the size of the woodchips increases. (Paus et al., 2014) evaluated the effects of compost under different volume fractions, they found that increasing the volume fractions of compost leads to reduced hydraulic conductivity and a net increase in phosphorus, although heavy metals removal was efficient. Hunt et al. (2006) found that high P-index media can result in a 240% increase of total phosphorus, while low P-index media can decrease phosphorus by 65%. The results from these studies and others show that while general pollutant removal and heavy metals reduction could be achieved successfully, phosphorus removal using natural materials still varies significantly and should not be applied on a wide scale. They also indicate the need for other types of additives that would guarantee more stable results in the long term.

1.5 Water Treatment Residuals (WTRs)

WTRs have been the main focus of many researchers over the past decade for their excellent ability in removing phosphorus. Numerous studies found that because of WTRs strong affinity for dissolved phosphorus, WTRs achieved consistently high removal rates even for long periods (Dayton & Basta, 2005; Ippolito, 2015; Makris et al., 2004; Mortula & Gagnon, 2006; Soleimanifar et al., 2016; Zohar et al., 2017). WTRs are by-products of the coagulation and flocculation processes of water treatment (O'Kelly, 2008). Aluminum sulfate [$Al_2(SO_4)_3 \bullet 14H_2O$] and ferric chloride $FeCl_3$ are commonly applied as coagulants in the drinking water treatment process, which leads to WTRs to become rich in Al and Fe oxyhydroxides that have a strong affinity for anionic species (Ippolito et al., 2011). The dominant mechanism of phosphorus sorption in WTRs is via ligand exchange in which the phosphate anion forms a covalent bond with the metallic cation at the sorbent surface; this process happens through a fast reaction phase (Loganathan et al., 2014; Makris et al., 2004; Y. Yang et al., 2006).

WTRs performance in phosphorus removal is proved to be very good by many studies. Removal rates varied between different publications based on different conditions explained later, but the quality that has been consistent among most research is the ability of WTRs to prevent leaching. Mortula & Gagnon (2006) studied the use of alum-based WTRs (Al-WTR) in aquaculture; phosphorus's removal rate was found to be 94-99%. Leaching was minimal and was identified non-toxic to aquatic life in addition to effective organic matter removal. Zhao et al. (2007) investigated the long-term efficiency of Al-WTR in a reed bed wastewater treatment for 193 days and found a stable performance of pollutant reduction. In the first 140 days, Al-WTRs were able to achieve removal rates of 90.5% for phosphorus, 68.5% for BOD_5, 67.1% for COD, and 98.5% for suspended solids. After 140 days, removal rates were 91.8% for phosphorus, 77.7% for BOD_5, 82.1% for COD, and 92.8% for S.S., noting that leaching of Al was negligible. Bayley et al. (2008) studied the co-application of WTR with biosolids for 13 years with an initial application in 1991 and a re-application in 2003, and they found that the WTRs were stable and provided a significant phosphorus sink. Bai et al. (2014) evaluated the performance of five different types of WTR, where ferric chloride, polymeric aluminum, and calcium hydrogen carbonate were used in the treatment process. Phosphorus removal rates ranged between 74-99%, where Al and Fe based WTR found to achieve better adsorption and insignificant desorption. In addition to phosphorus, WTRs have also been found to remove other pollutants. Bai et al. (2014), Ippolito et al. (2011), and Zhao et al. (2007) found that WTRs can effectively remove BOD_5, COD, S.S., nitrogen, arsenic, and selenium with stable performance.

Some factors have been observed to affect the performance of WTRs, including pH levels and particle size. WTRs adsorption was found to be optimal at low pH levels (Babatunde et al., 2009; Castaldi et al., 2014; Razali et al., 2007). Particle size of WTR has also been found to affect adsorption; C. Wang et al. (2011) observed a range of sizes and found that particles with 0.6-0.9mm achieved maximum phosphorus removal. Lee et al. (2015) also evaluated the use of different particle sizes found that phosphorus removal was better with the use of smaller particles, as the optimal performance was with particles with sizes less than 1.18mm. There is also some concern about using WTR, which includes its effects on vegetation, performance under anaerobic conditions, and the release of heavy metals. Banet et al. (2020) assessed the use of WTR as a source of plant-available P and found that WTR did not affect soil organic P. Oladeji et al. (2007) found that an application rate of 10-15 g WTR/kg soil is ideal as it leads for the soil phosphorus storage capacity to be zero which is better for plant growth. Oliver et al. (2011) evaluated WTRs capacity to retain phosphorus under anaerobic conditions and found that the phosphorus retention rate was >98% regardless of aerobic or anaerobic conditions. Ippolito et al. (2011) and Mortula & Gagnon (2006) have found negligible release of heavy metals that were deemed safe for aquatic life.

Given the excellent potential for WTRs in dissolved phosphorus removal, this study investigated the efficiency of using this material as an amendment of stormwater BMPs on a city-wide in Fort Collins, Colorado. The goals were achieved by estimating the dissolved phosphorus loads introduced through stormwater runoff using the Simple Method, estimating the dissolved phosphorus loads that could be removed by WTRs, and calculating the amount of WTRs needed for an efficient, safe, and long-term reduction of dissolved phosphorus in stormwater BMPs. This study also investigated the cost of switching the disposing of WTRs from landfills to stormwater BMPs throughout the city of Fort Collins.

2.0 Chapter 2: Hydrologic Efficiency Assessment of Al-WTRs in Stormwater BMPs for Phosphorus Removal

2.1 Introduction

The purpose of this chapter was to quantify the amounts of phosphorus introduced to the system in Fort Collins, Colorado. It also aims to assess the performance and quantity required of water treatment residuals (WTRs) as an amendment in stormwater best management practices (BMPs) for phosphorus removal from stormwater runoff.

2.1.1 Objectives

Objectives of the chapter are:

- Identify the amount of dissolved phosphorus introduced through stormwater runoff in Fort Collins.
- Calculate how much dissolved phosphorus can be removed by WTRs produced by the treatment plant of Fort Collins.
- Estimate the amount of WTRs needed to remove the dissolved phosphorus introduced through the stormwater system in Fort Collins.

2.1.2 Background

Nutrient pollution in the stormwater system is one of many environmental issues caused by urban development. It comes as a result of the extreme changes of the stormwater runoff characteristics such as increased volumes and peak rates, frequency and intensity of storm events, done by changes in climate profile and increased impervious cover (Booth, 2005; Dietz & Clausen, 2008; Hatt et al., 2004; Pyke et al., 2011; Walsh et al., 2005). The decrease in pre-developed open spaces has led to an increase in pollutants carried by urban stormwater runoffs like heavy metals, organic matter, and dissolved nutrients, and those pollutants will be discharged directly into lakes, streams, and rivers.

Excess nutrients have led to damaging more than 10,000 water bodies and deteriorating the biological condition in 46% of river and stream miles in the United States. High concentrations of phosphorus along with nitrogen resulted in several environmental issues like eutrophication, acidification, water quality degradation, drinking water pollution, and intrusion to the balance of ecosystems. Damages done by eutrophication is estimated to cost over $2 billion annually in the United States (Carpenter et al., 1998; Dodds et al., 2009; Hsieh et al., 2007; Oliver et al., 2011; Schindler, 2006; Shapiro, 2013; USEPA, 2017).

Many sources have been identified for excess nutrient disposal in water bodies, and they include atmospheric deposition, agriculture and irrigation, wastewater treatment plants, and stormwater runoff (USEPA 2020). Although contributions from atmospheric deposition and agriculture are larger than other sources, contributions from wastewater and stormwater are concerning and cannot be ignored (Badruzzaman et al., 2012; Puckett, 1995). This chapter will focus on the contributions of the urban stormwater system.

The 1972 expansion of the Clean Water Act (CWA), which was implemented by the U.S. Environmental Protection Agency (EPA), to eliminate the disposal of pollutants in water bodies by 1985 was the first step to identify nutrient pollution in water bodies, but it failed to achieve its goal. After that, Section 402(p) was introduced to CWA in 1987 by the congress directing the EPA to include stormwater under the National Pollutant Discharge Elimination System (NPDES), a program that was controlling the discharges from industrial and municipal sources. The EPA implemented Section 402(p) through two phases; Phase I in 1990 and Phase II in 1999, in which NPDES permits were required for municipal separate storm sewer systems (MS4s).

According to the EPA regulations, permittees are required to present a stormwater management plan that shows the control measures used to prevent stormwater from polluting neighboring water bodies. Those control measures are referred to as Stormwater Control Measures (SCM), Best Management Practices (BMP), or Low Impact Development (LID) (Fletcher et al., 2015); however, the term of choice in this chapter will be Best Management Practices (BMPs).

In Colorado, nutrient pollution was brought to the forefront by the approval of Regulation 85 in 2012, in which a maximum threshold was set for phosphorus and nitrogen concentrations in point source discharges such as wastewater treatment plants. The regulation, which has an enforcement date of 2027, allows for water quality trading between point sources and nonpoint sources. Voluntary actions were recommended for limiting excess nutrient discharges from nonpoint sources, with potential regulations that might take place if deemed necessary. (BMPs) were encouraged for nonpoint sources to reduce excess phosphorus and nitrogen discharges in receiving water bodies.

BMPs is a term used to describe natural-based technologies employed near the source to restore the pre-development hydrologic conditions in the post-development phase while reducing the amounts of pollutants discharged in receiving water bodies through different techniques including infiltration and detention (De Paola et al., 2018; Joksimovic & Alam, 2014). BMPs are cost-effective and efficient technologies that mimic pre-development characteristics of urban stormwater runoff (Bedan & Clausen, 2009; Dietz & Clausen, 2008; Houle et al., 2013). One BMP type is the bioretention cell (or rain garden) is one of the most implemented BMPs in the United States (A. P. Davis et al., 2009).

The primary tool used in a bioretention cell design is the filter media, which consists of sand for hydraulic conductivity, topsoil for water and nutrient detention, and compost as an organic matter source to promote vegetation (Hsieh & Davis, 2005; Iqbal et al., 2015; Palmer et al., 2013; UDFCD, 2010). Bioretention systems have proved to be effective in removing heavy metals, nutrients, COD, BOD, and total suspended solids (Hunt et al., 2006; Jiang et al., 2017; Shrestha et al., 2018; F. Yang et al., 2020). However, using compost leads to nutrient leaching due to nutrient availability like phosphorus and nitrogen in compost. To address the issue with compost, additives or alternative materials have been researched to reduce nutrient leaching and improve the function of bioretention systems, including mulch and other natural materials, water treatment residuals, and biochar (de Rozari et al., 2016; Hunt et al., 2006; Paus et al., 2014; Reddy et al., 2014). Additives enhance vegetation growth, increase water infiltration, and decrease pollutants loading with some additives targeting specific pollutants. This study will focus on phosphorus removal using water treatment residuals (WTRs).

WTRs are among the most promising materials to be used as an amendment in BMPs for phosphorus removal, as research has found that they have an excellent ability to adsorb phosphorus. WTRs are by-products of the coagulation and flocculation processes of water treatment, in which Aluminum sulfate $[Al_2(SO_4)_3 \cdot 14H_2O]$ and ferric chloride $FeCl_3$ are commonly applied as coagulants in the drinking water treatment process. The result is that WTRs are rich in Al and Fe oxyhydroxides that have a strong affinity for anionic species (Ippolito et al., 2011; O'Kelly, 2008). Along with the ability for WTRs to remove phosphorus, they also retain that phosphorus without any leaching even at the full saturation point (Dayton & Basta, 2005; Ippolito, 2015; Makris et al., 2004; Mortula & Gagnon, 2006; Soleimanifar et al., 2016; Zohar et al., 2017).

WTRs have been found to perform better at low pH levels and when smaller particle sizes are used (Babatunde et al., 2009; Castaldi et al., 2014; Lee et al., 2015; Razali et al., 2007;

C. Wang et al., 2011). Some of the concerns of using WTRs are their effects on vegetation, performance under anaerobic conditions, and the release of heavy metals. Nevertheless, most of these concerns were determined to be minimal. Banet et al. (2020) found that WTRs did not affect soil organic phosphorus concentrations, while Oladeji et al. (2007) found the application of 10-15 g WTRs/kg soil had led for the soil phosphorus storage capacity to be zero, which is efficient for plant growth due to increased phosphorus availability for vegetation. Also, it has been found that WTRs performance was consistent in aerobic and anaerobic conditions, while the release of the heavy metal was negligible and deemed safe (Ippolito et al., 2011; Mortula & Gagnon, 2006; Oliver et al., 2011).

Given the potential for removing dissolved phosphorus by WTRs, this study investigated the efficiency of using this material as an amendment of stormwater BMPs on a city-wide scale in Fort Collins, Colorado. The primary objectives of the study included estimating the dissolved phosphorus loads introduced through stormwater runoff using the Simple Method, estimating the dissolved phosphorus loads that could be removed by WTRs, and calculating the amount of WTRs needed for an efficient, safe, and long-term reduction of dissolved phosphorus in stormwater BMPs.

2.2 Methodology

The goal of this section was to describe the methodology used to assess dissolved phosphorus removal capabilities of WTRs when applied to stormwater BMPs across the city of Fort Collins. This was done by first calculating the amount of phosphorus load available in stormwater runoff and then evaluating how that load could be reduced using WTRs. After that, the minimum and ideal amounts of WTRs were calculated to ensure efficient removal of dissolved phosphorus.

2.2.1 The Simple Method

The Simple Method was used to estimate dissolved phosphorus loads by estimating the runoff volume of an area and then multiplying it by the pollutant concentrations. The Simple Method is often used for relatively small sites, which ideally is less than a square mile (Schueler, 1987). In comparison between the Simple Method and complex computerized models, estimation of pollutant loads on an annual basis yielded similar results with less margin of error, which means that the Simple Method is better used for annual loads estimation than event-based estimation (Chandler, 1994). In addition, the number of parameters required to use the Simple Method is low and delivers precise estimates sufficient for decision-making at the planning level (Houlahan et al., 1992) (Schueler, 1987). The Simple Method is shown in **Equation 1** below,

$$\mathrm{L} = \mathrm{P} * \mathrm{Pr} * \mathrm{Rv} * \mathrm{A} * \mathrm{C} * 0.226 \qquad \textbf{Equation 1}$$

Where:

L: Estimated pollutant export (lbs.)

P: Rainfall precipitation depth (inches)

Pr: Factor for storms that produce no runoff

Rv: Runoff coefficient, the fraction of rainfall that converts to runoff

C: Mean concentration of pollutant (mg/l)

A: Drainage Area (acres)

The Simple Method was used to estimate the annual phosphorus loads in the City of Fort Collins for the period between 2007 and 2019. Precipitation data were collected on an hourly basis and were obtained from the weather station at the Department of Atmospheric Science at Colorado State University in Fort Collins, and shown in **Table 2-1**. The data were evaluated to filter events that did not meet the minimum threshold of Water Quality Capture Volume (WQCV), in which storm events with depths less than 0.1 inches were disregarded because these events do not develop runoff. Small rain events that do not produce runoff account for more than 60% of total annual rain events on average in the Denver Area, as seen in **Table 2-2** (UDFCD, 2010).

Table 2-1: Number of Significant Rain Events and Total Precipitation Depths between 2007 and 2019

Year	Number of Significant Rain Events	Total Precipitation (in)
2007	21	10.12
2008	22	11.96
2009	41	18.88
2010	28	12.34
2011	32	15.51
2012	18	7.21
2013	33	15.49
2014	33	13.07
2015	38	16.31
2016	27	9.21
2017	36	14.58
2018	32	12.48
2019	48	14.66
Average	**31**	**13.22**

WQCV, which is the volume of water that BMPs in Colorado are designed to treat, was defined using an analysis of rainfall and runoff characteristics of 36 years of stormwater events (UDFCD, 2010; Urbonas et al., 1989). The use of WQCV in designing stormwater utilities is to decrease the effects of stormwater runoff pollution on the water quality of receiving water bodies.

Table 2-2: Number of Runoff-Producing Rain Events in Denver Area (UDFCD, 2010)

Total Rainfall Depth (inches)	Percent of Total Storm Events	Percentile of Runoff-producing Storms
0.0 - 0.1	60.90%	0.00%
0.1 - 0.5	29.40%	75.20%
0.5 - 1.0	6.30%	91.10%

1.0 - 1.5	2.10%	96.60%
1.5 - 2.0	0.80%	98.60%
2.0 - 3.0	0.30%	99.40%
3.0 - 4.0	0.20%	99.90%
> 5.0	<0.1%	100%
Total	**100%**	**100%**

After collecting precipitation, the value of Pr was decided. Pr is a factor that accounts for the portion of rainfall that does not produce significant runoff, or runoffs that get trapped in surface depressions and ultimately lost due to evaporation or infiltration (Schueler, 1987). Schueler recommended, based on his analysis, that the value of Pr should be set to 0.9 for annual or seasonal calculations. However, in the case of this study, small rain events (precipitation depth is less than 0.1 inch) have already been disregarded to meet the WQCV minimum threshold, and as a result, the value of Pr was set to 1.0.

The third parameter for this equation was Rv, which is a factor that measures a site response to rainfall events. Rv is referred to as the runoff coefficient, and it represents the portion of the rainfall that becomes runoff after taking into consideration infiltration, surface depression storage, and evaporation. The difference between Rv and Pr is that Rv accounts for losses in rain events that produce runoff; meanwhile, Pr accounts for annual precipitation that does not produce any measurable runoff. Analysis of over 50 sites found that the value of Rv varies among different sites and is affected mainly by site imperviousness. Variables like precipitation volume, intensity, and duration had little effects on the value of Rv (Schueler, 1987). Schueler conducted linear regression analysis on Rv mean values computed for 44 different sites and related Rv to a single factor, which is the level of imperviousness. **Figure 3** shows the mean values of Rv plotted versus the level of imperviousness.

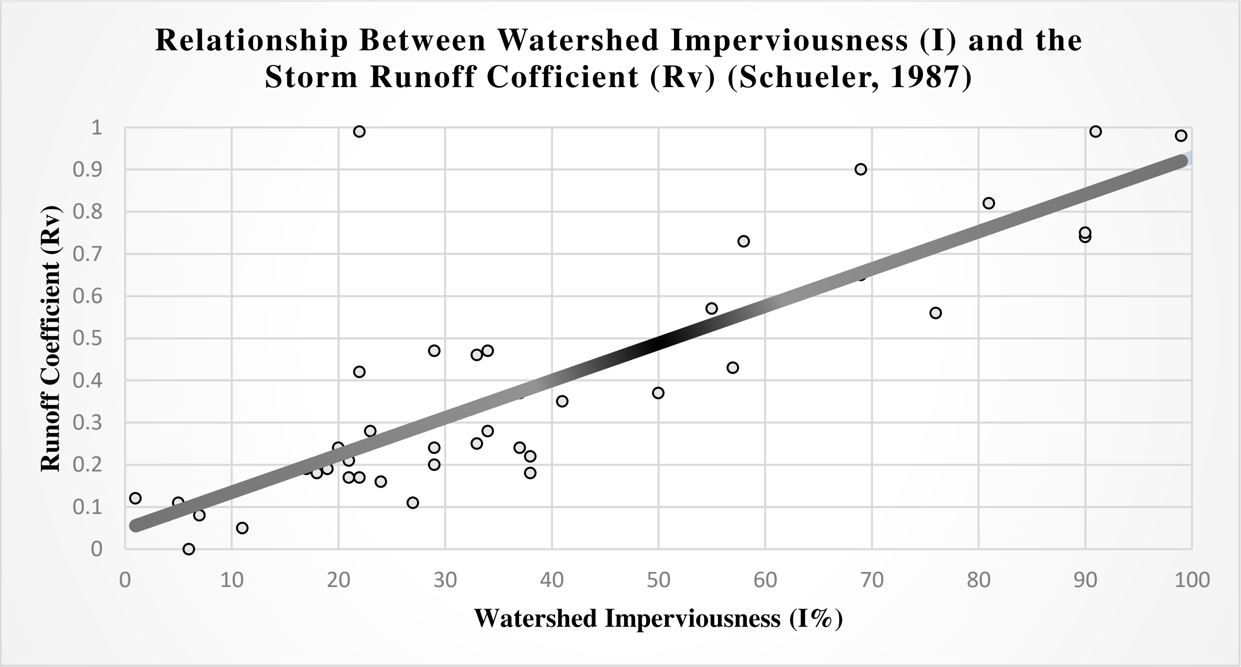

Figure 3: Relationship between Imperviousness (I) and Runoff Coefficient (Rv) in 44 Urban Catchments (Schueler, 1987)

The best fit line was determined with an R^2 value of 0.71. The linear equation resulted from the regression is shown below in **Equation 2**. **Equation 2** is used to calculate the value of Rv based on the value of the imperviousness level.

$$\mathrm{Rv} = 0.05 + 0.009 * \mathrm{I} \qquad \textbf{Equation 2}$$

Where:

Rv: Runoff Coefficient

I: Level of Imperviousness

The National Land Cover Database (NLCD) was used to determine imperviousness levels for each location that used the Simple Method. NLCD is a Landsat-based service with a 30-m resolution raster provided by the U.S. Geological Survey (USGS) and the Multi-Resolution Land Characteristics (MRLC) consortium. NLCD aims to provide spatial and temporal land surface data, including land cover type and percent imperviousness levels (USGS, 2020). The NLCD map of Fort Collins is shown in **Figure 4**.

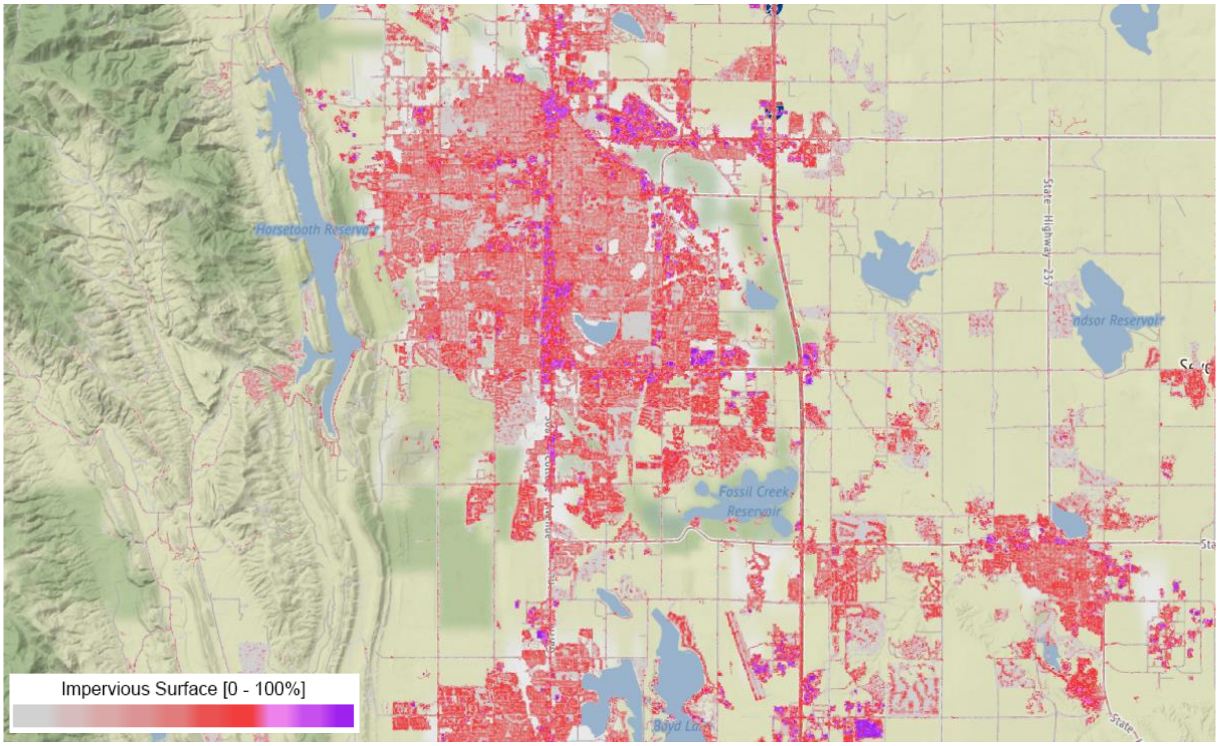

Figure 4: NLCD 2016 Impervious Surface of Fort Collins (MRLC, 2020)

The fourth parameter to be calculated is the drainage area for each BMP. The drainage areas were determined from drainage reports for each BMP and provided as shapefiles by the City of Fort Collins. The drainage area is used in the Simple Method to calculate the runoff volume by multiplying it by precipitation depth. The first four parameters are used to estimate the volume of generated runoff, taking into account runoff losses and small events.

The final parameter needed to calculate the load of pollutants is C, the concentration of pollutants. For this study, three types of BMPs were selected: rain gardens, extended detention basins, and wetlands. Concentrations were collected for both influents and effluents under the current stormwater practices and after the application of WTR, in which the influents were used to represent the concentration of dissolved phosphorus in stormwater runoff. For rain gardens, influent and effluent concentrations of dissolved phosphorus were obtained from a column study done by the Colorado Stormwater Center at Colorado State University. In this study, filter media of the current practices were used in addition to different applications of WTR. The column study is discussed in detail in the next section.

For extended detention basins and wetlands, phosphorus concentrations for influents and effluents were collected from the International Stormwater BMP Database for the current practice's values. For effluent concentrations of phosphorus post-application of WTRs, it was assumed that extended detention basins were able to achieve a 93% removal rate, while wetlands were assumed to be able to achieve 90% based on literature. The higher removal rate of the extended detention basins was assumed as a result of longer detention times. BMP Database dissolved phosphorus concentrations for various BMPs are shown in **Table 2-3**.

Table 2-3: Summary of Dissolved Phosphorus Concentrations in Influents and Effluents (mg/l) (BMP Database, 2012)

BMP Category	25th		Median		75th	
	In	Out	In	Out	In	Out
Grass Strip	0.06	0.18	0.08	0.25	0.14	0.38
Bioretention	0.11	0.07	0.25	0.13	0.46	0.19
Bioswale	0.03	0.05	0.06	0.07	0.09	0.26
Composite	0.08	0.05	0.16	0.08	0.26	0.13
Detention Basin	0.07	0.07	0.10	0.11	0.17	0.16
Media Filter	0.05	0.04	0.08	0.08	0.15	0.14
Retention Pond	0.07	0.03	0.13	0.06	0.21	0.14
Wetland Basin	0.03	0.03	0.08	0.05	0.13	0.13
Wetland Channel	0.05	0.06	0.08	0.09	0.15	0.14

The Simple Method was modified to estimate pollutant loads from BMPs. BMPs' primary function is to treat water and remove pollutants, but that does not necessarily mean treating all received stormwater. This is one of the key points for using WQCV in the design of stormwater BMPs, as the Mile High Flood District (MHFD) in Colorado found that the optimal capture and treat efficiency for BMPs is for the 80th percentile runoff-producing events, as this capture volume allows for BMPs to treat 80-90% of total suspended solids (UDFCD, 2010). The 80th percentile runoff-producing events match a 0.6-inch precipitation depth, optimizing the BMPs' performance in capturing and treating most of the runoff-producing events in an area-feasible manner.

Another key feature of many BMPs is that they also reduce the runoff volume and, subsequently, many pollutants in that volume. Volume reduction occurs in some types of BMPs due to evaporation, infiltration, evapotranspiration, percolation, or re-using of stored water (Poresky et al., 2011). The performance of BMPs in volume reduction depends on soil type, connectivity to the storm sewer system, climate, and non-potable water needs (Poresky et al., 2011). **Table 2-4** shows percent volume reductions for different types of BMPs.

Table 2-4: Percent Volume Reduction for Various BMPs (BMP Database, 2011)

BMP Category	25th Percentile	Median	75th Percentile	Average
Biofilter - Grass Strips	18%	34%	54%	38%
Biofilter - Grass Swales	35%	42%	65%	48%
Bioretention (with underdrain)	45%	57%	74%	61%
Detention Basins	26%	33%	43%	33%

In this study, WQCV or the captured volume was calculated for each runoff-producing event. Captured volumes were calculated by multiplying the drainage area by a precipitation depth of 0.6 inches, the maximum threshold for the WQCV. The additional quantity from larger events was considered to have bypassed or overflown the facility. From the captured volumes, volumes were reduced by the values in **Table 2-4**, accounting for the volume reduction process in the BMP. Phosphorus loads introduced to the system were then calculated for each event and then aggregated into total annual runoffs and total annual treated volume to assess the phosphorus reduction from BMPs.

2.2.2 Selected Locations

For this study, 15 BMPs were selected with different locations and drainage areas; all of them are existing and operational in Fort Collins, Colorado. The 15 BMPs included five rain gardens, five wetlands, and five extended detention basins, all of them providing water quality treatment. The selection of 15 BMPs was used to account for the BMPs' characteristics variability in terms of loading ratio or the ratio of drainage area to the BMP area. The selection was beneficial in assessing how WTRs perform under different circumstances, as shown in **Table 2-5.**

Rain gardens (or bioretention cells) do not require large areas to be installed and can fit under street landscaping, backyards, or parking lots. The design of rain gardens and the use of filter media allows for multiple processes of water treatment, including absorption, adsorption, and infiltration, in addition to a detention time of stormwater of 12 hours on average. Extended detention basins and wetlands require larger areas than rain gardens, hence their ability to capture larger volumes of water. While extended detention basins can hold water up to 40 hours with a volume reduction of 33% on average, wetlands can hold stormwater for 24 hours but with no significant reduction in stored volumes.

Table 2-5: Characteristics of Selected BMPs

BMP	Area of Drainage (ft^2)	Area of BMP (ft^2)	Imperviousness % (NLCD 2016)
Rain Garden 1	151,504	4,612	70.7
Rain Garden 2	93,724	3,000	64.4
Rain Garden 3	44,264	1,562	55.8
Rain Garden 4	90,108	2,800	71.3
Rain Garden 5	27,474	580	52.0
Extended Detention Basin 1	667,921	24,000	62.7

Extended Detention Basin 2	1,354,224	79,000	46.5
Extended Detention Basin 3	9,518,808	188,825	32.8
Extended Detention Basin 4	9,312,862	490,000	27.6
Extended Detention Basin 5	2,875,715	121,500	59.8
Constructed Wetland 1	2,564,550	50,126	29.3
Constructed Wetland 2	3,335,051	240,800	37.8
Constructed Wetland 3	2,798,222	192,478	40.6
Constructed Wetland 4	2,638,120	157,100	38.9
Constructed Wetland 5	2,303,670	121,210	37.8

The selected types of BMPs for this study offer stormwater treatment and may additionally be used for flood control. Their current designs allow for moderate performance when it comes to targeted nutrients like phosphorus, but they also offer flexibility for improvements such as the application of WTRs. The filter media in rain gardens and the large surface areas of extended detention basins and constructed wetlands, along with good detention times, low to moderate maintenance, and lengthy lifespans, make the use of these BMPs very efficient and cost-effective in removing pollutants and reducing their discharge in water bodies.

Table 2-6 from the Urban Storm Drainage Criteria Manual published by (UDFCD, 2010) shows a performance summary of the selected types of BMPs in this study. Examples of selected BMPs and their locations are shown in **Figure 5**.

Table 2-6: Performance Summary of Selected BMPs (UDFCD, 2010)

	BMP Type		
	Rain Gardens	Extended Detention Basins	Constructed Wetlands
Function			
Volume Reduction	Good	Somewhat	Low
WQCV Capture	Yes	Yes	Yes
WQCV + Flood Control	Yes	Yes	Yes
Typical Effectiveness for Targeted Pollutants			
Sediments/Solids	V. Good	Good	V. Good
Nutrients	Moderate	Moderate	Moderate
Total Metals	Good	Moderate	Good

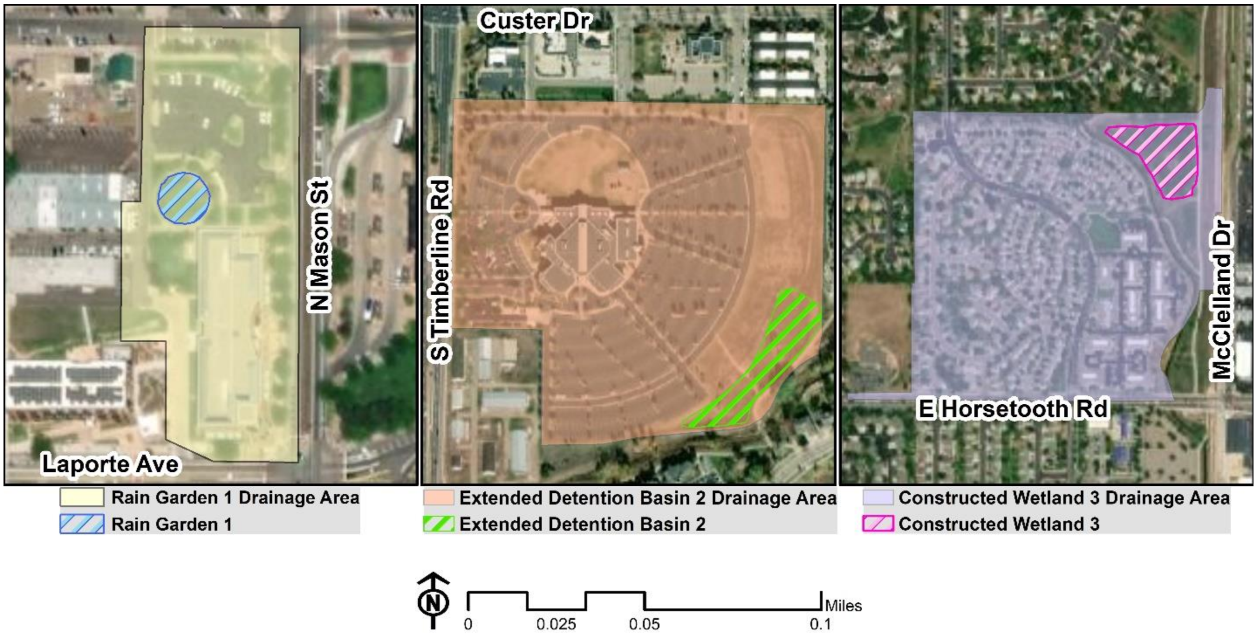

Figure 5: Examples of Selected BMPs

2.2.3 Column Study

To assess the performance of WTRs in phosphorus removal, a column study was conducted at the Colorado Stormwater Center at Colorado State University. The relative ease of construction and the flexibility of the design elements of rain gardens, in addition to the promising potential of WTRs as a phosphorus removal tool, provided the motivation to study the efficiency of WTRs under various conditions. This column study tested different settings of WTRs application versus the use of the current practices filter media composition.

The filter media composition under the current practices in the City of Fort Collins consists of 60-70% sand, 5-10% shredded paper, 5-10% topsoil, and 10-20% leaf compost by volume (City of Fort Collins, 2011). After monitoring phosphorus concentrations using this filer media, influent concentrations were found to be 0.3 mg/l and 0.2 mg/l on average for total and dissolved phosphorus respectively, while the effluent concentrations of total and dissolved phosphorus were 0.9 mg/l and 0.65 mg/l on average. Those numbers, shown in **Figure 6** below, indicate that this filter media mix is significantly increasing phosphorus concentrations, potentially resulting in a net export of phosphorus from rain gardens under the current practices.

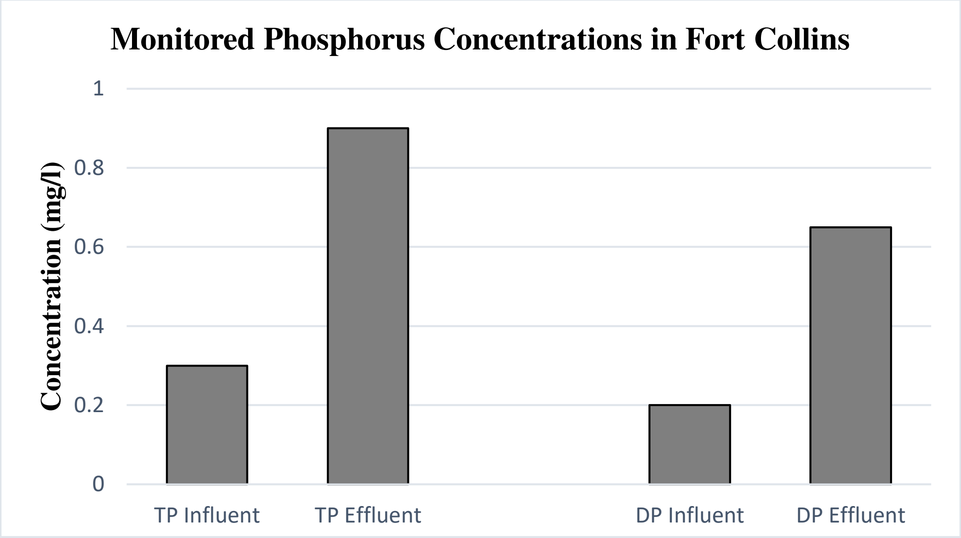

Figure 6: Monitored Phosphorus Concentrations in Rain Gardens - Fort Collins, CO

For the column study, a wooden structure – shown in **Figure 7 -** was constructed to house 15 PVC columns that would each be filled with one of five different treatments. Each column first received 10 inches of #4 gravel, followed by 6 inches of pea-gravel, regardless of treatment. The gravel layers were then topped with the following combinations.

- Bioretention Sand Media (BSM) only
- BSM mixed with an inch worth of Al-WTR
- BSM topped with 1 inch of Al-WTR
- BSM topped with 0.5 inches of Al-WTR
- 1 inch of Al-WTR topped the BSM layer

Figure 7: Support structure for columns containing filtration mixtures. Covered effluent catchment containers were placed below each column.

Each treatment was replicated in 3 different columns. Historical precipitation data between 2007 and 2017 from a monitoring site near the City of Fort Collins was used to determine the appropriate volume of stormwater necessary to simulate the average annual runoff that could be processed by the system. The volume to pour through each column when simulating a storm event was determined using the average depth of runoff, which is around 6.22 inches that is capable of being treated per significant event. The annual volume was then determined using the per storm event volume combined with the average number of runoff-producing events, which is 31 events per year over the data collection period. A 55-gallon barrel was filled with synthetic stormwater that was specially formulated to reflect the average dissolved phosphorus concentration typically found in runoff from the site using sodium phosphate through the addition of sodium phosphate to tap water.

Stormwater runoff data for a Fort Collins rain garden was monitored between 2013 and 2015 was used to estimate the appropriate influent dissolved phosphorus concentration that was the target for the stormwater mixture. Effluent from each column was collected in catchment containers following each storm. Samples from each container were then bottled and sent off to be analyzed for dissolved phosphorus concentration. Two full years of rainfall simulation took place from January to August of 2019. The results of the column study are discussed in the results section.

2.2.4 Application of WTRs

To incorporate the application of WTRs in the Simple Method, concentrations of effluents post-application had to be calculated. Rain gardens design allows for multiple scenarios of WTRs application. WTRs may be applied on top of the filter media, mixed with the filer media, or applied on the bottom of the filter media, noting that selecting the preferred scenario depends on the cost of application and desired phosphorus removal efficiency. For extended detention basins and constructed wetlands, WTRs were assumed to be applied to the surface of the BMP and was the only application method considered.

WTRs efficiency in phosphorus removal was assessed by comparing the dissolved phosphorus loads prior to application (current conditions) to those of the post-application. Phosphorus concentrations were acquired from the column study for rain gardens with various application strategies. However, for extended detention basins and constructed wetlands, the International BMP Database was used for performance under current practices and literature for their performance using WTRs. For phosphorus concentrations in extended detention basins and constructed wetlands in the post-application phase of WTRs, it was assumed based on the literature review that constructed wetlands could achieve 90% phosphorus removal and 93% for extended detention basins because of longer detention times of stormwater.

The amount of WTRs applied for each technology was determined using two concepts: Phosphorus Storage Capacity (PSC) and Phosphorus Saturation Ratio (PSR). PSC refers to the soil's ability to absorb phosphorus before leaching happens, with values ranging between positive in which the soil can still receive phosphorus and negative in which that soil cannot retain phosphorus and starts leaching (Nair & Harris, 2014). PSR is a ratio between the phosphorus content to the aluminum and iron content, and it defines the threshold, after which phosphorus leaching could become a problem (Nair et al., 2019). (Ippolito, 2015) calculated the PSC for Al-WTRs for a constructed wetland in Boise, Idaho, to quantify the required amount of WTRs needed for efficient and long-term phosphorus removal. **Equation 3** was used in this study to calculate the PSC for WTRs generated in the treatment plant in Fort Collins.

$$\text{Al–WTR}_{\text{PSC}} = [(0.15 - \text{Al–WTR}_{\text{PSI}}) * (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})] * 31 \qquad \textbf{Equation 3}$$

$$\text{Al–WTR}_{\text{PSI}} = (\text{P}_{\text{ox}}) \,/\, (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}) \qquad \textbf{Equation 4}$$

Where:

$\text{Al-WTR}_{\text{PSC}}$: Phosphorus Storage Capacity (mg kg^{-1})

$\text{Al-WTR}_{\text{PSI}}$: Phosphorus Sorption Index

P_{ox}: Amorphous Phosphorus Concentration (mmol kg^{-1})

Al_{ox}: Amorphous Aluminum Concentration (mmol kg^{-1})

Fe_{ox}: Amorphous Iron Concentration (mmol kg^{-1})

The minimum amount of WTRs needed to achieve efficient removal of dissolved phosphorus was calculated by dividing the generated dissolved phosphorus loads by the PSC of the WTRs.

2.3 Results and Discussion

After collecting the data for the area parameter, events runoff volumes were calculated for each BMP, taking into account volume reductions by each BMP, and the runoff coefficient Rv represented by the imperviousness level. Captured volumes were then calculated for each BMP based on the WQCV and then the treated volumes, which were calculated after taking into account the volumes lost because of the volume reduced by each BMP. Event volumes were then aggregated for each year. **Figure 8**, **Figure 9**, and **Figure 10** show the 13-year averages of the study period between 2007 and 2019 for annual runoff volumes, captured volumes, and treated volumes for rain gardens, extended detention basins, and constructed wetlands.

The total land area of Fort Collins is around 38,000 acres, and the total drainage area treated by the selected BMPs is approximately 850 acres, which is almost 2.5% of the city's areas, and 9.7% of the total treated area. The total drainage area of existing rain gardens, extended detention basins, and constructed wetlands in Fort Collins equals around 8,750 acres, and that comprises almost 40% of the total area treated in Fort Collins.

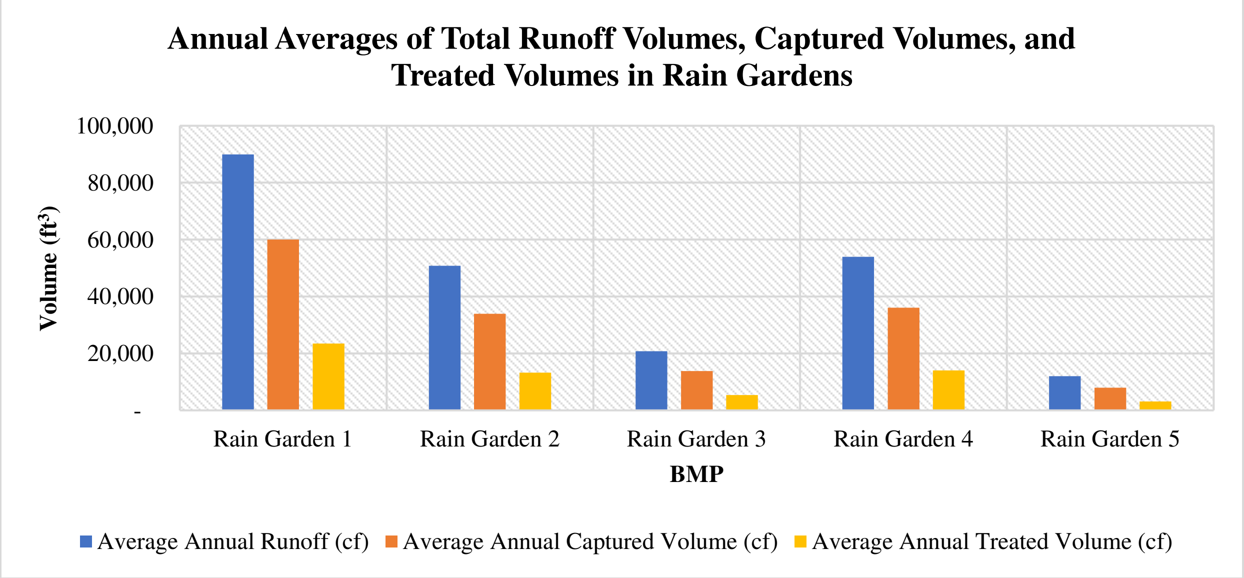

Figure 8: Annual Averages of Total Runoff Volumes, Captured Volumes, and Treated Volumes in Rain Gardens

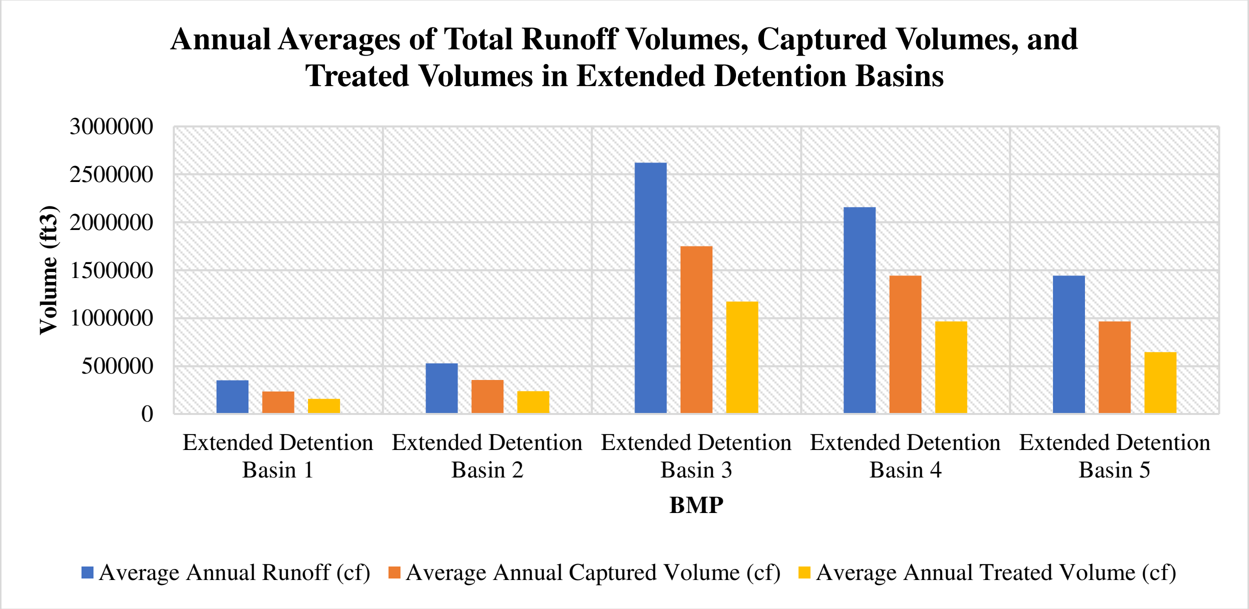

Figure 9: Annual Averages of Total Runoff Volumes, Captured Volumes, and Treated Volumes in Extended Detention Basins

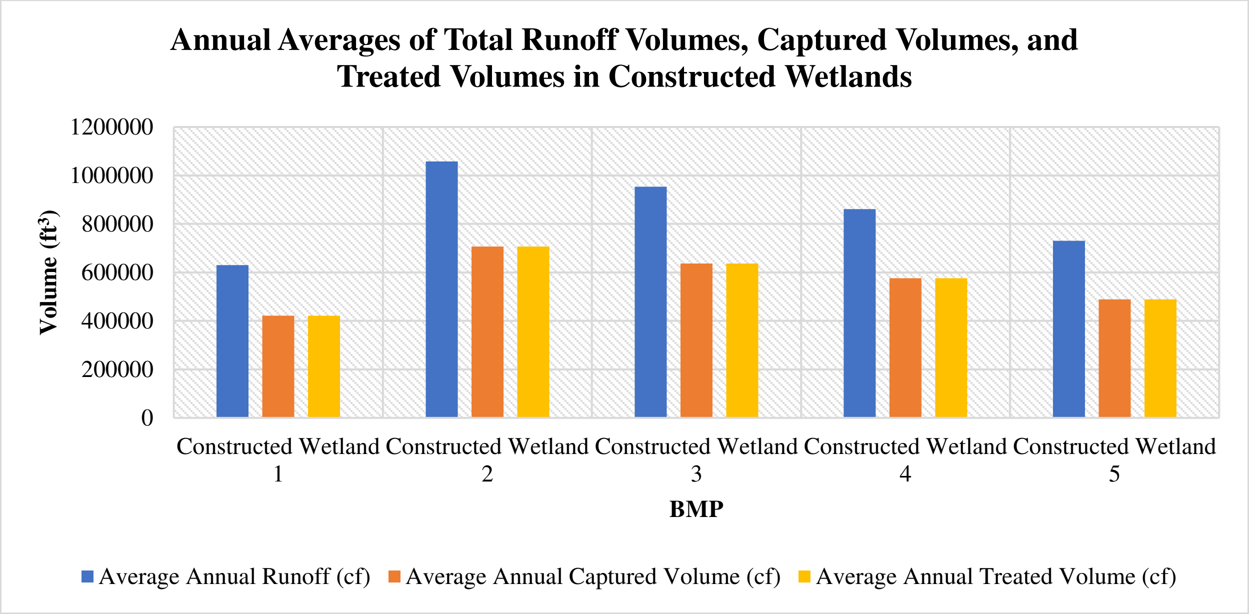

Figure 10: Annual Averages of Total Runoff Volumes, Captured Volumes, and Treated Volumes in Constructed Wetlands

As shown in **Figure 8**, **Figure 9**, and **Figure 10**, the selected BMPs were not able to capture the runoff volume in its entirety, as the average percentage of captured volume to total runoff volume was around 70%. This was due to the assumption that BMPs were designed to capture runoffs from only 0.6-inches storm events. As a result, around 30% of the runoff volume introduced to the BMPs system will not be captured and will end up bypassing the treatment system to the receiving water bodies. Of the total captured volume, only the portion not removed by the practice through infiltration or evapotranspiration became treated volume. Since constructed wetlands do not offer measurable volume reduction, all the captured volume was considered treated with no losses. Meanwhile, rain gardens reduce captured volumes by 61% on average, and extended detention basins reduce 33% of the captured volumes on average, according to the International BMP Database.

Table 2-7 shows the dissolved phosphorus concentrations in influents used in this study, while **Table 2-8** shows the effluents' concentrations of dissolved phosphorus under the current practices and with the application of WTRs. **Table 2-7** shows that the influent concentration for rain gardens is higher than those of the extended detention basins and constructed wetlands. This could be because of the difference in the drainage area characteristics around rain gardens, as generally rain gardens are used in parking lots and residential spaces, which might lead to higher pollutant concentrations, as opposed to open spaces that surround extended detention basins and constructed wetlands.

Table 2-7: Dissolved Phosphorus Concentrations in the BMPs Influents

BMP	DP Influent Concentration (mg/l)
Rain Gardens	0.25
Extended Detention Basins	0.10
Constructed Wetlands	0.08

Table 2-8: Dissolved Phosphorus Concentrations in the BMPs Effluents

BMP Type	Application Layer	DP Effluent Concentration (mg/l)
Rain Gardens	No WTR	0.996
	WTR - Top 0.5 inches	0.855
	WTR - Top 1 inch	0.844
	WTR - Mixed	0.376

	WTR - Bottom 1 inch	0.288
Extended Detention Basins	No WTR	0.110
	WTR - Top	0.010
Constructed Wetlands	No WTR	0.050
	WTR Top	0.008

The concentrations for rain gardens shown in **Table 2-8** are the column study results, and it is noticed that the concentrations were improved by applying WTRs from the current filter media mix. The pre-application of WTRs concentrations for extended detention basins and constructed wetlands shown in **Table 2-8** are from the BMP Database report done by (Geosyntec Consultants & Wright Water Engineers, 2012), while the ones of post-application of WTRs are based on the assumption that WTRs would achieve 90% removal in constructed wetlands and 93% in extended detention basins due to longer detention time of stormwater.

Using phosphorus concentrations of BMPs influents and effluents, the Simple Method calculated dissolved phosphorus load under the current practices (**Figure 11**). It was found that the runoff from the drainage areas of the selected BMPs generated, on average, was around 70 lbs. of dissolved phosphorus annually. As established earlier in this study, the total drainage area of the selected BMPs represents 2.5% of the total city area. Assuming that the precipitation is distributed equally, and Fort Collins consists of similar drainage areas and BMPs, this would mean that over 3000 lbs. of dissolved phosphorus are introduced by the stormwater system annually. Also, **Figure 11Figure** ***13*** shows that the selected BMPs were able to reduce the net amount of dissolved phosphorus by nearly half, which was due mainly to the volume reduction offered by these BMPs since the concentrations of dissolved phosphorus in the effluents were higher than the influents.

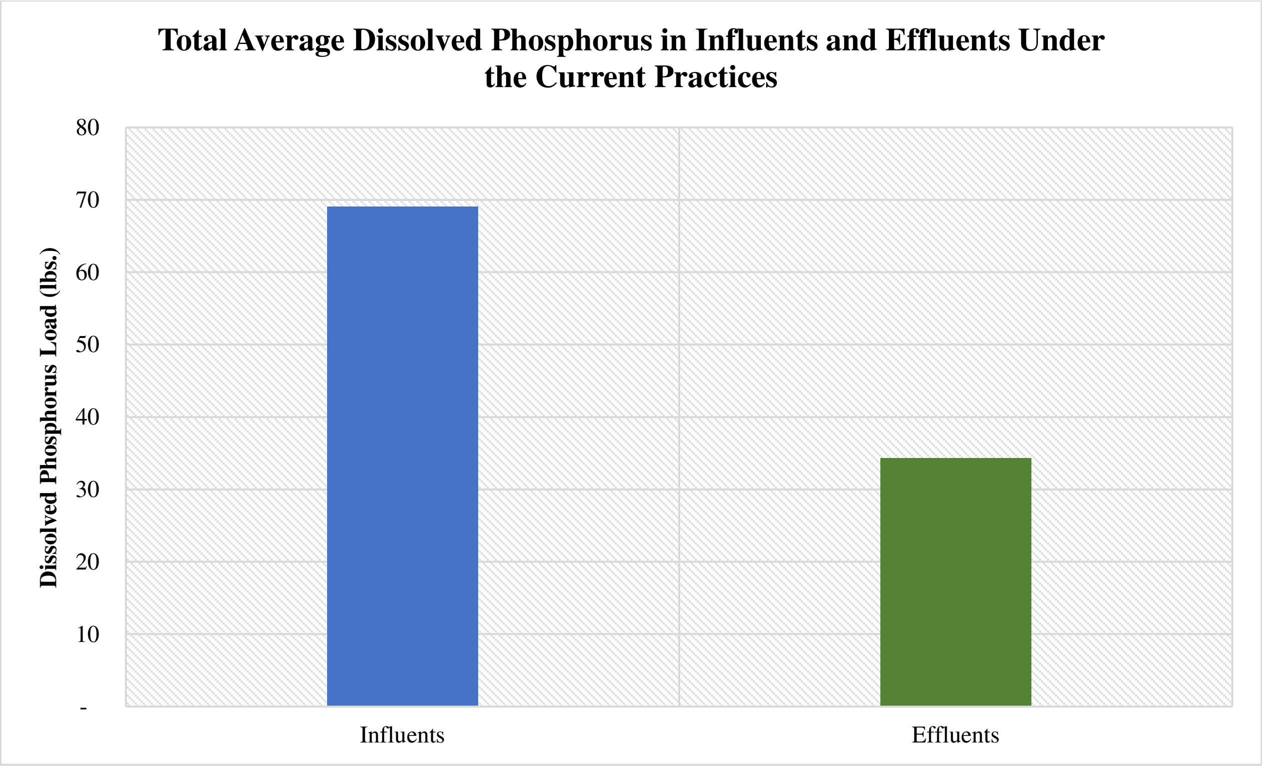

Figure 11: Total Average Dissolved Phosphorus in Effluents and Effluents - Current Practices

As shown in **Figure 11**, BMPs reduced the total net amount of dissolved phosphorus by nearly half due mainly to the volume reduction offered by these BMPs since the concentrations of dissolved phosphorus in the effluents are higher than those in the influents. However, **Figure 12** shows that it was not the case for rain gardens, as it can be noticed that even with volume reduction, the amount of dissolved phosphorus had stayed the same if not increased due to high concentrations in effluents. This is likely because of the filter media's current mix, which has compost, which acts as a dissolved phosphorus source. Even though current practices reduced the dissolved phosphorus load by half, improvements can still be made using WTRs as an amendment in BMPs.

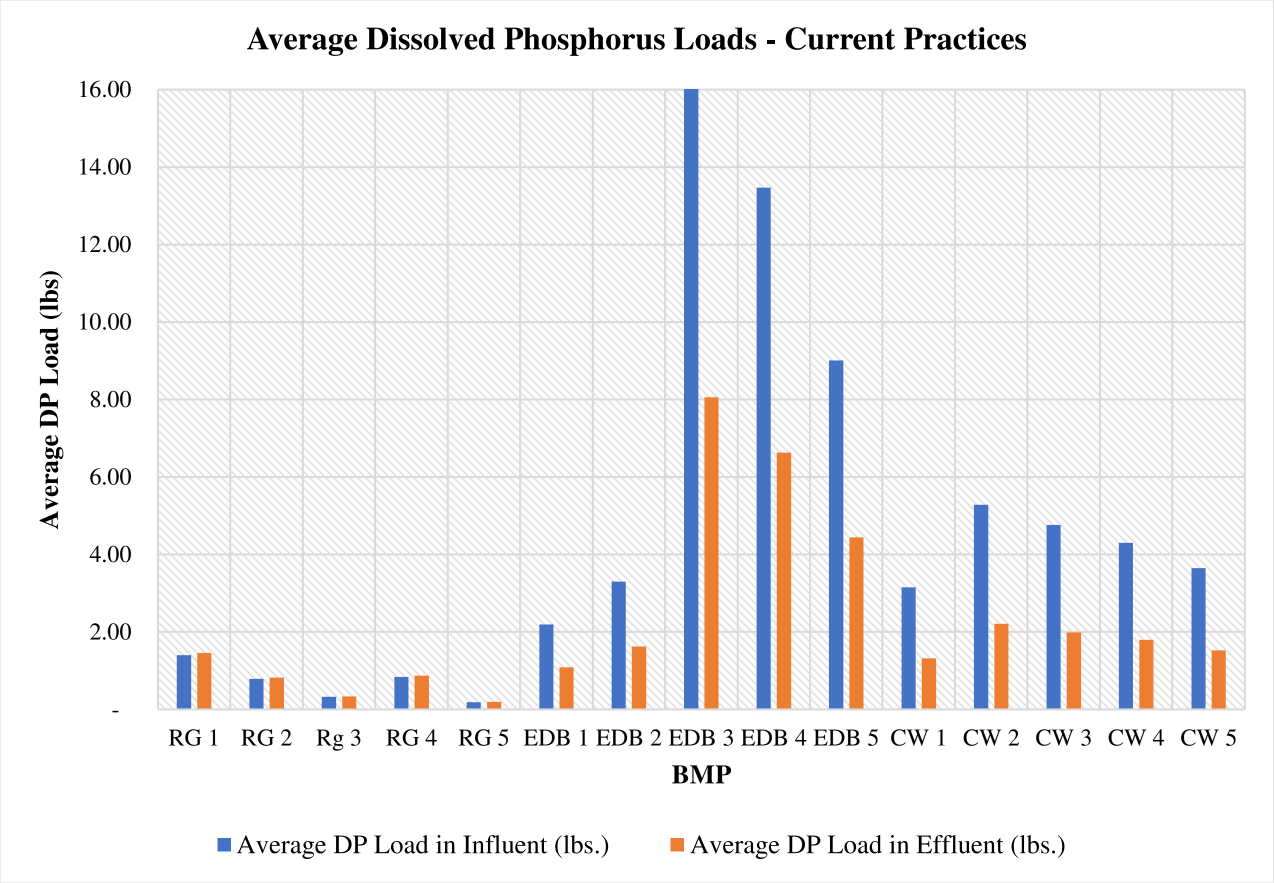

Figure 12: Average DP Loads - Current Practices

It is noticed from **Figure 12** that the contributions of extended detention basins and constructed wetlands are higher than those of rain gardens due to larger drainage areas. However, the higher concentrations of dissolved phosphorus in rain gardens can make up for their smaller drainage areas and lead to high contributions, given that they are easier to construct and require less space. For example, Rain Garden 1 generated 1.40 lbs. of phosphorus on average, which is around half what Extended Detention Basin 1 generated, but the drainage area of Rain Garden 1 is almost one-fifth of the area of Extended Detention Basin 1. Also, the total drainage area of rain gardens in this study represents 1% of the total drainage area of the other two BMPs, but its contribution of dissolved phosphorus equals around 5% of the total.

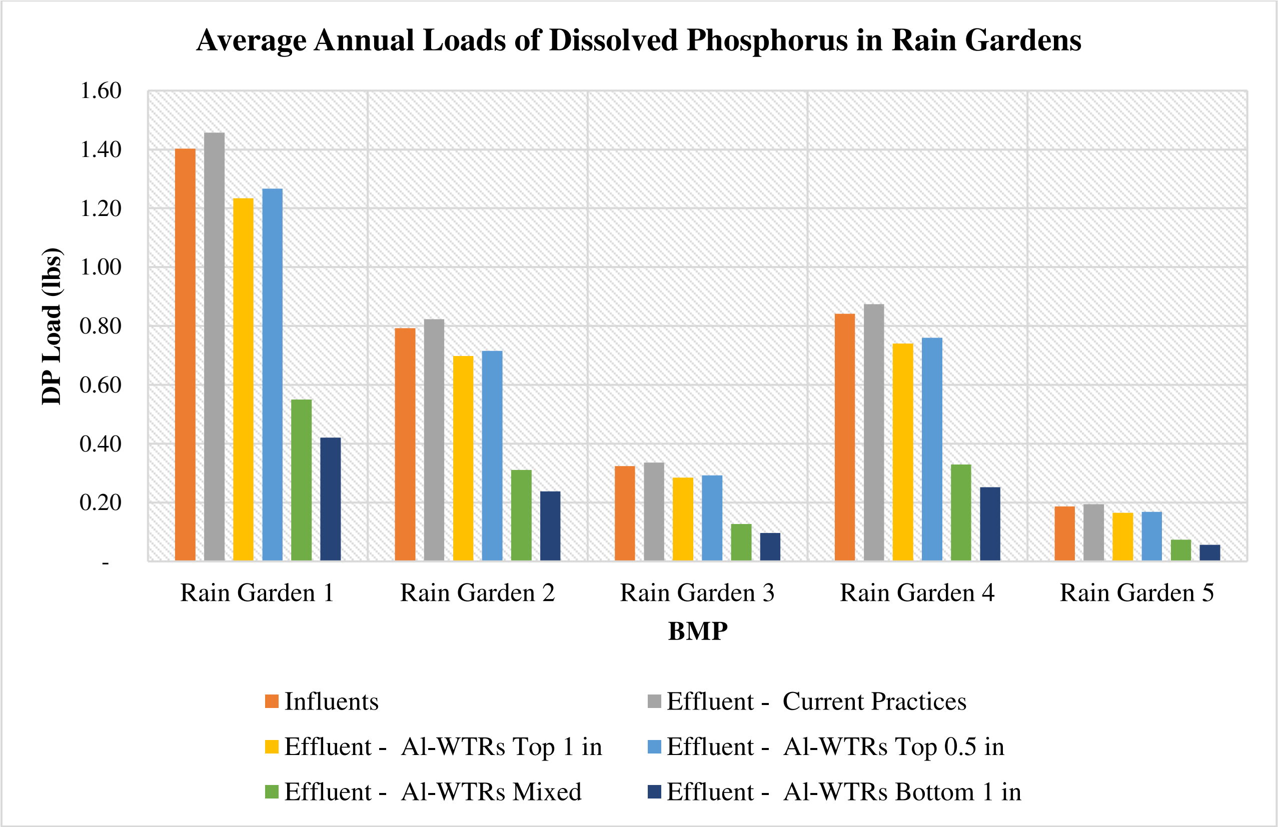

Figure 13: Average Annual Loads of Dissolved Phosphorus in Rain Gardens

Figure 13 shows a comparison between the loads of phosphorus generated by runoff and the phosphorus loads in effluents pre- and post-application of Al-WTRs using different application strategies for rain gardens. As shown in the figure, the current practices in rain gardens lead to an increase in the amounts of dissolved phosphorus that will be discharged to receiving water bodies. Even if the contribution of rain gardens represents around 5% of the total load generated dissolved phosphorus by the selected BMPs drainage areas, the potential of introducing more rain gardens in the future and the relatively smaller drainage areas needed to generate this amount of dissolved phosphorus increase the significance of this contribution and the issues it can cause.

However, the application of Al-WTRs improved the phosphorus-removal performance of rain gardens. The performance of Al-WTRs depended on the application method and the amount applied, with the bottom-layer application achieving the highest phosphorus removal followed by mixed application, then top-layer applications with a slight difference due to the amount applied. Although the bottom-layer application of Al-WTRs achieved the highest removals, the cost of such an application is also the highest for existing rain gardens. Mixed application of WTRs can also be costly for existing rain gardens, but it reduced dissolved phosphorus loads by more than half, which is slightly less than what bottom-layer application did but significantly better than current practices and top-layer applications. Mixing WTRs with the bioretention sand mix could be considered for new rain gardens as it has an extra factor of safety that it is less likely to export anything harmful from the WTRs such as aluminum and uranium. Top-layer applications might be the most feasible for existing rain gardens since they do not require major restructuring of the filter media and cost less than the other two options.

For extended detention basins and constructed wetlands, since they do not require filter media installation, WTRs were assumed to be applied to the BMP's surface, and the amounts required determined by the Phosphorus Storage Capacity (PSC) of Al-WTRs. **Figure 14** below shows a comparison between the loads of phosphorus generated by runoff and the loads of phosphorus in effluents pre- and post-application of Al-WTRs in extended detention basins and constructed wetlands. Those two BMPs were responsible for introducing 95% of the dissolved phosphorus in the selected location in this study, but as shown in the figure, current practices were able to reduce that amount by half. On the other hand, the application of Al-WTRs would be a considerable incentive given that they were able almost to eliminate dissolved phosphorus generated through the stormwater runoff.

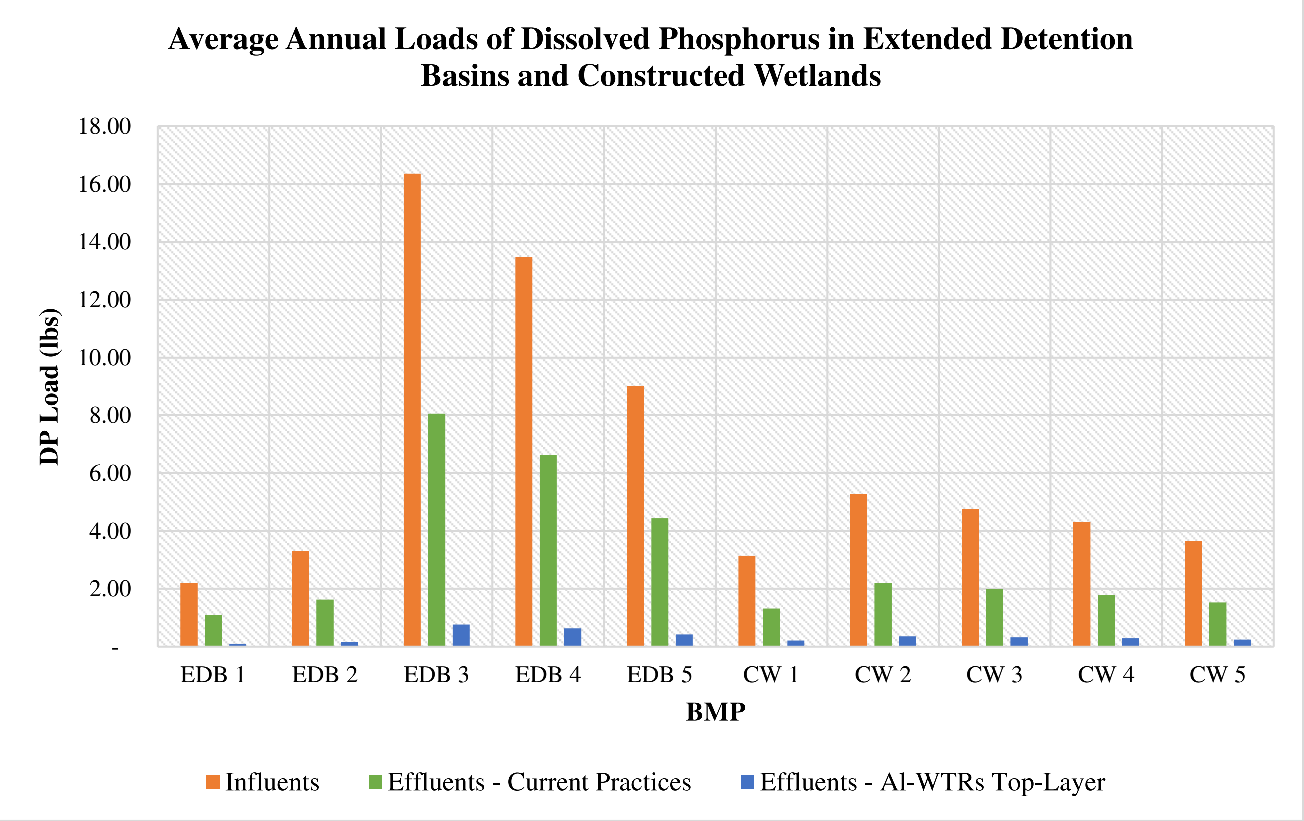

Figure 14: Average Annual Loads of Dissolved Phosphorus in Extended Detention Basins and Constructed Wetlands

Using the effluent concentrations of top Al-WTRs application in rain gardens and surface application in extended detention basins and constructed wetlands, dissolved phosphorus loads in effluents were calculated for all BMPs in Fort Collins and shown in **Figure 15**. It is shown that BMPs reduced total dissolved phosphorus loads in all rain gardens, extended detention basins, and constructed wetlands in Fort Collins from 841 lbs. to only 49 lbs., which is 94% removal.

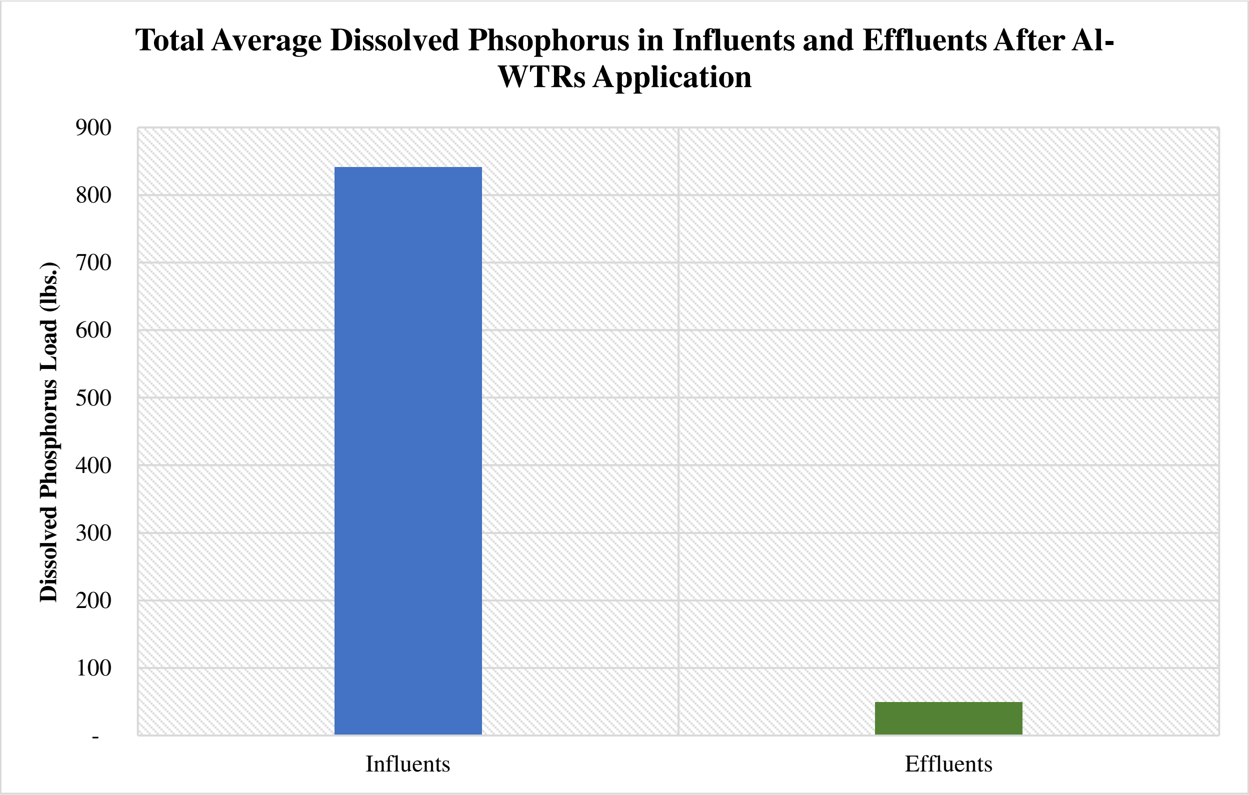

Figure 15: Total Average Dissolved Phosphorus in Influents and Effluents After Al-WTRs Application

After determining the efficiency of using AL-WTRs as an amendment in BMPs for dissolved phosphorus removal, the amount of Al-WTRs needed was calculated using **Equation 3** to get the Phosphorus Storage Capacity (PSC) of Al-WTRs. PSC was needed to calculate the amount of dissolved phosphorus that could be adsorbed by a unit weight of Al-WTRs. The result of the equation was that a kilogram of Al-WTRs could adsorb 10,778 mg of dissolved phosphorus, which also means that a ton of Al-WTRs can remove 21.556 pounds of dissolved phosphorus.

To calculate Al-WTRs minimum quantity needed for rain gardens, extended detention, basins, and constructed wetlands in the city of Fort Collins, average dissolved phosphorus generation rates were calculated for each BMP, then multiplied by the total drainage area of each BMP. **Table 2-9** below shows the average generation rates of dissolved phosphorus in Fort

Collins. Because of the high concentrations of dissolved phosphorus in rain gardens, the average generation rate is greater than the other two BMPs, but the larger drainage areas of extended detention basins and constructed wetlands generate a higher amount of dissolved phosphorus and would require large amounts of Al-WTRs.

Table 2-9: Generation Rates of Dissolved Phosphorus in the Selected BMPs

BMP	Drainage Area (acres)	Average DP Load in Influent (lbs.)	DP Generation Rate (lbs./acre)	Average DP Generation Rate (lbs./acre)
Rain Garden 1	3	1.40	0.40	0.36
Rain Garden 2	2	0.79	0.37	
Rain Garden 3	1	0.32	0.32	
Rain Garden 4	2	0.84	0.41	
Rain Garden 5	1	0.19	0.30	
Extended Detention Basin 1	15	2.20	0.14	0.10
Extended Detention Basin 2	31	3.30	0.11	
Extended Detention Basin 3	218	16.36	0.07	
Extended Detention Basin 4	214	13.47	0.06	
Extended Detention Basin 5	66	9.01	0.14	
Constructed Wetland 1	59	3.15	0.05	0.07
Constructed Wetland 2	77	5.28	0.07	
Constructed Wetland 3	64	4.76	0.07	
Constructed Wetland 4	61	4.30	0.07	
Constructed Wetland 5	53	3.65	0.07	

The total drainage area for rain gardens, extended detention basins, and constructed wetlands in Fort Collins equals around 8,720 acres. Average generation rates were multiplied by the total drainage area to each BMP to calculate the dissolved phosphorus load and, subsequentially, the Al-WTRs quantities to treat all BMPs in Fort Collins for one year.

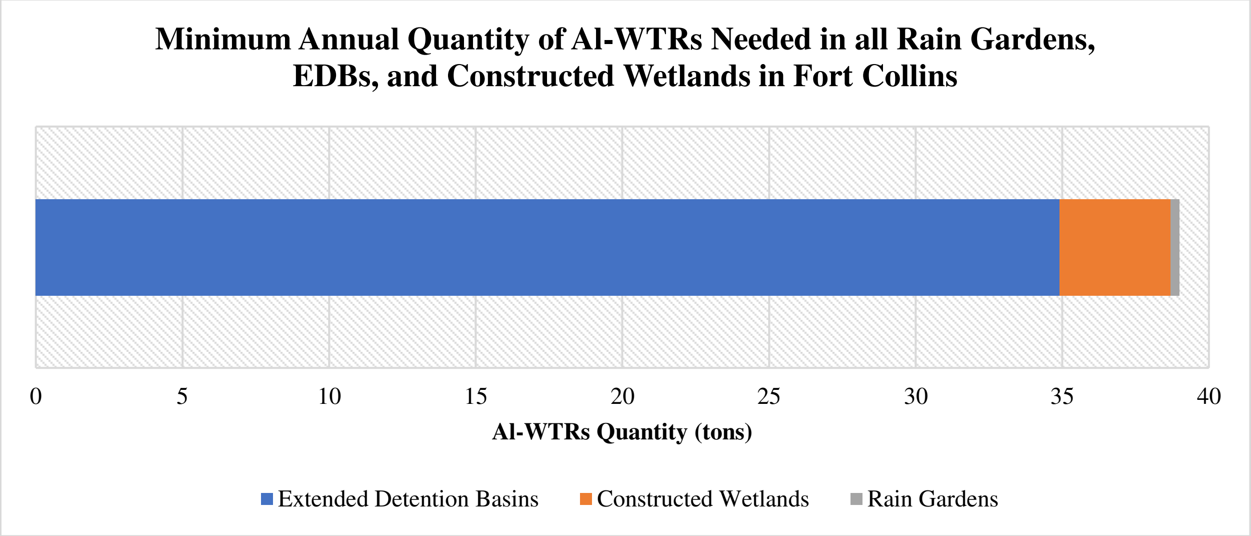

Figure 16: Minimum Quantity of Al-WTRs Needed to Cover All Rain Gardens, EDBs, and Constructed Wetlands in Fort Collins for One Year

Figure 16 above shows that, ideally, a minimum of 39 tons of Al-WTRs would be needed to remove 841 lbs. of dissolved phosphorus generated by the 8,723 acres of drainage area per year. For this study, it was assumed that Al-WTRs would be applied to remove dissolved phosphorus for 50 years, which means 1,950 tons of Al-WTRs were needed, as shown in **Figure 17**.

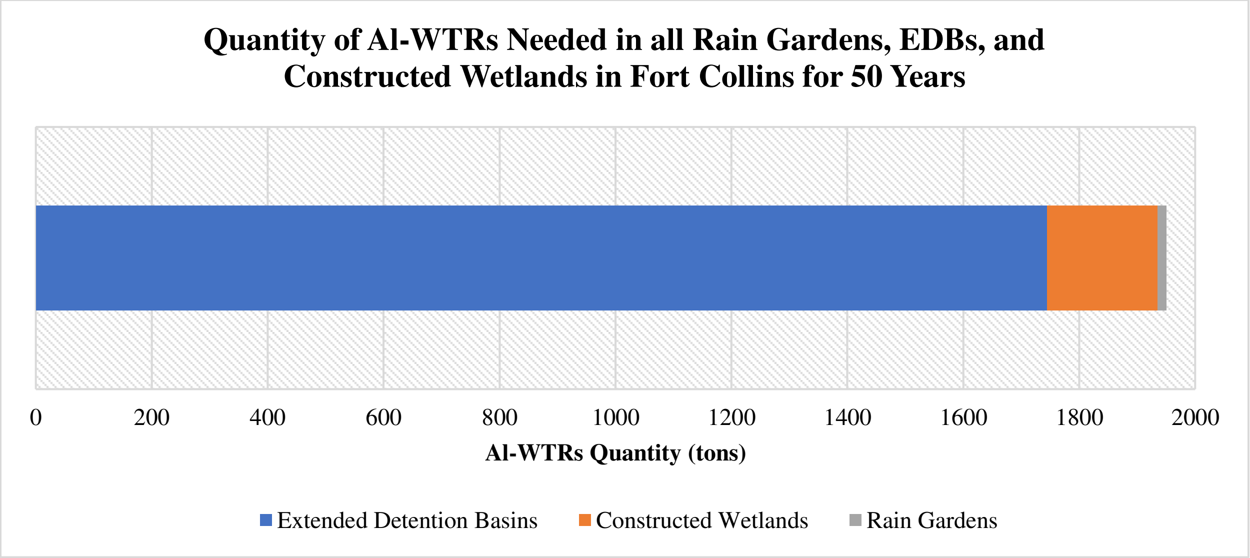

Figure 17: Quantity of Al-WTRs Needed to Cover All Rain Gardens, EDBs, and Constructed Wetlands in Fort Collins for 50 Years

The quantity shown in **Figure 17** was based on the PSC of Al-WTRs measured in the laboratory, but realistically, the quantity of WTRs would have to be increased. The synthetic stormwater used in the column study was formulated only to simulate dissolved phosphorus concentrations in stormwater runoff. However, multiple factors might affect the performance of Al-WTRs and their phosphorus storage capacity. First, stormwater runoff contains numerous pollutants in a dissolved state such as nitrogen, zinc, nickel, copper, arsenic, nonylphenols, petroleum hydrocarbons, PCBs, and PAHs (Aryal et al., 2005; Bressy et al., 2012; Kayhanian et al., 2012; LeFevre et al., 2015). The presence of such dissolved pollutants might affect the performance of Al-WTRs in removing dissolved phosphorus as they might compete for the surface area of the Al-WTRs particles and affect the material's phosphorus storage capacity. Also, if the annual precipitation exceeded the average in one year, that cause the WTRs to reach their saturation faster and then the need for the WTRs to be replaced.

In this study, a final option was considered for applying WTRs as a 0.5 inch-layer to the BMP's entire surface area. Such an application would reduce any potential conflict of competing pollutants on the efficiency of WTRs and ensure long-term use before they would reach their maximum phosphorus capacity and need to be replaced. The density of the Al-WTRs used in this study was calculated in the laboratory, and it equals 60.1 lbs./ft^3 and was used to calculate the amount of WTRs needed to cover all existing rain gardens, extended detention basins, and constructed wetlands in Fort Collins, as shown in **Figure 18**.

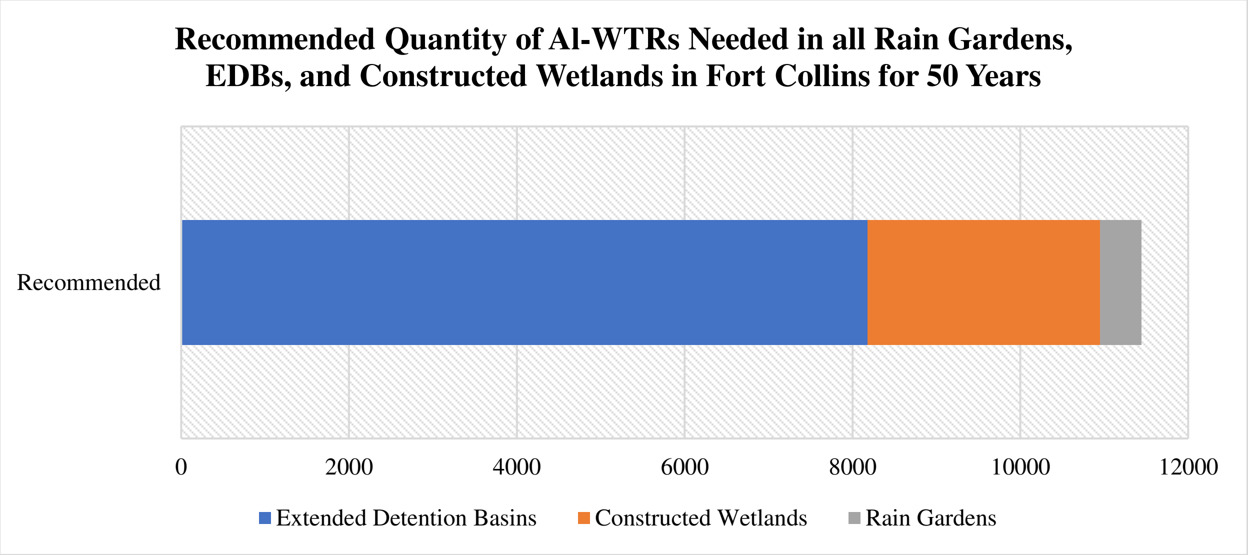

Figure 18: Recommended Quantity of Al-WTRs Needed to Cover All Rain Gardens, EDBs, and Constructed Wetlands in Fort Collins for 50 Years

The amount of Al-WTRs needed to cover the total BMP areas of rain gardens, extended detention basins, and constructed wetlands in Fort Collins equals 11,433 tons. However, that amount of Al-WTRs is more than what the City of Fort Collins produces annually at its treatment plant. As a result, **Table 2-10** below shows multiple scenarios of how the application of Al-WTRs would take place, assuming a percentage of coverage of the total BMP area and the desired amount of Al-WTRs to be applied.

The production of Al-WTRs in the water treatment plant in Fort Collins is around 1,000 tons annually. Based on the production rate, **Figure 19** below shows the approximate number of years it would take the City of Fort Collins to cover all existing rain gardens, extended detention basins, and constructed wetlands in the city using different application rates of Al-WTRs. ***Table 2-10*** shows that it would take 11 years to cover all existing BMPs in the city with a 0.5-inch layer of WTRs.

Table 2-10: Al-WTRs Quantities for Varying Coverage Scenarios of all BMPs in Fort Collins

Al-WTRs Quantity (tons)

		Depth of Application Layer (in)			
		0.5	0.75	1	2
Percent Coverage of Total BMP Area	**5 %**	572	857	1,143	2,287
	10 %	1,143	1,715	2,287	4,573
	20 %	2,287	3,430	4,573	9,146
	30 %	3,430	5,145	6,860	13,720
	40 %	4,573	6,860	9,146	18,293
	50 %	5,717	8,575	11,433	22,866
	60 %	6,860	10,290	13,720	27,439
	70 %	8,003	12,005	16,006	32,012
	80 %	9,146	13,720	18,293	36,586
	90 %	10,290	15,435	20,579	41,159
	100 %	11,433	17,150	22,866	45,732

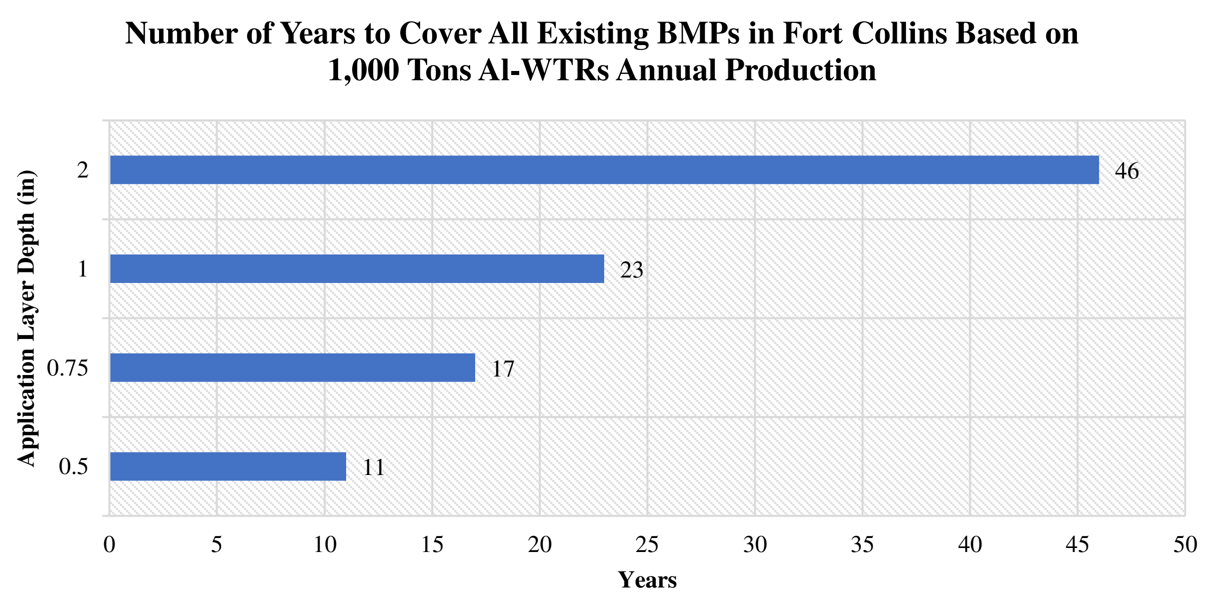

Figure 19: Approximate Number of Years to Cover All Existing BMPs Based on the Current Production of Al-WTRs in Fort Collins

2.4 Conclusion

For this study, the goal was to investigate nutrient pollution, specifically excess dissolved phosphorus, through the studying of Al-WTRs as a mechanism to mitigate the pollution. The approach involved quantifying the amount of dissolved phosphorus in stormwater runoff, the efficiency of Al-WTRs in dissolved phosphorus removal, and the required amount to Al-WTRs to achieve reliable removal rates.

The Simple Method was used to quantify the amounts of dissolved phosphorus introduced to the system through stormwater runoff. The Simple Method was to calculate dissolved phosphorus loads in Best Management Practices (BMPs). Dissolved phosphorus loads were calculated based on average precipitation of 13 years between 2007 and 2019. The runoff volumes, captured volumes, and treated volumes in 15 selected stormwater BMPs in Fort Collins, Colorado: five rain gardens, five extended detention basins, and five constructed wetlands. Concentrations of dissolved phosphorus were acquired from a column study for rain gardens and the International BMP Database for the other two BMP types. It was found that an average of 70 pounds of dissolved phosphorus is introduced annually in the selected BMPs and an excess of 3000 pounds throughout the whole city. Although most of the contributions came from extended detention basins and constructed wetlands due to large drainage areas, the higher concentrations of dissolved phosphorus in rain gardens effluents resulted in significant impacts despite their small drainage areas.

Al-WTRs efficiency in dissolved phosphorus removal was assessed by comparing pre- and post-application removal rates. Dissolved phosphorus quantities were calculated pre-application of Al-WTRs using effluent concentrations acquired from a column study and the BMP Database, in which DP concentration in rain gardens was 0.966 mg/l, 0.11 mg/l for extended detention basins, and 0.05 mg/l for constructed wetlands. After that, dissolved phosphorus loads were calculated post-application and using different settings to identify the most efficient removal rate. In rain gardens, a bottom-layer application of Al-WTRs resulted in the best removal of dissolved phosphorus with a 0.288 mg/l effluent concentration of DP, followed by mixing Al-WTRs with the filter media layers with 0.376 mg/l, and then the top-layer application with 0.844 mg/l and 0.866 mg/l for 1-inch layers and 0.5-inch layers, respectively.

For extended detention basins and constructed wetlands, it was assumed that they could achieve 93% and 90% removal rates, respectively, based on previous publications.

Finally, Phosphorus Storage Capacity (PSC) was used to quantify the minimum and ideal required amounts of Al-WTRs needed for efficient removal of dissolved phosphorus. It was found that the PCS of the Al-WTRs used in this study was 21.556 pounds dissolved phosphorus per one ton of Al-WTRs. From this rate, it was found that a minimum of 3.2 tons of Al-WTRs was needed to remove the dissolved phosphorus in the selected 15 BMPs, and 39 tons for all BMPs in Fort Collins. To ensure maximum efficiency and long-term reliable use of Al-WTRs, it is recommended to use 0.5 inch-layer of Al-WTRs regardless of the BMP area, in which 11,433 tons of Al-WTRs are to be used to cover the selected BMPs type in all of Fort Collins or 54.5 tons Al-WTRs per one acre of BMPs, and it would divert WTRs from the water treatment plant to stormwater practices for 11 years.

3.0 Chapter 3: Cost Estimation of Using Al-WTRs as a Stormwater BMPs Amendment in Fort Collins

3.1 Introduction

The goal of this chapter seeks to estimate the cost of current practices of Al-WTRs disposal in Fort Collins, Colorado. It also aims to estimate the cost of switching the use of Al-WTRs from disposal in landfills to utilize the material as an amendment in stormwater BMPs.

3.1.1 Objectives

Objectives of the chapter are to:

- Estimate the current and future cost of disposing of the Al-WTRs into the City's landfill.
- Estimate the cost of using Al-WTRs as an amendment in stormwater BMPs in Fort Collins for phosphorus removal.

3.1.2 Background

Phosphorus and nitrogen excessive discharge into water bodies is an emerging environmental issue. Excess nutrients or nutrient pollution can lead to numerous problems such as eutrophication, acidification, and water quality impairment (Oliver et al., 2011)(Hsieh et al., 2007). There are various sources that lead to excess nutrient disposal in water bodies, including atmospheric deposition, agriculture and irrigation, wastewater treatment plants, and stormwater runoff (USEPA 2020). Federal and local regulations were established to mitigate the effects of nutrient pollution, especially with the massive cost of the damages of this phenomenon. In this chapter, the focus will be on investigating the direct cost of phosphorus removal from stormwater in Fort Collins, Colorado.

Federal regulation of stormwater started in 1972 by expanding the Clean Water Act (CWA) to eliminate the disposal of pollutants into water bodies. In 1987, Section 402(p) was introduced with the purpose of including stormwater under the National Pollutant Discharge System (NPDES), a program that was controlling the discharges from industrial and municipal sources. Implementation of Section 402(p), which required permits for municipal separate storm sewer systems (MS4s), went through two phases in which Phase I took place in 1990 and was followed by Phase II in 1999. EPA regulation requires permittees to utilize control measures to mitigate the pollution of water bodies by stormwater runoff. In this study, the term of choice for these stormwater control measures will be Best Management Practices (BMPs).

The state of Colorado introduced Regulation 85 in 2012, in which the concentrations of phosphorus and nitrogen in wastewater treatment plant discharges have to meet a certain threshold (CDPHE, 2012). While the regulation does not set the same threshold for nonpoint sources in general and stormwater discharges specifically, it allows for water quality trading between point sources and nonpoint sources. It also recommends the use of Best Management Practices (BMPs) for nonpoint sources to reduce excess phosphorus and nitrogen discharges in receiving water bodies, with potential regulations that might take place in 2022 if deemed necessary (CSU, 2020).

The cost of nutrient pollution can be divided into two types; direct cost and indirect or external cost (USEPA, 2015). The first type is the cost of nutrient elimination at the sources point, which is generally carried by federal and local agencies. After an outbreak of blue-green algae in Grand Lake St. Marys in 2010, the estimated cost incurred by the City of Celina was more than $13 million for the installation and operation of treatment controls and algae testing equipment (Davenport & Drake, 2011). (Dunlap et al., 2015) investigated the total costs incurred by the City of Waco, Texas between 2002-2012, which were spent to address poor drinking water quality due to nutrient pollution, in which the estimation was $70.2 million mostly for upgrades of drinking water treatment equipment in addition to $10.3 million loss in revenue. According to Regulation 85 in Colorado, discharges from WWTPs shall not have more than 15 mg/l total nitrogen and more than 1 mg/l total phosphorus. However, to achieve these concentrations, necessary upgrades to WWTPs technologies and equipment have to take place, which will have direct costs on the operating agencies. To reach 15 mg/l total nitrogen, it can cost up to 22.17 $/gpd in capital cost and 0.51 $/gpd in O&M, while the capital cost of achieving 1 mg/l total phosphorus can be up to 22.17 or 98.40 $/gpd depending the adopted technology with O&M cost between 1.85-2.33 $/gpd.

The other type of cost is related to the impacts or damages of excess nutrients, which is referred to as external costs; these costs include the economic losses in tourism and recreation, commercial fishing, property values, and human health (USEPA, 2015). In 2007, algal blooms in the Grand Lake St. Marys in Ohio had affected water-based recreation, and the estimated cost of the damages to local businesses was $35-$45 million (Davenport & Drake, 2011). In Texas, the effects of algal blooms on local businesses in the Possum King Lake vicinity resulted in a 5% decrease in the total economic output of the affected counties in 2001, along with a 57% decline in the state park visitation during the same year (Oh & Ditton, 2005). After an algal bloom that hit southern New England water in 2005, shellfish beds in northeastern states, including Maine and New Hampshire, were closed during the harvesting season, and the losses were estimated to be around $3 million (Jin et al., 2008). An outbreak of Domoic Acid (DA) produced by algae on the west coast of the United States in 1991, crab fishing losses in southwest Washington were estimated to be $7 million (Lewitus et al., 2012).

With increasing population and urban development, nutrient pollution is going to keep rising along with the costs to eliminate the problem and external costs of damages to local economies. Regulations are getting more stringent due to the urgency to find a proper solution to the issue, although it focuses mostly on point sources of nutrients right now. The needed strategy to address nutrient pollution has to integrate the use of all available tools and tackle all known sources such as agriculture and stormwater. The utilization of BMPs in stormwater can be a cost-effective and long-term mechanism to reduce the discharge of phosphorus and nitrogen into water bodies. WTRs have shown great potential to eliminate excess nutrients, and with the proper use of this material, stormwater can be of great benefit in reducing the net generation of nutrients into the ecosystem.

3.2 Methodology

The current practices of the City of Fort Collins are to dispose of the WTRs produced in the drinking water treatment plant in the Larimer County Landfill. The current site of the landfill located on Taft Hill Road is expected to be full by 2024, and the City is looking for cost-effective alternatives. One alternative to landfilling WTRs in the landfill is to utilize the material into stormwater BMPs to eliminate excess nutrients from being discharged into water bodies. This chapter will estimate the cost of three scenarios; disposing of WTRs into the current landfill location, disposing WTRs into a new landfill location, and using WTRs as an amendment into selected stormwater BMPs (rain gardens, extended detention basins, and constructed wetlands) around Fort Collins.

The total land area of Fort Collins is around 38,000 acres, and the total drainage area of existing rain gardens, extended detention basins, and constructed wetlands in Fort Collins equals around 8,750 acres treated by around 210 acres of BMPs. The cost estimation will be based on an application of a 0.5 inch-layer of WTRs, as described in **2.3** of this study, which means that an acre of BMPs will require 54.5 tons of Al-WTRs. The annual production of Al-WTRs in the treatment plant in Fort Collins is estimated to be around 1,000 tons, which could cover around 10% of the total BMPs area of all rain gardens, extended detention basins, and constructed wetlands, as established in **Table 2-10. Figure 20** shows the distribution of BMPs around Fort Collins.

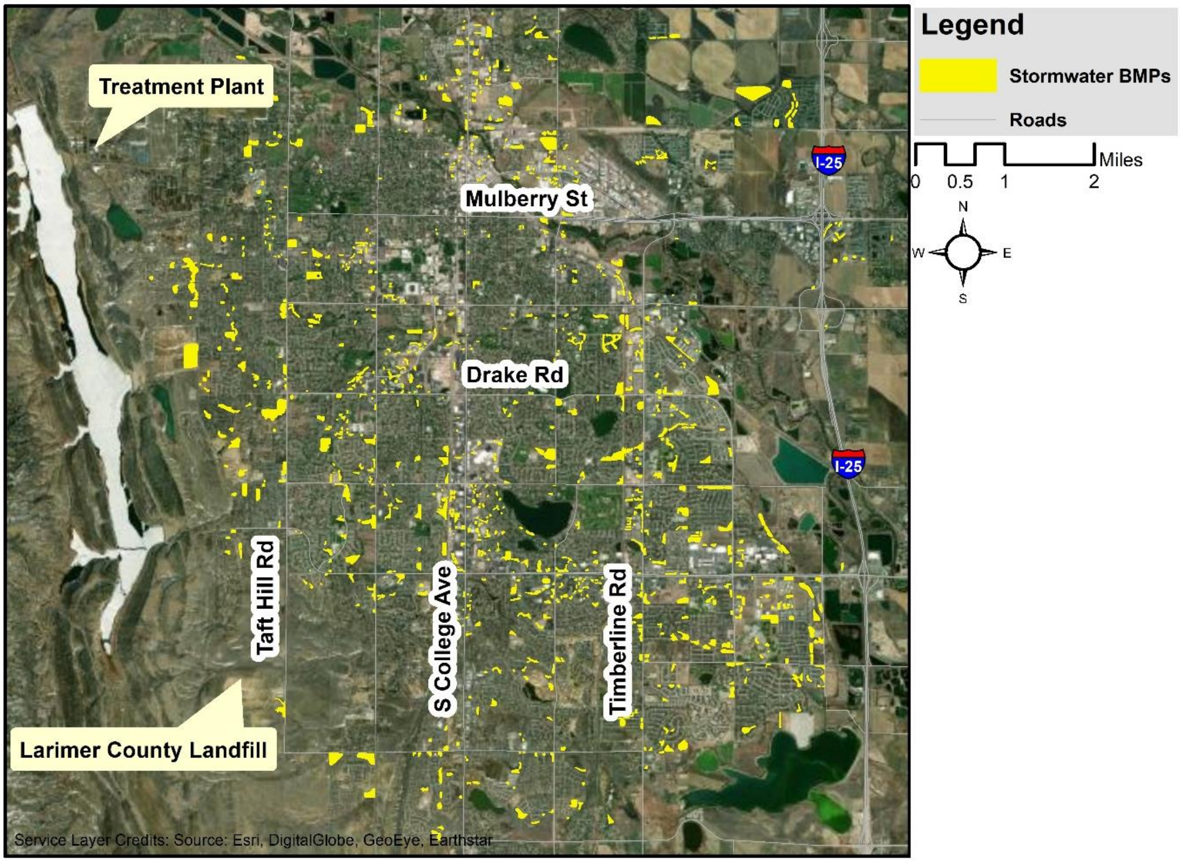

Figure 20: Distribution of Stormwater BMPs around Fort Collins

3.2.1 Cost Estimation Factors

3.2.1.1 Transportation

Transportation is the main factor in all three scenarios, and it includes contract fees for the trucks used in the process, the capacity of trucks, and fuel cost. Two trucking companies in

Fort Collins were contacted for data collection, and both companies had worked with the City of Fort Collins for WTRs transportation from the treatment plant to the landfill. The parameters used to estimate the transportation fees included destination, distance, loads transported, and time needed to finish the job. In the first scenario, the destination was the Larimer County Landfill located on Taft Hill Road, and the on-way distance covered per trip was 8.4 road miles, as shown in **Figure 21**. Trucks used were the biggest available with 25 tons maximum capacity and fuel consumption of five miles per gallon. The average time required for one trip from the treatment plant to the landfill, including loading, traffic, and unloading, was one hour. In this scenario, the trucking companies were paid $1,000 per truck for a full day job.

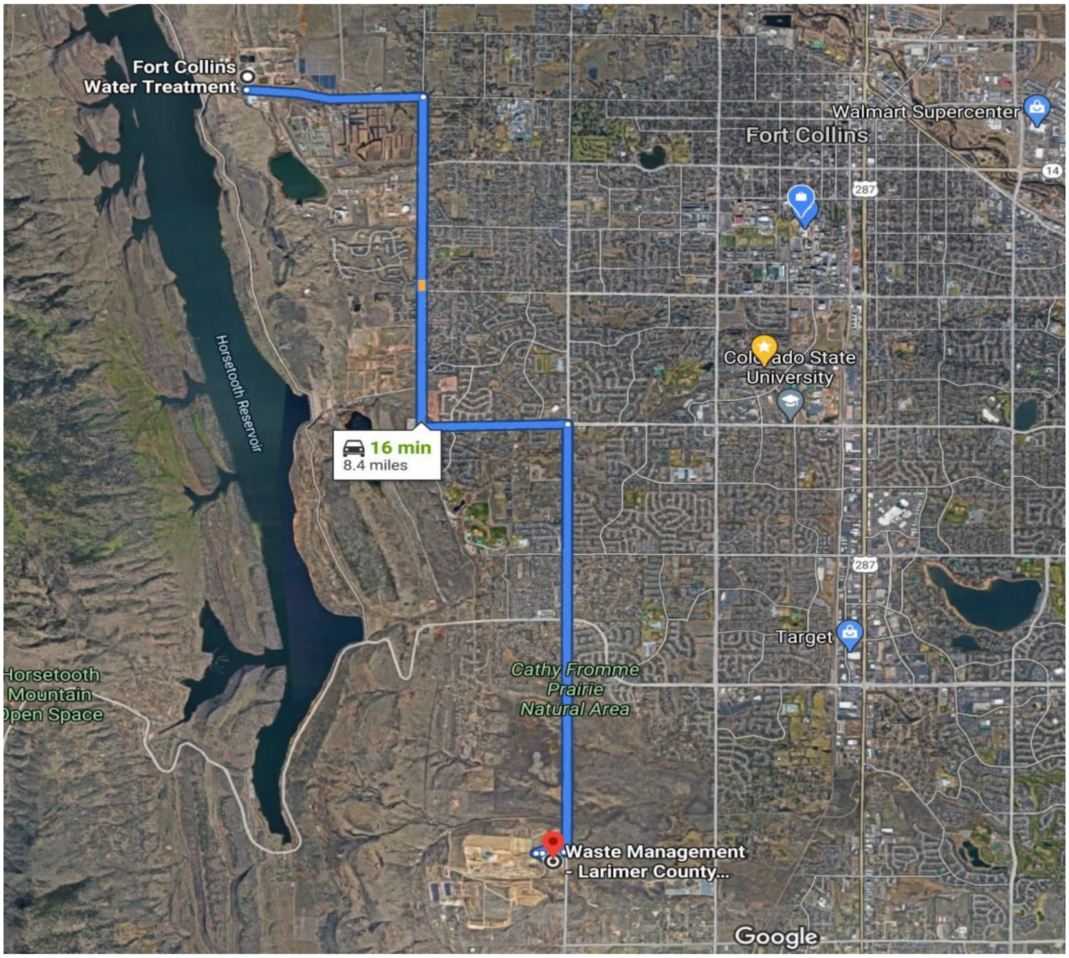

Figure 21: Driving Distance between the Treatment Plant and the County Landfill in Fort Collins

In the second scenario, the distance was doubled based on the information provided by the City of Fort Collins, which affected the time required per trip, fuel cost, and the number of trucks needed. The time required to finish one trip was multiplied by 1.5, which meant more trucks were needed to transport the whole amount of Al-WTRs to the landfill in one day, and higher fuel cost. This scenario was assumed to take place in 2024, and it was assumed that the fee per truck would increase 6.25% annually, which means that by 2024, the trucking company would have to be paid $1,250 per truck for 8 hours.

In the third scenario, Al-WTRs would not be transported to a landfill, but they would be transported to stormwater BMPs scattered around Fort Collins. The distance was calculated based on the average between the distance needed to cover the BMPs closest to the treatment plant and the distance needed to cover BMPs farthest from the treatment plant. Also, it was assumed that one trip would need 2 hours on average due to higher traffic, increased stoppage time, and partial unloading. This scenario was assumed to occur in 2024, so the fee per truck was also assumed to be $1,250 for 8 hours.

In all three scenarios, trucks with a maximum capacity of 25 tons were assumed to be used. Fuel consumption of five miles per gallon was used based on the information provided by the trucking companies. The estimation of transportation costs was done based on the assumption that the treatment plant's total production of Al-WTRs had to be transported in one day (8 hours). According to the trucking companies, fuel cost is separate from the trucking fees, as fuel costs are calculated based on the actual consumption of the trucks. Fuel costs were calculated based on the average distances covered by all trucks, using the average diesel prices of 2019.

3.2.1.2 Tipping/Application

The second factor in the cost estimation was the tipping fees paid to the Larimer County Landfills as in the first two scenarios, or the Al-WTRs application fees paid for an applicator/trucking companies as in the third scenario. The Larimer County Landfill has set a tipping fee based on the type of the material and weight of the load to be landfilled, as shown in **Table 3-1**. Tipping fees at the Larimer County Landfill were increased in 2018 by almost 10% due to the increasing operating costs the facility, and are expected to increase again in the next couple of years, as the landfill is expected to reach its full capacity by 2024.

Table 3-1: Larimer County Landfill 2020 Fees

Waste Type	2020 Fee	2020 State Surcharge	2020 Total Fee
Green Waste	$6 per cubic yard	recycled - no surcharge	$6 per cubic yard
Compacted	$8.20 per cubic yard	35₵ + 15₵ per CY commercial diversion fee	$8.20 per cubic yard + CO surcharge
Rubble, concrete, dirt, sludge	$18 per cubic yard	9₵ per car 18₵ per truck 35₵ per CY commercial + 15₵ per CY commercial diversion fee	$18 per cubic yard + CO surcharge

For the first scenario, a tipping fee of $18 per cubic yard of Al-WTRs was used, in addition to a state surcharge for using trucks. In the second scenario, tipping fees were assumed to increase by 10% by 2024, similar to what happened in 2018. With that assumption, a tipping fee of $20 per cubic yard was used in the cost estimation of the second scenario, including the state surcharge.

For the third scenario, there were no tipping fees included in the cost estimation because the Al-WTRs would not be landfilled, but it would be applied on top of stormwater BMPs. The application fee estimation process was similar to that of the transportation fees, in which a contractor was contacted for information about applicators fees. Since rain gardens are smaller in area compared to extended detention basins and constructed wetlands, trucks would not be able to apply the Al-WTRs directly on top of it and would require special equipment to do so. Based on that, two types of trucks were assumed to be used in this process: small trucks for rain gardens and big trucks for extended detention basins and constructed wetlands.

For both types of trucks, it was assumed that they would cover an average distance of 30 miles per day. Big trucks had a load capacity of 15 tons and fuel consumption of 5 miles per gallon, while small trucks have a load capacity of 5 tons and fuel consumption of 10 miles to the gallon. It was assumed that small trucks would be able to apply 25 tons in 2.5 hours due to limited accessibility, while big trucks would be able to apply 25 tons in 1 hour. In this scenario, big trucks would cost $850 per truck, while small trucks would cost $500 per truck, and both costs would be for 8 hours. The cost of fuel was estimated using average diesel prices of 2019 in Fort Collins.

In this scenario, the cost of application depended on the type of truck used. It was estimated that there are around 16 acres of existing rain gardens in Fort Collins, and each acre would require 54.5 tons of Al-WTRs, which equals 872 tons for all existing rain gardens. This meant that the annual production tons of Al-WTRs would be sufficient to cover all the rain gardens in Fort Collins, and there would be no need to utilize the big trucks that year.

3.2.1.3 Staff

The final factor for the cost estimation was the compensation paid for staff time and labor. It was assumed that there would be one worker with each truck, in which their responsibility would include loading, unloading, and supervision of Al-WTRs application as in the third scenario. The compensation was estimated to be $20 per hour based on the information collected from the trucking companies, although staff in this chapter might include City workers.

3.3 Results and Discussion

The cost estimation of Al-WTRs uses Fort Collins was based on three main factors: transportation fees, tipping/application fees, and staff time compensation. Three scenarios were considered in this chapter; the first scenario, which is the current practice by the City of Fort Collins, estimated the cost of disposing of the Al-WTRs produced in the water treatment plant of Fort Collins to the Larimer County Landfill. The second scenario, which is expected to take place in 2024, estimated the cost of disposing of the same Al-WTRs to a new landfill, and the third scenario investigated the cost of utilizing the Al-WTRs into stormwater BMPs around Fort Collins. The amount of Al-WTRs produced annually by the treatment plant is around 1,000 tons.

3.3.1 Scenario 1 – Disposing of Al-WTRs in the Larimer County Landfill

As shown in **Table 3-2**, the total cost for the disposal of 1,000 tons of Al-WTRs to the Larimer County Landfill is $28,183.35. The biggest component in this estimation is the tipping fees that have to be paid to the landfill, then transportation trucks' fees, after which come staff compensation and fuel, respectively. This scenario represents the current practice by the City of Fort Collins, but it is anticipated to stop in 2024 as the Larimer County Landfill is expected to reach full capacity in that year.

For the cost estimation of transportation, trucking contractors in Fort Collins were contacted for data. Trucks that would be used have a maximum capacity of 25 tons and a mileage of five miles per gallon. Based on the data provided by the contractors, it would take one hour for a truck to transport one load from the water treatment plant to the landfill, including loading and unloading. Trucks were expected to be paid for a full 8-hour day, regardless of the number of trips. The distance covered during that day would be reflected in the fuel cost estimation.

The maximum capacity a truck can transport per trip is 25 tons and could do eight loads in a day. For 1,000 tons of Al-WTRs and eight trips a day per truck, five trucks would be needed to transport the whole amount in one day. Each truck would be paid $1,000, which results in $5,000 for all trucks, not including fuel compensation. If a truck did not work for a full day, the fee would decrease and would be based on an agreement between the contractor and the City.

Table 3-2: Cost Estimation of Scenario 1

Scenario 1	
Transportation - Trucks	
Time to transport one load (hrs.)	1
Fee per truck per day	$1,000
Number of loads per day	8
Number of trucks needed	5
Total Trucking Fees	$5,000
Transportation - Fuel	
Diesel cost (per gallon)	$2.90
Average distance (miles)	68
Trucks mileage (mpg)	5
Cost of fuel per truck	$39.44
Total cost of fuel	$197.20
Total Cost of Transportation	$5,197.20
Tipping Fees	
Al-WTRs volume (cubic yards)	1232.51
Landfill fee per cubic yard	$18
State surcharge per truck	$0.18
Total cost of tipping	$22,186.15
Staff Compensation	
Working hours	8
Average compensation (per hour)	$20
Number of workers	5
Total Cost of Staff	$800.00
Total Cost	**$28,183.35**

For fuel cost estimation, average diesel prices of 2019 in Fort Collins were used because 2020 prices were abnormally lower than the average. The average distance a truck would cover was estimated based on the driving distance from the treatment plant to the landfill, which is 8.5 miles, multiplied by the expected number of trips, which would equal 68 miles per day. The fuel consumption of a truck was 5 miles per gallon, which results in $39.44 in fuel compensation per truck and $197.20 for all five trucks. The total transportation cost would equal $5197.20, as shown in **Table 3-2**.

For tipping fees, the Larimer County Landfill had set a fee of $18 per cubic yard of Al-WTRs, in addition to a state surcharge of $0.18 per truck. The density of Al-WTRs is 60.1 lbs./ft^3, so 1,000 tons would equal 1,232.51 cubic yards. This, in addition to the state surcharge, would result in $22,186.15 in tipping fees that would have paid to the landfill. The final component of the cost estimation is staff compensation, in which it was assumed that each truck would need one worker, and $20 would be paid per hour for eight hours, which resulted in $800.

This scenario is the current practice by the City of Fort Collins. According to the City, the landfill's current location is expected to reach full capacity by 2024, and the plan is to move to a new location twice as far. The new location is expected to increase landfill tipping fees, and the higher distance will result in an increase in fuel costs. Tipping fees for Al-WTRs were increased in 2018 by 10% and is expected to increase again in the next four years by a similar percentage. Also, it is expected that trucking fees will increase by 2024 due to higher living expenses and operation and maintenance costs for the contractors. Scenario 2 in this chapter investigated the expected increase in the costs of disposal of the Al-WTRs by 2024.

3.3.2 Scenario 2 - Disposing of Al-WTRs in the New Landfill

The second scenario in this chapter is similar to the first scenario but with a few differences. The destination was changed to the new location of the landfill, which was estimated to be twice as far. This scenario was expected to take place in 2024, and this was reflected mainly in the tipping fees and trucking fees. **Table 3-3** below shows the total estimated cost of the disposal of Al-WTRs in the second scenario.

Table 3-3: Cost Estimation of Scenario 2

Scenario 2	
Transportation - Trucks	
Time to transfer one load (hrs.)	1.5
Fee per truck per day	$1,250
Number of loads per day	5
Number of trucks needed	8
Total Trucking Fees	$10,000
Transportation - Fuel	
Diesel cost (per gallon)	$2.90
Average distance (miles)	85
Trucks mileage (mpg)	5
Cost of fuel per truck	$49.30
Total Cost of Fuel	$394.40
Total Cost of Transportation	$10,394.40
Tipping Fees	
Al-WTRs volume (cubic yards)	1232.51
Landfill fee per cubic yard	$19.8
State surcharge per truck	$0.20
Total Cost of Tipping	$24,405.36
Staff Compensation	
Working hours	8
Average compensation (per hour)	$20
Number of workers (per truck)	8
Total Cost of Staff	$1,280.00
Total Cost	**$36,079.76**

The total estimated cost of the second scenario was $36,079.76, which is almost $8,000 more than the first scenario. The difference was due to increased fees for trucks, a higher number of required trucks for transportation, and higher tipping fees. Fuel prices and staff compensation were assumed to remain the same as the first scenario. Since this scenario was expected to start in 2024, it was assumed that the fees paid for trucks would increase by 25% or 6.25% annually, which meant that fees per truck would equal $1,250 per day.

The location of the new landfill was unknown, but it was assumed to be twice as far based on information from the City. This meant that a trip from the treatment plant to the landfill would be 17 miles and that it would take a truck 1.5 hours to finish one trip, including loading and unloading. The number of trucks needed to transport the Al-WTRs was increased to eight, with each truck making five trips that day. As a result, the total fees that would be paid for trucks equals $10,000, which is double the amount of the first scenario. In the fuel costs estimation, diesel prices were assumed to remain the same as in the first scenario. However, the distance was increased to 85 miles per truck, assuming that it would cover 17 miles five times, which resulted in fuel compensation of $394.4 for all trucks.

Tipping fees were the most significant expense in this cost estimation, with $24,405.36 would be paid to the landfill. Tipping fees were increased in 2018 by 10%, and it was assumed that it would increase again by the same percentage by 2024. The landfill fee would be $19.80 per cubic yard, in addition to $0.20 per truck as a state surcharge, with 1232.5 cubic yards of Al-WTRs that would be landfilled in addition to eight trucks. Staff compensation was assumed to remain the same as in the first scenario with $20 per hour and one worker per truck, but the higher number of trucks in this scenario resulted in increased expense from $800 to $1200.

3.3.3 Scenario 3 – Al-WTRs as an Amendment in Stormwater BMPs

The third scenario is different from the first two scenarios because Al-WTRs would not be disposed of in a landfill, but they would be utilized into stormwater BMPs around Fort Collins. This meant that there would be no tipping fees as they were replaced with application fees, which resulted in a lower expense. In this scenario, Al-WTRs would be transported to different locations around the city – shown in **Figure 20** – and would be applied onto the stormwater BMPs. In this chapter, it was assumed that a 0.5-inch layer would be applied on top of all rain gardens, extended detention basins, and constructed wetlands in Fort Collins. The total area of those BMPs is estimated to be 209 acres, with each acre requiring 54.5 tons of Al-WTRs. This scenario was assumed to start in 2024.

The 1,000 tons of Al-WTRs produced each year by the treatment plant would cover 9% of the total selected BMPs types in Fort Collins. Out of the 209 acres, rain gardens' total area is estimated to be 18 acres, which means that one year's production of Al-WTRs would cover all that area. Due to the smaller area of rain gardens compared to extended detention basins and constructed wetlands, different tools were assumed to be used in applying WTRs, which was reflected in the cost estimation. Information regarding the costs of the Al-WTRs application was collected from several contractors that offer similar services.

For rain gardens, smaller trucks with a load capacity of five tons would be used for easier accessibility, better fuel consumption, and cheaper fees. For extended detention basins and constructed wetlands, bigger trucks with a load capacity of 15 tons were used. These trucks offer faster Al-WTRs application in larger areas, but they have higher fuel consumption and higher fees. It was assumed that rain gardens would be covered in the first year, and then after that would be extended detention basins and constructed wetlands.

Table 3-4: Cost Estimation of Scenario 3 - Rain Gardens

Scenario 3 - Rain Gardens	
Transportation - Trucks	
Time to transfer one load (hrs.)	2
Fee per truck per day	$1,250
Number of loads per day	4
Number of trucks needed	10
Total Trucking Fees	$12,500
Transportation - Fuel	
Diesel cost (per gallon)	$2.90
Average distance (miles)	68

Trucks mileage (mpg)	5
Cost of fuel per truck	$39.44
Total Cost of Fuel	$394.40
Total Cost of Transportation	$12,894.40
Application - Trucks	
Time to apply one load (hrs.)	2.5
Fee per truck per day	$500
Number of loads per day	3
Number of trucks needed	14
Total Trucking Fees	$7,000
Application - Fuel	
Diesel cost (per gallon)	$2.90
Average distance (miles)	60
Trucks mileage (mpg)	10
Cost of fuel per truck	$17.40
Total Cost of Fuel	$243.60
Total Cost of Application	$7,243.60
Staff Compensation	
Working hours	8
Average compensation (per hour)	$20
Number of workers (per Truck)	24
Total Cost of Staff	$3,840.00
Total Cost	**$23,978.00**

As shown in **Table 3-4**, the total cost of the third scenario in the case of the application of Al-WTRs in rain gardens is $23,978, which is almost 4,000 less than the first scenario and $12,000 than the second scenario. This cost estimation was for one year only, assuming that the City of Fort Collins would opt to cover all rain gardens before moving on with the other two BMPs. The first component of this estimation was the transportation of Al-WTRs to BMPs locations around the city. Due to the variance of BMPs' locations and increased traffic and stoppage times, it was assumed that it would take a truck two hours to transport 25 tons of Al-WTRs to their destination. One truck could make four trips a day, which meant that ten trucks would be needed to finish the job. Trucks’ fees were assumed to be $1,250 per truck, which is the same as the second scenario. For fuel costs, the prices of diesel were assumed to be the same as the other two scenarios. The distance was estimated based on the longest trip a truck would have to make from the treatment plant multiplied by four, which resulted in 68 miles. The total cost of transportation was estimated to be $12,894.

Application fees were estimated in a similar way to transportation fees. In the case of rain gardens, small trucks with 5 tons of load capacity were used, with a fee of $500 per truck. It was estimated that it would take a truck 2.5 hours to apply 25 tons of Al-WTRs on top of rain gardens, which meant that one truck could finish three loads per day. That resulted in needing 14 trucks to apply the 1,000 tons of Al-WTRs in one day, with an estimated cost of $7,000. For fuel cost estimation, small trucks had a fuel consumption of 10 miles per gallon, and they were assumed to cover 60 miles on average. For staff compensation, the hourly wage was assumed to remain at $20 per hour, and one worker would be needed per truck. Since there were more trucks in this scenario and assuming one worker per truck, 24 workers were needed, with total compensation of $3,840 per day.

Table 3-5: Cost Estimation of Scenario 3 - Extended Detention Basins and Constructed Wetlands

Scenario 3 - EDBs and Constructed Wetlands	
Transportation - Trucks	
Time to transfer one load (hrs.)	2
Fee per truck per day	$1,250
Number of loads per day	4
Number of trucks needed	10
Total Trucking Fees	$12,500
Transportation - Fuel	
Diesel cost (per gallon)	$2.90
Average distance (miles)	68
Trucks mileage (mpg)	5
Cost of fuel per truck	$39.44
Total Cost of Fuel	$394.40

Total Cost of Transportation	$12,894.40
Application - Trucks	
Time to apply one load (hrs.)	1.5
Fee per truck per day	$850
Number of loads per day	5
Number of trucks needed	8
Total Trucking Fees	$6,800
Application - Fuel	
Diesel cost (per gallon)	$2.90
Average distance (miles)	60
Trucks mileage (mpg)	5
Cost of fuel per truck	$34.80
Total Cost of Fuel	$278.40
Total Cost of Application	$7,078.40
Staff Compensation	
Working hours	8
Average compensation (per hour)	$20
Number of workers (per Truck)	18
Total Cost of Staff	$2,880.00
Total Cost	**$22,852.80**

Table 3-5 shows the estimated cost of the third scenario for Al-WTRs application on extended detention basins and constructed wetlands. The total estimated cost was around $22,853, which is $5,000 cheaper than the first scenario and $13,000 than the second scenario. The estimated cost for transporting Al-WTRs to BMPs' locations was the same as for rain gardens, and it was $12,894. The difference was in the cost of application since the trucks used in the application process were bigger than those used for rain gardens. While the bigger applicators had a higher fee per truck with $850, the higher capacity of 15 tons and the faster application time resulted in fewer trucks that would be used.

With an estimated time of 1.5 hours to apply 25 tons of Al-WTRs, one truck could apply five loads per day as opposed to only three by the small trucks; eight trucks were required to apply the 1,000 tons of Al-WTRs in one day. It was also assumed that a truck would cover 60 miles in a day, and with fuel consumption of 5 miles to the gallon, fuel cost for all trucks was estimated to $278.4 and a total cost of application around $7000. Staff hourly compensation was assumed to remain at $20 per hour, and with a total of 18 workers needed, the total compensation for staff was estimated to be $2,880.

The total area of extended detention basins and constructed wetlands in Fort Collins is estimated to be around 194 acres, in addition to 16 acres of rain gardens. This scenario estimated the cost of applying 1,000 tons on 9% of the total area, which means that it would take the City of Fort Collins ten years to cover the whole area, assuming that the annual production of Al-WTRs and the area of BMPs remain the same for that period. This means that the City would save theoretically an average of $13,000 annually for 11 years from the application of Al-WTRs into stormwater BMPs.

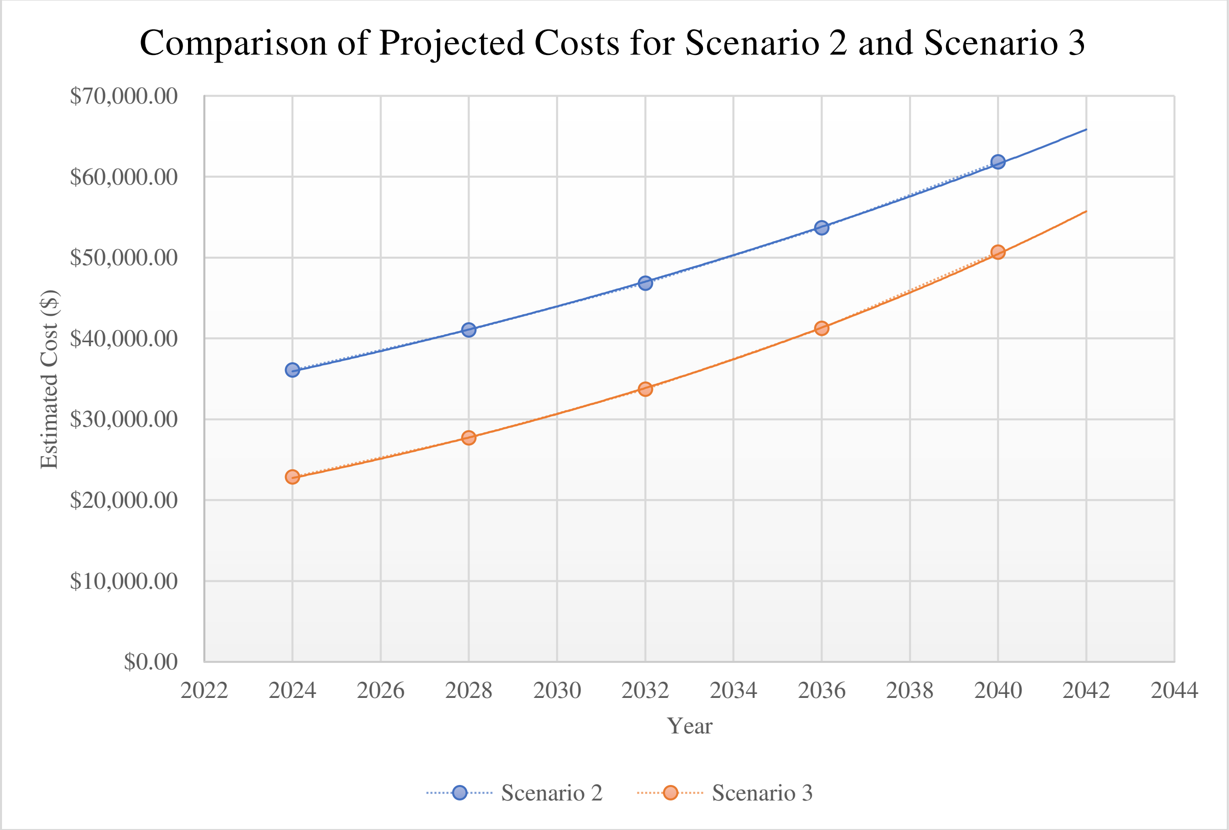

Figure 22: Comparison of Project Costs for Scenario 2 and Scenario 3

Assuming that fuel prices and staff compensation will remain the same as in 2020, **Figure 22** shows a comparison of the projected costs of the second and third scenarios. It was assumed that trucks' fees and tipping fees are the only variables along the next 22 years. Trucks' fees are assumed to increase by 6.25% annually, while tipping fees are assumed to increase by 10% every four years. As shown in the figure, disposing of the Al-WTRs into the landfill will be more expensive for the City, at least for the next 20 years, in addition to no benefits. On the other hand, reusing Al-WTRs in stormwater BMPs provides numerous benefits for the City of Fort Collins financially and environmentally. As established in chapter two of this study, Al-WTRs is a cost-effective tool in eliminating excess nutrients in general and phosphorus in specific.

3.3.4 Triple Bottom Analysis

Table 3-6: Triple Bottom Line Analysis of All Scenarios

	Economic	**Environmental**	**Social**
Scenario 1 & 2	(-) Increasing Tipping Fees. (-) Landfills have specific capacities. (-) Increasing land ownership prices and rentals fees.	(+) No concerns about WTRs landfilling. (-) Lost of Al-WTRs benefits in pollutant removal.	(-) Land value near landfills might decrease.
Scenario 3	(+) Application in existing BMPs costs less than landfilling. (+) Application in yet-to-be constructed BMPs cost even less than in existing BMPs.	(+) Sustainable use of waste material. (+) Aligns with Zero Waste Strategy – No waste in landfills. (+) Effective removal of dissolved phosphorus. (+) An advantage for the City against any potential regulations for stormwater nutrient discharges. (-) Concerns of radioactive and aluminum export.	(+) Improved water quality for potable and recreational use. (-) Requires CDPHE approval.

The selection of the best scenario does not depend only on the economic value but also on its environmental and social impacts. The first and second scenarios, on the one hand, have higher costs than the third one, and it is expected to increase with time since tipping fees and land ownership costs are expected to increase. On the other hand, landfilling WTRs will eliminate the concerns of WTRs exporting aluminum or radioactive material to water bodies. However, the excellent potential for WTRs to remove dissolved phosphorus from stormwater runoff will be wasted. Additionally, with the expected increase in WTRs production, more lands will be utilized as landfills, which might affect the nearby land value and affect landowners.

For the third scenario, the economic value of applying WTRs in existing stormwater BMPs was lower than landfilling the material. Moreover, the cost is expected to be even lower for new BMPs since transportation costs will decrease. Meanwhile, there are several environmental benefits for WTRs use in BMPs. WTRs can be a valuable tool in removing dissolved phosphorus in specific and other dissolved pollutants in general. Also, utilizing WTRs in stormwater BMPs ensures sustainable use of this waste material since the current production is expected to increase with population growth.

While Regulation 85 has focused on point source discharges, for now, there is a potential for future regulations on nonpoint sources such as stormwater. By utilizing Al-WTRs in stormwater BMPs, the City will have an advantage in achieving limited discharges of nutrients into receiving water bodies. Also, Regulation 85 offers the permittees a chance for water quality trading between point sources and nonpoint sources, and by eliminating excess nutrients from stormwater, the City could potentially save on the expenses paid for controlling point source nutrient pollution. In addition to that., the City of Fort Collins had set its Zero Waste Strategy in 1999, which is a long-term plan to divert 50% of waste from landfills, and then in 2013, updated the strategy to reach zero waste by 2030 (Zero Waste Associates, 2013). Utilizing the annually produced Al-WTRs into stormwater BMPs aligns with the City's plan to achieve that vision.

However, there are multiple concerns about using WTRs, including exporting harmful substances such as aluminum and radioactive materials into effluent leaving the BMPs, which requires more research to address those issues. Also, the Department of Public Health and Environment in Colorado (CDPHE) has to approve the integration of WTRs into the City's stormwater BMPs system. Nevertheless, the expected improvement of water quality will result in safe potable use of the water resources in the city in addition to boosted aquatic recreational activities around the city.

3.4 Conclusion

This chapter aimed to estimate the costs of different methods of Al-WTRs disposal in Fort Collins, Colorado. Three scenarios were investigated; the first scenario estimated the cost of disposing of Al-WTRs into the Larimer County Landfill, which is the current practice by the City. The second scenario estimated the costs of Al-WTRs disposal into a new location of the landfill, while the third scenario assessed the costs of using Al-WTRs as an amendment in stormwater BMPs. The water treatment plant in Fort Collins produces an average of 1,000 tons of Al-WTRs annually, and all of that amount is disposed of in the Larimer County Landfill. The cost estimation of the three scenarios was based on transportation costs, tipping/application fees, and staff compensation. Transportation and application costs data was collected from several trucking contractors, and tipping fees were collected from the website of the Larimer County Landfill.

The total estimated cost of the first scenario was $28,183.35, in which the cost of transportation was $5,197, the cost of tipping $22,186, and staff compensation were around

$800. Five trucks with a load capacity of 25 tons were needed to transport the 1,000 tons of Al-WTRs, with each truck costing $1000. Fuel compensation was calculated based on the fuel consumption of the trucks and the average distance expected to be covered by the trucks from the treatment plant to the landfill, which was 68 miles, based on the average diesel prices of 2019 in Fort Collins. Tipping fees were estimated based on the landfill fees per cubic yard of Al-WTRs, which was $18, while the total amount of Al-WTRs was estimated to be around 1,232 cubic yards. For staff time compensation, it was assumed that one worker would be needed per truck and would be compensated by $20 per hour.

The second scenario was the most expensive one, with a total estimated cost of $36,079.76, in which the cost of transportation was $10,394.40, the cost of tipping $24,405.36, and $1,280 for staff compensation. In this scenario, the location of the new landfill was estimated to be twice as far of the current one; this resulted in longer trips and more trucks. Also, this scenario was expected to start in 2024, which was reflected in the tipping fees as they were increased by 10%, and the trucks' fees, which was increased by 25%. Eight trucks with a load capacity of 25 tons were needed, with each truck costing $1,250. The average distance increased from 68 to 85 miles, while the fuel prices were assumed to remain the same as in the first scenario. With the 10% increase, the tipping fees were raised to $19.8 per cubic yard compared to $18 in the first scenario. Staff compensation was calculated in the same way as the first scenario, and it was assumed that the hourly compensation would remain at $20 per hour.

This scenario was different from the first two, in which the Al-WTRs would not be landfilled, but instead, they would be applied to stormwater BMPs around Fort Collins. The selected BMPs were rain gardens, extended detention basins, and constructed wetlands. The annual production of Al-WTRs would be able to cover 9% of the total BMPs area in one year, which meant that it would take the City ten years to cover all the extended detention basins and constructed wetlands, and one additional year for rain gardens. The annual production of Al-WTRs would cover all rain gardens in one year with an estimated cost of $23,978, while the estimated cost for the other two BMPs would be $22,852.80.

For transportation of the Al-WTRs in this scenario, the destination was variable and depended on the location of the BMPs. It was assumed that it would take two hours for a truck to transport 25 tons from the treatment plant to the desired location. Ten trucks with a load capacity of 25 tons were needed, with each truck making four trips in a day and costing $1,250. The distance was calculated based on the longest route from the treatment plan to the BMPs' location four times a day, which equaled 68 miles, and fuel prices were assumed to remain the same as the first scenario.

In this scenario, the destination of the Al-WTRs was to stormwater BMPs, which meant there were no tipping fees. Instead, the cost of applying the Al-WTRs was estimated based on data collected by contractors. For rain gardens, small trucks with a load capacity of 5 tons were assumed to be used for easier accessibility. Fourteen trucks were expected to be used as each truck would be able to apply 25 tons in 2.5 hours, and the fee per truck was $500. For extended detention basins and constructed wetlands, trucks with a load capacity of 15 tons were used for easier and faster application rates. Eight trucks were needed as it would take one truck 1.5 hours to apply 25 tons of Al-WTRs, with a fee of $850 per truck. For fuel compensation, a distance of 60 miles was assumed to be covered for moving between different BMPs and operating the equipment, with fuel prices assumed to remain the same as in the first scenario. Staff compensation was calculated based on an hourly wage of $20 and the assumption that one worker would be needed per truck, whether it was for transportation or application of Al-WTRs.

The third scenario was found to be the cheapest compared to the other two scenarios, as the City would be able to save an average of $13,000 for the next eleven years compared to the second scenario. Also, this scenario would align with the Zero Waste Vision set by the City of Fort Collins, which aims to eliminate the landfilling of waste by 2030. The utilization of Al-WTRs offers a cost-effective measure to comply with Regulation 85 in Colorado, given the opportunity for water quality trading between point sources and nonpoint. The potential of Al-WTRs in eliminating excess nutrients such as phosphorus in stormwater presents another advantage for the third scenario. **Figure 23*: Summary of Total Estimated Costs*** below summarizes the total cost of each scenario, with the third scenario showing the estimated cost of Al-WTRs application in extended detention basins and constructed wetlands.

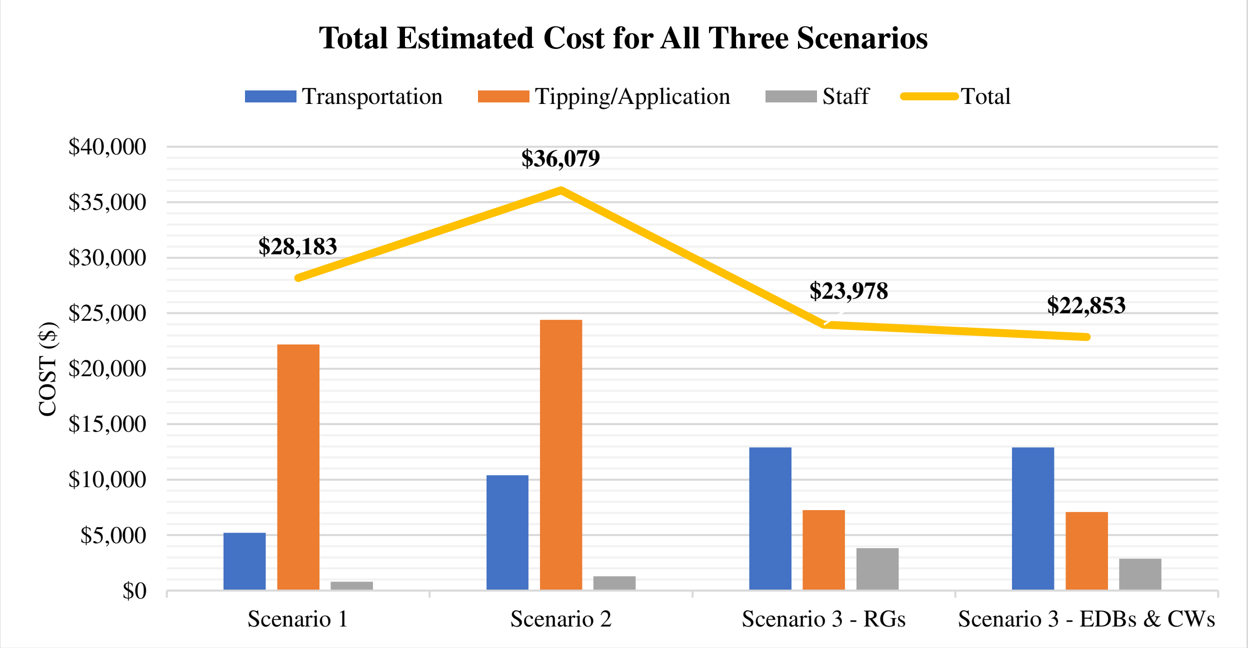

Figure 23: Summary of Total Estimated Costs

4.0 Chapter 4: Conclusion

This research aimed to evaluate the potential benefits of diverting alum-based water treatment residuals (Al-WTRs) as an amendment in stormwater Best Management Practices (BMPs) for treating stormwater runoff instead of being disposed of in landfills. It was hoped that this material's beneficial use could result in a safe and significant reduction in dissolved phosphorus input into water bodies. It was also hoped that Al-WTRs could be a sustainable and cost-effective tool in eliminating excess discharging of dissolved phosphorus in stormwater runoff. Al-WTRs efficiency in dissolved phosphorus removal was evaluated in the second chapter, while the third chapter estimated the cost of utilizing this material in stormwater BMPs in Fort Collins, Colorado.

Chapter two aimed to achieve three main objectives; estimate the amount of dissolved phosphorus introduced to the system through stormwater runoff, evaluate the efficiency of Al-WTRs in phosphorus removal, and determine the ideal rate of application of Al-WTRs into stormwater BMPs to achieve the desired removal of dissolved phosphorus. An adjusted equation of the Simple Method was used to quantify dissolved phosphorus amounts in stormwater runoff, in which average precipitation between the years of 2007 and 2019 was used in the calculations. The areas used in the equation represent 15 different BMPs in Fort Collins; five rain gardens, five extended detention basins, and five constructed wetlands. The average generated runoff volumes, captured volumes, and treated volumes were calculated. Concentrations of dissolved phosphorus were collected from two sources: a column study for rain gardens and the International BMP Database for extended detention basins and constructed wetlands. It was found that an average of 70 pounds of dissolved phosphorus was generated through the selected

BMPs, while it was estimated that more than 3000 pounds were discharged to receiving water bodies by the stormwater runoff throughout the city of Fort Collins.

Al-WTRs efficiency in dissolved phosphorus removal was assessed by comparing dissolved phosphorus quantities between influents and effluents pre- and post-application of Al-WTRs. Dissolved phosphorus effluent concentrations used in the pre-application calculations were 0.966 mg/l for rain gardens, 0.11 mg/l for extended detention basins, and 0.08 mg/l for constructed wetlands. For the post-application of WTRs concentrations, it was assumed that constructed wetlands and extended detention basins were able to achieve 90% and 93% removal rates, respectively. In rain gardens, it was found through the column study that the bottom-layer application of Al-WTRs resulted in the best removal of dissolved phosphorus with a 0.288 mg/l effluent concentration, 0.376 mg/l for mixing Al-WTRs with the filter media layers, and then the top-layer application with 0.844 mg/l and 0.866 mg/l for 1-inch layers and 0.5-inch layers, respectively. It was noticed that there was an export of dissolved phosphorus in rain gardens using the current filter media mix.

For calculating the ideal application rates of Al-WTRs, Phosphorus Storage Capacity (PSC) was used to quantify the minimum required amount of Al-WTRs needed for efficient removal of dissolved phosphorus for one year. It was found that the PCS of the Al-WTRs used in this study was 21.556 pounds dissolved phosphorus per one ton of Al-WTRs. Based on this figure, it was found that a minimum of 3.2 tons of Al-WTRs was needed to achieve a significant reduction of the dissolved phosphorus in the selected 15 BMPs, and 39 tons for all rain gardens, extended detention basins, and constructed wetlands in Fort Collins for one year. To ensure maximum efficiency and long-term reliable use of Al-WTRs, it was recommended to use 0.5 inch-layer of Al-WTRs regardless of the BMP area, in which 11,433 tons of Al-WTRs are to be used to cover the selected BMPs type in all of Fort Collins or 54.5 tons Al-WTRs per one acre of BMPs.

The third chapter estimated the cost of Al-WTRs into stormwater BMPs in Fort Collins, in addition to the costs of two other scenarios. The first scenario estimated the cost of disposing of Al-WTRs into the Larimer County Landfill, the second scenario estimated the costs of Al-WTRs disposal into a new location of the landfill, and the third scenario assessed the costs of using Al-WTRs as an amendment in stormwater BMPs. The cost estimation process was based on that the drinking water treatment plant in Fort Collins produces an average of 1,000 tons of Al-WTRs annually. The three components of the cost estimation were transportation fees, tipping/application fees, and staff compensation.

It was found that the first scenario would cost $28,183.35, in which $5,197 for transportation, $22,186.15 for tipping, and $800 for staff compensation. The second scenario was estimated to cost $36.079.76, in which $10,394.40 for transportation, $24,405.36 for tipping, and $1280 for staff. While the third scenario that includes applying Al-WTRs in stormwater BMPs, the estimated cost was $22,852.80, as transportation cost $12894.40, application cost $7078.40, and $2,880 for staff compensation. The third scenario was the cheapest and most feasible out of the three scenarios; it would also potentially save an average of $13,000 annually for the City of Fort Collins.

The excellent potential for WTRs in removing dissolved phosphorus combined with good economic and social benefits makes this material a handy tool in improving water quality. Such practice can ensure efficient dissolved pollutants removal in addition to a beneficial use of the WTRs produced by the City, which would turn this material from waste to become a resource.

References

Aryal, R. K., Furumai, H., Nakajima, F., & Boller, M. (2005). Dynamic behavior of fractional suspended solids and particle-bound polycyclic aromatic hydrocarbons in highway runoff. *Water Research*, *39*(20), 5126–5134. https://doi.org/10.1016/j.watres.2005.09.045

Babatunde, A. O., Zhao, Y. Q., Burke, A. M., Morris, M. A., & Hanrahan, J. P. (2009). Characterization of aluminium-based water treatment residual for potential phosphorus removal in engineered wetlands. *Environmental Pollution*, *157*(10), 2830–2836. https://doi.org/10.1016/j.envpol.2009.04.016

Badruzzaman, M., Pinzon, J., Oppenheimer, J., & Jacangelo, J. G. (2012). Sources of nutrients impacting surface waters in Florida: A review. *Journal of Environmental Management*, *109*, 80–92. https://doi.org/10.1016/j.jenvman.2012.04.040

Bai, L., Wang, C., He, L., & Pei, Y. (2014). Influence of the inherent properties of drinking water treatment residuals on their phosphorus adsorption capacities. *Journal of Environmental Sciences*, *26*(12). https://doi.org/10.1017/CBO9781107415324.004

Banet, T., Massey, M. S., Zohar, I., Litaor, M. I., & Ippolito, J. A. (2020). Assessing modified aluminum-based water treatment residuals as a plant-available phosphorus source. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2020.125949

Bayley, R. M., Ippolito, J. A., Stromberger, M. E., Barbarick, K. A., & Paschke, M. W. (2008). Water Treatment Residuals and Biosolids Coapplications Affect Semiarid Rangeland Phosphorus Cycling. *Soil Science Society of America Journal*, *72*(3), 711–719. https://doi.org/10.2136/sssaj2007.0109

Bedan, E. S., & Clausen, J. C. (2009). Stormwater runoff quality and quantity from traditional and low impact development watersheds. *Journal of the American Water Resources*

Association, *45*(4), 998–1008. https://doi.org/10.1111/j.1752-1688.2009.00342.x

Booth, D. B. (2005). Challenges and prospects for restoring urban streams: A perspective from the Pacific Northwest of North America. *Journal of the North American Benthological Society*, *24*(3), 724–737. https://doi.org/10.18990887-3593(2005)024\2.0.CO;2

Booth, D. B., & Jackson, C. R. (1997). URBANIZATION OF AQUATIC SYSTEMS: DEGRADATION THRESHOLDS, STORMWATER DETECTION, AND THE LIMITS OF MITIGATION. *JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION*, *33*(5).

Bressy, A., Gromaire, M. C., Lorgeoux, C., Saad, M., Leroy, F., & Chebbo, G. (2012). Towards the determination of an optimal scale for stormwater quality management: Micropollutants in a small residential catchment. *Water Research*, *46*(20), 6799–6810. https://doi.org/10.1016/j.watres.2011.12.017

Brown, S., Corfman, A., Mendrey, K., Kurtz, K., & Grothkopp, F. (2015). Stormwater Bioretention Systems: Testing the Phosphorus Saturation Index and Compost Feedstocks as Predictive Tools for System Performance. *Journal of Environmental Quality*, *45*(1), 98–106. https://doi.org/10.2134/jeq2014.10.0414

Cai, W. J., Hu, X., Huang, W. J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., Chou, W. C., Zhai, W., Hollibaugh, J. T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M., & Gong, G. C. (2011). Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience*, *4*(11), 766–770. https://doi.org/10.1038/ngeo1297

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, *8*(3), 559–568. https://doi.org/10.1890/1051-

0761(1998)008[0559:NPOSWW]2.0.CO;2

Castaldi, P., Mele, E., Silvetti, M., Garau, G., & Deiana, S. (2014). Water treatment residues as accumulators of oxoanions in soil. Sorption of arsenate and phosphate anions from an aqueous solution. *Journal of Hazardous Materials*, *264*, 144–152. https://doi.org/10.1016/j.jhazmat.2013.10.037

CDPHE. (2012). *Colorado Department of Public Health and Environment Water Quality Control Commission. Nutrients Management Control Regulation, Pub. L. No. 85*.

Chandler, B. R. D. (1994). ESTIMATING ANNUAL URBAN NONPOINT POLLUTANT LOADS. *Journal of Management in Engineering*, *10*(6), 50–59.

Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. *Nature Education Knowledge*. https://www.nature.com/scitable/knowledge/library/eutrophication-causes-consequences-and-controls-in-aquatic-102364466/

City of Fort Collins. (2011). *Bioretention Sand Media Specification*. 2–3. http://www.fcgov.com/utilities/img/site_specific/uploads/Bioretention_Sand_Media_Specs.pdf

CSU. (2020). *Colorado AG Water Quality - Regulation 85*. https://coagnutrients.colostate.edu/colorado-regulation-85

Davenport, T. E., & Drake, W. (2011). Grand Lake St. Marys, Ohio—The case for source water protection: Nutrients and algae blooms. *Lakeline Magazine*, *31*, 41–46.

Davis, A. (2008). Field Performance of Bioretention: Hydrology Impacts. *Journal of Environmental Engineering*, *136*(9). https://doi.org/10.1061/(ASCE)1084-0699(2008)13:2(90)

Davis, A. P. ., Hunt, W. F., Traver, R. G., & Clar, M. (2009). Bioretention Technology: Overview of Current Practice and Future Needs. *Journal of Environmental Engineering*, *135*(3). https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(109)

Dayton, E. A., & Basta, N. T. (2005). Use of Drinking Water Treatment Residuals as a Potential Best Management Practice to Reduce Phosphorus Risk Index Scores. *Journal of Environmental Quality*, *34*(6), 2112–2117. https://doi.org/10.2134/jeq2005.0083

De Paola, F., Giugni, M., Pugliese, F., & Romano, P. (2018). Optimal Design of LIDs in Urban Stormwater Systems Using a Harmony-Search Decision Support System. *Water Resources Management*, *32*(15), 4933–4951. https://doi.org/10.1007/s11269-018-2064-8

de Rozari, P., Greenway, M., & El Hanandeh, A. (2016). Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms. *Science of the Total Environment*, *569–570*, 123–133. https://doi.org/10.1016/j.scitotenv.2016.06.096

Dietz, M. E., & Clausen, J. C. (2008). Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management*, *87*(4), 560–566. https://doi.org/10.1016/j.jenvman.2007.03.026

Djodjic, F., Börling, K., & Bergström, L. (2004). Phosphorus Leaching in Relation to Soil Type and Soil Phosphorus Content. *Journal of Environmental Quality*, *33*(2), 678–684. https://doi.org/10.2134/jeq2004.6780

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., Schloesser, J. T., & Thornbrugh, D. J. (2009). Eutrophication of U. S. freshwaters: Analysis of potential economic damages. *Environmental Science and Technology*, *43*(1), 12–19. https://doi.org/10.1021/es801217q

Dunlap, C. R., Sklenar, K. S., & Blake, L. J. (2015). A costly endeavor: Addressing algae problems in a water supply. *Journal - American Water Works Association*, *107*(5), E255–E262. https://doi.org/10.5942/jawwa.2015.107.0055

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, *12*(7), 525–542. https://doi.org/10.1080/1573062X.2014.916314

Geosyntec Consultants, & Wright Water Engineers. (2012). *International Stormwater Best Management Practices (BMP) Database Pollutant Category Summary Statistical Addendum : TSS , Bacteria , Nutrients , and Metals July 2012*. *July*.

Hatt, B. E., Fletcher, T. D., Walsh, C. J., & Taylor, S. L. (2004). The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental Management*, *34*(1), 112–124. https://doi.org/10.1007/s00267-004-0221-8

Houlahan, J., Marcus, W. A., & Shirmohammadi, A. (1992). Estimating Maryland Critical Area Acvs Impact on Future Nonpoint Pollution Along the Rhode Rwer Estuary. *JAWRA Journal of the American Water Resources Association*, *28*(3), 553–567. https://doi.org/10.1111/j.1752-1688.1992.tb03177.x

Houle, J. J., Roseen, R. M., Ballestero, T. P., Puls, T. A., & Sherrard, J. (2013). Comparison of Maintenance Cost, Labor Demands, and System Performance for LID and Conventional Stormwater Management. *Journal of Environmental Engineering (United States)*, *139*(7), 932–938. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000698

Hsieh, C., & Davis, A. P. (2005). Evaluation and Optimization of Bioretention Media for

Treatment of Urban Storm Water Runoff. *Journal of Environmental Engineering*, *131*(11), 1521–1531. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:11(1521)

Hsieh, C., Davis, A. P., & Needelman, B. A. (2007). Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. *Water Environment Research*, *79*(2), 177–184. https://doi.org/10.2175/106143006x111745

Hunt, W. F., Jarrett, A. R., Smith, J. T., & Sharkey, L. J. (2006). Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *Journal of Irrigation and Drainage Engineering*, *132*(6), 600–608. https://doi.org/10.1061/(ASCE)0733-9437(2006)132:6(600)

Hurley, S., Shrestha, P., & Cording, A. (2017). Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure. *Journal of Sustainable Water in the Built Environment*, *3*(3), 1–8. https://doi.org/10.1061/JSWBAY.0000821

Ippolito, J. A. (2015). Aluminum-Based Water Treatment Residual Use in a Constructed Wetland for Capturing Urban Runoff Phosphorus: Column Study. *Water, Air, and Soil Pollution*, *226*(10). https://doi.org/10.1007/s11270-015-2604-2

Ippolito, J. A., Barbarick, K. A., & Elliott, H. A. (2011). Drinking Water Treatment Residuals: A Review of Recent Uses. *Journal of Environmental Quality*, *40*(1), 1–12. https://doi.org/10.2134/jeq2010.0242

Iqbal, H., Garcia-Perez, M., & Flury, M. (2015). Effect of biochar on leaching of organic carbon, nitrogen, and phosphorus from compost in bioretention systems. *Science of the Total Environment*, *521–522*, 37–45. https://doi.org/10.1016/j.scitotenv.2015.03.060

Jiang, C., Li, J., Li, H., Li, Y., & Chen, L. (2017). Field Performance of Bioretention Systems for Runoff Quantity Regulation and Pollutant Removal. *Water, Air, and Soil Pollution*, *228*(12). https://doi.org/10.1007/s11270-017-3636-6

Jin, D., Thunberg, E., & Hoagland, P. (2008). Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. *Ocean and Coastal Management*, *51*(5), 420–429. https://doi.org/10.1016/j.ocecoaman.2008.01.004

Joksimovic, D., & Alam, Z. (2014). Cost efficiency of Low Impact Development (LID) stormwater management practices. *Procedia Engineering*, *89*(Lid), 734–741. https://doi.org/10.1016/j.proeng.2014.11.501

Kayhanian, M., Fruchtman, B. D., Gulliver, J. S., Montanaro, C., Ranieri, E., & Wuertz, S. (2012). Review of highway runoff characteristics: Comparative analysis and universal implications. *Water Research*, *46*(20), 6609–6624. https://doi.org/10.1016/j.watres.2012.07.026

Lee, L., Wang, B., Guo, H., Hu, J., & Ong, S. (2015). Aluminum-Based Water Treatment Residue Reuse for Phosphorus Removal. *Water*, *7*(12), 1480–1496. https://doi.org/10.3390/w7041480

LeFevre, G. H., Paus, K. H., Natarajan, P., Gulliver, J. S., Novak, P. J., & Hozalski, R. M. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *Journal of Environmental Engineering*, *141*(1), 04014050. https://doi.org/10.1061/(asce)ee.1943-7870.0000876

Lewitus, A. J., Horner, R. A., Caron, D. A., Garcia-Mendoza, E., Hickey, B. M., Hunter, M., Huppert, D. D., Kudela, R. M., Langlois, G. W., Largier, J. L., Lessard, E. J., RaLonde, R., Jack Rensel, J. E., Strutton, P. G., Trainer, V. L., & Tweddle, J. F. (2012). Harmful algal blooms along the North American west coast region: History, trends, causes, and impacts. *Harmful Algae*, *19*, 133–159. https://doi.org/10.1016/j.hal.2012.06.009

Loganathan, P., Vigneswaran, S., Kandasamy, J., & Bolan, N. S. (2014). Removal and recovery of phosphate from water using sorption. *Critical Reviews in Environmental Science and Technology*, *44*(8), 847–907. https://doi.org/10.1080/10643389.2012.741311

Makris, K. C., El-Shall, H., Harris, W. G., O'Connor, G. A., & Obreza, T. A. (2004). Intraparticle phosphorus diffusion in a drinking water treatment residual at room temperature. *Journal of Colloid and Interface Science*, *277*(2), 417–423. https://doi.org/10.1016/j.jcis.2004.05.001

Mortula, M. M., & Gagnon, G. A. (2006). Alum residuals as a low technology for phosphorus removal from aquaculture processing water. *Aquacultural Engineering*, *36*(3), 233–238. https://doi.org/10.1016/j.aquaeng.2006.12.003

Muerdter, C. P., Wong, C. K., & Lefevre, G. H. (2018). Emerging investigator series: The role of vegetation in bioretention for stormwater treatment in the built environment: Pollutant removal, hydrologic function, and ancillary benefits. *Environmental Science: Water Research and Technology*, *4*(5), 592–612. https://doi.org/10.1039/c7ew00511c

Mullane, J. M., Flury, M., Iqbal, H., Freeze, P. M., Hinman, C., Cogger, C. G., & Shi, Z. (2015). Intermittent rainstorms cause pulses of nitrogen, phosphorus, and copper in leachate from compost in bioretention systems. *Science of the Total Environment*, *537*, 294–303. https://doi.org/10.1016/j.scitotenv.2015.07.157

Nair, V. D., & Harris, W. G. (2014). *Soil Phosphorus Storage Capacity for Environmental Risk Assessment*. *2014*, 1–10.

Nair, V. D., Harris, W. G., Chakraborty, D., & Chrysostome, M. (2019). *Understanding Soil Phosphorus Storage Capacity 1*. 1–3.

O'Kelly, B. C. (2008). Geotechnical properties of a municipal water treatment sludge incorporating a coagulant. *Canadian Geotechnical Journal*, *45*(5), 715–725. https://doi.org/10.1139/T07-109

Oh, C., & Ditton, R. B. (2005). *Estimating the Economic Impacts of Golden Alga (Prymnesium parvum) on Recreational Fishing at Possum Kingdom Lake , Texas*.

Oladeji, O. O., O'Connor, G. A., Sartain, J. B., & Nair, V. D. (2007). Controlled Application Rate of Water Treatment Residual for Agronomic and Environmental Benefits. *Journal of Environmental Quality*, *36*(6), 1715–1724. https://doi.org/10.2134/jeq2007.0160

Oliver, I. W., Grant, C. D., & Murray, R. S. (2011). Assessing effects of aerobic and anaerobic conditions on phosphorus sorption and retention capacity of water treatment residuals. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2010.11.016

Palmer, E. T., Poor, C. J., Hinman, C., & Stark, J. D. (2013). Nitrate and Phosphate Removal through Enhanced Bioretention Media: Mesocosm Study. *Water Environment Research*, *85*(9), 823–832. https://doi.org/10.2175/106143013x13736496908997

Paus, K. H., Morgan, J., Gulliver, J. S., & Hozalski, R. M. (2014). Effects of bioretention media compost volume fraction on toxic metals removal, hydraulic conductivity, and phosphorous release. *Journal of Environmental Engineering (United States)*, *140*(10), 1–9. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000846

Peterson, I. J., Igielski, S., & Davis, A. P. (2015). Enhanced Denitrification in Bioretention Using Woodchips as an Organic Carbon Source. *Journal of Sustainable Water in the Built Environment*, *1*(4), 1–9. https://doi.org/10.1061/JSWBAY.0000800

Poresky, A., Clary, J., Strecker, E., & Earles, A. (2011). Technical Summary: Volume Reduction. *International Stormwater Best Management Practices (BMP) Database*, *January*, International Stormwater BMP Database.

Prince George's County. (1999). *Low-Impact Development Design Strategies An Integrated Design Approach Low-Impact Development : An Integrated Design Approach* (Issue June).

Prince George's County. (2007). Bioretention Manual, Prince George's County, Maryland. *Environmental Services Division Department of Environmental Resources*.

Puckett, L. J. (1995). Identifying the Major Sources of Nutrient Water Pollution: A national watershed-based analysis connects nonpoint and point sources of nitrogen and phosphorus with regional land use and other factors. *Environmental Science and Technology*, *29*(9), 408A-414A. https://doi.org/10.1021/es00009a001

Pyke, C., Warren, M. P., Johnson, T., LaGro, J., Scharfenberg, J., Groth, P., Freed, R., Schroeer, W., & Main, E. (2011). Assessment of low impact development for managing stormwater with changing precipitation due to climate change. *Landscape and Urban Planning*, *103*(2), 166–173. https://doi.org/10.1016/j.landurbplan.2011.07.006

Razali, M., Zhao, Y. Q., & Bruen, M. (2007). Effectiveness of a drinking-water treatment sludge in removing different phosphorus species from aqueous solution. *Separation and Purification Technology*, *55*(3), 300–306. https://doi.org/10.1016/j.seppur.2006.12.004

Reddy, K. R., Xie, T., & Dastgheibi, S. (2014). Evaluation of biochar as a potential filter media for the removal of mixed contaminants from urban storm water runoff. *Journal of Environmental Engineering (United States)*, *140*(12), 1–10. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000872

Roy-Poirier, A., Champagne, P., & Filion, Y. (2010). Review of bioretention system research and design: Past, present, and future. *Journal of Environmental Engineering*, *136*(9), 878–889. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000227

Saeed, T., & Sun, G. (2011). A comparative study on the removal of nutrients and organic matter in wetland reactors employing organic media. *Chemical Engineering Journal*, *171*(2), 439–447. https://doi.org/10.1016/j.cej.2011.03.101

Schindler, D. W. (2006). Recent advances in the understanding and management of eutrophication. *American Society of Limnology and Oceanography*, *7*(51), 356–363.

Schueler, T. R. (1987). *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*. Department of Environmental Programs, Metropolitan Washington Council of Governments.

Shapiro, M. H. (2013). *EPA Testimony Statement on Nutrient Trading and Water Quality*. 1–10. http://www.epa.gov/ocir/hearings/pdf/nutrient_trading_and_water_quality.pdf

Shrestha, P., Hurley, S. E., & Wemple, B. C. (2018). Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems. *Ecological Engineering*, *112*(August 2017), 116–131. https://doi.org/10.1016/j.ecoleng.2017.12.004

Smil, V. (2000). PHOSPHORUS IN THE ENVIRONMENT: Natural Flows and Human Interferences. *Annual Review of Energy and the Environment*, *25*(1), 53–88. https://doi.org/10.1146/annurev.energy.25.1.53

Soleimanifar, H., Deng, Y., Wu, L., & Sarkar, D. (2016). Water treatment residual (WTR)-coated wood mulch for alleviation of toxic metals and phosphorus from polluted urban stormwater runoff. *Chemosphere*, *154*, 289–292. https://doi.org/10.1016/j.chemosphere.2016.03.101

UDFCD, U. D. and F. C. D. (2010). *Urban Storm Drainage Criteria Manual Volume 3, Stormwater Quality*. http://udfcd.org/volume-three

Urbonas, B., Guo, J., & Tucker, S. (1989). Sizing a Capture Volume for Stormwater Quality

Enhancement. In *Flood Hazard News: Vol. Vol.19* (Issue No. 1).

USEPA. (2009). *Managing Stormwater with Low Impact Development Practices : Addressing Barriers to LID*.

USEPA. (2015). *A Compilation of Cost Data Associated with the Impacts and Control of Nutrient Pollution* (Issue May).

USEPA. (2017). *National Water Quality Inventory: Report to Congress, EPA 841-R-16-011. August*.

Wallace, R. B., Baumann, H., Grear, J. S., Aller, R. C., & Gobler, C. J. (2014). Coastal ocean acidification: The other eutrophication problem. *Estuarine, Coastal and Shelf Science*, *148*, 1–13. https://doi.org/10.1016/j.ecss.2014.05.027

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3), 706–723. https://doi.org/10.1899/04-028.1

Wang, C., Guo, W., Tian, B., Pei, Y., & Zhang, K. (2011). Characteristics and kinetics of phosphate adsorption on dewatered ferric-alum residuals. *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, *46*(14), 1632–1639. https://doi.org/10.1080/10934529.2011.623643

Wang, X., Shuster, W., Pal, C., Buchberger, S., Bonta, J., & Avadhanula, K. (2010). Low impact development design-integrating suitability analysis and site planning for reduction of post-development stormwater quantity. *Sustainability*, *2*(8), 2467–2482. https://doi.org/10.3390/su2082467

Yang, F., Fu, D., Liu, S., Zevenbergen, C., & Singh, R. P. (2020). Hydrologic and Pollutant

Removal Performance of Media Layers in Bioretention. *Water (Switzerland)*, *12*(3). https://doi.org/10.3390/w12030921

Yang, Y., Zhao, Y. Q., Babatunde, A. O., Wang, L., Ren, Y. X., & Han, Y. (2006). Characteristics and mechanisms of phosphate adsorption on dewatered alum sludge. *Separation and Purification Technology*, *51*(2), 193–200. https://doi.org/10.1016/j.seppur.2006.01.013

Zero Waste Associates. (2013). *Road to Zero Waste Plan* (Issue December). http://www.fcgov.com/recycling/pdf/RZW_Report_Jan2014.pdf

Zhao, Y. Q., Babatunde, A. O., Razali, M., & Harty, F. (2007). Use of dewatered alum sludge as a substrate in reed bed treatment systems for wastewater treatment. *Journal of Environmental Science and Health, Part A*, *43*(1), 105–110. https://doi.org/10.1080/10934520701750264

Zohar, I., Ippolito, J. A., Massey, M. S., & Litaor, I. M. (2017). Innovative approach for recycling phosphorous from agro-wastewaters using water treatment residuals (WTR). *Chemosphere*, *168*, 234–243. https://doi.org/10.1016/j.chemosphere.2016.10.041