Prepared for: City of Fort Collins

# Water Treatment Residual (WTR) Amendment in Stormwater Systems for Phosphorus Reduction and Waste Removal


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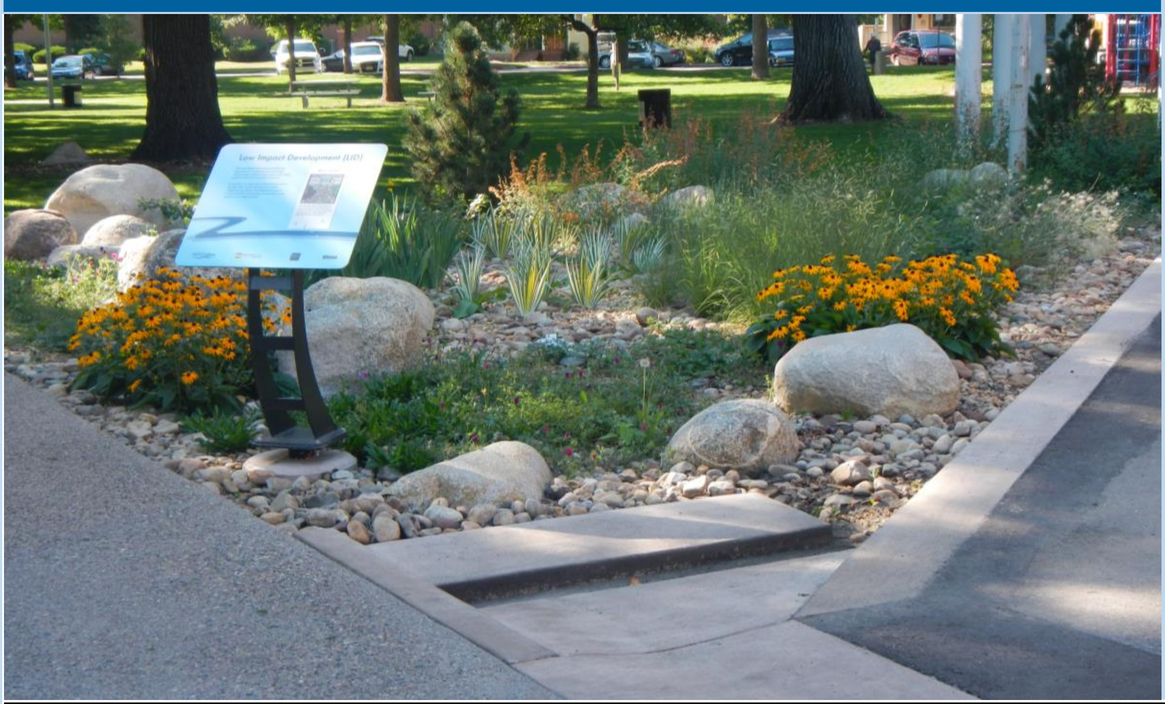


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**Additional Attachments**

## Introduction

City of Fort Collins Utilities (City) has requested research services from the Colorado State University (CSU) Colorado Stormwater Center to improve the understanding of stormwater management practices within the City. The primary thrust of this research effort was to understand the effects and potential benefits as well as risks of using water treatment residuals (WTRs) as an amendment to stormwater systems to improve phosphorus removal as well as divert waste as a part of the zero waste initiative adopted by the City of Fort Collins. Contained below you will find a summary of the background that lead to this research effort as well as a brief discussion of three research activities that were conducted to accomplish the primary goal of the study. Finally, there are three attachments to this summary which provides details to each of the research activities.

## Background

In Spring 2012, the City constructed a rain garden (a LID-type water quality treatment facility at the Utility Service Center (USC) located at 700 Wood Street) to better understand the performance of rain garden systems in Fort Collins, considering the unique hydrology of the Northern Colorado region. Given the City's requirement for installing LID-type stormwater facilities for future development, it is important to understand how these facilities will operate in the semi-arid climate of Fort Collins.

CSU has previously monitored this rain garden during the summers of 2013-2015. Prior to the 2014 sampling season, the rain garden underdrain system was retrofitted to evaluate how performance was affected by the underdrain design. Results of the modified design showed significantly higher performance in terms of runoff and pollutant reduction. Despite achieving runoff and pollutant reduction, the rain garden still allowed for increased concentrations of several nutrients exiting the facility, particularly phosphorus.

Based on the results of previous monitoring, CSU was tasked by the City to perform a literature review on potential bioretention filtration amendments to capture and thus reduce phosphorus exiting the system. The literature review resulted in a recommendation by CSU for the City to consider piloting the use of water treatment residuals (WTRs) as an amendment to rain garden filter media. Reviewed performance of WTRs for mitigating the export of phosphorus from engineered wetlands indicated that WTRs could be an effective amendment to treat phosphorus in stormwater. From this review it was determined that CSU would perform research activities to verify this potential use of WTRs would be feasibly for the City.

CSU performed three different research activities: a column study to evaluate application methodologies that yielded the optimal pollutant removal, a field study to verify real-world application effectiveness as well as potential adverse consequences that may occur from a real-world application, and a city wide analysis to determine the potential effectiveness of phosphorus reduction as well as the amount of waste material (WTRs) that could be diverted from the landfill. Each of these activities are introduced below and presented in full as separate attached documents.

## Column Study to Verify WTR Effectiveness

The first activity included conducting column study to evaluate the effectiveness of WTRs for dissolved phosphorus pollutant removal when added using various methodologies to filter media. The column study was conducted during 2018 and 2019. During this time two separate water years and their corresponding dissolved phosphorus concentrations (0.23 mg/l) were poured through 15 columns testing four different application processes as well as three columns which included filter media without the WTR amendment to use as a control. The four application methods included two different top applications at varying amounts of WTRs (0.5” and 1.0”) on top of 17.5” and 17” of filter media respectively, a bottom application of WTRs (1”) below 17” of filter media and a mixed application (1 part WTR 17 parts filter media). It was found through the column study that the bottom-layer application of WTRs resulted in the best removal of dissolved phosphorus with a 0.288 mg/l effluent concentration, 0.376 mg/l 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. All of these are compared to the media mix which exported dissolved phosphorus at 1.483 mg/l.

For more information about the column study see the summary provided in Attachment 1.

## Field Application of WTRs at 700 Wood Street

The second activity conducted a field application of WTRs at 700 wood street. The purpose of this activity was to establish that WTRs were effective at removing phosphorus outside of the laboratory condition. Another objective of this study was to determine if any harmful unintended consequences occurred in the field condition. WTRs were applied to a rain garden at 700 Wood Street in the summer of 2019. However, because of the time that WTRs were applied and the weather conditions during the summer of 2019, only a single sample was collected in that year. For this reason, the monitoring was postponed until 2020.

Site monitoring was conducted from May – October of 2020. Sample results were somewhat variable for influent and effluent total phosphorus concentrations, with an overall average increase of 6%. Dissolved phosphorus concentrations were found to increase by 78% from influent to effluent on average. Although these findings support the previous research that indicated phosphorus was leaching from the system, a comparison with the historical data indicates that the magnitude of the increase was reduced. The comparison showed a very similar level of influent total and dissolved phosphorus concentrations, while the effluent concentrations for each were clearly different. Total and dissolved phosphorus concentrations prior to the WTR application were 0.722 ppm and 0.539 ppm, respectively, while total and dissolved phosphorus concentrations following the application were 0.322 ppm and 0.224 ppm, respectively. These reductions show about a 57% decrease in total and dissolved phosphorus concentrations after the application of WTRs. These results are highly promising as they indicate that water treatment residuals could be a viable option for enhancing the phosphorus removal capabilities of bioretention cells.

In light of these findings it is recommended that WTR related research continue at other locations in Fort Collins with varied approaches to application including: additional surface applications on existing installations, applications where WTRs are thoroughly mixed into the BRC filter media before filling a cell at a new installation, and creating distinct layers at different depths in the BRC filter media profile while filling new cells with traditional BRC filter media.

Although leaching is still taking place, the nature of a surface application is such that phosphorus being leached from within the BRC does not have an opportunity to directly interact with the WTRs. The only possibility for reducing effluent phosphorus concentrations with WTRs is to offset leaching to some degree by reducing concentrations in the influent as it infiltrates the surface of the BRC. Considering how brief the interaction between the influent and the surface applied WTRs is, the reductions in phosphorus leaching from pre to post WTR application are impressive. Another potential explanation for lower phosphorus effluent concentrations in the current study is the possibility that leaching has caused the phosphorus reserves in the BRC filter media to deplete over time. Considering that the configuration of a traditional BRC does not allow for a control treatment, data to confirm or deny this potential influence does not currently exist. At a minimum, it is recommended that soil samples be collected and analyzed annually in order to better understand how phosphorus levels change in the BRC filter media over time.

The comparison of data between current and past research projects at the BRC research site brought up a couple other trends worth noting. Findings from the 2013-2015 project showed an average reduction in total nitrogen concentration from influent to effluent of about 25%. Current research is reporting that there was not a reduction in total nitrogen concentration, but there was an average increase of about 29%. Obviously, this is a complete reversal from a total nitrogen perspective. However, the components that make up total nitrogen values displayed similar behavior. Both the current and past research projects showed a general trend of decrease in TKN concentrations from influent to effluent and a general trend of increase in nitrate concentrations. The difference that drove the reversal when focusing on total nitrogen was that the current TKN reductions were not enough to outweigh the increases in nitrate. As a result, current findings suggest that the BRC is leaching nitrate, and to an extent that total nitrogen is increasing as well. It is recommended that further research be conducted to explore options to address this issue. Another instance where current and past data did not agree is in stormwater runoff volume reduction. The 2013-2015 study reported an overall volume reduction of 25% before adding the temporary underdrain modification, and an 88% reduction after adding the modification. As previously stated, the current study did not use the temporary modification. Current findings support an overall average volume reduction of about 89%, which closely aligns with previously observed reductions after the modification had been added. This presents a large discrepancy with the 2013-2015 data, the cause of which is unknown. It is recommended that further investigation into this disagreement be conducted.

In accordance with the Beneficial Use Plan, monitoring efforts relating to exportation of harmful byproducts from the WTRs yielded promising initial results. Aluminum, manganese, Gross Alpha and Gross Beta were shown to decrease from the influent to the effluent over the 2020 monitoring season. Although analyses for Radium-226 and Radium-228 were only requested a single time throughout the year, the preliminary results were encouraging. Radium-226 had non-detect results for both the influent and the effluent and Radium-228 showed a reduction from an influent result of 0.71-pCi/L to a non-detect effluent result. The observed increase in uranium was the only concerning result regarding contaminants potentially leaching from the WTRs themselves. Considering the limited number of samples in the dataset, further monitoring of all harmful contaminants listed in the Beneficial Use Plan is necessary to confirm the safety of using WTRs on a larger scale.

For more information regarding the field application of WTRs at 700 Wood Street see the report provided in Attachment 2.

## Citywide Analysis of WTRs

The third and final activity aimed to evaluate the potential benefits of diverting alum-based water treatment residuals (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 WTRs could be a sustainable and cost-effective tool in eliminating excess discharging of dissolved phosphorus in stormwater runoff. WTRs efficiency in dissolved phosphorus removal was evaluated first, while the estimated the cost and potential waste diversion of utilizing this material in stormwater BMPs in Fort Collins, Colorado was evaluated next.

The first part of this analysis two aimed to achieve three main objectives; estimate the amount of dissolved phosphorus introduced to the system through stormwater runoff, evaluate the efficiency of  WTRs in phosphorus removal, and determine the ideal rate of application of 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 74 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. WTRs efficiency in dissolved phosphorus removal was assessed by comparing dissolved phosphorus quantities between influents and effluents pre- and post-application of 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 WTRs resulted in the best removal of dissolved phosphorus with a 0.288 mg/l effluent concentration, 0.376 mg/l mixing 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 WTRs, Phosphorus Storage Capacity (PSC) was used to quantify the minimum required amount of WTRs needed for efficient removal of dissolved phosphorus for one year. It was found that the PCS of the WTRs used in this study was 21.556 pounds dissolved phosphorus per one ton of WTRs. Based on this figure, it was found that a minimum of 3.2 tons of 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 WTRs, it was recommended to use 0.5 inch-layer of WTRs regardless of the BMP area, in which 11,433 tons of WTRs are to be used to cover the selected BMP types in all of Fort Collins or 54.5 tons WTRs per one acre of BMPs.

After this, the estimated cost of diverting WTRs into stormwater BMPs in Fort Collins, compared to the costs of two other scenarios were evaluated. The first scenario estimated the cost of disposing of WTRs into the Larimer County Landfill, the second scenario estimated the costs of WTRs disposal into a new location of the landfill, and the third scenario assessed the costs of using 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 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.

The third activity was completed as a Master's Thesis for Omar Shehab at Colorado State University.  The thesis is provided as Attachment 3.

## Questions

If there are any questions regarding the work outlined in this summary or the attached reports please contact the Colorado Stormwater Center at Colorado State University.

# Attachment 1

CIVIL & ENVIRONMENTAL ENGINEERING
COLORADO STATE UNIVERSITY

COLORADO STORMWATER CENTER

# Performance Evaluation of BSM Amended with Al-WTR as a Means of Enhancing Phosphorus Removal from Stormwater Treated via Bioretention Cell

## Introduction

Bioretention cells have proven effective for reducing a variety of contaminants commonly found in stormwater runoff. One possible area of improvement that deserves attention is the phosphorus content of effluent leaving these systems, as studies have observed phosphorus being exported from bioretention cells. One possible solution for addressing this shortcoming is the addition of aluminum based water treatment residuals (Al-WTR). Al-WTR are commonly used to treat drinking water and, upon reaching the end of their usefulness for this purpose, are often destined for the landfill. It has been proven that Al-WTR at this stage still possess a substantial ability to treat water for other purposes. Using Al-WTR to amend the usual bioretention soil media (BSM) that makes up the filter layer of these systems could prove beneficial in a number of ways. A column study designed to simulate full-scale bioretention cells was used to evaluate phosphorus removal at different Al-WTR application rates and locations in the profile. Following a successful 2 year rainfall simulation through the columns, a field scale surface application of Al-WTR was carried out on a bioretention cell located at 700 Wood St. in Fort Collins, CO.

## Material & Methods

A wooden structure was constructed to house 16 PVC columns that would each be filled with one of six different treatments (see Figure 1). 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 either BSM only, BSM mixed with an inch worth of Al-WTR, BSM topped with 1 inch of Al-WTR, BSM topped with 1/2 inch of Al-WTR, BSM with 1 inch of Al-WTR on top of the pea-gravel layer, but below the BSM layer, or a mixture of biochar/sand/zeolite (results for this treatment are not discussed in this paper). Each treatment was replicated in 3 different columns, except for the biochar/sand/zeolite mix, which was used to fill a single column. Historical precipitation data (2007-2017) from the bioretention cell located at 700 Wood St. 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 (~6.22”) that is capable of being treated per significant event. The annual volume was then determined using the per storm volume in combination with the average number of significant events (~30) over the data collection period. A 55-gallon barrel was filled with synthetic stormwater that was specifically formulated to reflect the average dissolved phosphorus concentration typically found in runoff from the site. Historical data from this site (2013-2015) was also used to arrive at the appropriate dissolved phosphorus concentration (~0.23 mg/L) that would be 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 complete years of rainfall simulation took place from January to August of 2019. During the summer of that same year, a surface application of aluminum based water treatment residuals was accomplished at

*Figure 1: Support structure for columns containing filtration mixtures. Covered effluent catchment containers were placed below each column.*

700 Wood St. The material was applied, and uniformly spread by hand using shovels and rakes. Only one rainfall event produced enough runoff to sample during the first season.

# Results & Discussion

## Lab Scale

There were obvious differences in the dissolved phosphorus effluent concentration between certain treatments. The top performing treatments for each year of precipitation simulation, in terms of the average percent reduction from the control (Media only), were Bottom Applied 1" (Yr1: 70.8%, Yr2: 92.7%) and Mixed 1" (Yr1: 60.0%, Yr2: 81.2%), followed by Top Applied 1" (Yr1: 13.2%, Yr2: 14.5%) and Top Applied 0.5" (Yr1: 12.8%, Yr2: 11.2%). At the conclusion of the first year of precipitation simulations (storms 1-30), it was clear that two of the treatments displayed an impressive reduction in effluent dissolved phosphorus concentration, but there was still an overall net export from each system. For the columns containing the control treatments, the average concentration across all storms in the first year was 1.00 mg/L, while the average for the top performing treatment was 0.29 mg/L. When compared to the average influent concentration (0.23 mg/L), it becomes clear that even the top performing treatment showed a slight net export. It is worth mentioning that, for storms 3, 5, and 10, the effluent from the Bottom Applied 1" treatments had an average dissolved phosphorus concentration that was slightly lower than that of the influent. These results, displayed in Figure 2, suggested that there is a possibility that the addition of Al-WTR to bioretention cells could result in these systems becoming net

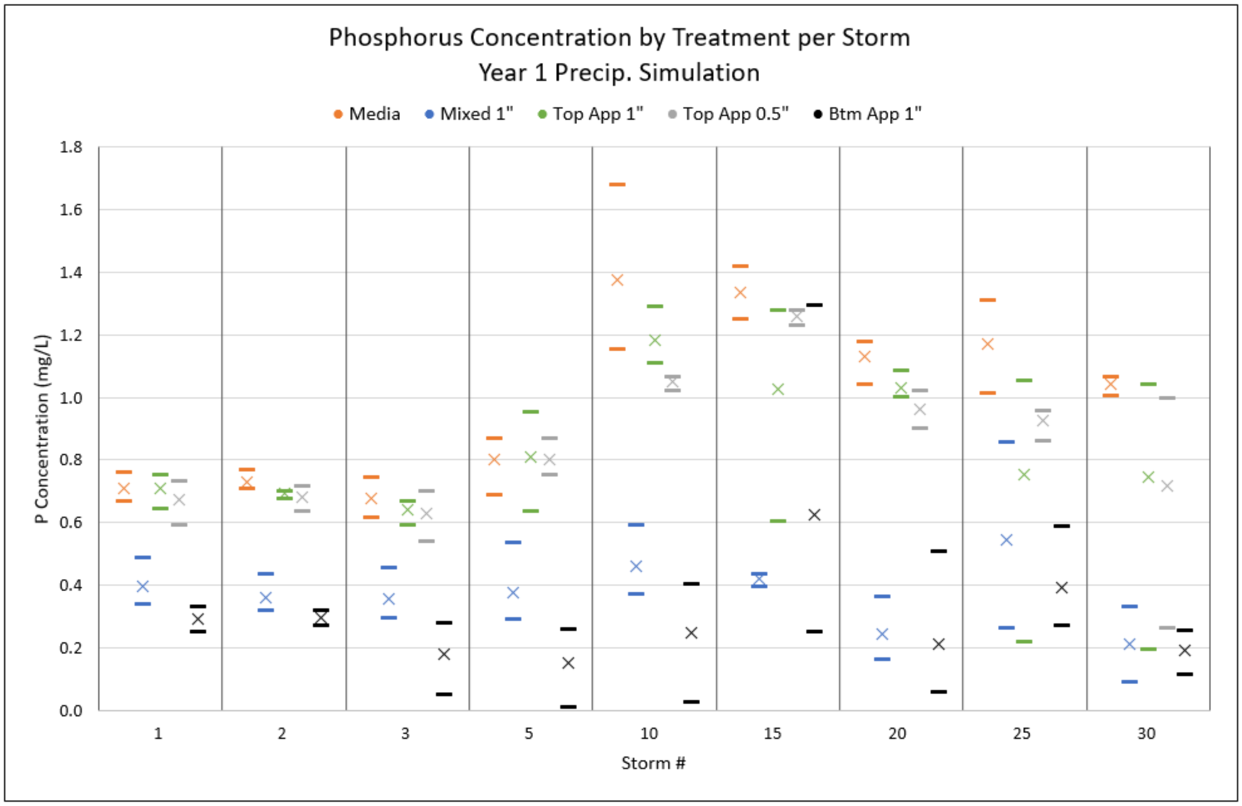


*Figure 2: The min, max, and average for each treatment, per storm, are displayed above. Sub-surface applied treatments have resulted in greater P removal.*

phosphorus reducers, instead of net exporters. Once the data from the second year simulation (displayed in Figure 3) was analyzed, these suspicions were given even more validity as a general increase in performance was observed across treatments. In this year (storms 31-60), the average dissolved phosphorus concentration across all storms for the control treatments was 0.87 mg/L, while the averages for the Bottom Applied 1" and Mixed 1" were 0.11 and 0.16 mg/L, respectively. When compared to the average influent concentration (0.20 mg/L), the suspected possibility of transforming a system that is traditionally thought of as a net phosphorus exporter, into a net reducer, was confirmed. The results from the first two years of simulations indicate that the degree to which phosphorus is reduced can depend highly on the location of Al-WTR application within a cell's profile. A suspected driver behind these differences has been identified through an observed similarity between the two most successful treatments, which is contact time. It is believed that the Bottom Applied 1" and Mixed 1" treatments have a greater contract time between the synthetic stormwater and Al-WTR, which is attributed to percolation rates being generally lower than the rate of initial water infiltration. Sub-surface applied Al-WTR will experience a rate of flow associated with that of percolation, while surface applied materials will experience rates of flow commonly associated with initial infiltration. Lower flow rates result in greater contact duration, and greater contact duration can result in an increased opportunity to adsorb phosphorus.

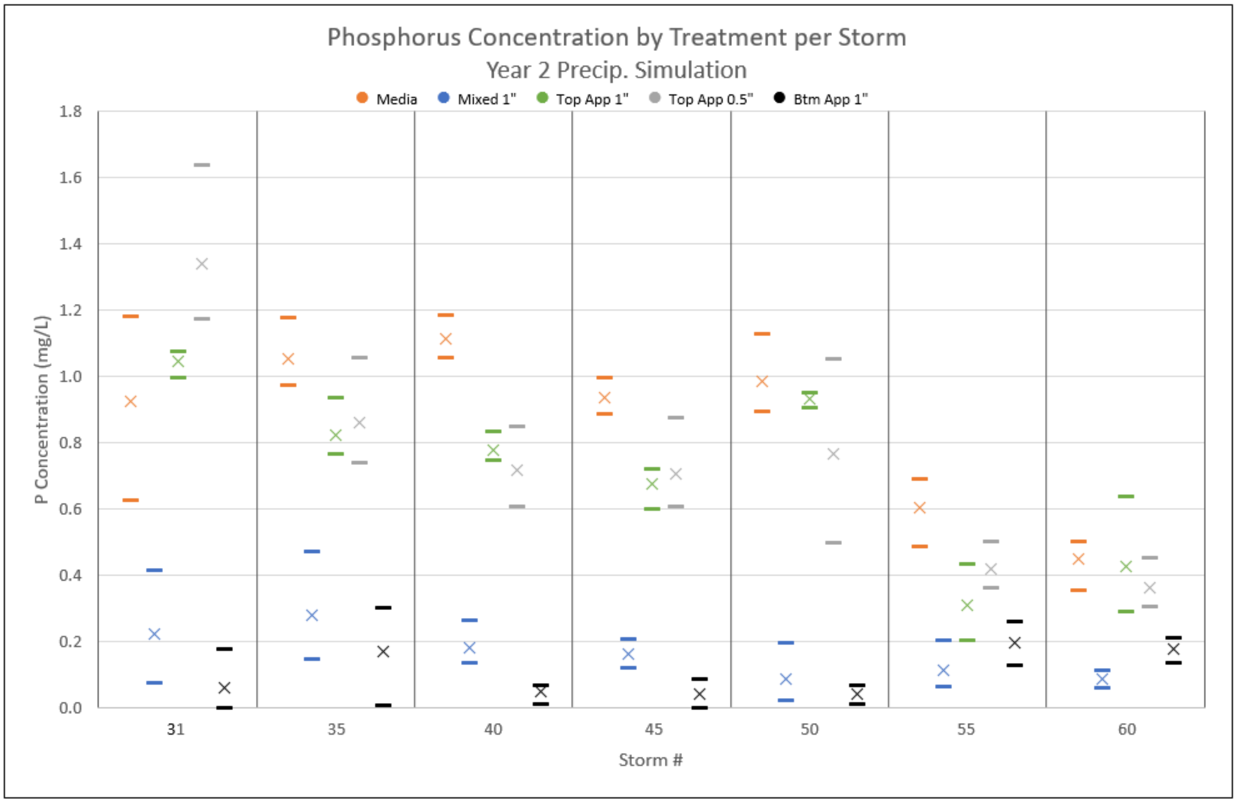


*Figure 3: The subsurface applied treatments continue to out-perform the other treatments. Notice their general increase in performance, in addition to the non-detects. These results suggest net phosphorus reduction is possible for these systems.*

## Field Scale

The summer of 2019 produced very few rainfall events that surpassed the threshold set (0.20") to trigger a sampling event. As a result, there is only a single set of influent/effluent samples to compare with historical performance data from the bioretention cell at 700 Wood St. This single sample set did, however, provide a promising glimpse of what may be to come for future research at this site. The results, displayed in Figure 4, showed a 61.1% reduction in total phosphorus concentration following the application of Al-WTR, and a 56.6% post-application reduction in dissolved phosphorus concentration. Another way to think about this comparison is, prior to application, the total and dissolved concentrations of phosphors were increasing by about 150 and 170%, respectively, while after application, increases were only about 17 and 20%, respectively. Influent concentrations were consistent with historical data. These results are encouraging, although it should be noted that there was still a small net export of phosphorus for this first set of samples.

## Conclusion

Both the lab and field scale Al-WTR experiments have produced results that indicate a beneficial use for this waste product may be on the horizon. The net phosphorus reduction, non-detects, and general increase in performance are all hopeful observations taken from the research conducted through the

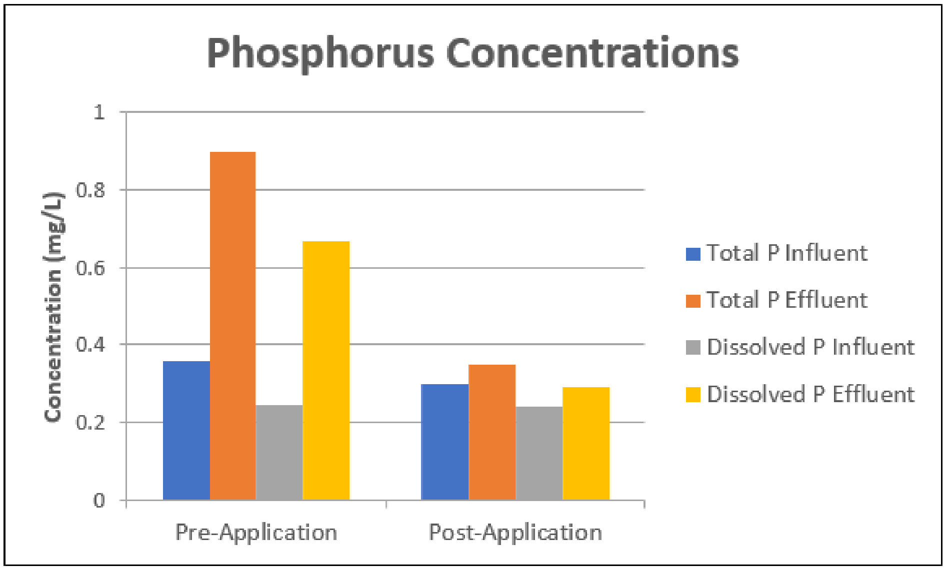


*Figure 4: Bioretention cell performance comparison before, and after, application of aluminum based water treatment residuals. Preliminary results show an impressive reduction in P.*

column study. The data from 700 Wood St., although extremely limited in quantity, showed a very impressive reduction as well. It is, however, premature to draw any definitive conclusions considering the duration of each study is quite small in comparison to the lifespan of a typical bioretention cell, which can be as long as a few decades. It is recommended that both of these experiments continue so that a better understanding of the long-term performance of these systems may be achieved.

# Attachment 2

Prepared for: City of Fort Collins

# Enhancing Phosphorus Removal Capabilities of Bioretention Cells through Application of Water Treatment Residuals

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## Background

Many of the pollutants commonly found in urban stormwater runoff are notorious for the harmful impacts they can inflict on sensitive ecosystems found within the lakes, rivers, and streams that receive stormwater during and after precipitation events. The large volume of water produced by these events is also of concern as this can cause issues such as erosion of stream banks and dramatic temperature fluctuations. One of the tools that stormwater managers use to combat these negative effects is a type of Low Impact Development (LID) called the bioretention cell (BRC). Due to a lack of data relating to the performance of these systems in Colorado, the City of Fort Collins Stormwater Utility constructed a BRC in 2012 to serve as a research and demonstration site at their headquarters located at 700 Wood Street, Fort Collins, Colorado. A collaborative research effort with the Colorado Stormwater Center at Colorado State University was carried out from 2013-2015.

Although the research that took place from 2013-2015 yielded many positive results, the researchers involved drew attention to a concerning trend that had emerged. The BRC appeared to be leaching phosphorus into the runoff, causing the effluent concentrations to be greater than the influent concentrations. The extent of the leaching was such that, even after considering volume reduction of the BRC, there was an overall net export of phosphorus. It was speculated in the report that the source of the phosphorus contribution was the organic compost contained in the filter media mix, which calls for 10-20% by volume per specification.

After the field research was completed, a literature review was conducted to identify potential amendments that could reduce the exportation of phosphorus from the BRC. From this review, a solution was proposed that suggested amending the existing filter media mix by adding water treatment residuals (WTRs). WTRs are a by-product of the drinking water treatment process that research has shown to possess a high capacity for adsorbing phosphorus. A column study designed to simulate full-scale bioretention cells was used to evaluate phosphorus removal at different WTR application rates and locations in the profile. Following a successful 2-year rainfall simulation through the columns, WTRs were surface applied to the BRC field site. The City of Fort Collins drinking water plant generates about 1,000 tons of WTRs per year. If proven to be effective at reducing phosphorus concentrations in urban stormwater runoff, WTRs could be diverted from local landfills when applied to stormwater BMPs throughout the City.

## Objectives

The primary objective of this study was to investigate the effectiveness of using WTRs to enhance the phosphorus removal capabilities of bioretention cells. This was achieved by monitoring the BRC located at 700 Word Street during precipitation events that occurred from May to October 2020. Monitoring efforts consisted of collecting influent and effluent water quality samples, in addition to quantifying the volume of water entering and exiting the system by maintaining a water budget.

BRC water quality was also monitored for any indication that the applied WTRs were exporting harmful byproducts. In accordance with regulations, use of WTRs for the purpose of stormwater treatment requires that a beneficial use plan be prepared and approved in order to evaluate any potential impacts to human health and the environment. One of the main concerns when repurposing WTRs for any intended use is the potential release of harmful substances into the environment. An important part of the beneficial use plan is the implementation of a detailed monitoring plan to track the concentration of heavy metals and radioactive contaminants present in effluent treated at the application site. This data is essential for developing a better understanding of the safety and efficacy of using WTRs to enhance the performance of stormwater BMPs. For a complete list of requested water quality analyses, see “Water Quality” in the “Methods” section.

The information obtained during this investigation was compared with data gathered at this site during the previous research project. This comparison was essential to draw conclusions regarding whether the phosphorus removal capabilities of the BRC had been enhanced following an application of WTRs. The results of the historical comparison will be used to identify topics for future WTR research, in addition to informing decisions at the City level for implementing WTR applications on a broader scale.

Another objective of this study was to build upon the collection of data that exists as a result of the previous research project that took place at this site from 2013-2015. This was achieved by emphasizing overall stormwater runoff volume reduction in addition to water quality parameters that were common between the two studies, such as total suspended solids (TSS) and total nitrogen and its components. The similarities and differences that arise between the two datasets can be used to gain a better understanding of the long-term performance of these systems and identify areas for potential improvement in research methods.

## Site Description

The BRC, or rain garden, at the City of Fort Collins Stormwater Utility Headquarters is located at 700 Wood Street, Fort Collins, Colorado. Runoff comes from the on-site parking lot with a 99,000 square foot area. The BRC has a total surface area of approximately 1,900 square feet. The rain garden is divided into two cells, defined as the East Cell and the West Cell in this report. The East Cell has an approximate surface area of 890 square feet and the West Cell has an approximate surface area of 988 square feet. As a result of grading during construction, during a runoff event, the East Cell receives approximately 85% of the total parking lot runoff and the West Cell receives approximately 15%.

Runoff from each cell first enters a forebay comprised of pea gravel where trash and large particulates are removed. After flowing through the forebay, runoff enters the "ponding area" where runoff infiltrates through the filter media and into the gravel storage reservoir below. Runoff that accumulates in the gravel storage reservoir can either infiltrate into the groundwater or discharge through the underdrain which is connected to the stormwater drainage system. As shown in Figure 1, the bioretention cell includes approximately 18 in. of filter media, 6 in. of pea gravel, and 16 in. of CDOT #4 aggregate. The CDOT #4 aggregate comprise the gravel storage reservoir previously mentioned and the pea gravel is used as a diaphragm to keep the filter media and storage layer separate. The underdrain is a 6-inch perforated PVC pipe and acts to discharge water from the gravel storage reservoir once water reaches a certain depth. One underdrain serves both the east and west cells and water passing through the underdrain is discharged into the storm sewer. It should be noted that a riser used in previous research that effectively raised the height of the underdrain to approximately 12-inches above the bottom of the gravel storage reservoir was not utilized for this study.

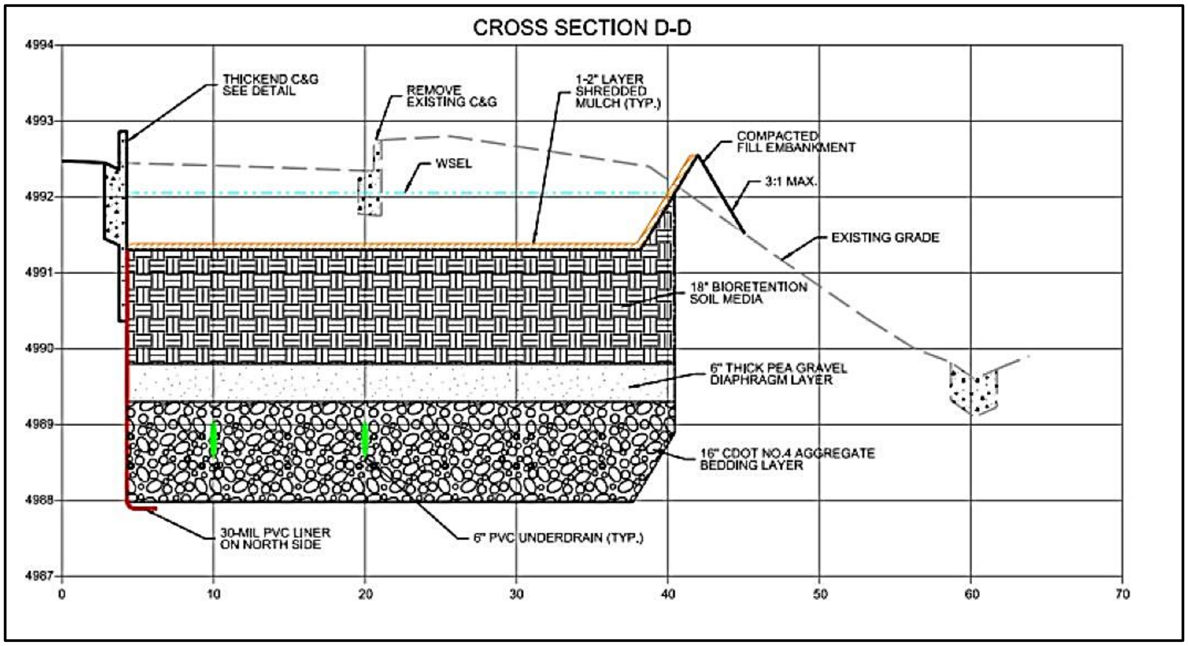


**Figure 1.** Cross section of bioretention cell layers.

## Methods

A variety of instruments and procedures were used to investigate the performance of the BRC. Two ISCO 6712 samplers each equipped with 730-Bubbler Flow Modules were installed on-site. Flow readings recorded by the ISCO 6712 samplers were used to measure the volumetric flow rates and stormwater runoff volumes entering the East H-Flume and exiting the bioretention cell through the underdrain. Volumetric flow rates entering the West H-Flume were measured using an Onset HOBO Water Level Data Logger that was installed in the base of the flume. The ISCO 6712 samplers collected water quality samples from the East H-Flume inlet, and from the underdrain, during runoff events. The samples were analyzed to determine the influent and effluent pollutant concentrations.

Site monitoring activities took place from May to October of 2019 and 2020. May to October was defined as the runoff period as this is the time of year when a majority of the precipitation falls in the form of rain. Monitoring was only conducted during the spring-fall seasons because the samplers are not intended to be operated in sub-freezing conditions. The following sections provide greater detail regarding monitoring activities, equipment, and methods.

## Soil Interactions

Soil moisture readings were taken three days per week using a FieldScout TDR 100 Soil Moisture Meter with medium length rods and corresponding rod setting. Additional readings were taken the day before an anticipated storm event and the day after a storm event. The cells were divided into six different sections as shown in Figure 2. Readings were taken in each section and used to calculate the average daily soil moisture per cell for the days in which site visits took place.

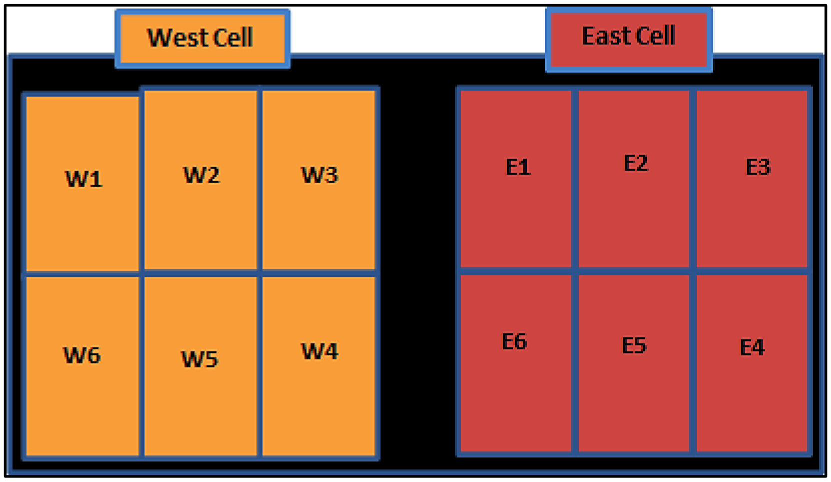


**Figure 2.** East and West Cell sections for soil moisture readings.

Calculating Soil Retention:

Soil retention was calculated by subtracting the average volumetric water content for the day before the storm from the average volumetric water content for the day after the storm event. This difference was then multiplied by the depth of the engineered BRC filter media and the total surface area of the BRC. See Equation (1).

**Equation (1)** $$\Delta S = (VWC_2 - VWC_1) \times D \times A$$

Where:

$\Delta S$ = Soil Retention

D = Depth of Engineered Media = 1.5 feet

A = Area of Both Bioretention Cells = 1900 ft$^2$

$VWC_1$ = Average volumetric water content for the day before the storm.

$VWC_2$ = Average volumetric water content for the day after the storm.

Calculating Evapotranspiration:

Evapotranspiration was also calculated based on average volumetric water content (VWC) readings. First, the average volumetric content for the day before the next storm event was subtracted from the average volumetric content for the day after the storm. This difference was then multiplied by the depth of the engineered BRC filter media and the total surface area of the BRC to calculate the evapotranspiration as a volume as shown in Equation (2).

**Equation (2)** $$ET = (VWC_2 – VWC_3) \text{ x } D \text{ x } A$$

Where:

ET = Evapotranspiration

D = Depth of Engineered Media = 1.5 feet

A = Area of Both Bioretention Cells = 1900 $ft^2$

$VWC_3$ = Average volumetric water content for the day before the next storm.

$VWC_2$ = Average volumetric water content for the day after the storm.

## East H-Flume Inflow Volumes

East H-Flume flow readings were measured by the 730 Bubbler Module and retrieved from the ISCO 6712 sampler. The samplers were set to record readings at a time interval of every 5-minutes. Cumulative flow volumes were calculated by multiplying the flow rate by the time interval and then summing the volumes for each time interval over the course of the storm as shown in Equation (3).

**Equation (3)** $$V_{E\text{-}FLUME} = \sum(Q_{E\text{-}FLUME\text{-}N} \text{ x } T_N)$$

Where:

$V_{E\text{-}FLUME}$ = Total East H-Flume Flow Volume ($ft^3$)

$Q_{E\text{-}FLUME}$ = East H-Flume Flow Reading per Time Interval *N* (c.f.s.)

$T_N$ = Time Interval *N* (seconds)

## West H-Flume Flow Volumes

Flows through the West H-flume were measured using pressure readings from Onset HOBO Water Level Data Loggers. One HOBO was installed inside the structure for the ISCOs to monitor atmospheric pressure readings, while another HOBO was installed in a notch in the West H-Flume to monitor pressure as it changed with water depth. The water depth was calculated by subtracting the atmospheric pressure from the pressure in the flume, then dividing the difference by the specific weight of water as shown in Equation (4).

**Equation (4)** $$D = \frac{(P_W - P_{atm})}{\Upsilon}$$

Where:

$D$ = Measured Water Depth (inches)

$P_W$ = West H-Flume Pressure Reading (psi)

$P_{ATM}$ = Atmospheric Pressure Reading (psi)

$\Upsilon$ = Specific Weight of Water (psia)

The depth calculated using Equation (4) was then used to determine the volumetric flow rate through the flume. After calculating the water depth in the West 0.5-ft-H-Flume, the volumetric flow was determined using a depth to discharge relationship. The reference table for this relationship can be found in Appendix C: 0.5 ft. H-Flume Depth to Discharge Table. The discharge, or volumetric flow rate, was multiplied by the time interval for the pressure readings to find the incremental flow volume for that time interval. These incremental volumes were then summed up to find the total volume that passed through the West Flume as shown in Equation (5).

**Equation (5)** $$V_{W\text{-}FLUME} = \sum (Q_{W\text{-}FLUME\text{-}N} \times T_N)$$

Where:

$V_{W\text{-}FLUME}$ = Total West H-Flume Volume ($ft^3$)

$Q_{W\text{-}FLUME}$ = West H-Flume Flow Reading per Time Interval *N* (c.f.s.)

$T_N$ = Time Interval *N* (seconds)

## Influent

Influent refers to the total volume of stormwater runoff entering the bioretention cell. Influent was assumed to be equal to the sum of the calculated volumes that flowed through the East H-Flume and the West H-Flume as shown in Equation (6).

**Equation (6)** $$V_{TI} = V_{E\text{-}FLUME} + V_{W\text{-}FLUME}$$

Where:

$V_{TI}$ = Influent Volume ($ft^3$)

$V_{E\text{-}FLUME}$ = Total East H-Flume Volume ($ft^3$)

$V_{W\text{-}FLUME}$ = Total West H-Flume Volume ($ft^3$)

Influent Distribution Between Flumes

The distribution of stormwater runoff between the two H-Flumes is found by dividing the respective measured inflow volumes by the total inflow volume. Equation (7) shows the method for finding the influent distribution for the East H-Flume, while Equation (8) shows the method for finding the influent distribution for the West H-Flume.

**Equation (7)** $$I_E = \frac{V_{E-FLUME}}{V_{TI}} = \frac{V_{E-FLUME}}{(V_{E-FLUME} + V_{W-FLUME})}$$

Where:

$I_E$ = Percentage of total influent going through the East H-Flume.

$V_{TI}$ = Influent Volume ($ft^3$)

$V_{E\text{-}FLUME}$ = Total East H-Flume Volume ($ft^3$)

$V_{W\text{-}FLUME}$ = Total West H-Flume Volume ($ft^3$)

**Equation (8)** $$I_W = \frac{V_{W-FLUME}}{V_{TI}} = \frac{V_{W-FLUME}}{(V_{E-FLUME} + V_{W-FLUME})}$$

Where:

$I_W$ = Percentage of total influent going through the East H-Flume.

$V_{TI}$ = Influent Volume ($ft^3$)

$V_{E\text{-}FLUME}$ = Total East H-Flume Volume ($ft^3$)

$V_{W\text{-}FLUME}$ = Total West H-Flume Volume ($ft^3$)

Table 1 summarizes the total volumes entering each H-Flume and the total influent entering the system. Table 2 summarizes the percentage of the total influent that each H-Flume received. The average distribution of influent for the West H-Flume and the East H-Flume was 14% and 86% respectively.

**Table 1.** Water quantity data for sampled storm events.

| Date of Storm | West H-Flume Volume (cubic feet) | East H-Flume Volume (cubic feet) | Total Influent Volume (cubic feet) |
|---|---|---|---|
| 5/24/2020 | 345 | 2480 | 2825 |
| 6/8/2020 | 244 | 3135 | 3379 |
| 8/1/2020 | 178 | 907 | 1085 |
| 8/29/2020 | 167 | 858 | 1025 |
| 9/8/2020 | 1188 | 5640 | 6828 |

**Table 2.** Calculated influent percentage H-flume distributions for sampled storm events.

| Percentage of Total Influent Volume | | |
|---|---|---|
| **Date of Storm** | **West H-Flume** | **East H-Flume** |
| 5/24/2020 | 12% | 88% |
| 6/8/2020 | 7% | 93% |
| 8/1/2020 | 16% | 84% |
| 8/29/2020 | 16% | 84% |
| 9/8/2020 | 17% | 83% |
| **Averages:** | **14%** | **86%** |

### Effluent & Water Volume Reduction

Underdrain flow readings were measured by the 730 Bubbler Module and retrieved from the ISCO 6712 sampler. The samplers were set to record readings at a time interval of every 5-minutes. Flow volumes through the underdrain pipe, also referred to as effluent flow volumes for the BRC, were calculated as shown in Equation (9). Incremental flow rates were multiplied by the time step to find incremental flow volumes. The total sum of these incremental flow volumes equals the total effluent volume through the underdrain pipe.

**Equation (9)** $V_{UNDERDRAIN} = \sum (Q_{UNDERDRAIN\text{-}N} \times T_N)$

Where:

$V_{UNDERDRAIN}$ = Total Underdrain Volume ($ft^3$)

$Q_{UNDERDRAIN\text{-}N}$ = Underdrain Flow Reading per Time Interval *N* (c.f.s.)

$T_N$ = Time Interval *N* (seconds)

The total volume through the underdrain was compared to the total influent volume to measure the water volume reduction for each storm. Water volume reduction was measured using the total influent volume from the H-flumes and the total effluent volume from the underdrain. For Equation (10) a negative value indicates that the underdrain pipe had less water flowing through it than what flowed through the H-flumes. For Equation (11) a positive value indicates a reduction in stormwater runoff volume from the influent to the underdrain pipe.

**Equation (10)** $\Delta V = (V_{TE} - V_{TI})$

Where:

$\Delta V$ = Change in Water Volume ($ft^3$)

$V_{TE}$ = Total Effluent Volume ($ft^3$)

$V_{TI}$ = Total Influent Volume ($ft^3$)

**Equation (11)** $P.R. = 1 - \left(\frac{V_{TE}}{V_{TI}}\right)$

Where:

P.R. = Percent (%) Reduction

$V_{TE}$ = Total Effluent Volume ($ft^3$)

$V_{TI}$ = Total Influent Volume ($ft^3$)

<u>Estimating Infiltration:</u>

After having calculated the soil retention in Equation (1), evapotranspiration (ET) in Equation (2), total influent volume in Equation (6), and total stormwater volume that passed through the underdrain pipe in Equation (6), infiltration was calculated according to Equation (12). Soil retention and total stormwater volume were then subtracted from the total influent volume.

**Equation (12)** $$I = V_{TI} - (\Delta S + ET) - V_{UNDERDRAIN}$$

Where:

$I$ = Total Infiltration Volume ($ft^3$)

$V_{TI}$ = Total Influent Volume ($ft^3$)

$\Delta S$ = Soil Retention ($ft^3$)

$ET$ = Evapotranspiration

$V_{UNDERDRAIN}$ = Total stormwater volume that passed through the underdrain pipe ($ft^3$)

## Water Quality

Storm events sampled for water quality, also referred to as sampled storm events, were defined as storm events with at least 0.2-inches of cumulative precipitation. Water quality samples were taken from the East H-flume and the underdrain using ISCO 6712 automated samplers. Water quality samples were not taken from the West H-Flume based on the assumption that the stormwater runoff quality would be the same for both H-flumes. Each sampler took a 500-mL sample based on a set sampling interval volume. Due to varying rainfall intensities and runoff flow rates throughout storm events, regular site checks were performed to adjust the set volumes for the sampling intervals as needed. The 500-mL samples were used to create two composite samples, the first for water entering the East H-flume and the second for water exiting the underdrain. The composite stormwater samples were submitted to M.M.S. Environmental Labs for analysis. The analyses requested depended on the total cumulative precipitation of the storm.

### Small Storm Water Quality Testing

Small storms were defined as storms with at least 0.2-inches and less than 0.3-inches of cumulative precipitation. The following analyses were requested for small storms:

- Total Suspended Solids
- P-Total
- P-Dissolved
- TKN
- NO3 as N
- NO2 as N
- Ammonia as N

- E. Coli (if able to be delivered to lab within four hours)
- Aluminum
- Iron

<u>Large Storm Water Quality Testing</u>

Large storms were defined as storms with more than 0.3-inches in cumulative precipitation. The following analyses were requested for large storms in addition to the small storm request list:

- Chromium
- Copper
- Manganese
- Potassium
- Zinc
- Gross Alpha
- Gross Beta
- Radium 226 + Radium 228
- Uranium

Of the five storm events, three exceeded 0.3-inches in cumulative precipitation. The additional testing listed above was requested for storms on:

- May 24th, 2020
- June 9th, 2020
- September 8th, 2020

Further discussion on trends in water quality results can be found in the "Results and Discussion" section of this report. A tabulated summary of water quality results can be found in Appendix B: Water Quality Data.

Percent reduction was calculated by comparing pollutant concentrations for the influent composite sample to concentrations for the effluent composite sample. When using Equation (13) to calculate the percent reduction, a positive percentage indicates a reduction in pollutant concentration, while a negative percentage indicates an increase in pollutant concentration.

**Equation (13)** $$\text{P.R.} = 1 - \left(\frac{C_2}{C_1}\right)$$

Where:

P.R. = Percent (%) Reduction

$C_1$ = Influent Concentration

$C_2$ = Effluent Concentration

In cases where the concentration level was a non-detect (ND), the method detection limit (MDL) was assumed as the concentration to make a conservative measure of the percent reduction. The MDL value was entered for non-detect results in the "Results" section and indicated with an asterisk (*). Non-detect values were left with the "ND" notation for the complete set of tabulated lab results in "Appendix B: Water Quality Data".

<u>Example Calculation:</u>

**Table 3:** Instance where the effluent concentration is a non-detect (ND) for Nitrogen, Total Kjeldahl as N.

| Date of Storm | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| 9/8/2020 | 1.3 | ND | 33.1% |

$$\text{P.R.} = 1 - \left(\frac{MDL\ (ppm)}{1.3-ppm}\right)$$

Where the method detection limit (MDL) for Nitrogen, Total Kjeldahl as N is 0.87 ppm.

$$\text{P.R.} = 1 - \left(\frac{0.87\ \ (ppm)}{1.3-ppm}\right) = 33.1\%$$

## Pollutant Load Reduction

Load reduction for each of the sampled storm events was calculated in pounds based on the concentration and water volume data. Specific load reduction results for total phosphorus, dissolved phosphorus, total suspended solids (TSS), Nitrogen Total Kjeldahl as N (TKN), and nitrate as N can be found in the "Load Reductions" section.

For sampled runoff events, the influent pollutant concentrations in ppm were converted to pounds per cubic foot and multiplied by the total influent volume in cubic feet. This gave the calculated influent pollutant load in pounds as shown in Equation (14).

**Equation (14)** $P_{INF}$ (lbs.) = $C_1$ (ppm) x (6.23567 x $10^{-5}$ (lbs./ft.$^3$)) x $V_{TI}$ (ft.$^3$)

Where:

$P_{INF}$ = Calculated Pollutant Influent (lbs.)

$C_1$ = Measured Influent Concentration (ppm)

$V_{TI}$ = Measured Influent Volume (ft$^3$)

1-ppm = 6.23567 x $10^{-5}$ (lbs./ft.$^3$)

Similarly, the effluent pollutant concentrations in ppm were converted to pounds per cubic foot and multiplied by the total volume through the underdrain pipe. This gave the calculated effluent pollutant load in pounds as shown in Equation (15).

**Equation (15)** $P_{EFF}$ (lbs.) = $C_2$ (ppm) x (6.23567 x $10^{-5}$ (lbs./ft.$^3$)) x $V_{UNDERDRAIN}$ (ft$^3$)

Where:

$P_{EFF}$ = Calculated Pollutant Effluent Load (lbs.)

$C_2$ = Measured Effluent Concentration (ppm)

$V_{UNDERDRAIN}$ = Measured Total Underdrain Volume (ft$^3$)

1-ppm = 6.23567 x $10^{-5}$ (lbs./ft.$^3$)

The amount of pollutant load removed in pounds was calculated by subtracting the pollutant effluent load from the pollutant influent load as shown in Equation (16).

**Equation (16)** $P_{REM} = P_{EFF} - P_{INF}$

Where:

$P_{REM}$ = Measured Pollutant Effluent Load Removed (lbs.)

$P_{EFF}$ = Measured Pollutant Effluent Load (lbs.)

$P_{INF}$ = Measured Pollutant Influent Load (lbs.)

## Results and Discussion

Five storm events were sampled and analyzed to acquire water quality and quantity data during the 2020 monitoring period, which lasted from May to October. Water level and flow readings gathered by the ISCO 6712 samplers during these events formed the basis for runoff volume reduction calculations. Concentrations from the lab results were used to calculate pollutant reductions or increases for each of the five sampled storm events and to track trends across the 2020 monitoring season. Load reductions were calculated using the concentration and water volume data for each sampled storm event. Specific load reduction results for total phosphorus, dissolved phosphorus, total suspended solids (TSS), Nitrogen Total Kjeldahl as N (TKN), and nitrate as N can be found in the "Load Reductions" section.

## Water Quantity Results

Stormwater volume reduction is often used to help quantify overall BRC performance. Reducing the total stormwater discharge can in turn lead to a reduction in pollutant loads and rapid temperature fluctuations within receiving waters following a storm event. For this reason, flow rates recorded for the H-flumes and the underdrain pipe were used to calculate the accumulated volumes for the influent and effluent over the duration of the storm. A comparison of these calculated influent and effluent volumes for each monitored storm is shown in Figure 3. Table 4 summarizes total influent and effluent volumes, volume reduction in cubic feet, and volume percent reduction for each storm sampled during the 2020 monitoring season. The average percent volume reduction from influent to effluent was 88.7%. The minimum volume percent reduction was 86.1%, which corresponded to the September 8$^{th}$ snowstorm.

A brief description and accompanying figures for each of the sampled storm events during the 2020 monitoring season is included in this section of the report. Cumulative precipitation based on readings from both the Fort Collins Flood Warning System Utility Service Center Sensor and the on-site ISCO rain gauge were collected to provide information regarding the storm's duration, total depth, and intensity. Accumulated volumes for the H-flumes and the underdrain over the duration of the storm are also included.

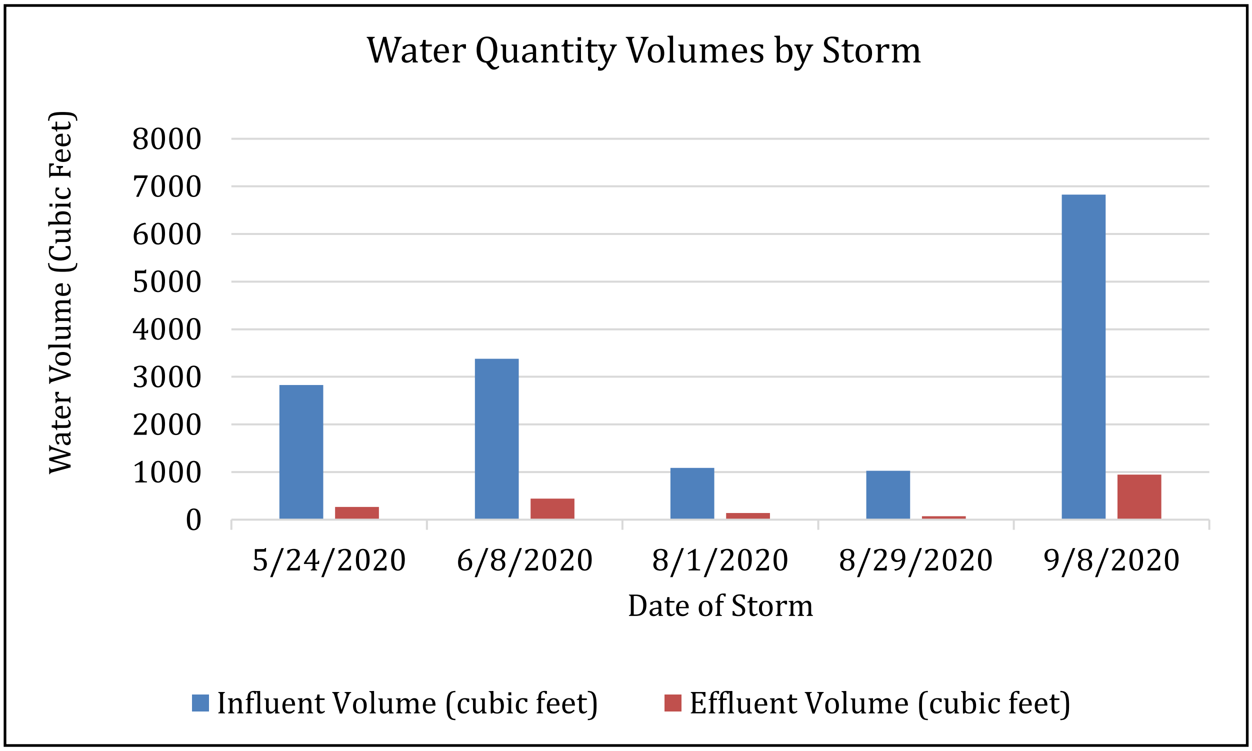


**Figure 3.** Water quantity influent and effluent volumes by storm.

**Table 4:** Summary of volume reduction by storm.

| Date of Storm | Influent Volume (cubic feet) | Effluent Volume (cubic feet) | Change in Volume (cubic feet) | Volume Reduction (%) |
|---|---|---|---|---|
| 5/24/2020 | 2825 | 264 | 2561 | 90.7% |
| 6/8/2020 | 3379 | 441 | 2938 | 86.9% |
| 8/1/2020 | 1085 | 142 | 943 | 86.9% |
| 8/29/2020 | 1025 | 72 | 953 | 93.0% |
| 9/8/2020 | 6828 | 948 | 5880 | 86.1% |
| | | | **Average % Reduction:** | **88.7%** |

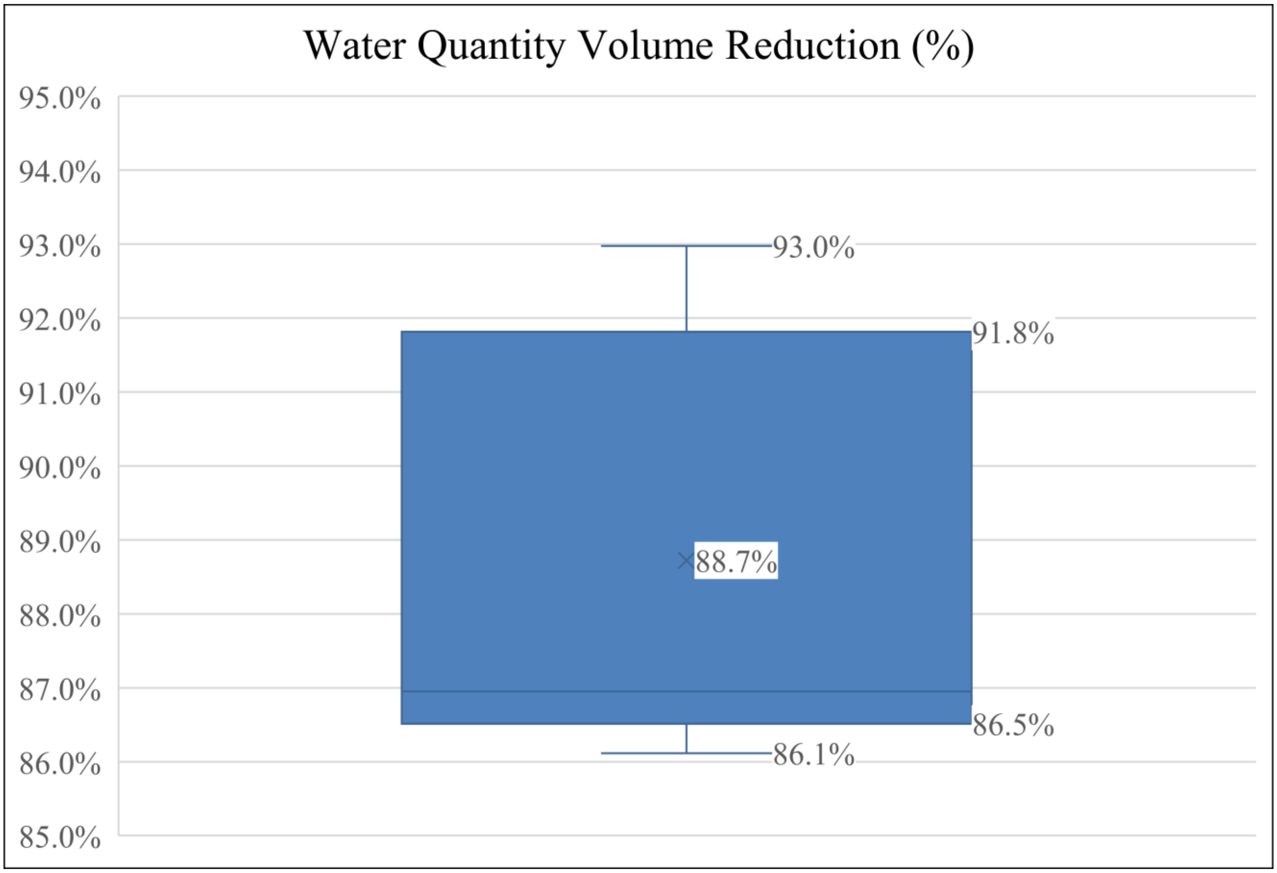


**Figure 4.** Water quantity volume reduction percentages boxplot.

May 24th, 2020 Storm Event.

The first sampled storm event of the 2020 monitoring season had a cumulative precipitation of 0.47-inches over the course of just over 4-hours from 12:40 to 16:50 MST. Cumulative precipitation over the duration of the storm is shown in Figure 5. Accumulated volumes for the flumes and underdrain are shown in Figure 6. The influent to effluent volume was reduced by 90.7% with a decrease in volume of 2561 cubic-feet.

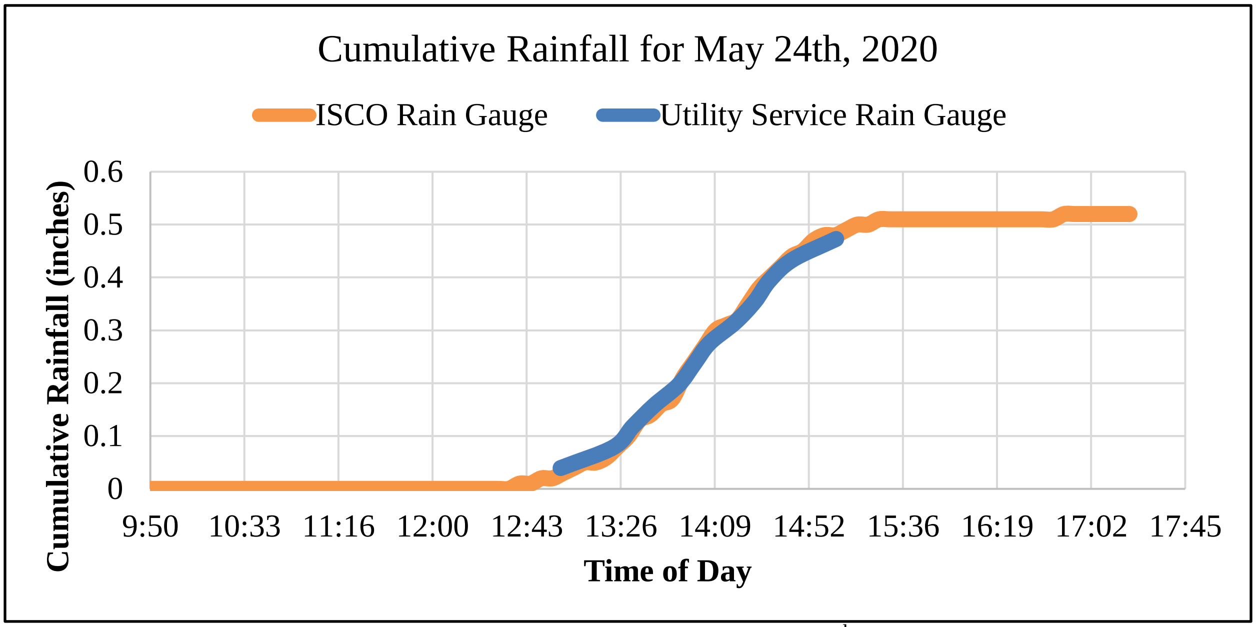


**Figure 5.** Cumulative precipitation for May 24th, 2020 storm.

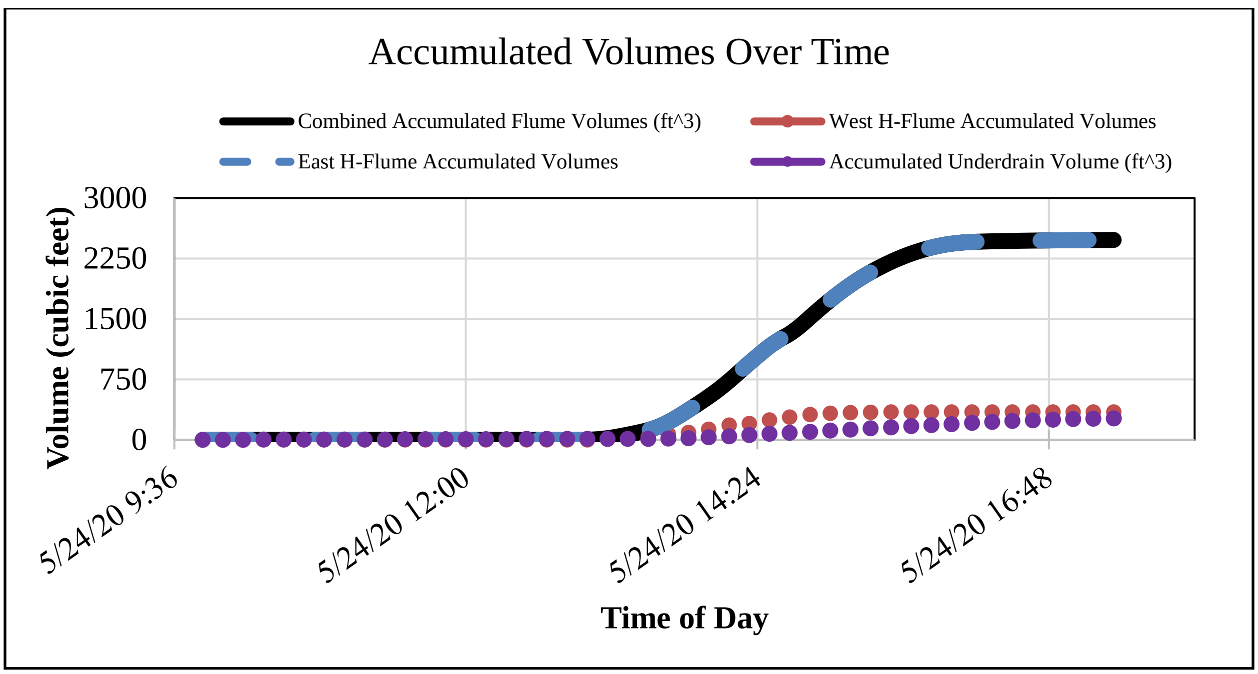


**Figure 6.** Accumulated volumes over time for the flumes and underdrain pipe.

June 8th, 2020 Storm Event.

The second sampled storm event of the 2020 monitoring season had a cumulative precipitation of 0.47-inches over the course of approximately 8-hours spanning from 22:00 MST June 8th 2020 to 5:45 MST June 9th 2020. Cumulative precipitation over the duration of the storm is shown in Figure 7. Accumulated volumes for the flumes and underdrain are shown in Figure 8. The influent to effluent volume was reduced by 86.9% with a decrease in volume of 2938 cubic-feet.

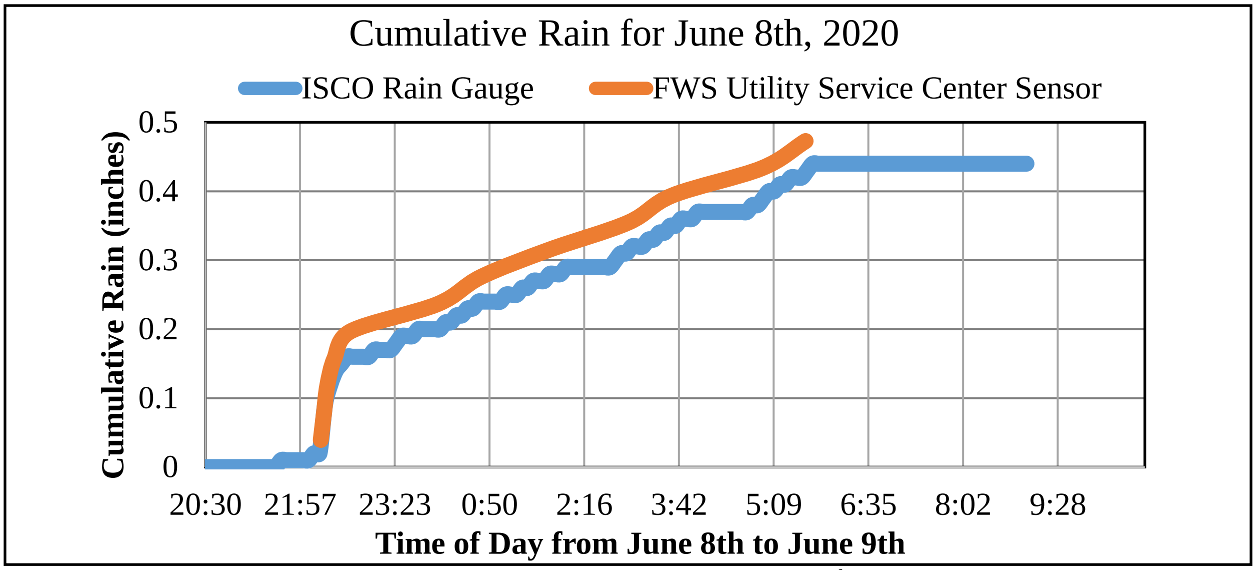


**Figure 7.** Cumulative precipitation for June 8th, 2020 storm.

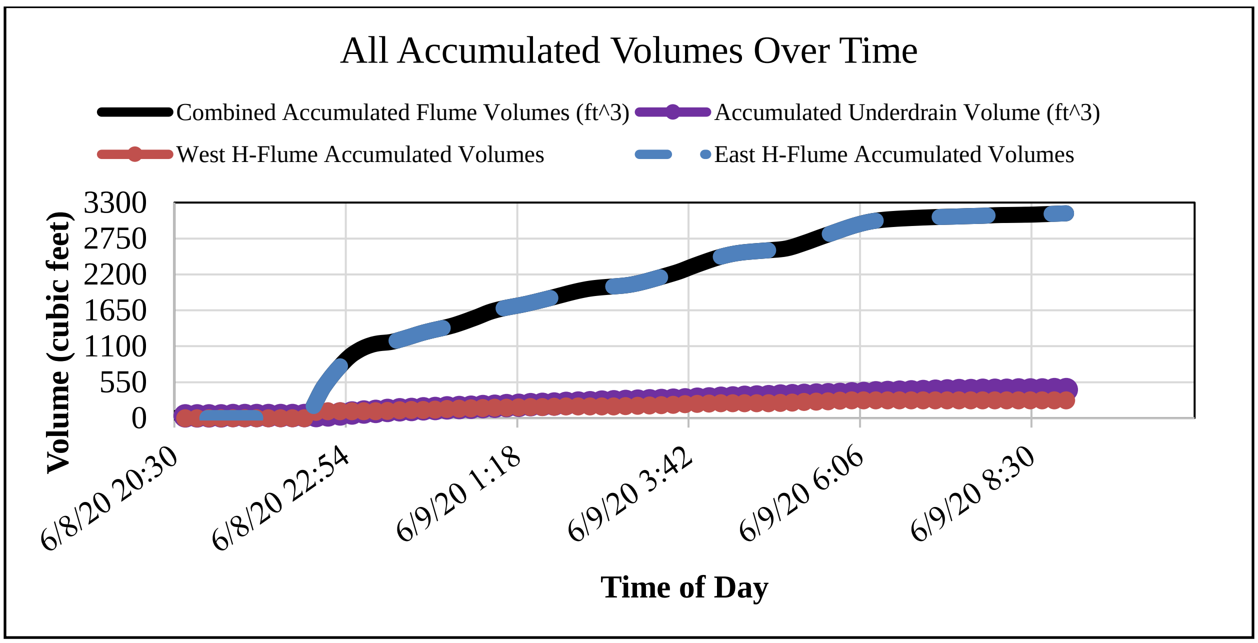


**Figure 8.** Accumulated volumes over time for the flumes and underdrain pipe for the June 8th, 2020 storm.

August 1st, 2020 Storm Event.

The third sampled storm event of the 2020 monitoring season had a cumulative precipitation of 0.28-inches. The first 0.24-inches of precipitation fell within approximately 10-minutes from 14:05 to 14:15 MST on August 1st, 2020. An additional 0.04-inches of precipitation fell from 20:15 to 20:35 MST. Cumulative precipitation over the duration of the storm is shown in Figure 9. Cumulative precipitation over the first twenty-minutes is shown in Figure 10. Accumulated volumes for the flumes and underdrain are shown in Figure 11. The influent to effluent volume was reduced by 86.9% with a decrease in volume of 943 cubic-feet.

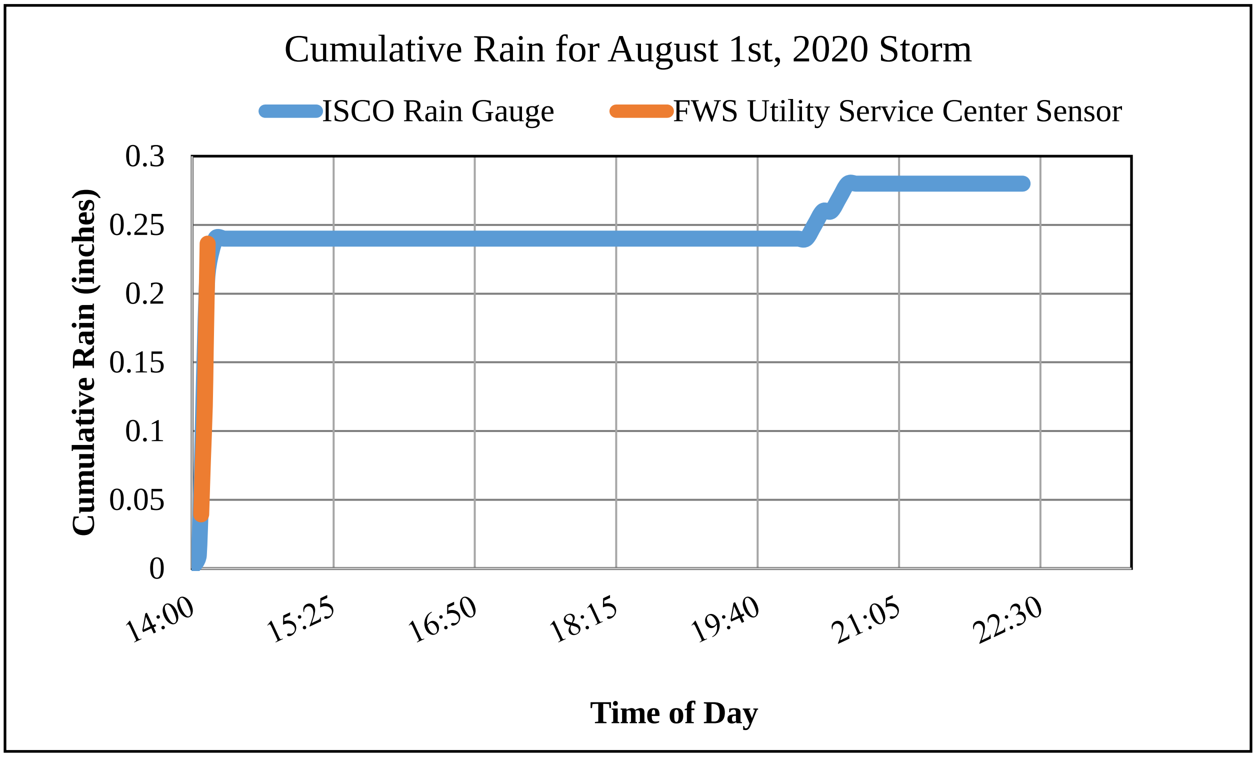


**Figure 9.** Cumulative precipitation for August 1st, 2020 storm.

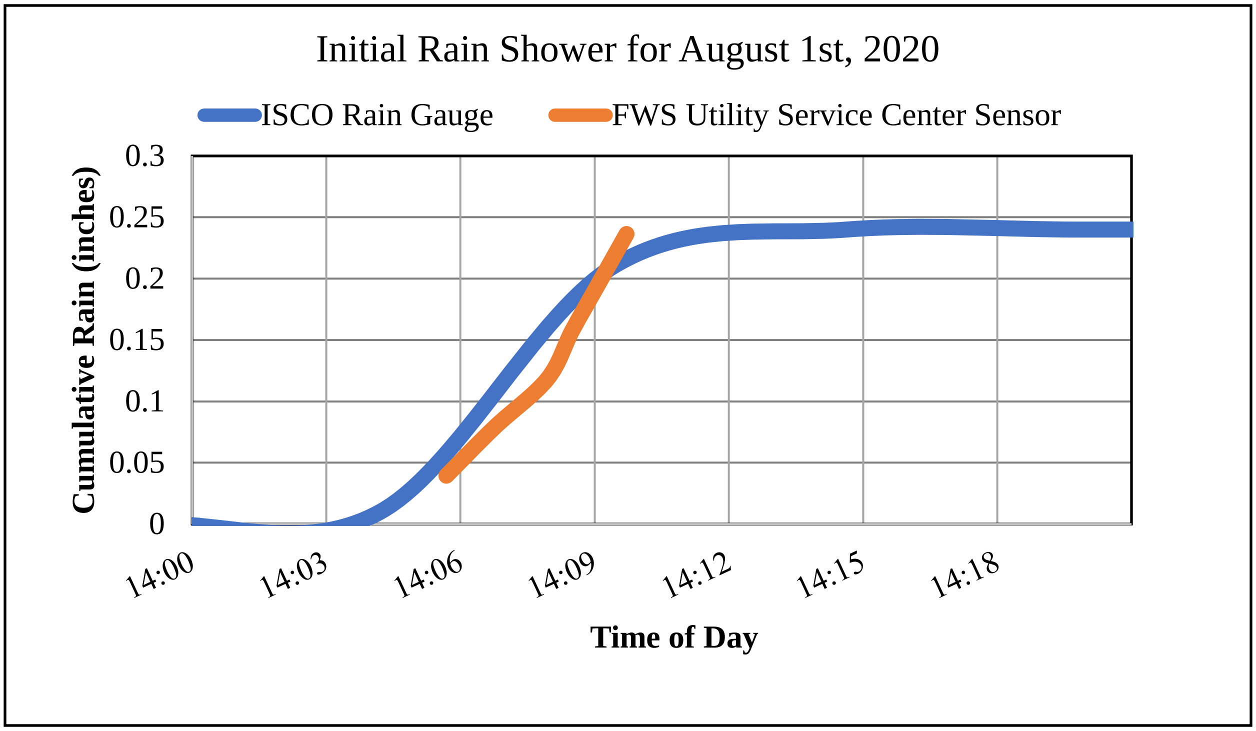


**Figure 10.** First 0.24-inches of cumulative rain for August 1st, 2020 storm.

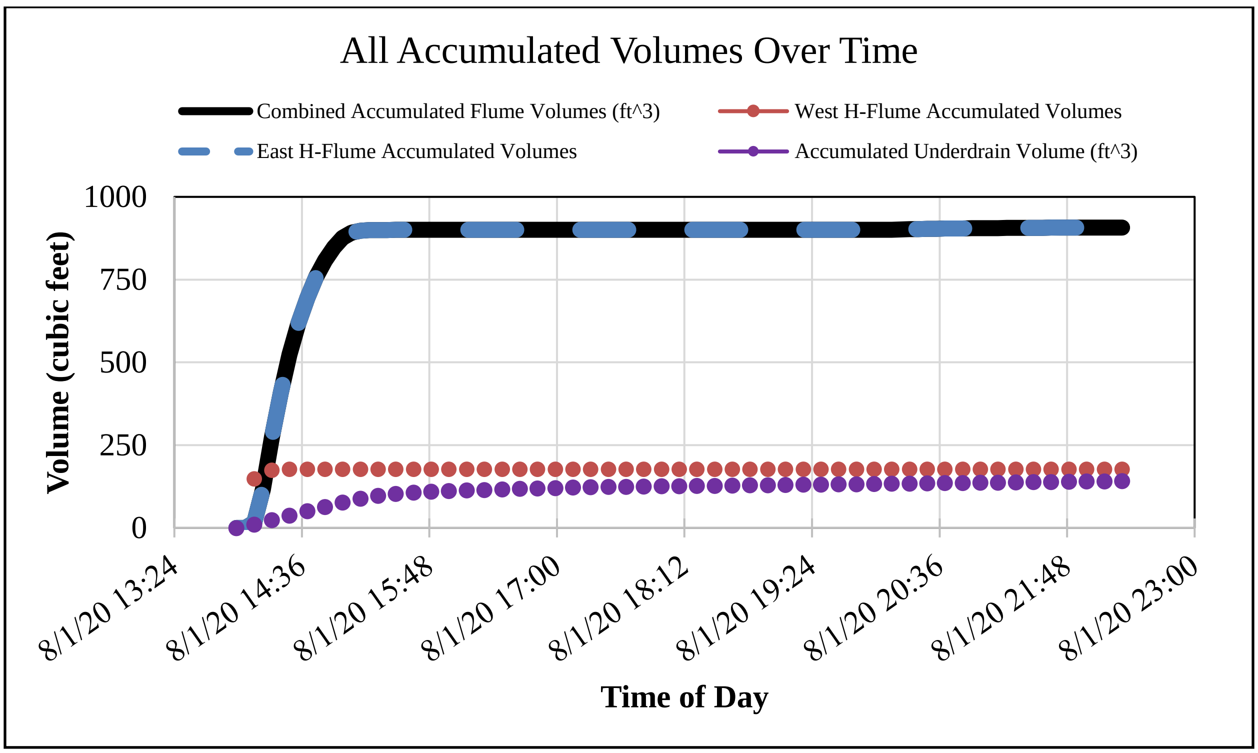


**Figure 11.** Accumulated volumes over time for the flumes and underdrain pipe for the August 1st, 2020 storm.

August 29th, 2020 Storm Event.

The fourth sampled storm event of the 2020 monitoring season had a cumulative precipitation of 0.20-inches over the course of 1.5-hours from 19:00 MST to 20:30 MST on August 29th, 2020. Cumulative precipitation over the duration of the storm is shown in Figure 12. Accumulated volumes for the flumes and underdrain are shown in Figure 13. The influent to effluent volume was reduced by 93.0% with a decrease in volume of 953 cubic-feet.

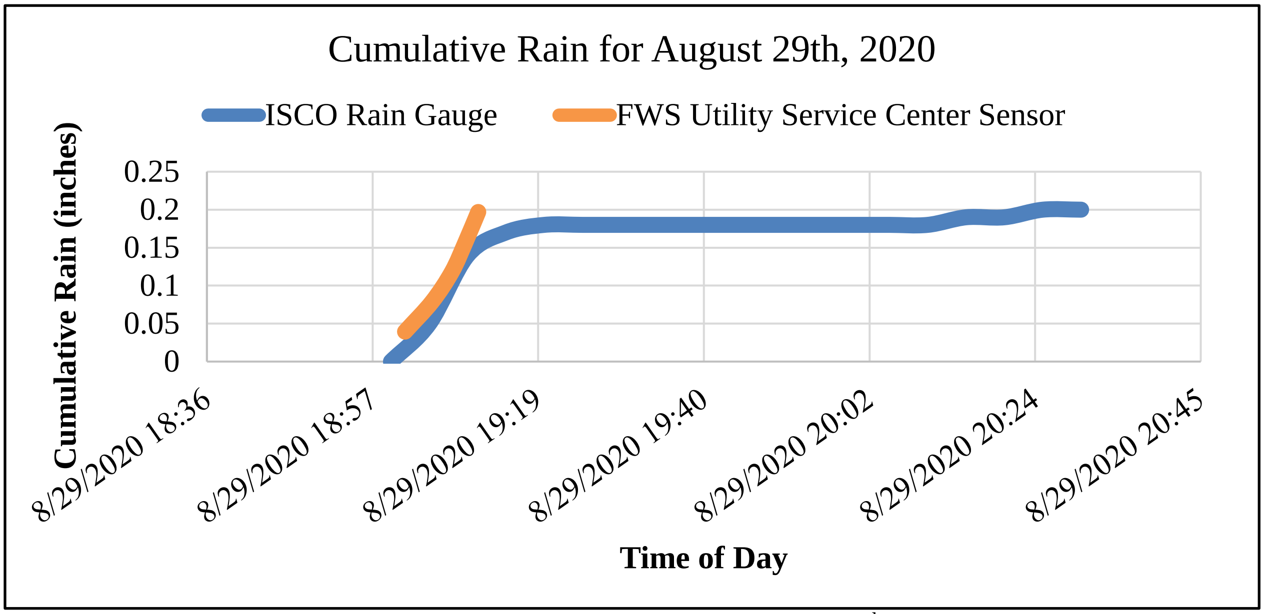


**Figure 12.** Cumulative precipitation for August 29th, 2020 storm.

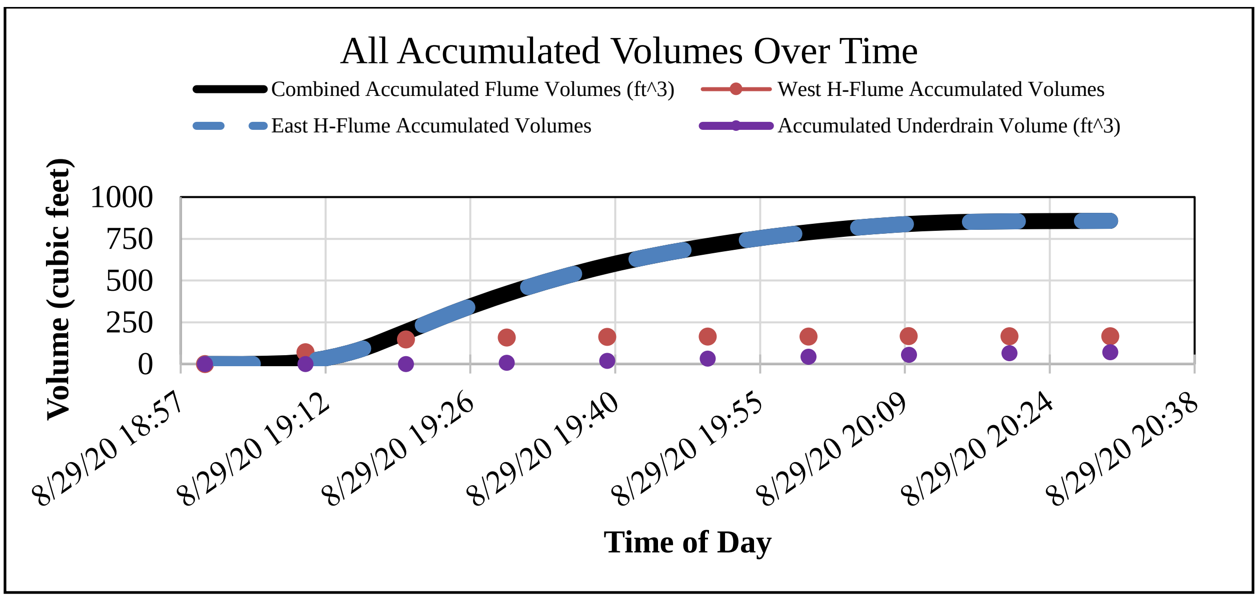


**Figure 13.** Accumulated volumes over time for the flumes and underdrain pipe for the August 29th, 2020 storm.

September 8th, 2020 Storm Event.

The fifth and final sampled storm event of the 2020 monitoring season had a cumulative precipitation of 1.34-inches between 23:00 MST September 7th, 2020 and 16:00 MST September 9th, 2020. While a snowstorm, the decision was made to sample based on the reasoning that it was still warm enough for the snow to melt on contact with the pavement. Methods used for infiltration and cell volume calculations may not apply to this situation as the snow and ice layer remained over the bioretention cell following the storm. Cumulative precipitation over the duration of the storm is shown in Figure 14. Accumulated volumes for the flumes and underdrain are shown in Figure 15. The influent to effluent volume was reduced by 86.1% with a decrease in volume by 5880 cubic-feet.

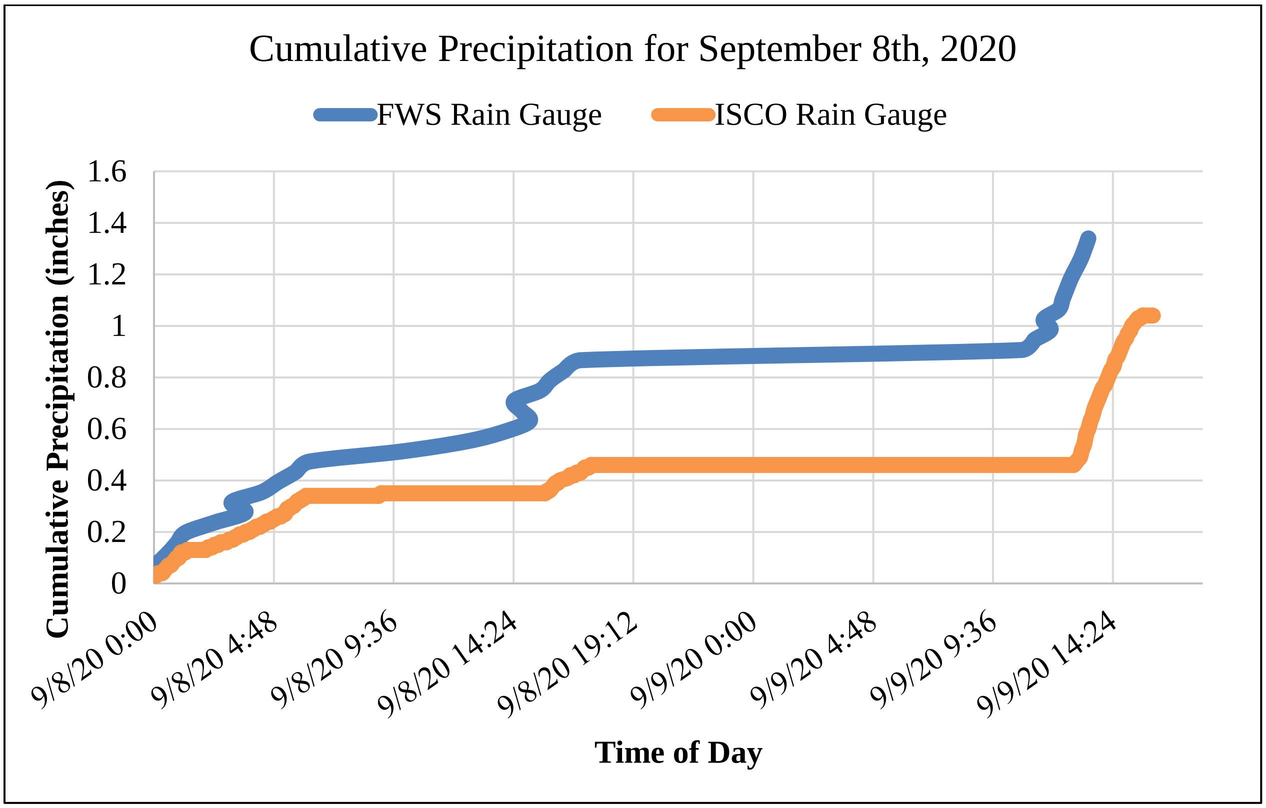


**Figure 14.** Cumulative precipitation for September 8th, 2020 storm.

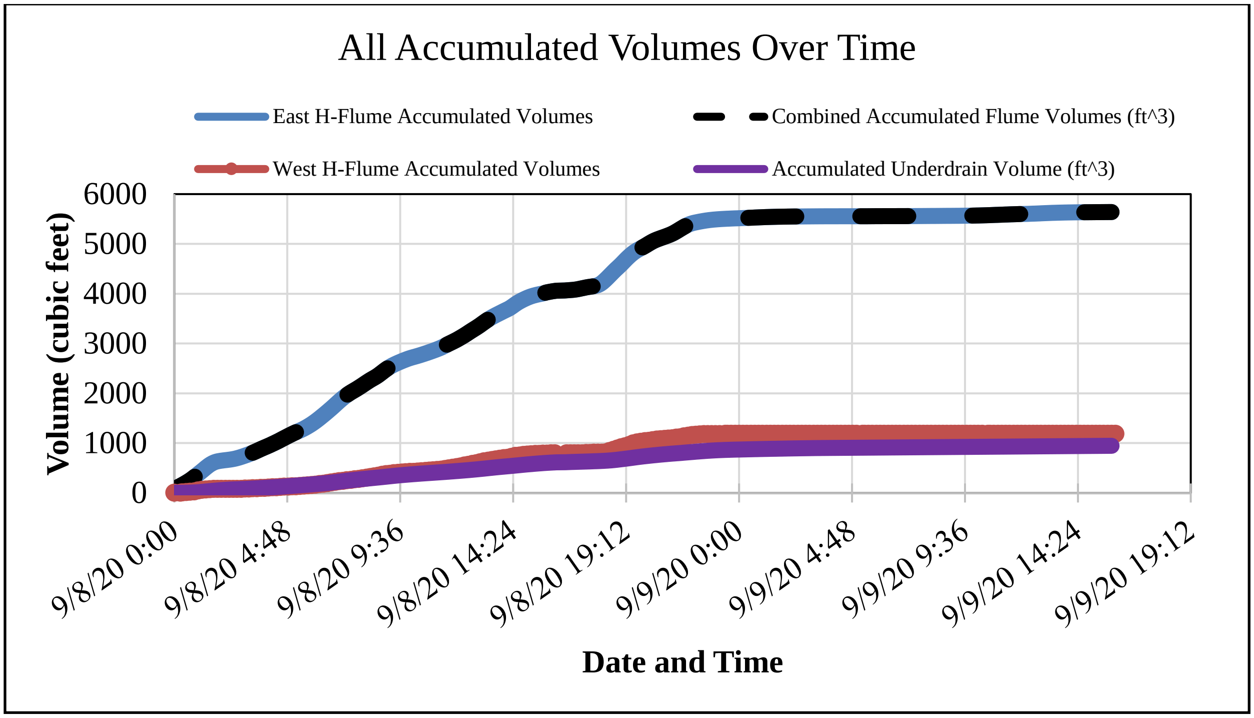


**Figure 15.** Accumulated volumes over time for the flumes and underdrain pipe for September 8th, 2020 storm.

### Water Quality Results

This section discusses observed trends in water quality for the 2020 monitoring season by comparing influent and effluent pollutant concentrations for each sampled storm. Trends in BRC performance relating to pollutant removal can be found by comparing the influent to effluent concentrations for multiple storm events. Pollutant removal is achieved when stormwater runoff filters through the specialized media in the rain garden, after which a portion of the effluent infiltrates to the groundwater below.

It should be known that an unexpected variable arose in the last half of the study that could have impacted water quality results and comparisons. The Cameron Peak Fire started August 13th, 2020 and burned through the end of the 2020 monitoring period. Ash was observed periodically falling across the City of Fort Collins, including the BRC field site at 700 Wood Street.
The following subsections discuss water quality results for pollutants that were a primary focus of this study: total phosphorus, dissolved phosphorus, total suspended solids (TSS), Nitrogen Total Kjeldahl as N (TKN), and nitrate as N. The sections that display total and dissolved

phosphorus results from the 2020 monitoring season are followed by a “Historical Phosphorus Comparison” section. The “Historical Phosphorus Comparison” section compares the current monitoring results to pre-WTR application phosphorus results. The historical comparison is important as the focus of the 2020 monitoring season was to observe if the WTR surface application would reduce the amount of phosphorus being exported from the BRC.

Additional pollutants with an observed trend are discussed in the “Other Observed Trends” section. A complete table of lab results from sampled runoff events is located in “Appendix B: Water Quality Data”. As previously stated, the September $8^{th}$ sampled storm event was a snowstorm. Influent concentrations for TKN, nitrate as N, and TSS tended to be lower for this storm when compared to rain events. However, dissolved phosphorus concentrations were higher for the September $8^{th}$ snowstorm event compared to dissolved phosphorus concentrations observed for rain events. The form of precipitation may have affected pollutant removal by the bioretention cell for this storm event.

## Total Phosphorus

Total phosphorus concentrations across the season, displayed in Figure 16., were mixed between increases and decreases of both small and moderated amounts. This can make it difficult to draw any meaningful conclusions. However, three out of five storms showed very similar influent and effluent concentrations, and the seasonal average of each was nearly identical. This does not suggest that treatment of this pollutant was not taking place. Recalling the fact that the WTRs were surface applied, the WTR’s were not able to physically or chemically interact with phosphorus potentially leaching from the BRC. This indicates that the surface applied WTR’s reduced influent total phosphorus concentrations enough to offset phosphorus leaching from the BRC into the effluent.

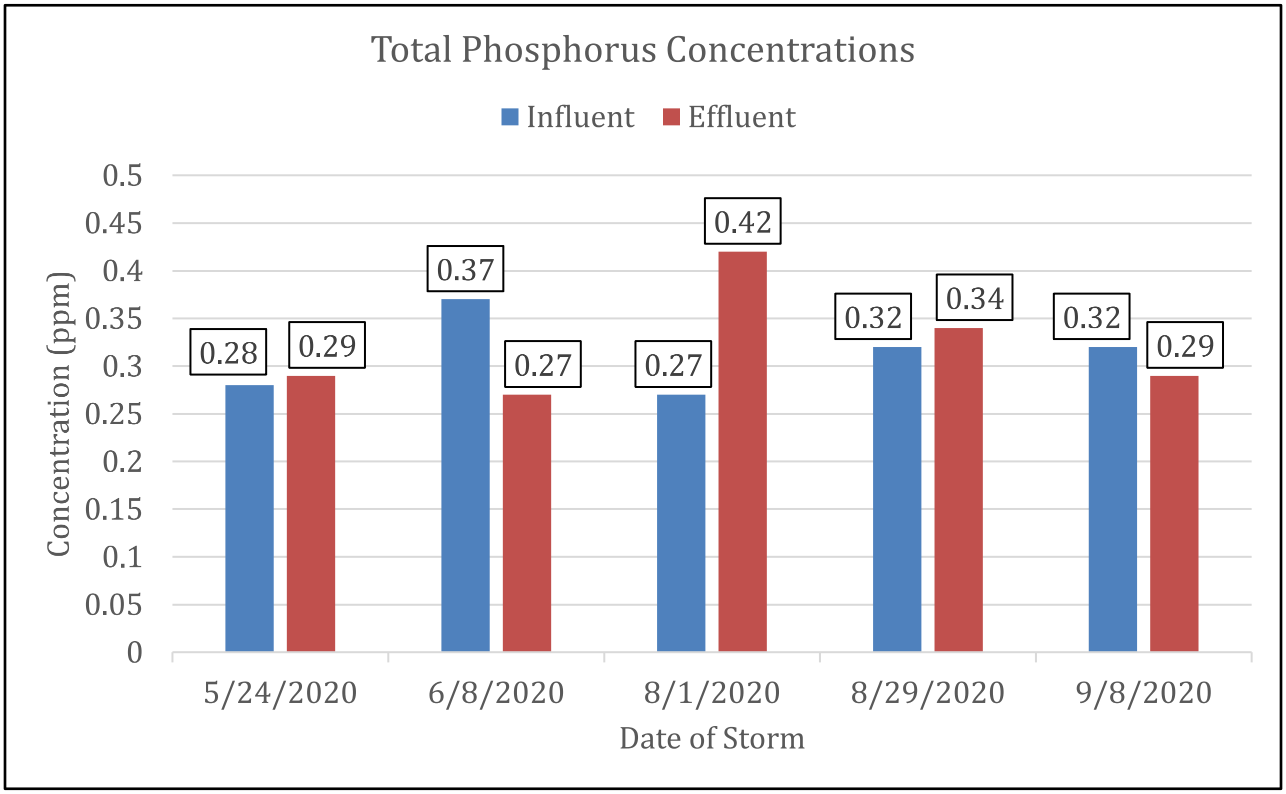


**Figure 16.** Total phosphorus influent and effluent concentrations by storm.

**Table 5.** Summary of Total Phosphorus concentrations by storm.

| Date of Storm | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| 5/24/2020 | 0.28 | 0.29 | -3.6% |
| 6/8/2020 | 0.37 | 0.27 | 27.0% |
| 8/1/2020 | 0.27 | 0.42 | -55.6% |
| 8/29/2020 | 0.32 | 0.34 | -6.3% |
| 9/8/2020 | 0.32 | 0.29 | 9.4% |
| **Averages:** | **0.31** | **0.32** | **-6%** |

## Dissolved Phosphorus

The dissolved phosphorus concentrations throughout the 2020 monitoring period show a general trend of increase from influent to effluent, with an average increase of 78% for the 2020 monitoring season. The sample results displayed in Figure 17. confirm that every storm, expect the September 8th snowstorm, exhibits behavior consistent with this trend. Although this trend is concerning, it is not surprising considering the brief period of contact the WTRs have with runoff as it infiltrates the system, and the general challenges that exist when attempting to treat dissolved containments with filtration systems such as a BRC. That being said, it is still possible that progress is taking place in regard to reducing influent dissolved phosphorus concentrations from levels that would have been present in the absence of a WTR application. The comparison to historical data from this site that follows will be key to understanding if gains are being made.

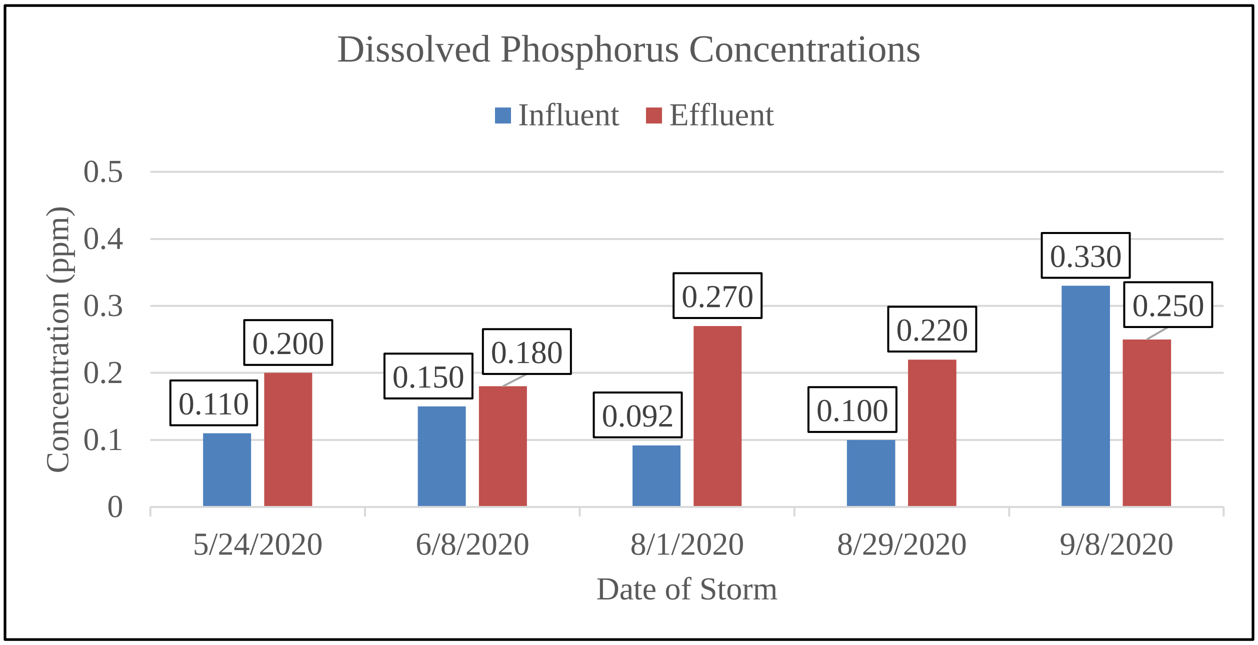


**Figure 17.** Dissolved phosphorus influent and effluent concentrations by storm.

**Table 6.** Summary of Dissolved Phosphorus concentrations by storm.

| Date of Storm | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| 5/24/2020 | 0.11 | 0.2 | -81.8% |
| 6/8/2020 | 0.15 | 0.18 | -20.0% |
| 8/1/2020 | 0.092 | 0.27 | -193.5% |
| 8/29/2020 | 0.1 | 0.22 | -120.0% |
| 9/8/2020 | 0.33 | 0.25 | 24.2% |
| **Averages:** | **0.16** | **0.22** | **-78%** |

## Historical Phosphorus Comparison

A comparison of influent and effluent phosphorus concentrations, before and after WTR application, is shown in Figure 18. and summarized in Table 7. Values for the historical average concentrations are based on the reported values and data in "Appendix B: Water Quality Raw Data" from the 2015 report. Current and historical influent concentrations for total and dissolved phosphorus are quite similar. However, the effluent concentrations for each parameter, following the WTR application, show approximately a 57% reduction. The concentration of total phosphorus Pre-WTR Application was 0.722-ppm, while Post-WTR Application concentration was 0.322-ppm. Additionally, the concentration of dissolved phosphorus Pre-WTR Application was 0.539-ppm, while Post-WTR Application concentration was 0.224-ppm. This indicates that a surface application of WTRs to an existing BRC could improve phosphorus concentrations in urban stormwater runoff, partially offsetting the issue of phosphorus leaching previously observed at this site.

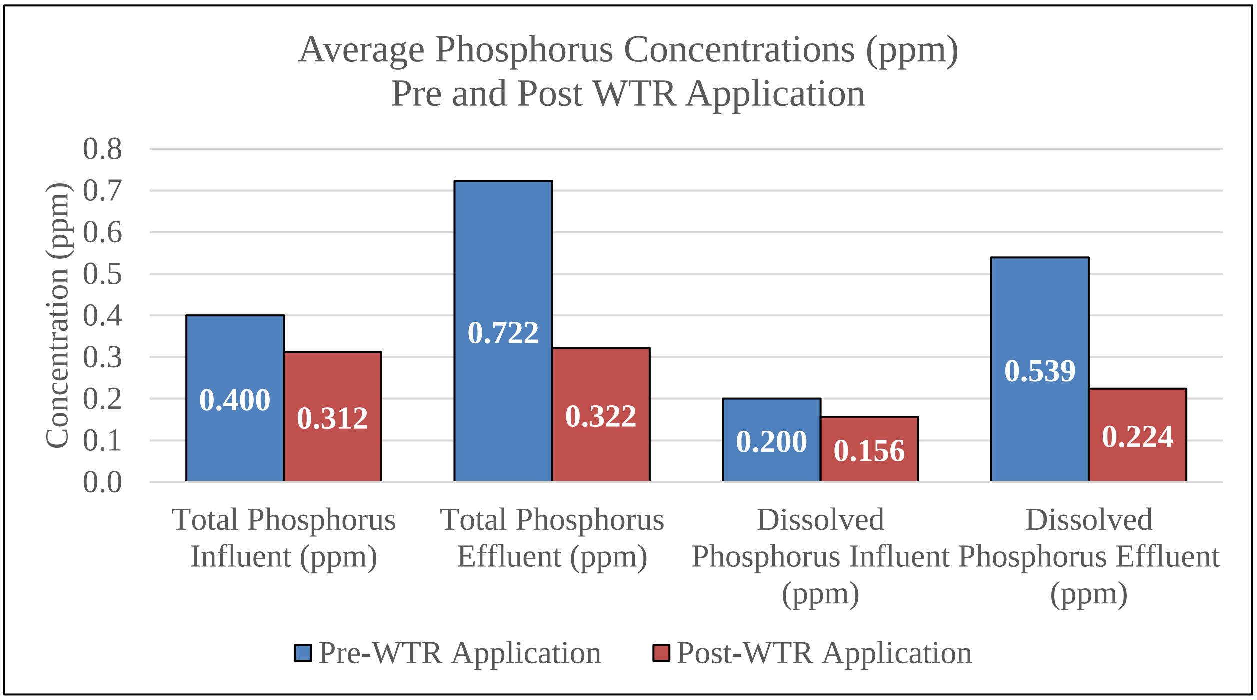


**Figure 18.** Average phosphorus concentrations (ppm) pre and post WTR application.

**Table 7.** Summary of average phosphorus concentrations pre and post WTR application.

| Average Concentrations (ppm) | | |
|---|---|---|
| | **Pre-WTR Application** | **Post-WTR Application** |
| Total Phosphorus Influent (ppm) | 0.400 | 0.312 |
| Total Phosphorus Effluent (ppm) | 0.722 | 0.322 |
| Dissolved Phosphorus Influent (ppm) | 0.200 | 0.156 |
| Dissolved Phosphorus Enfluent (ppm) | 0.539 | 0.224 |

Total Suspended Solids

The total suspended solids concentration showed a consistent decrease from the influent to the effluent for all five of the sampled storm events. The concentration of total suspended solids was reduced by an average of 63.9% from the influent to the effluent. This average concentration rate of reduction by percent is consistent with the TSS data from the 2015 report which indicated a TSS percent reduction of 64.7%. The lowest rate of reduction was 20%, which corresponded the September 8th snowstorm. This low rate of reduction could also be attributed to the influent concentration only being 5-ppm.

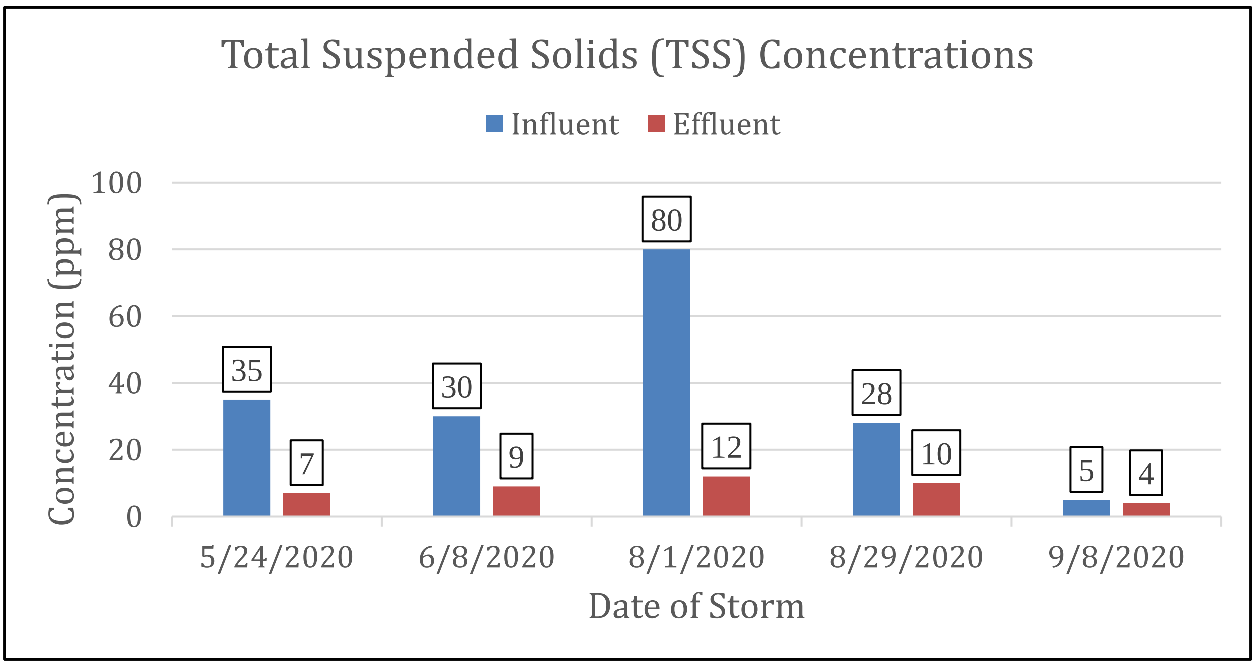


**Figure 19.** Total Suspended Solids (TSS) concentrations.

**Table 8.** Summary table of influent and effluent concentrations for TSS.

| Date of Storm | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| 5/24/2020 | 35 | 7 | 80.0% |
| 6/8/2020 | 30 | 9 | 70.0% |
| 8/1/2020 | 80 | 12 | 85.0% |
| 8/29/2020 | 28 | 10 | 64.3% |
| 9/8/2020 | 5 | 4 | 20.0% |
| **Averages:** | **35.6** | **8.4** | **63.9%** |

Nitrogen Total Kjeldahl as N

There was a slight increase in TKN concentration from the influent to the effluent for the first sampled storm event, followed by a trend of reduction for the remainder to the monitoring period (see Figure 20.). The average TKN concentration reduction was 17% for the 2020 monitoring season, which is less than the 26% TKN reduction in the 2015 report. It should be noted that the effluent concentration for the September 8th storm was a non-detect (ND). Consequently, the method detection limit (MDL) was used as the assumed effluent concentration to make a conservative measure of the percent reduction.

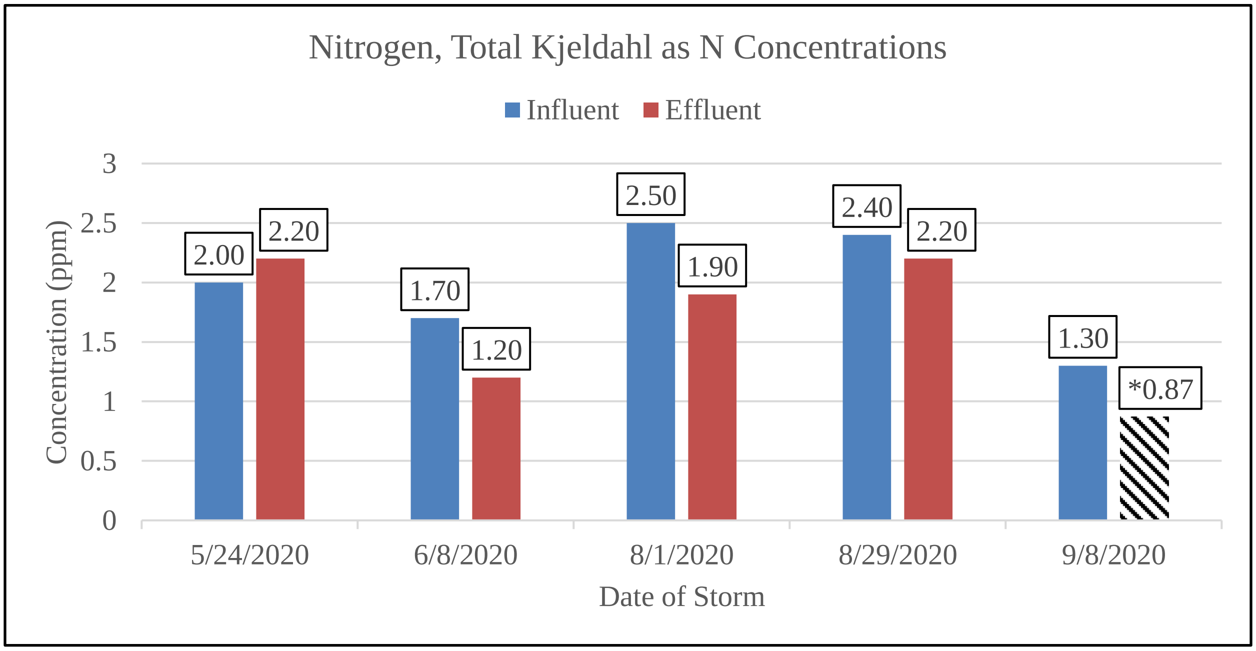


**Figure 20.** TKN Influent and Effluent Concentrations by storm.

**Table 9.** Summary of Nitrogen, Total Kjeldahl as N concentrations by storm.

| Date of Storm | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| 5/24/2020 | 2 | 2.2 | -10.0% |
| 6/8/2020 | 1.7 | 1.2 | 29.4% |
| 8/1/2020 | 2.5 | 1.9 | 24.0% |
| 8/29/2020 | 2.4 | 2.2 | 8.3% |
| 9/8/2020 | 1.3 | *0.87 | 33.1% |
| **Averages:** | **1.98** | **1.67** | **17.0%** |

*Note: The effluent TKN concentration was a non-detect (ND). The method detection limit (MDL) of 0.87-ppm was assumed for calculations.

Nitrate as N

The sample results for Nitrate as N, displayed in Figure 21., show a consistent increase in concentration from the influent to the effluent across the entire season. This trend is consistent with data from previous research indicating that the BRC was leaching Nitrate as N. Three out of five storms experienced a relatively large percent increase, ranging from 323-607%.  The overall average Nitrate as N concentration increase for the 2020 monitoring season was 378.2%, which is larger than the 121% average increase for Nitrate as N concentrations in the 2015 report. A comparison of average Nitrate as N Concentrations pre and post WTR application is shown in Figure 22.

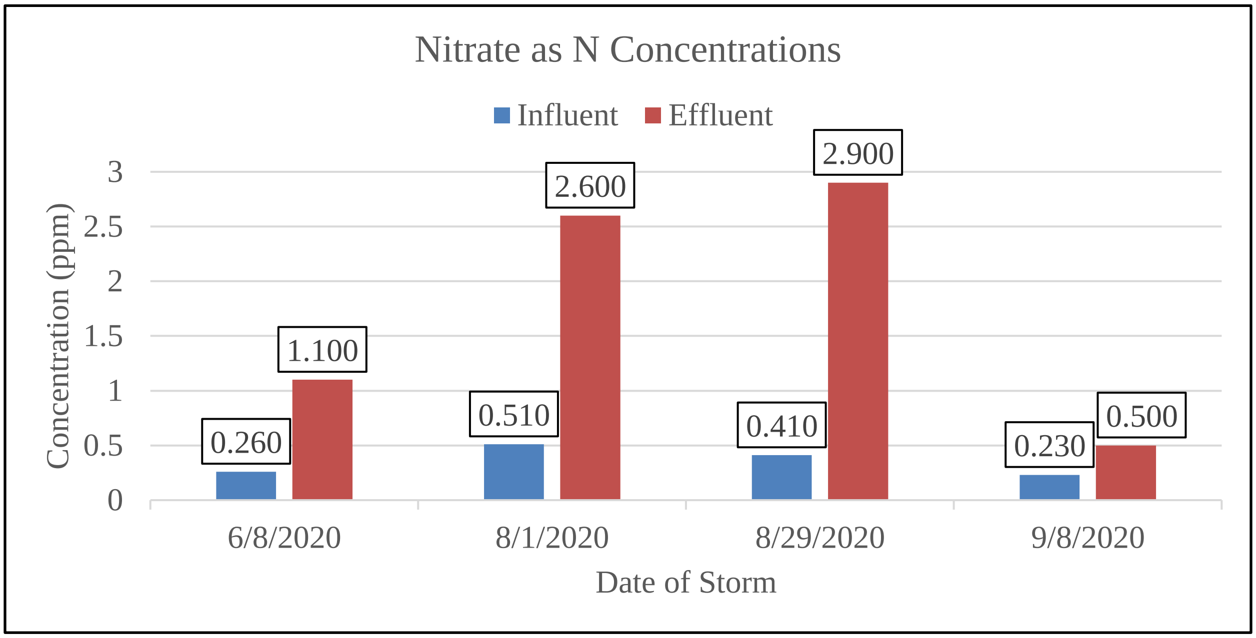


**Figure 21.** Nitrate as N concentrations for influent and effluent samples.

**Table 10.** Summary of nitrate concentrations by storm.

| Date of Storm | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| 6/8/2020 | 0.26 | 1.1 | -323.1% |
| 8/1/2020 | 0.51 | 2.6 | -409.8% |
| 8/29/2020 | 0.41 | 2.9 | -607.3% |
| 9/8/2020 | 0.23 | 0.5 | -117.4% |
| **Average:** | **0.3525** | **1.775** | **-378.2%** |

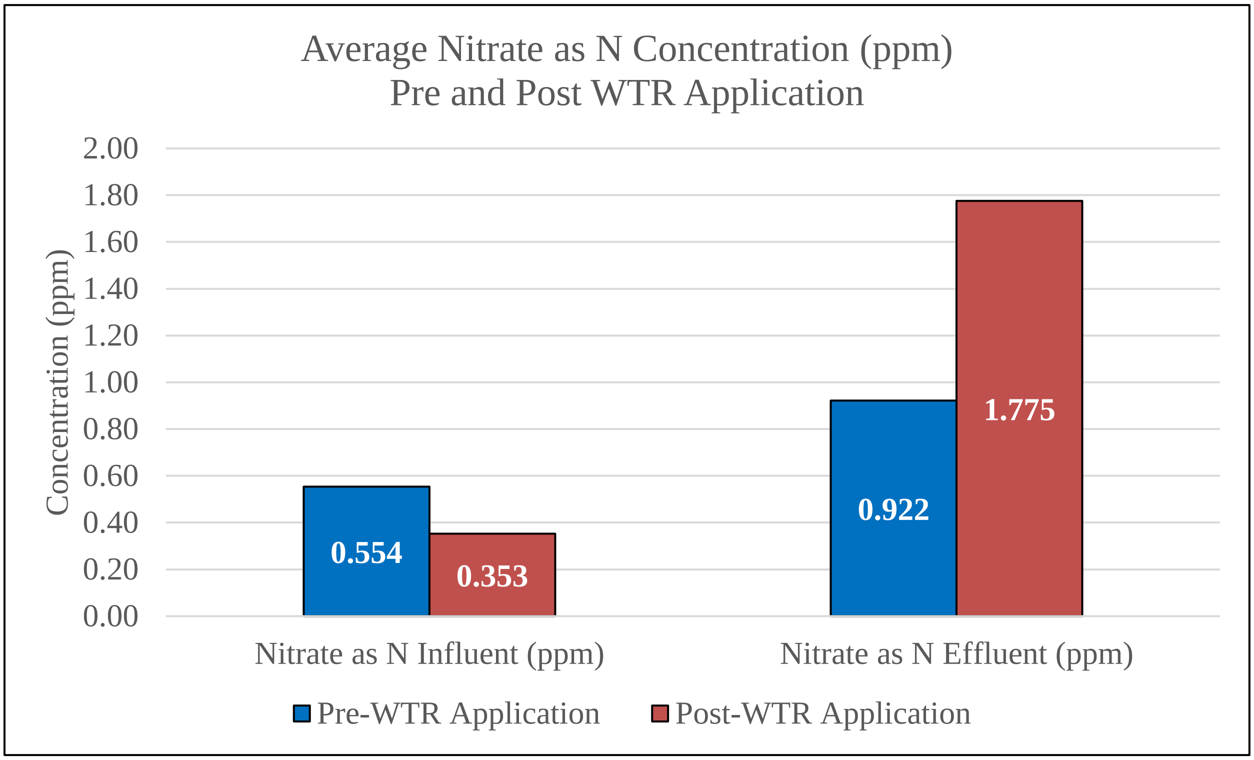


**Figure 22.** Average Nitrate as N concentrations (ppm) pre and post WTR application.

In regards to samples collected during the May 24th, 2020 storm, it should be noted that the laboratory performed a different type of test for nitrate and Nitrite as N that reported them as a combined value, hence the omission from Figure 21. And Table 10. The results from this test showed the influent concentration as a non-detect and the effluent concentration as 0.068-ppm. Considering that Nitrite as N results for all other storms were non-detects for both influent and effluent samples, it is reasonable to assume that there was a negligible amount of Nitrite as Nin the sample where the combined test was performed. Consequently, the sample results from the May 24th, 2020 storm support the trend that Nitrate as N is being exported by the BRC. Although TKN concentrations showed a trend of consistently decreasing, it appears the large increases in

Nitrate as N may outweigh those reductions from a Total Nitrogen perspective. This suggests that nitrogen leaching from the BRC may be causing effluent concentrations to rise.

Total nitrogen concentrations, based on the sum of Nitrate as N, TKN, and Nitrite as N concentrations, showed an overall increase from influent to effluent of 29% on average. Considering lab results for Nitrate as N were non-detects for influent and effluent across all storms, the method detection limit of 0.15-ppm was used when calculating Total Nitrogen. A summary of calculated influent and effluent Total Nitrogen concentrations, as well as concentration percent reductions, is shown in Table 11.

**Table 11.** Summary of Total Nitrogen concentrations by storm.

| **Total Nitrogen Influent, Effluent, and Percent Reduction for the 2020 Monitoring Season** | | | |
|---|---|---|---|
| **Date** | **Total Nitrogen Influent Concentration (ppm)** | **Total Nitrogen Effluent Concentration (ppm)** | **Concentration Percent (%) Reduction** |
| 5/24/2020 | 2.02 | 2.268 | -12% |
| 6/8/2020 | 2.11 | 2.45 | -16% |
| 8/1/2020 | 3.16 | 4.65 | -47% |
| 8/29/2020 | 2.96 | 5.25 | -77% |
| 9/8/2020 | 1.68 | 1.52 | 10% |
| **Averages:** | **2.39** | **3.23** | **-29%** |

## WTR Beneficial Use Compliance

Per the requirements of the WTR Beneficial Use Plan, samples were periodically analyzed for heavy metals and radioactive contaminants including Aluminum, Manganese, Uranium, Radium 226 and 228, Gross Alpha, and Gross Beta. The sample results displayed in Table 12. show there was a general reduction of all contaminants of concern from influent to effluent. The lone exception to this trend was Uranium, which experienced an average increase of about 142%.

**Table 12.** Summary of pollutants monitored for potential WTR impacts.

| Pollutant | Sample | 5/24/2020 | 6/8/2020 | 8/1/2020 | 8/29/2020 | 9/8/2020 | Average Percent (%) Reduction |
|---|---|---|---|---|---|---|---|
| Aluminum (ppm) | Influent | 1.02 | 1.08 | 2.14 | 0.77 | 0.28 | |
| | Effluent | 0.591 | 0.4 | 0.33 | 0.32 | 0.32 | |
| | Percent (%) Reduction | 42.06% | 62.96% | 84.58% | 58.44% | -14.29% | 46.75% |
| Manganese (ppm) | Influent | 0.019 | 0.025 | -- | -- | 0.063 | |
| | Effluent | 0.006 | 0.006 | -- | -- | 0.011 | |
| | Percent (%) Reduction | 68.42% | 76.00% | -- | -- | 82.54% | 75.65% |
| Gross Alpha (pCi/L) | Influent | -- | 2.8 | -- | -- | 15.7 | |
| | Effluent | -- | *2.5 | -- | -- | 1.06 | |
| | Percent (%) Reduction | -- | 10.71% | -- | -- | 93.25% | 51.98% |
| Gross Beta (pCi/L) | Influent | -- | 12.9 | -- | -- | 51 | |
| | Effluent | -- | 6 | -- | -- | 4.1 | |
| | Percent (%) Reduction | -- | 53.49% | -- | -- | 91.96% | 72.72% |
| Radium-226 (pCi/L) | Influent | -- | -- | -- | -- | ND | |
| | Effluent | -- | -- | -- | -- | ND | |
| | Percent (%) Reduction | -- | -- | -- | -- | N/A | N/A |
| Radium-228 (pCi/L) | Influent | -- | -- | -- | -- | 0.71 | |
| | Effluent | -- | -- | -- | -- | ND | |
| | Percent (%) Reduction | -- | -- | -- | -- | N/A | N/A |
| Uranium (ppb) | Influent | 0.12 | *0.1 | -- | -- | ND | |
| | Effluent | 0.4 | 0.15 | -- | -- | ND | |
| | Percent (%) Reduction | -233.33% | -50.00% | -- | -- | N/A | -141.67% |

An aluminum analysis was requested for all five sample events that occurred in 2020. There was a consistent trend of decrease in aluminum for the first four storms, followed by a slight increase on September 8th. Concentration reductions ranged from about 42% to 84.5%, with an overall season average of almost 47%. Considering a number of water quality results following the snowstorm have come back with values contradicting the seasonal trends, the aluminum removal capabilities of the system may be somewhat higher than the seasonal average is suggesting.

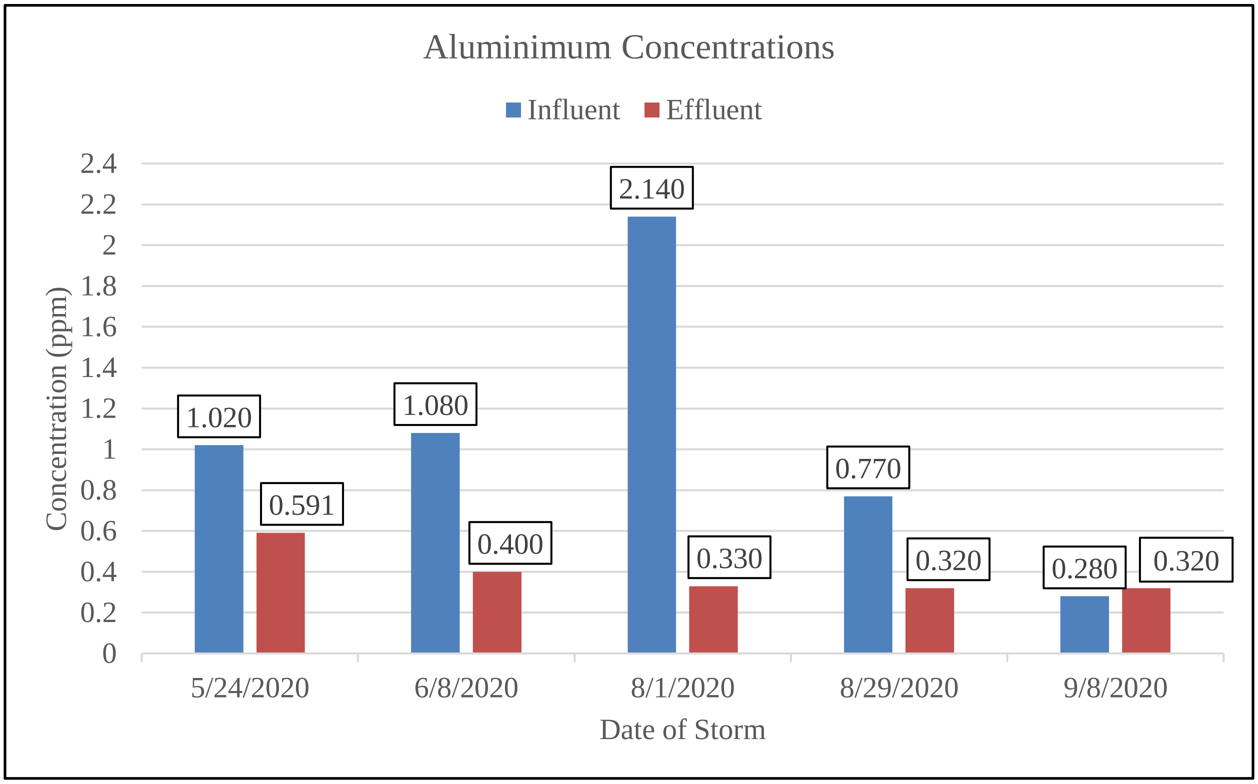


**Figure 23.** Aluminum concentrations for influent and effluent samples.

A manganese test was requested on three separate occasions in 2020, all showing relatively impressing reductions, which ranged from about 68.5% to 82.5%, with an overall season average of approximately 75.5%. Gross Alpha and Gross Beta, which were sampled twice throughout the season, both appear to show the beginning of what could be a respectable trend of decrease. Both tests on September 8th reported about a 92.5% decrease, while on June 8th the reductions were about 11% and 53.5%, respectively. It should be noted that the effluent sample results for Gross Alpha were a non-detect on June 8th, and as a result, the MDL value was used to make a conservative comparison. This suggests the actual reduction could be higher than the approximation of 11% is communicating. Radium 226 and Radium 228 analyses were only requested a single time throughout the 2020 monitoring season. The results for Radium 226 influent and effluent were both non-detects, while Radium 228 had an influent value of 0.71 pCi/l and a non-detect effluent value.

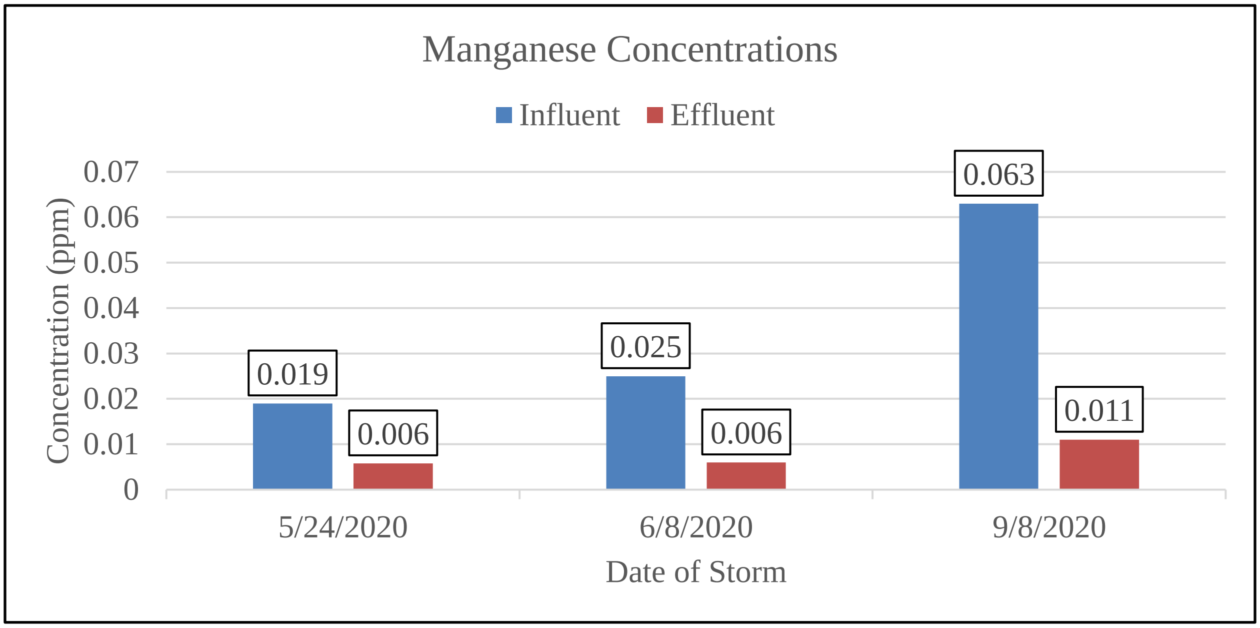


**Figure 24.** Manganese concentrations for influent and effluent samples.

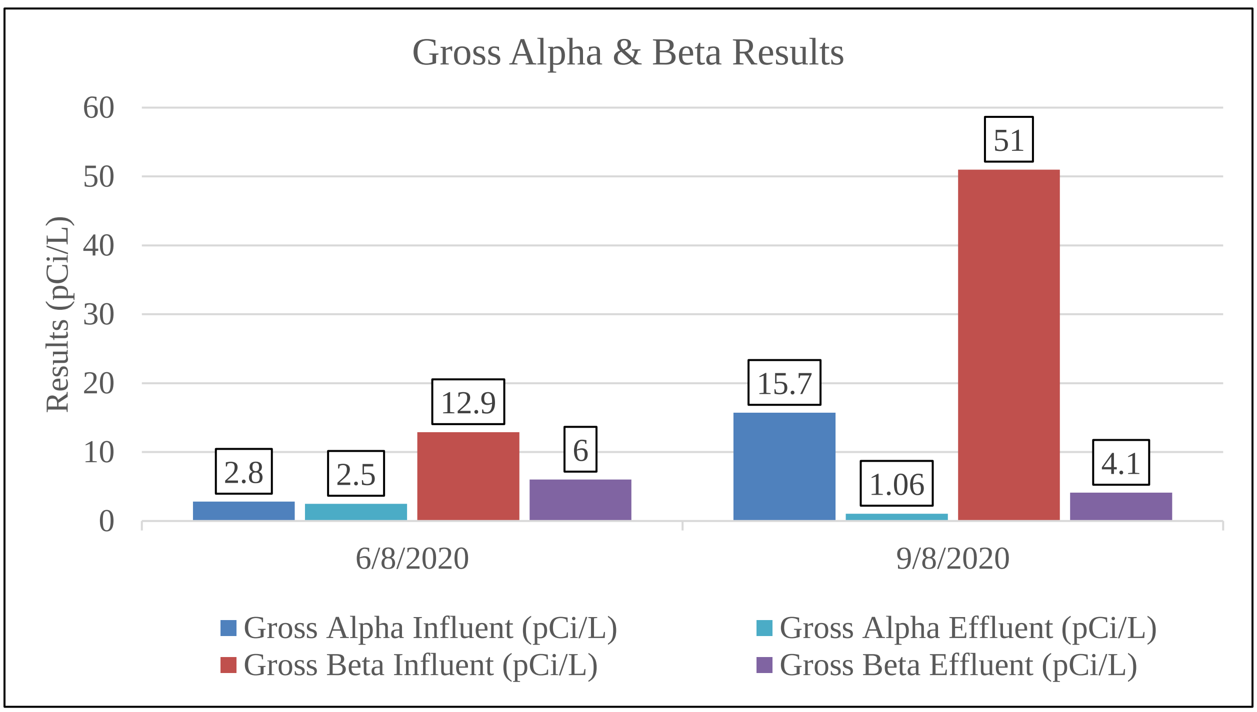


**Figure 25.** Gross Alpha & Beta Results for the 2020 monitoring season.

As previously mentioned, in regard to concerning contaminants leaching for the WTRs themselves, Uranium was the only pollutant where the results appeared to show a potential trend of increase. Uranium tests were requested on three different occasions, two of which showed and increase of about 233% and 50%, while the other reported back a set of non-detects for the influent and effluent. The non-detect results were obtained following the snowstorm, which makes it difficult to say for sure if this is a true contradiction of the trend that started with the two previous events. Given there appears to be a trend emerging that suggests Uranium may be leaching from the WTRs, this pollutant will need to continue to be closely monitored. Aside from Uranium, the results of the initial investigation regarding the potential release of harmful contaminants from WTRs have been quite promising.

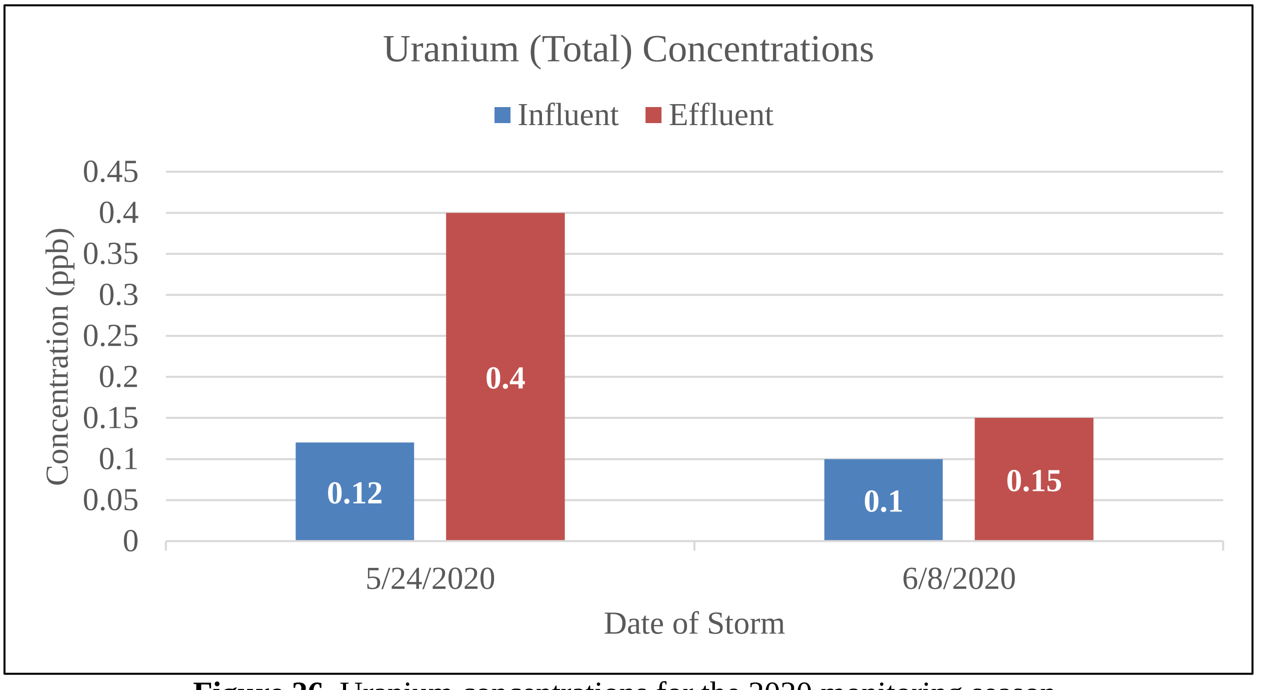


**Figure 26.** Uranium concentrations for the 2020 monitoring season.

## Other Observed Trends

Ammonia as N and iron showed a consistent decrease in concentrations from the influent to effluent. Figures for these pollutants with consistent trends are included in this section. There were not enough large sample events to determine a consistent trend for copper, potassium, and zinc. It should be noted that all results for nitrite and chromium. Observations for Nitrite as N prior to the 2020 monitoring season also showed a consistent trend of non-detects.

As previously mentioned, the September 8th, 2020 sampled event was a snowstorm. Both influent and effluent concentrations tended to be lower for ammonia as N, and iron for this event.

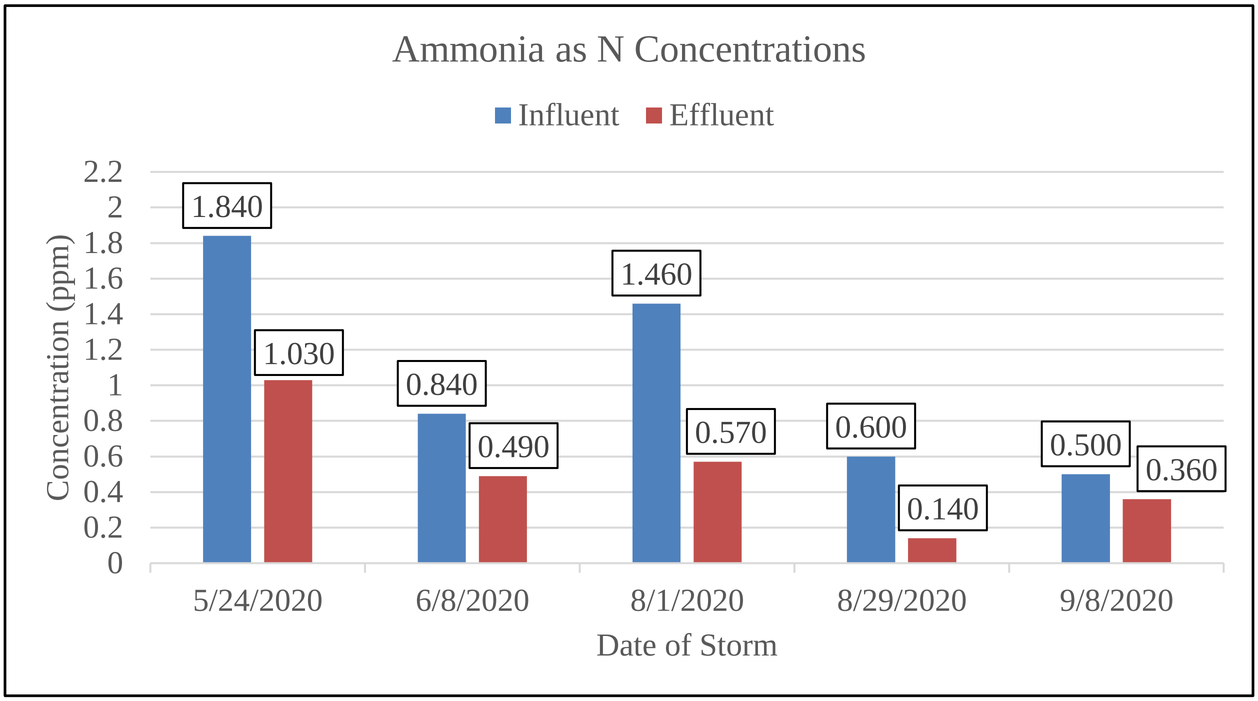


**Figure 27.** Ammonia as N concentrations for influent and effluent samples.

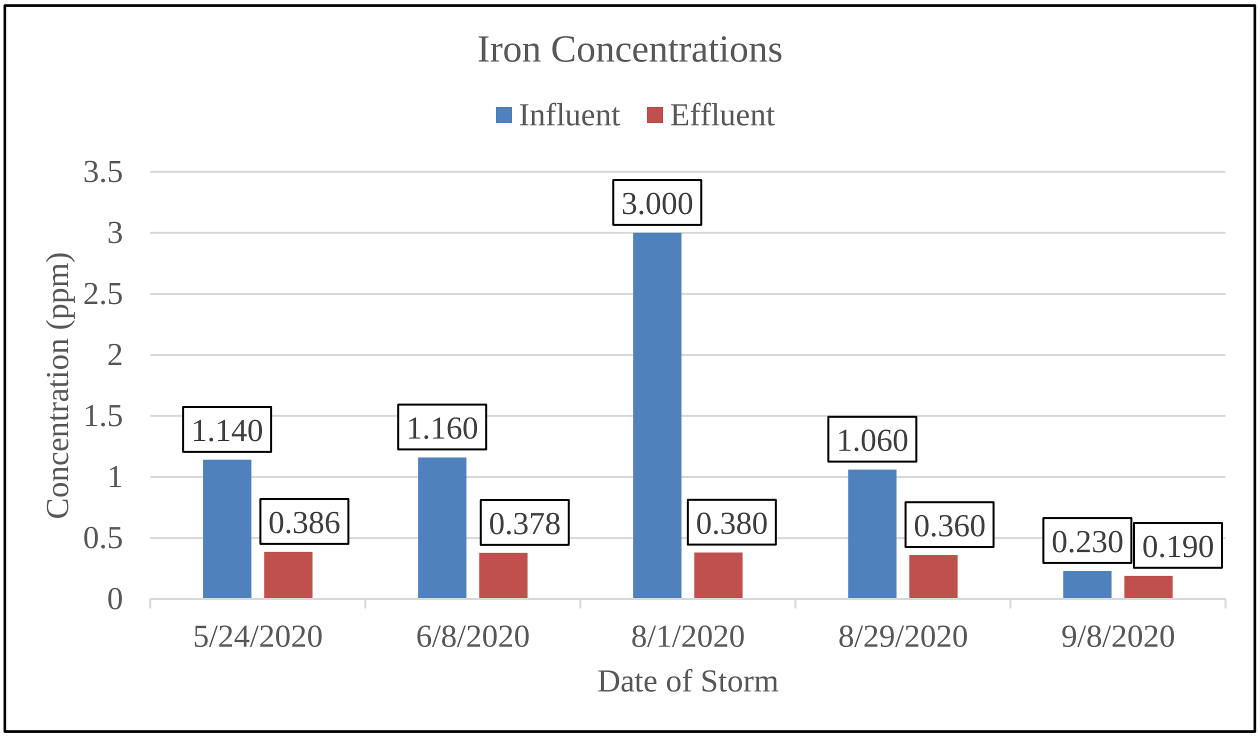


**Figure 28.** Iron concentrations for influent and effluent samples.

## Load Reductions

The "Load Reductions" section summarizes load reductions for total phosphorus, dissolved phosphorus, total suspended solids, TKN, and nitrate as N. These load reductions were calculated in pounds based on the pollutant concentrations and stormwater influent volumes. For a description of the methods used for these calculations, refer to "Pollutant Load Reduction" in the "Methods" section.

### Total Phosphorus Load Reduction

Figure 29. and Table 13 show the total phosphorus loads in pounds for the sampled storms during the 2020 monitoring season. While the effluent concentrations were larger than the influent concentrations for the May 24th, August 1st, and September 8th storms, the total phosphorus load leaving the BRC was less than the total phosphorus load entering the BRC for all storm events. This indicates the BRC's performance in reducing stormwater discharge was enough to offset the increase in total phosphorus concentrations. The largest observed influent and effluent values for Total Phosphorus Loads were for the September 8th, 2020 snowstorm.

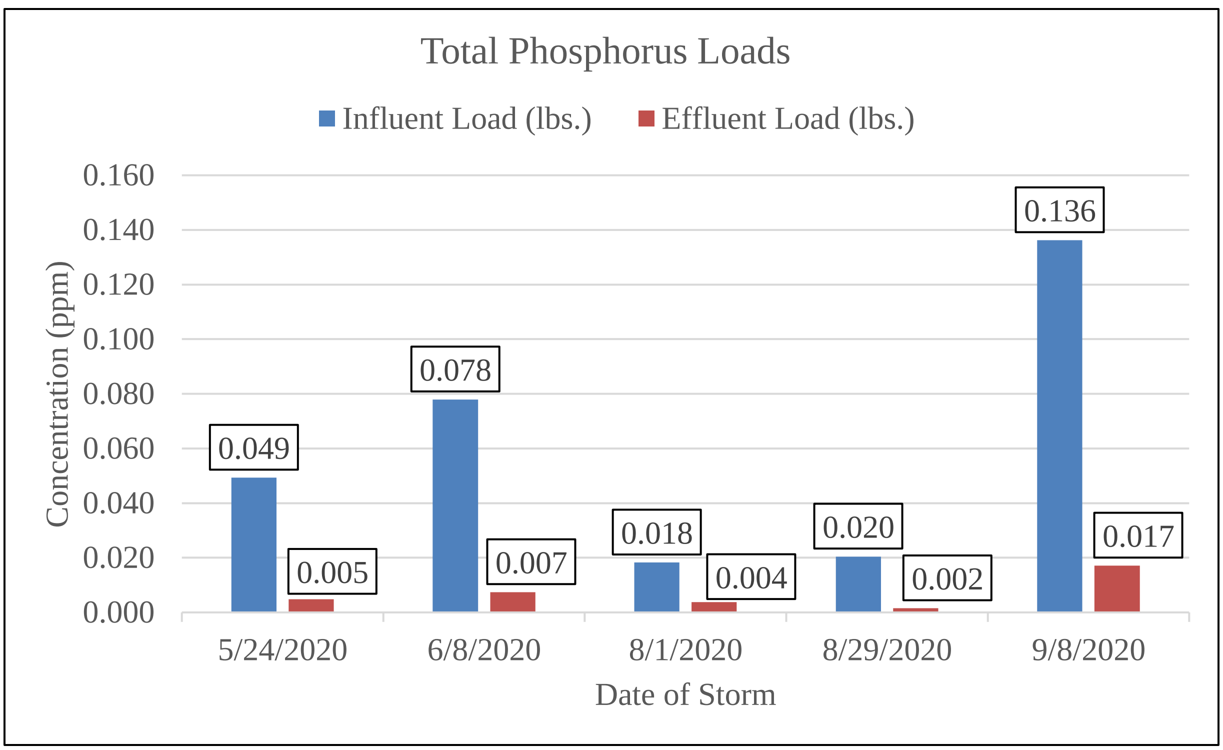


**Figure 29.** Total phosphorus loads for influent and effluent in pounds (lbs.)

**Table 13.** Total phosphorus loads for influent and effluent in pounds (lbs.)

| Date of Storm | Influent Load (lbs) | Effluent Load (lbs) | Load Reduction (lbs) |
|---|---|---|---|
| 5/24/2020 | 0.049 | 0.005 | 0.045 |
| 6/8/2020 | 0.078 | 0.007 | 0.071 |
| 8/1/2020 | 0.018 | 0.004 | 0.015 |
| 8/29/2020 | 0.020 | 0.002 | 0.019 |
| 9/8/2020 | 0.136 | 0.017 | 0.119 |
| **Averages:** | **0.060** | **0.007** | **0.054** |

Dissolved Phosphorus Load Reduction

Figure 30. and Table 14 show the dissolved phosphorus loads in pounds for the sampled storms during the 2020 monitoring season. Dissolved phosphorus concentrations had shown an increase from the influent to the effluent for the first four sampled storms. However, the dissolved phosphorus loads leaving the BRC were lower than the dissolved phosphorus loads entering the BRC for all five sampled storm events. This indicates the BRC's performance in reducing stormwater discharge was enough to offset the increase in dissolved phosphorus concentrations. The largest observed influent and effluent values for Dissolved Phosphorus Loads was for the September 8th, 2020 snowstorm.

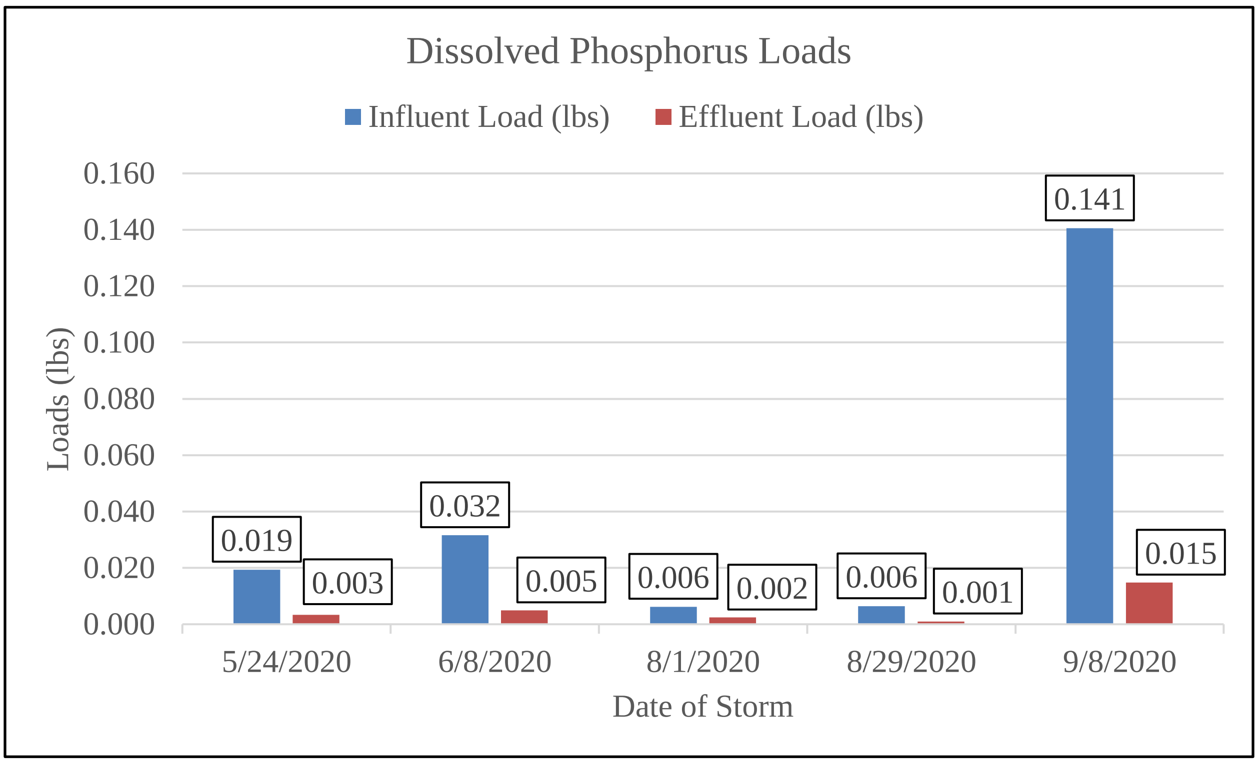


**Figure 30.** Dissolved phosphorus loads for influent and effluent in pounds (lbs.)

**Table 14.** Dissolved phosphorus loads for influent and effluent in pounds (lbs.)

| Date of Storm | Influent Load (lbs) | Effluent Load (lbs) | Load Reduction (lbs) |
|---|---|---|---|
| 5/24/2020 | 0.019 | 0.003 | 0.016 |
| 6/8/2020 | 0.032 | 0.005 | 0.027 |
| 8/1/2020 | 0.006 | 0.002 | 0.004 |
| 8/29/2020 | 0.006 | 0.001 | 0.005 |
| 9/8/2020 | 0.141 | 0.015 | 0.126 |
| **Averages:** | **0.041** | **0.005** | **0.036** |

Total Suspended Solids Load Reduction

Figure 31. and Table 15 show the TSS loads in pounds for the sampled storms during the 2020 monitoring season. Both the TSS loads and concentrations showed a decrease from the influent to the effluent for all five sample storm events. The lowest influent and effluent loads were for the August 29th, 2020 storm. The August 29th storm event had the lowest precipitation and the lowest influent volume of all the sampled storms during the 2020 season.

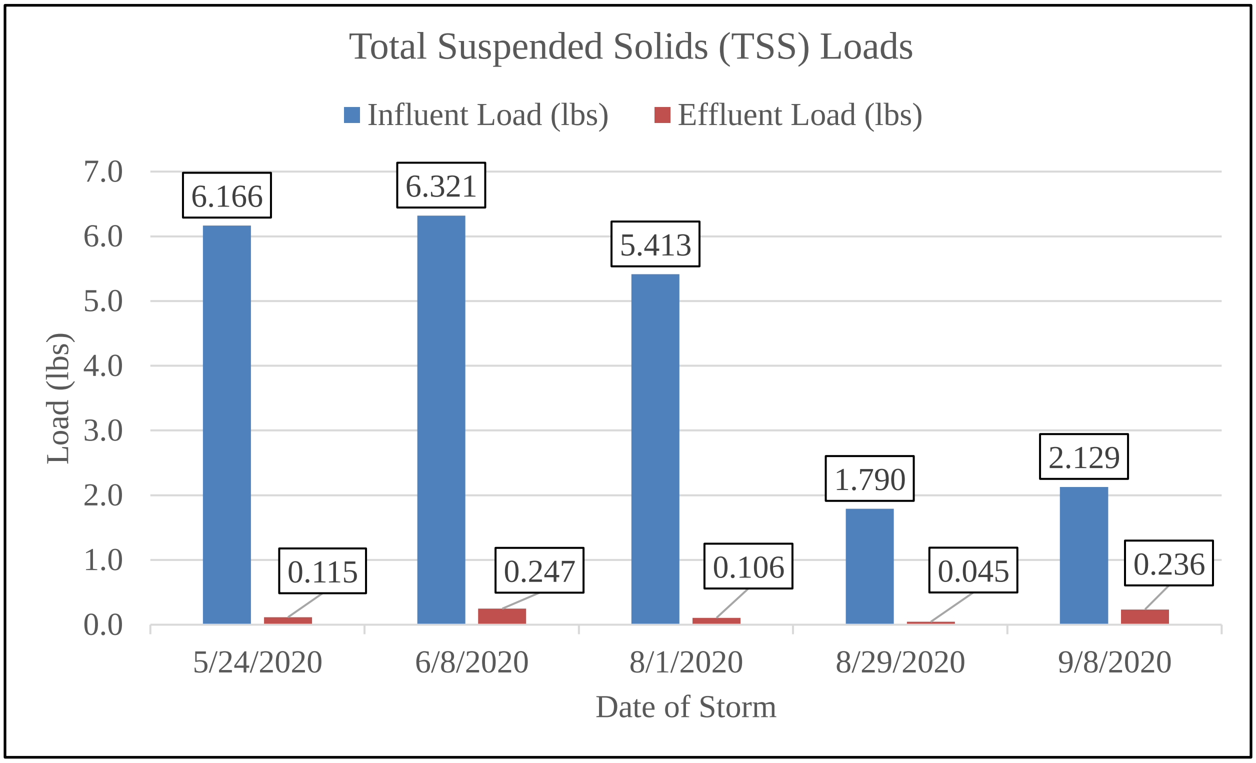


**Figure 31.** TSS loads for influent and effluent in pounds (lbs.)

**Table 15.** TSS loads for influent and effluent in pounds (lbs.)

| Date of Storm | Influent Load (lbs) | Effluent Load (lbs) | Load Reduction (lbs) |
|---|---|---|---|
| 5/24/2020 | 6.166 | 0.115 | 6.050 |
| 6/8/2020 | 6.321 | 0.247 | 6.074 |
| 8/1/2020 | 5.413 | 0.106 | 5.307 |
| 8/29/2020 | 1.790 | 0.045 | 1.745 |
| 9/8/2020 | 2.129 | 0.236 | 1.893 |
| **Averages:** | **4.364** | **0.150** | **4.213** |

Nitrogen, Total Kjeldahl as N (TKN) Load Reduction

Figure 32. and Table 16 show TKN loads in pounds for the sampled storms during the 2020 monitoring season. Both the TKN loads and concentrations showed a decrease from the influent to the effluent for all five sample storm events. The largest observed influent and effluent values for TKN loads were for the September 8th, 2020 snowstorm. The effluent load for the September 8th, 2020 snowstorm was calculated using the TKN method detection limit (MDL) of 0.87-ppm.

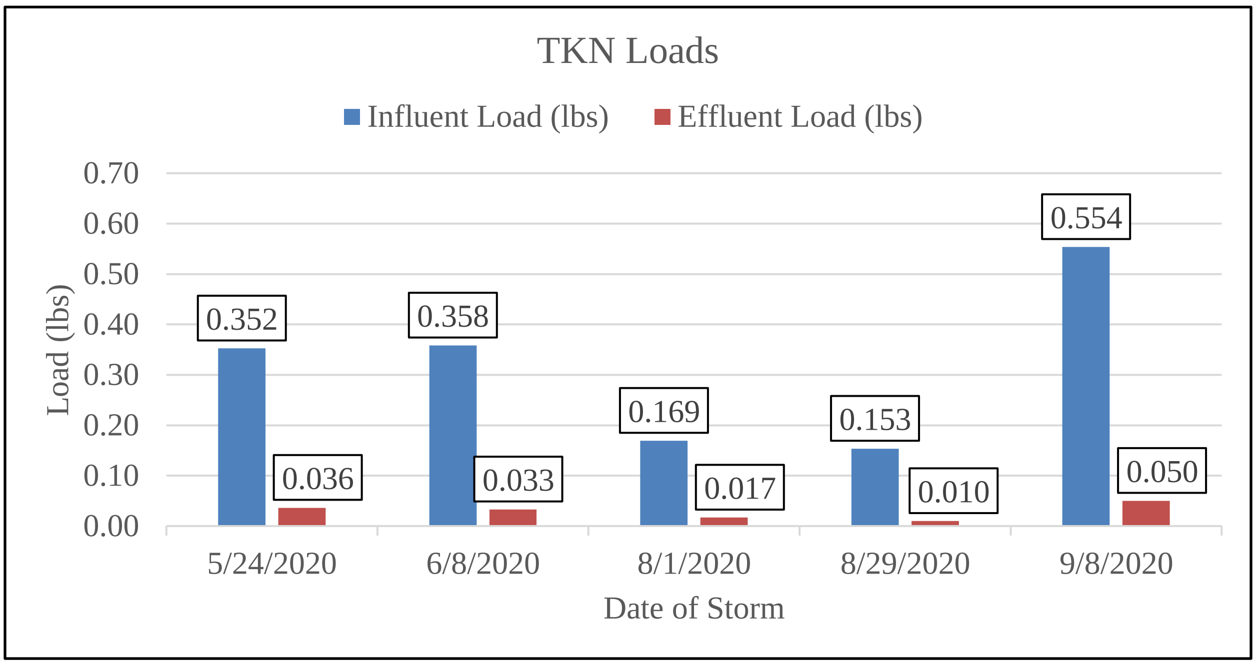


**Figure 32.** TKN loads for influent and effluent in pounds (lbs.)

**Table 16.** TKN loads for influent and effluent in pounds (lbs.)

| Date of Storm | Influent Load (lbs) | Effluent Load (lbs) | Load Reduction (lbs) |
|---|---|---|---|
| 5/24/2020 | 0.352 | 0.036 | 0.316 |
| 6/8/2020 | 0.358 | 0.033 | 0.325 |
| 8/1/2020 | 0.169 | 0.017 | 0.152 |
| 8/29/2020 | 0.153 | 0.010 | 0.144 |
| 9/8/2020 | 0.554 | 0.050 | 0.504 |
| **Averages:** | **0.317** | **0.193** | **0.288** |

Nitrate as N

Figure 33. and Table 17 show the Nitrate as N loads in pounds for the sampled storms during the 2020 monitoring season. While the Nitrate as N concentrations increased as discussed in the "Nitrate as N" section under 'Water Quality Results', the actual total load in pounds decreased. This can be attributed to the BRC's performance in reducing the total discharge volume. The largest observed influent value for Nitrate as N Loads was for the September 8th, 2020 snowstorm. The largest observed effluent load was 0.030-lbs for the May 24th, 2020 storm and September 8th, 2020 snowstorm.

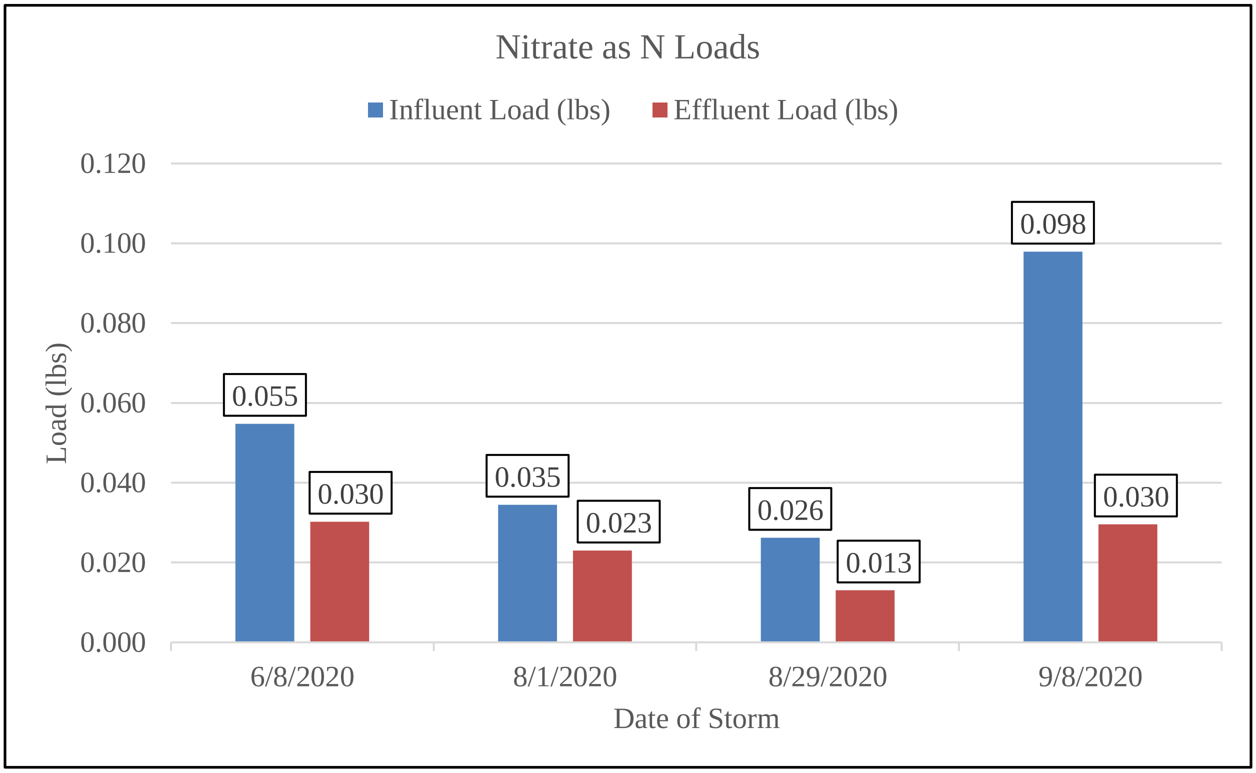


**Figure 33.** Nitrate as N loads for influent and effluent in pounds (lbs.)

**Table 17.** Nitrate as N loads for influent and effluent in pounds (lbs.)

| Date of Storm | Influent Load (lbs) | Effluent Load (lbs) | Load Reduction (lbs) |
|---|---|---|---|
| 6/8/2020 | 0.055 | 0.030 | 0.025 |
| 8/1/2020 | 0.035 | 0.023 | 0.011 |
| 8/29/2020 | 0.026 | 0.013 | 0.013 |
| 9/8/2020 | 0.098 | 0.030 | 0.068 |
| **Averages:** | **0.053** | **0.024** | **0.029** |

## Summary, Conclusions, & Recommendations

In 2012 the City of Fort Collins Stormwater Utility constructed a BRC research site at their headquarters located at 700 Wood Street, Fort Collins, Colorado. Shortly thereafter a collaborative research project with the Colorado Stormwater Center at Colorado State University was initiated with the intention of gathering data relating to the performance of these systems in the Colorado region. The analysis that ensued uncovered a concerning trend regarding effluent phosphorus concentrations. Results suggested that the BRC was contributing phosphorus to the runoff passing through the system, not treating it. Researchers involved in the project recommended that this trend continue to be studied through future investigations.

A new research collaboration with the Colorado Stormwater Center began in early 2019 to evaluate the effectiveness of reducing phosphorus concentrations in urban stormwater runoff by applying water treatment residuals to the surface of the BRC. Sample results were somewhat variable for influent and effluent total phosphorus concentrations, with an overall average increase of 6%. Dissolved phosphorus concentrations were found to increase by 78% from influent to effluent on average. Although these findings support the previous research that indicated phosphorus was leaching from the system, a comparison with the historical data indicates that the magnitude of the increase has gotten smaller. The comparison showed a very similar level of influent total and dissolved phosphorus concentrations, while the effluent concentrations for each were clearly different. Total and dissolved phosphorus concentrations prior to the WTR application were 0.722 ppm and 0.539 ppm, respectively, while total and dissolved phosphorus concentrations following the application were 0.322 ppm and 0.224 ppm, respectively. These reductions show about a 57% decrease in total and dissolved phosphorus concentrations after the application of WTRs. These results are highly promising as they indicate that water treatment residuals could be a viable option for enhancing the phosphorus removal capabilities of bioretention cells. In light of these findings it is recommended that WTR related research continue at other locations in Fort Collins with varied approaches to application including: additional surface applications on existing installations, applications where WTRs are thoroughly mixed into the BRC filter media before filling a cell at a new installation, and creating distinct layers at different depths in the BRC filter media profile while filling new cells with traditional BRC filter media.

Although leaching is still taking place, the nature of a surface application is such that phosphorus being leached from within the BRC does not have an opportunity to directly interact with the WTRs. The only possibility for reducing effluent phosphorus concentrations with WTRs is to offset leaching to some degree by reducing concentrations in the influent as it infiltrates the surface of the BRC. Considering how brief the interaction between the influent and the surface applied WTRs is, the reductions in phosphorus leaching from pre to post WTR application are impressive. Another potential explanation for lower phosphorus effluent concentrations in the current study is the possibility that leaching has caused the phosphorus reserves in the BRC filter media to deplete over time. Considering that the configuration of a traditional BRC does not allow for a control treatment, data to confirm or deny this potential influence does not currently exist. At a minimum, it is recommended that soil samples be collected and analyzed annually in order to better understand how phosphorus levels change in the BRC filter media over time.

The comparison of data between current and past research projects at the BRC research site brought up a couple other trends worth noting. Findings from the 2013-2015 project showed an average reduction in total nitrogen concentration from influent to effluent of about 25%. Current research is reporting that there was not a reduction in total nitrogen concentration, but there was an average increase of about 29%. Obviously, this is a complete reversal from a total nitrogen perspective. However, the components that make up total nitrogen values displayed similar behavior. Both the current and past research projects showed a general trend of decrease in TKN concentrations from influent to effluent and a general trend of increase in nitrate concentrations. The difference that drove the reversal when focusing on total nitrogen was that the current TKN reductions were not enough to outweigh the increases in nitrate. As a result, current findings suggest that the BRC is leaching nitrate, and to an extent that total nitrogen is increasing as well. It is recommended that further research be conducted to explore options to address this issue. Another instance where current and past data did not agree is in stormwater runoff volume reduction. The 2013-2015 study reported an overall volume reduction of 25% before adding the temporary underdrain modification, and an 88% reduction after adding the modification. As previously stated, the current study did not use the temporary modification. Current findings support an overall average volume reduction of about 89%, which closely aligns with previously observed reductions after the modification had been added. This presents a large discrepancy with the 2013-2015 data, the cause of which is unknown. It is recommended that further investigation into this disagreement be conducted.

In accordance with the Beneficial Use Plan, monitoring efforts relating to exportation of harmful byproducts from the WTRs yielded promising initial results. Aluminum, manganese, Gross Alpha and Gross Beta were shown to decrease from the influent to the effluent over the 2020 monitoring season. Although analyses for Radium-226 and Radium-228 were only requested a single time throughout the year, the preliminary results were encouraging. Radium-226 had non-detect results for both the influent and the effluent and Radium-228 showed a reduction from an influent result of 0.71-pCi/L to a non-detect effluent result. The observed increase in uranium was the only concerning result regarding contaminants potentially leaching from the WTRs themselves. Considering the limited number of samples in the dataset, further monitoring of all harmful contaminants listed in the Beneficial Use Plan is necessary to confirm the safety of using WTRs on a larger scale.

## Appendix A: Water Quantity Data

**Table 18.** Water quantity data for sampled storm events during the 2020 monitoring season.

| Date of Storm | Cumulative Precipitation (inches) | Inflow Volume (cubic feet) | Underdrain Discharge (cubic feet) | Infiltration and Soil Storage (cubic feet) | Soil Retention & Evapotranspiration (cubic feet) |
|---|---|---|---|---|---|
| 5/24/2020 | 0.47 | 2825 | 264 | 3038 | 164 |
| 6/8/2020 | 0.47 | 3379 | 441 | 54 | 276 |
| 8/1/2020 | 0.28 | 1085 | 142 | 1343 | 0 |
| 8/29/2020 | 0.20 | 1025 | 72 | 463 | 290 |
| 9/8/2020 | 1.04 | 6828 | 948 | 6802 | 5 |

## Appendix B: Water Quality Data

**Table 19:** Tabulated lab results for sampled runoff events during the 2020 monitoring season.

| Sample Date | Sample ID | Analysis | Results | Units | MDL | Notes |
|---|---|---|---|---|---|---|
| 2020.05.24 | Wood St-Influ | Aluminum | 1.02 | ppm | 0.05 | N/A |
| 2020.05.24 | Wood St-Influ | Ammonia as N | 1.84 | ppm | 0.05 | Exceeded hold time. |
| 2020.05.24 | Wood St-Influ | Chromium | ND | ppm | 0.005 | N/A |
| 2020.05.24 | Wood St-Influ | Copper | 0.012 | ppm | 0.005 | N/A |
| 2020.05.24 | Wood St-Influ | Iron | 1.14 | ppm | 0.01 | N/A |
| 2020.05.24 | Wood St-Influ | Manganese | 0.019 | ppm | 0.002 | N/A |
| 2020.05.24 | Wood St-Influ | Nitrate + Nitrite as N | ND | ppm | 0.02 | N/A |
| 2020.05.24 | Wood St-Influ | Nitrogen, Total Kjeldahl as N | 2.0 | ppm | 0.87 | N/A |
| 2020.05.24 | Wood St-Influ | Phosphorus, Dissolved | 0.11 | ppm | 0.05 | N/A |
| 2020.05.24 | Wood St-Influ | Phosphorus/Total | 0.28 | ppm | 0.05 | N/A |
| 2020.05.24 | Wood St-Influ | Potassium | 1.53 | ppm | 0.1 | N/A |
| 2020.05.24 | Wood St-Influ | Solids/Total Suspended (TSS) | 35 | ppm | 1 | N/A |
| 2020.05.24 | Wood St-Influ | Uranium - Total | 0.12 | ppb | 0.1 | N/A |
| 2020.05.24 | Wood St-Influ | Zinc | 0.023 | ppm | 0.003 | N/A |
| 2020.05.24 | Wood St-Efflu | Aluminum | 0.591 | ppm | 0.05 | N/A |
| 2020.05.24 | Wood St-Efflu | Ammonia as N | 1.03 | ppm | 0.05 | Exceeded hold time. |
| 2020.05.24 | Wood St-Efflu | Chromium | ND | ppm | 0.005 | N/A |
| 2020.05.24 | Wood St-Efflu | Copper | 0.011 | ppm | 0.005 | N/A |
| 2020.05.24 | Wood St-Efflu | Iron | 0.386 | ppm | 0.01 | N/A |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.05.24 | Wood St-Efflu | Manganese | 0.0058 | ppm | 0.002 | N/A |
| 2020.05.24 | Wood St-Efflu | Nitrate + Nitrite as N | 0.068 | ppm | 0.02 | N/A |
| 2020.05.24 | Wood St-Efflu | Nitrogen, Total Kjeldahl as N | 2.2 | ppm | 0.87 | N/A |
| 2020.05.24 | Wood St-Efflu | Phosphorus, Dissolved | 0.2 | ppm | 0.05 | N/A |
| 2020.05.24 | Wood St-Efflu | Phosphorus/Total | 0.29 | ppm | 0.05 | N/A |
| 2020.05.24 | Wood St-Efflu | Potassium | 2.28 | ppm | 0.1 | N/A |
| 2020.05.24 | Wood St-Efflu | Solids/Total Suspended (TSS) | 7 | ppm | 1 | N/A |
| 2020.05.24 | Wood St-Efflu | Uranium - Total | 0.4 | ppb | 0.1 | N/A |
| 2020.05.24 | Wood St-Efflu | Zinc | 0.024 | ppm | 0.003 | N/A |
| 2020.06.08 | Wood St-Influ | Aluminum | 1.08 | ppm | 0.05 | N/A |
| 2020.06.08 | Wood St-Influ | Ammonia as N | 0.84 | ppm | 0.03 | N/A |
| 2020.06.08 | Wood St-Influ | Chromium | ND | ppm | 0.005 | N/A |
| 2020.06.08 | Wood St-Influ | Copper | 0.006 | ppm | 0.005 | N/A |
| 2020.06.08 | Wood St-Influ | E. Coli | 1200 | cfu/100mL | 20 | N/A |
| 2020.06.08 | Wood St-Influ | Gross Alpha | 2.8 | pCi/L | 2.2 | +\- 1.4 pCi/L |
| 2020.06.08 | Wood St-Influ | Gross Beta | 12.9 | pCi/L | 2.9 | +\- 2.8 pCi/L |
| 2020.06.08 | Wood St-Influ | Iron | 1.16 | ppm | 0.01 | N/A |
| 2020.06.08 | Wood St-Influ | Manganese | 0.025 | ppm | 0.002 | N/A |
| 2020.06.08 | Wood St-Influ | Nitrate as N | 0.26 | ppm | 0.2 | N/A |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.06.08 | Wood St-Influ | Nitrite as N | ND | ppm | 0.15 | N/A |
| 2020.06.08 | Wood St-Influ | Phosphorus, Dissolved | 0.15 | ppm | 0.05 | N/A |
| 2020.06.08 | Wood St-Influ | Phosphorus/Total | 0.37 | ppm | 0.05 | N/A |
| 2020.06.08 | Wood St-Influ | Potassium | 1.72 | ppm | 0.1 | N/A |
| 2020.06.08 | Wood St-Influ | Solids/Total Suspended (TSS) | 30 | ppm | 1 | N/A |
| 2020.06.08 | Wood St-Influ | Uranium - Total | ND | ppb | 0.1 | N/A |
| 2020.06.08 | Wood St-Influ | Zinc | 0.034 | ppm | 0.003 | N/A |
| 2020.06.08 | Wood St-Efflu | Aluminum | 0.4 | ppm | 0.05 | N/A |
| 2020.06.08 | Wood St-Efflu | Ammonia as N | 0.49 | ppm | 0.05 | N/A |
| 2020.06.08 | Wood St-Efflu | Chromium | ND | ppm | 0.005 | N/A |
| 2020.06.08 | Wood St-Efflu | Copper | 0.007 | ppm | 0.005 | N/A |
| 2020.06.08 | Wood St-Efflu | E. Coli | 320 | cfu/100mL | 20 | N/A |
| 2020.06.08 | Wood St-Efflu | Gross Alpha | ND | pCi/L | 2.5 | +\- 1.4 pCi/L |
| 2020.06.08 | Wood St-Efflu | Gross Beta | 6 | pCi/L | 3 | +\- 1.9 pCi/L |
| 2020.06.08 | Wood St-Efflu | Iron | 0.378 | ppm | 0.01 | N/A |
| 2020.06.08 | Wood St-Efflu | Manganese | 0.006 | ppm | 0.002 | N/A |
| 2020.06.08 | Wood St-Efflu | Nitrate as N | 1.1 | ppm | 0.2 | N/A |
| 2020.06.08 | Wood St-Efflu | Nitrite as N | ND | ppm | 0.15 | N/A |
| 2020.06.08 | Wood St-Efflu | Nitrogen, Total Kjeldahl as N | 1.2 | ppm | 0.87 | N/A |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.06.08 | Wood St-Efflu | Phosphorus/Total | 0.27 | ppm | 0.05 | N/A |
| 2020.06.08 | Wood St-Efflu | Potassium | 1.64 | ppm | 0.1 | N/A |
| 2020.06.08 | Wood St-Efflu | Solids/Total Suspended (TSS) | 9 | ppm | 1 | N/A |
| 2020.06.08 | Wood St-Efflu | Uranium - Total | 0.15 | ppb | 0.1 | N/A |
| 2020.06.08 | Wood St-Efflu | Zinc | 0.015 | ppm | 0.003 | N/A |
| 2020.08.01 | Wood St-Influ | Aluminum | 2.14 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Influ | Ammonia as N | 1.46 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Influ | Iron | 3 | ppm | 0.01 | N/A |
| 2020.08.01 | Wood St-Influ | Nitrate as N | 0.51 | ppm | 0.2 | N/A |
| 2020.08.01 | Wood St-Influ | Nitrite as N | ND | ppm | 0.15 | N/A |
| 2020.08.01 | Wood St-Influ | Nitrogen, Total Kjeldahl as N | 2.5 | ppm | 0.87 | N/A |
| 2020.08.01 | Wood St-Influ | Phosphorus, Dissolved | 0.092 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Influ | Phosphorus/Total | 0.27 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Influ | Solids/Total Suspended (TSS) | 80 | ppm | 1 | N/A |
| 2020.08.01 | Wood St-Efflu | Aluminum | 0.33 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Efflu | Ammonia as N | 0.57 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Efflu | Iron | 0.38 | ppm | 0.01 | N/A |
| 2020.08.01 | Wood St-Efflu | Nitrate as N | 2.6 | ppm | 0.2 | N/A |
| 2020.08.01 | Wood St-Efflu | Nitrite as N | ND | ppm | 0.15 | N/A |
| 2020.08.01 | Wood St-Efflu | Nitrogen, Total Kjeldahl as N | 1.9 | ppm | 0.87 | N/A |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.08.01 | Wood St-Efflu | Phosphorus, Dissolved | 0.27 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Efflu | Phosphorus/Total | 0.42 | ppm | 0.05 | N/A |
| 2020.08.01 | Wood St-Efflu | Solids/Total Suspended (TSS) | 12 | ppm | 1 | N/A |
| 2020.08.29 | Wood St-Influ | Aluminum | 0.77 | ppm | 0.05 | N/A |
| 2020.08.29 | Wood St-Influ | Ammonia as N | 0.6 | ppm | 0.05 | N/A |
| 2020.08.29 | Wood St-Influ | Iron | 1.06 | ppm | 0.01 | N/A |
| 2020.08.29 | Wood St-Influ | Nitrate as N | 0.41 | mg/L | 0.2 | N/A |
| 2020.08.29 | Wood St-Influ | Nitrite as N | ND | mg/L | 0.15 | <0.15 mg/L |
| 2020.08.29 | Wood St-Influ | Nitrogen, Total Kjeldahl as N | 2.4 | mg/L | 0.87 | N/A |
| 2020.08.29 | Wood St-Influ | Phosphorus, Dissolved | 0.1 | mg/L | 0.05 | N/A |
| 2020.08.29 | Wood St-Influ | Phosphorus/Total | 0.32 | mg/L | 0.05 | N/A |
| 2020.08.29 | Wood St-Influ | Solids/Total Suspended (TSS) | 28 | ppm | 1 | N/A |
| 2020.08.29 | Wood St-Efflu | Aluminum | 0.32 | ppm | 0.05 | N/A |
| 2020.08.29 | Wood St-Efflu | Ammonia as N | 0.14 | ppm | 0.05 | N/A |
| 2020.08.29 | Wood St-Efflu | Iron | 0.36 | ppm | 0.01 | N/A |
| 2020.08.29 | Wood St-Efflu | Nitrate as N | 2.9 | mg/L | 0.2 | N/A |
| 2020.08.29 | Wood St-Efflu | Nitrite as N | ND | mg/L | 0.15 | <0.15 mg/L |
| 2020.08.29 | Wood St-Efflu | Nitrogen, Total Kjeldahl as N | 2.2 | mg/L | 0.87 | N/A |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.08.29 | Wood St-Efflu | Phosphorus, Dissolved | 0.22 | mg/L | 0.05 | N/A |
| 2020.08.29 | Wood St-Efflu | Phosphorus/total | 0.34 | mg/L | 0.05 | N/A |
| 2020.08.29 | Wood St-Efflu | Solids/Total Suspended (TSS) | 10 | ppm | 1 | N/A |
| 2020.09.08 | Wood St-Influ | Aluminum | 0.28 | ppm | 0.05 | N/A |
| 2020.09.08 | Wood St-Influ | Ammonia as N | 0.5 | ppm | 0.05 | N/A |
| 2020.09.08 | Wood St-Influ | Chromium | <0.005 | ppm | 0.005 | N/A |
| 2020.09.08 | Wood St-Influ | Copper | 0.008 | mg/L | 0.005 | N/A |
| 2020.09.08 | Wood St-Influ | Gross Alpha | 15.7 | pCi/L | 5.4 | +\- 4.9 pCi/l |
| 2020.09.08 | Wood St-Influ | Gross Beta | 51 | pCi/L | 11 | +\- 11 pCi/l |
| 2020.09.08 | Wood St-Influ | Iron | 0.23 | mg/L | 0.01 | N/A |
| 2020.09.08 | Wood St-Influ | Manganese | 0.063 | mg/L | 0.002 | N/A |
| 2020.09.08 | Wood St-Influ | Nitrate as N | 0.23 | ppm | 0.1 | N/A |
| 2020.09.08 | Wood St-Influ | Nitrite as N | ND | ppm | 0.1 | <0.15 mg/L |
| 2020.09.08 | Wood St-Influ | Nitrogen, Total Kjeldahl as N | 1.3 | ppm | 0.87 | N/A |
| 2020.09.08 | Wood St-Influ | Phosphorus, Dissolved | 0.33 | ppm | 0.05 | N/A |
| 2020.09.08 | Wood St-Influ | Phosphorus/Total | 0.32 | mg/L | 0.05 | N/A |
| 2020.09.08 | Wood St-Influ | Potassium | 1.65 | mg/L | 0.1 | N/A |
| 2020.09.08 | Wood St-Influ | Radium 226 | ND | pCi/L | 0.33 | <0.33 (+\- 0.18) pCi/l |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.09.08 | Wood St-Influ | Radium 228 | 0.71 | pCi/L | 0.69 | +\- 0.38 pCi/L |
| 2020.09.08 | Wood St-Influ | Solids/Total Suspended (TSS) | 5 | mg/L | 1 | N/A |
| 2020.09.08 | Wood St-Influ | Uranium - Total | ND | ppm | 0.0001 | <0.1 ug/L |
| 2020.09.08 | Wood St-Influ | Zinc | 0.011 | ppm | 0.003 | N/A |
| 2020.09.08 | Wood St-Efflu | Aluminum | 0.32 | ppm | 0.05 | N/A |
| 2020.09.08 | Wood St-Efflu | Ammonia as N | 0.36 | ppm | 0.05 | N/A |
| 2020.09.08 | Wood St-Efflu | Chromium | <0.005 | ppm | 0.005 | N/A |
| 2020.09.08 | Wood St-Efflu | Copper | 0.01 | ppm | 0.005 | N/A |
| 2020.09.08 | Wood St-Efflu | Gross Alpha | 1.06 | pCi/l | 1.04 | +\- 0.64 pCi/L |
| 2020.09.08 | Wood St-Efflu | Gross Beta | 4.1 | pCi/l | 1.8 | +\- 1.2 pCi/l |
| 2020.09.08 | Wood St-Efflu | Iron | 0.19 | ppm | 0.01 | N/A |
| 2020.09.08 | Wood St-Efflu | Manganese | 0.011 | ppm | 0.002 | N/A |
| 2020.09.08 | Wood St-Efflu | Nitrate as N | 0.5 | mg/L | 0.2 | N/A |
| 2020.09.08 | Wood St-Efflu | Nitrite as N | ND | mg/L | 0.15 | <0.15 mg/L |
| 2020.09.08 | Wood St-Efflu | Nitrogen, Total Kjeldahl as N | ND | mg/L | 0.87 | <0.1 ug/L |
| 2020.09.08 | Wood St-Efflu | Phosphorus, Dissolved | 0.25 | mg/L | 0.05 | N/A |
| 2020.09.08 | Wood St-Efflu | Phosphorus/Total | 0.29 | mg/L | 0.05 | N/A |
| 2020.09.08 | Wood St-Efflu | Potassium | 1.67 | ppm | 0.1 | N/A |

| Appendix B. continued | | | | | | |
|---|---|---|---|---|---|---|
| **Sample Date** | **Sample ID** | **Analysis** | **Results** | **Units** | **MDL** | **Notes** |
| 2020.09.08 | Wood St-Efflu | Radium 226 | ND | pCi/L | 0.3 | <0.3 (+\- 0.19) pCi/L |
| 2020.09.08 | Wood St-Efflu | Radium 228 | ND | pCi/L | 0.72 | < 0.72 (+\- 0.37) pCi/L |
| 2020.09.08 | Wood St-Efflu | Solids/Total Suspended (TSS) | 4 | ppm | 1 | N/A |
| 2020.09.08 | Wood St-Efflu | Uranium - Total | ND | ug/L | 0.000 1 | <0.1 ug/L |
| 2020.09.08 | Wood St-Efflu | Zinc | 0.01 | ppm | 0.003 | N/A |

**Table 20:** Tabulated concentrations for the sampled September 8$^{th}$, 2019 storm.

| Pollutant | Influent Concentration (ppm) | Effluent Concentration (ppm) | Percent (%) Reduction |
|---|---|---|---|
| Ammonia as N | 1.32 | 0.34 | 74.24% |
| Nitrate + Nitrite as N | 0.49 | 1.40 | -185.71% |
| Nitrogen, Total Kjeldahl as N | 3.00 | 2.80 | 6.67% |
| Dissolved Phosphorus | 0.24 | 0.29 | -20.83% |
| Total Phosphorus | 0.30 | 0.35 | -16.67% |
| Total Suspended Solids | 59 | 33 | 44.07% |

## Appendix C: 0.5 ft. H-Flume Depth to Discharge Table

The following discharge table was used to approximate flows for the West H-Flume based on calculated water depth. The discharge table is from the Open Channel Flow reference website.

**Table 21.** Depth to flow relationship for 0.5-ft.-H-Flumes from OpenChannelFlow.com

| Water Depth (feet) | Water Depth (inches) | Flow (CFS) |
|---|---|---|
| 0.01 | 0.12 | -- |
| 0.02 | 0.24 | 0.0004 |
| 0.03 | 0.36 | 0.0009 |
| 0.04 | 0.48 | 0.0016 |
| 0.05 | 0.6 | 0.0024 |
| 0.06 | 0.72 | 0.0035 |
| 0.07 | 0.84 | 0.0047 |
| 0.08 | 0.96 | 0.0063 |
| 0.09 | 1.08 | 0.008 |
| 0.1 | 1.2 | 0.0101 |
| 0.11 | 1.32 | 0.0122 |
| 0.12 | 1.44 | 0.0146 |
| 0.13 | 1.56 | 0.0173 |
| 0.14 | 1.68 | 0.0202 |
| 0.15 | 1.8 | 0.0233 |
| 0.16 | 1.92 | 0.0267 |
| 0.17 | 2.04 | 0.0304 |
| 0.18 | 2.16 | 0.0343 |
| 0.19 | 2.28 | 0.0385 |
| 0.2 | 2.4 | 0.0431 |
| 0.21 | 2.52 | 0.0479 |
| 0.22 | 2.64 | 0.053 |
| 0.23 | 2.76 | 0.0585 |
| 0.24 | 2.88 | 0.0643 |
| 0.25 | 3 | 0.0704 |
| 0.26 | 3.12 | 0.0767 |
| 0.27 | 3.24 | 0.0834 |
| 0.28 | 3.36 | 0.0905 |
| 0.29 | 3.48 | 0.0979 |
| 0.3 | 3.6 | 0.1057 |

# Attachment 3

THESIS

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

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In partial fulfillment of the requirements

For the degree of Master of Science

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Fall 2020

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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.

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# 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)

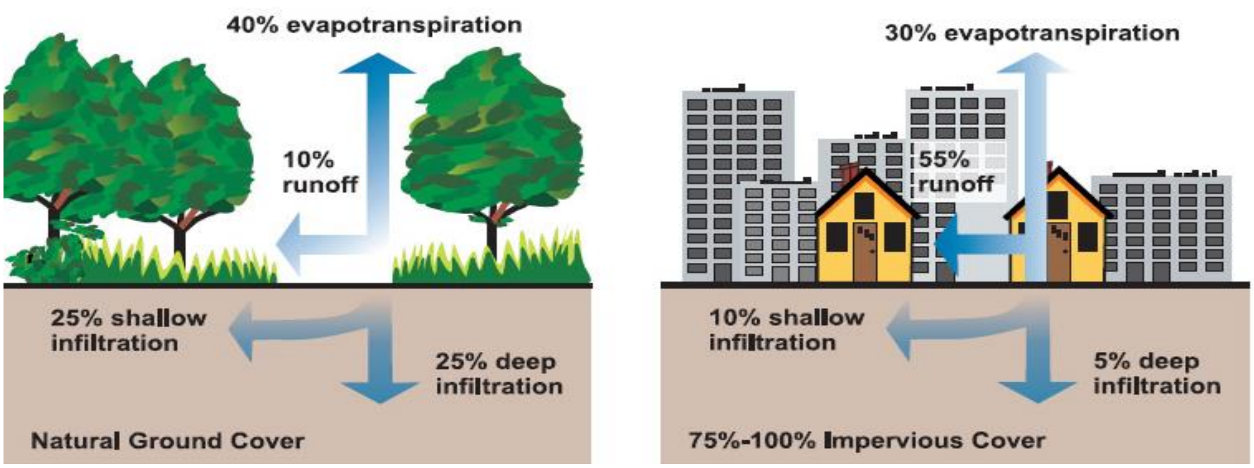


**Figure 1: Example of Pre and Post Development Effects on Stormwater**

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 [$Al_2(SO_4)_3 \bullet 14H_2O$] 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.

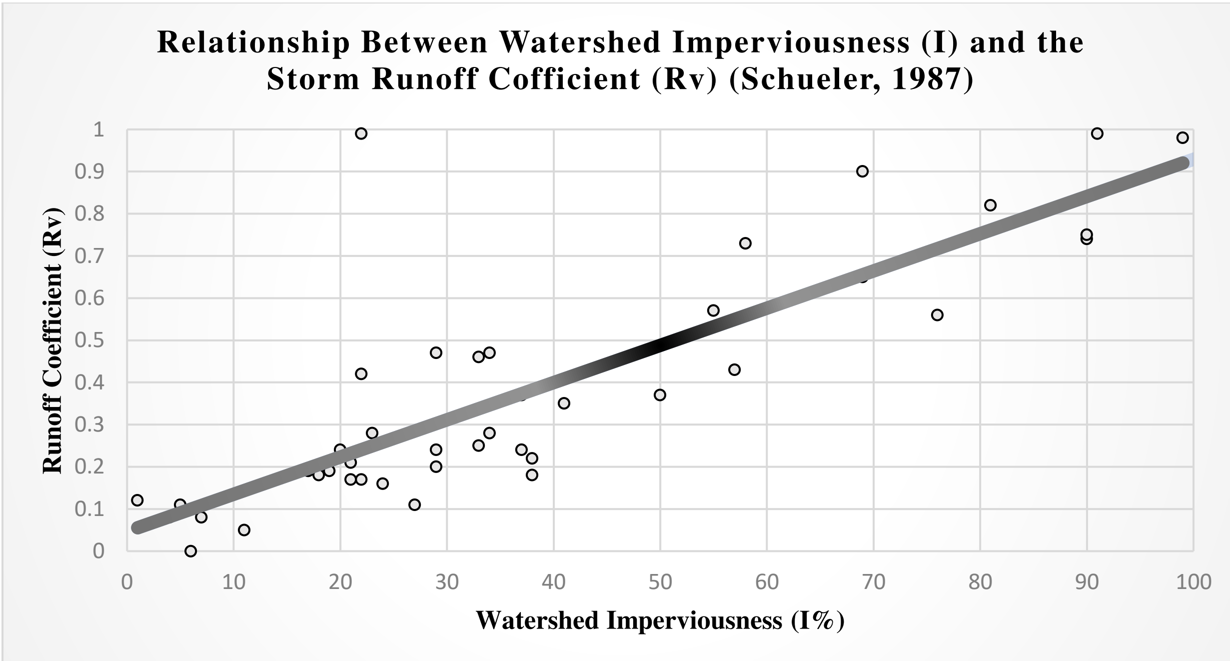


**Figure 3: Relationship between Imperviousness (I) and Runoff Coefficient (Rv) in 44 Urban Catchments (Schueler, 1987)**

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**.

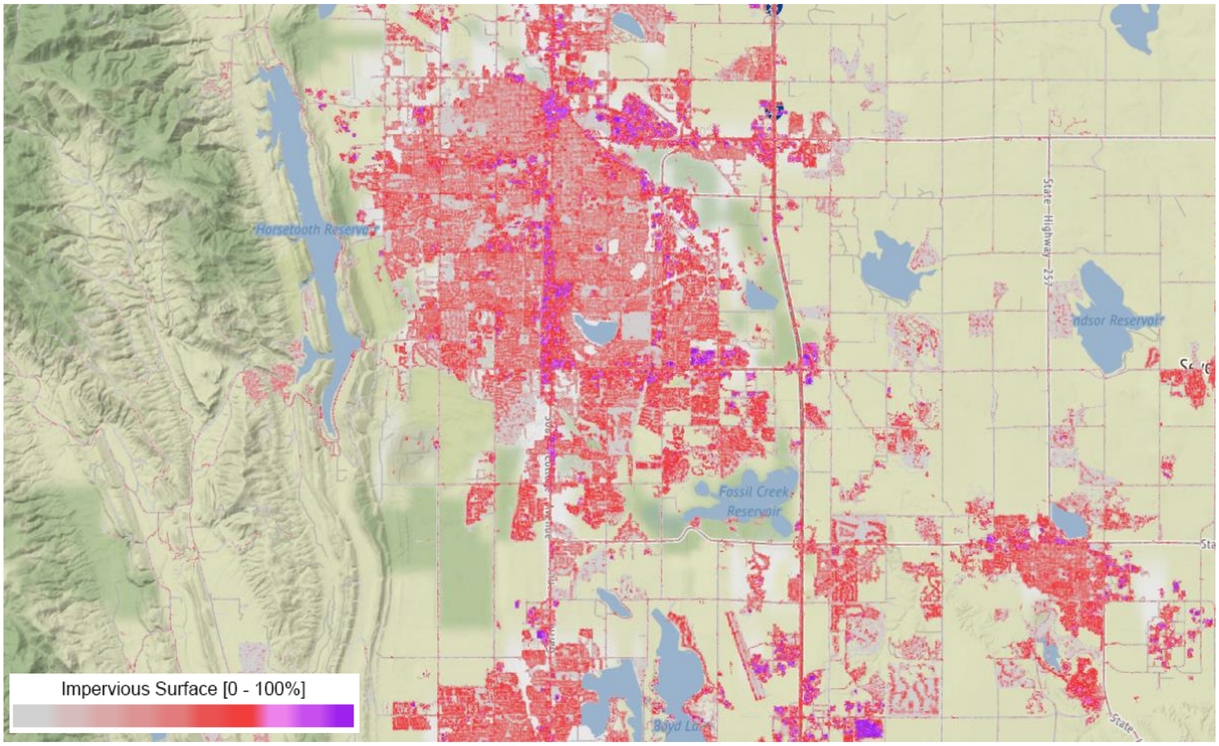


**Figure 4: NLCD 2016 Impervious Surface of Fort Collins (MRLC, 2020)**

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 80$^{th}$ percentile runoff-producing events, as this capture volume allows for BMPs to treat 80-90% of total suspended solids (UDFCD, 2010). The 80$^{th}$ 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 |

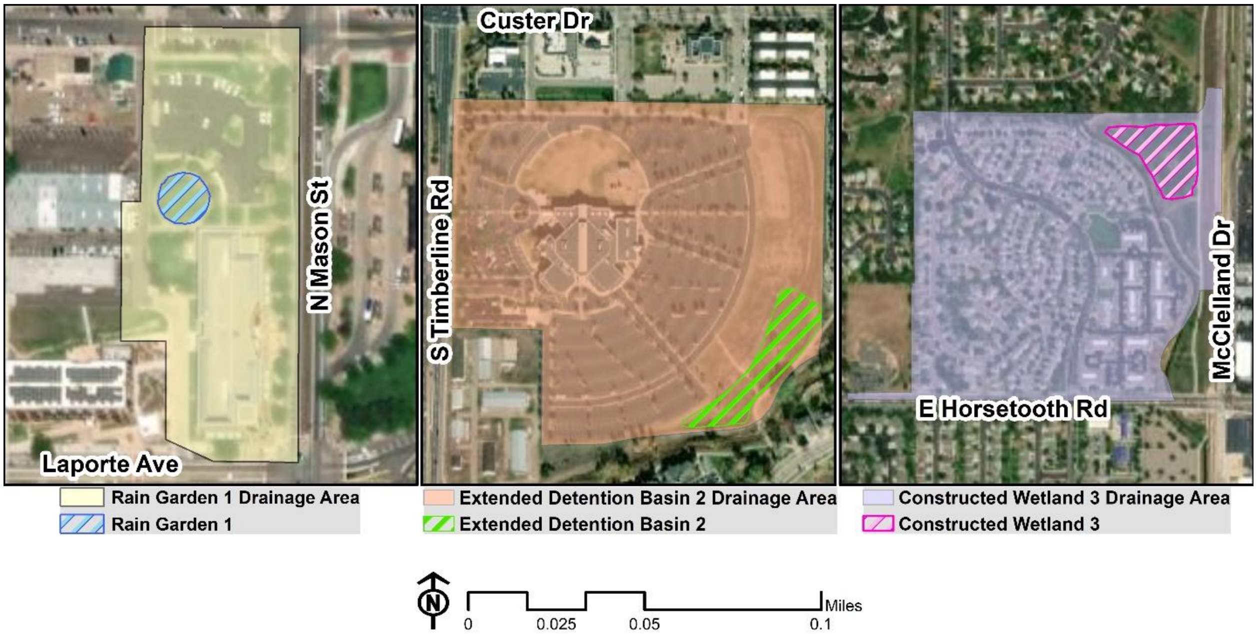


**Figure 5: Examples of Selected BMPs**

### 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.

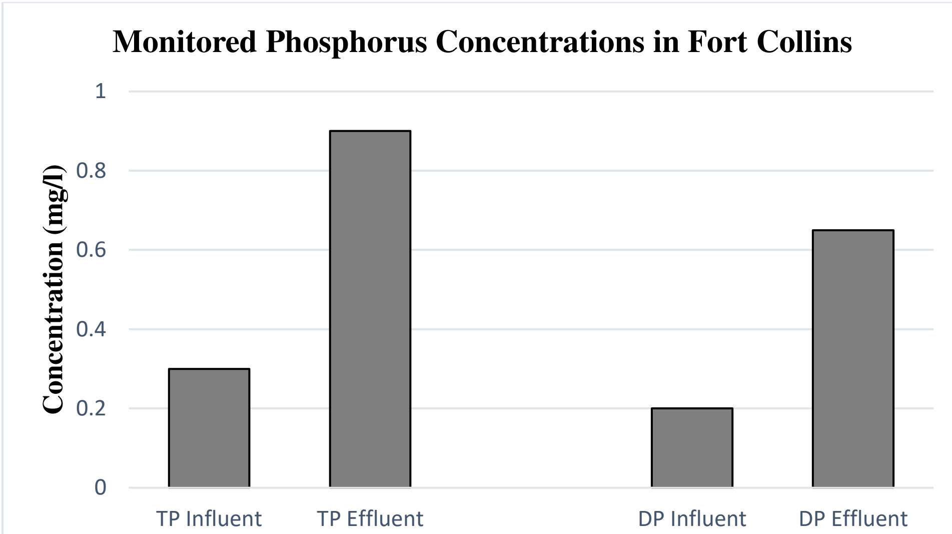


**Figure 6: Monitored Phosphorus Concentrations in Rain Gardens - Fort Collins, CO**

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.

$$\mathrm{Al\text{-}WTR_{PSC}} = [(0.15 - \mathrm{Al\text{-}WTR_{PSI}}) * (\mathrm{Al_{ox}} + \mathrm{Fe_{ox}})] * 31 \qquad \textbf{Equation 3}$$

$$\mathrm{Al\text{-}WTR_{PSI}} = (\mathrm{P_{ox}}) / (\mathrm{Al_{ox}} + \mathrm{Fe_{ox}}) \qquad \textbf{Equation 4}$$

Where:

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

$\mathrm{Al\text{-}WTR_{PSI}}$: 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.

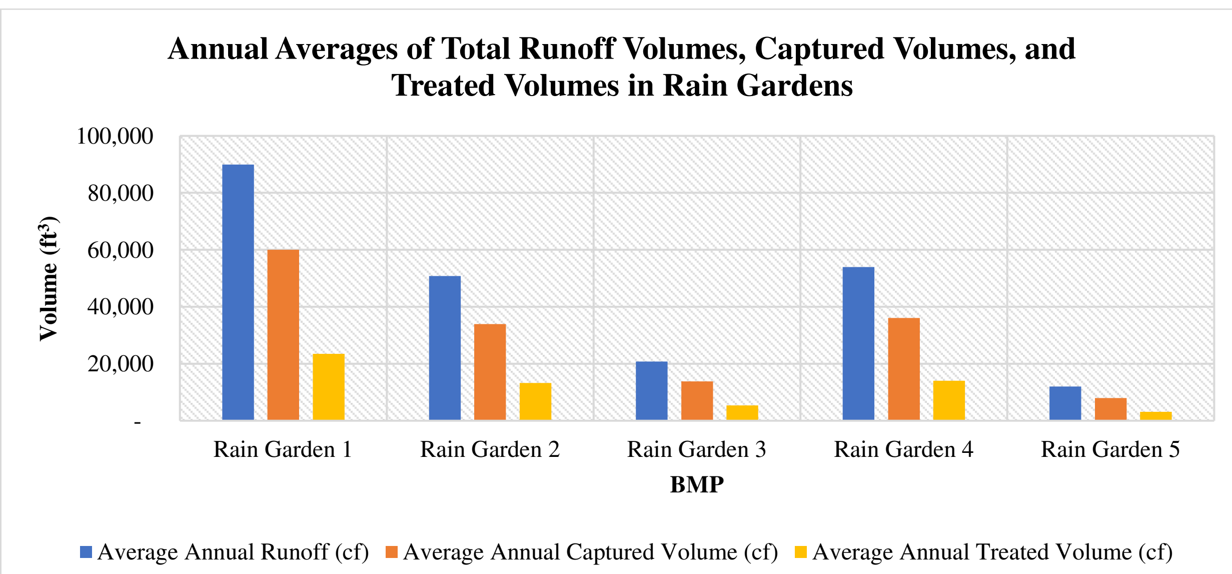


**Figure 8: Annual Averages of Total Runoff Volumes, Captured Volumes, and Treated Volumes in Rain Gardens**

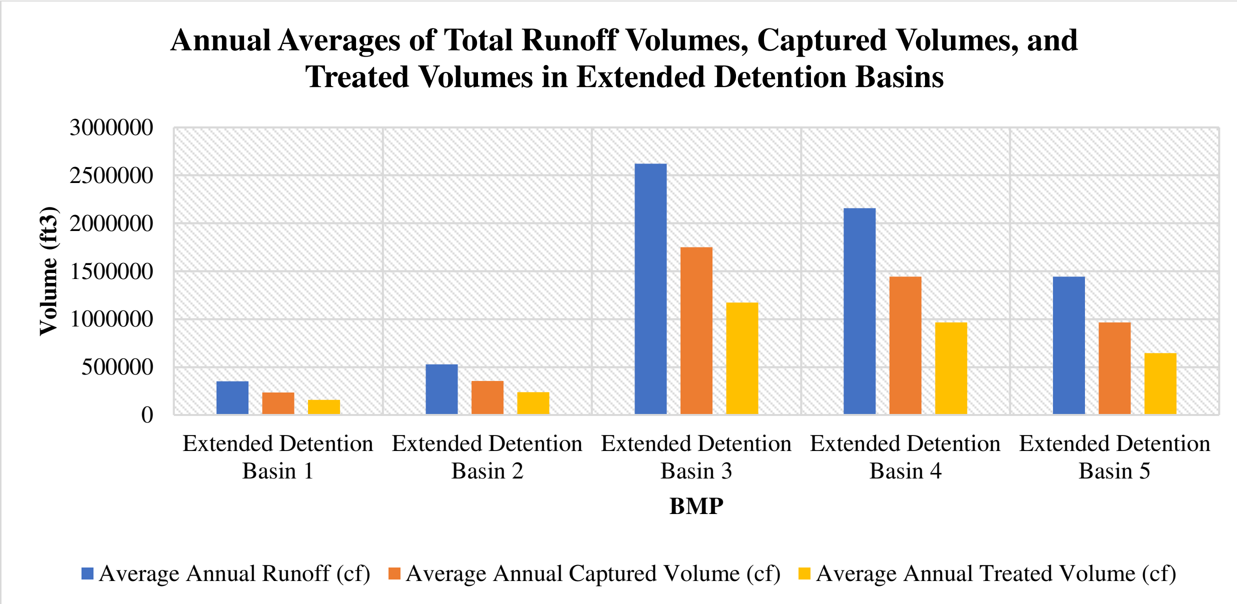


**Figure 9: Annual Averages of Total Runoff Volumes, Captured Volumes, and Treated Volumes in Extended Detention Basins**

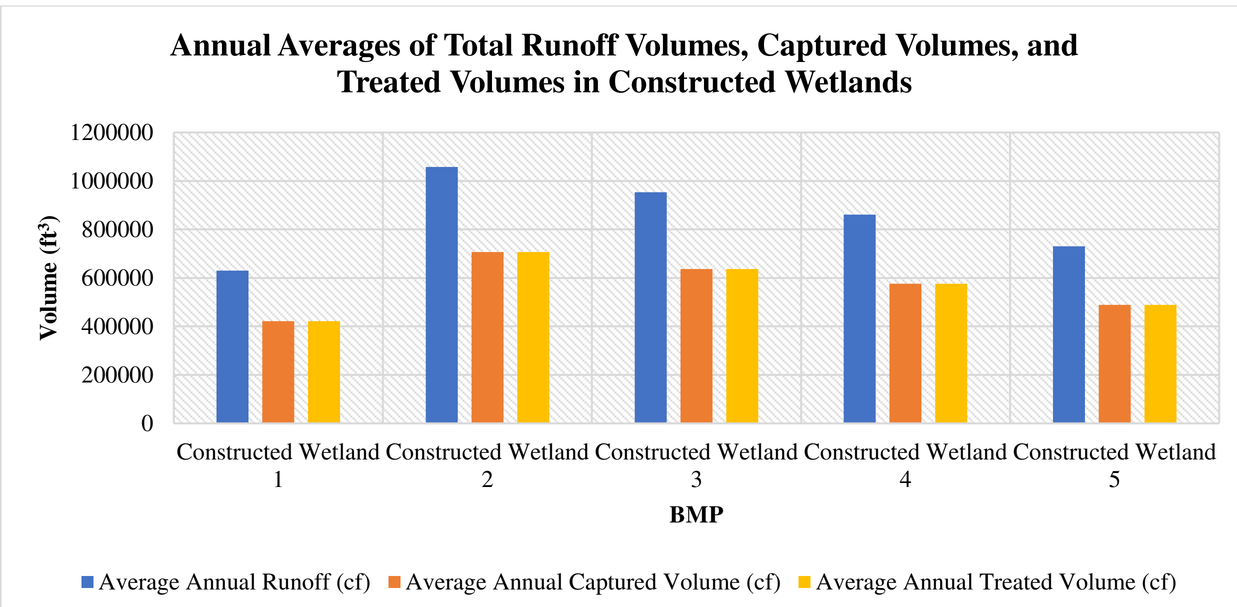


**Figure 10: Annual Averages of Total Runoff Volumes, Captured Volumes, and Treated Volumes in Constructed Wetlands**

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.

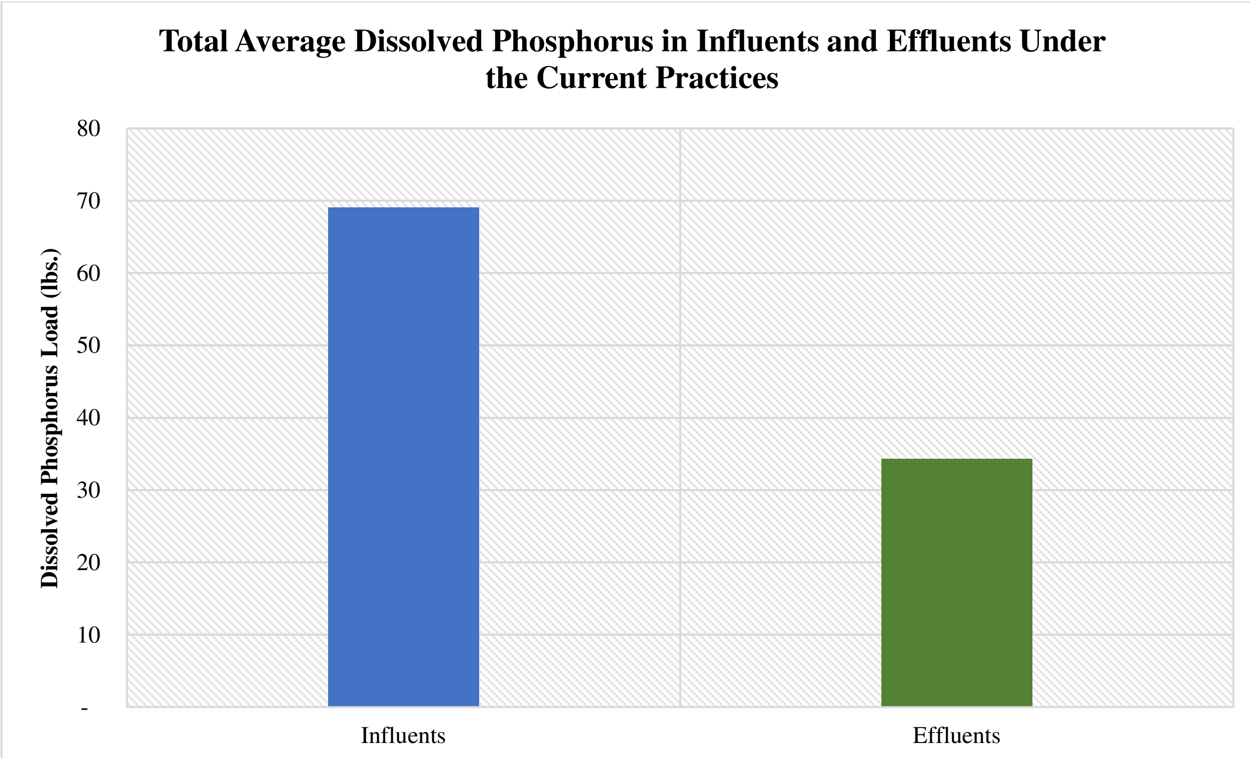


**Figure 11: Total Average Dissolved Phosphorus in Effluents and Effluents - Current Practices**

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.

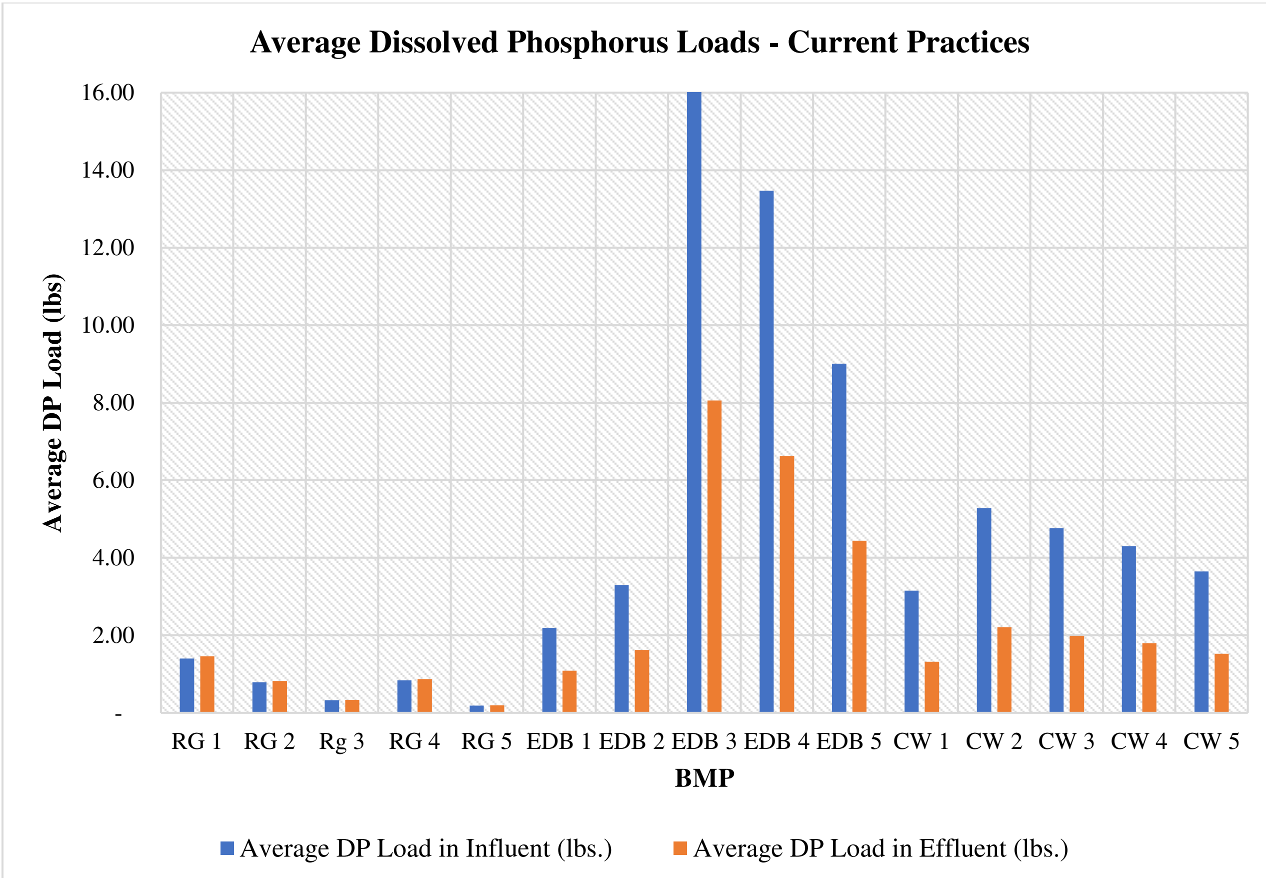


**Figure 12: Average DP Loads - Current Practices**

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.

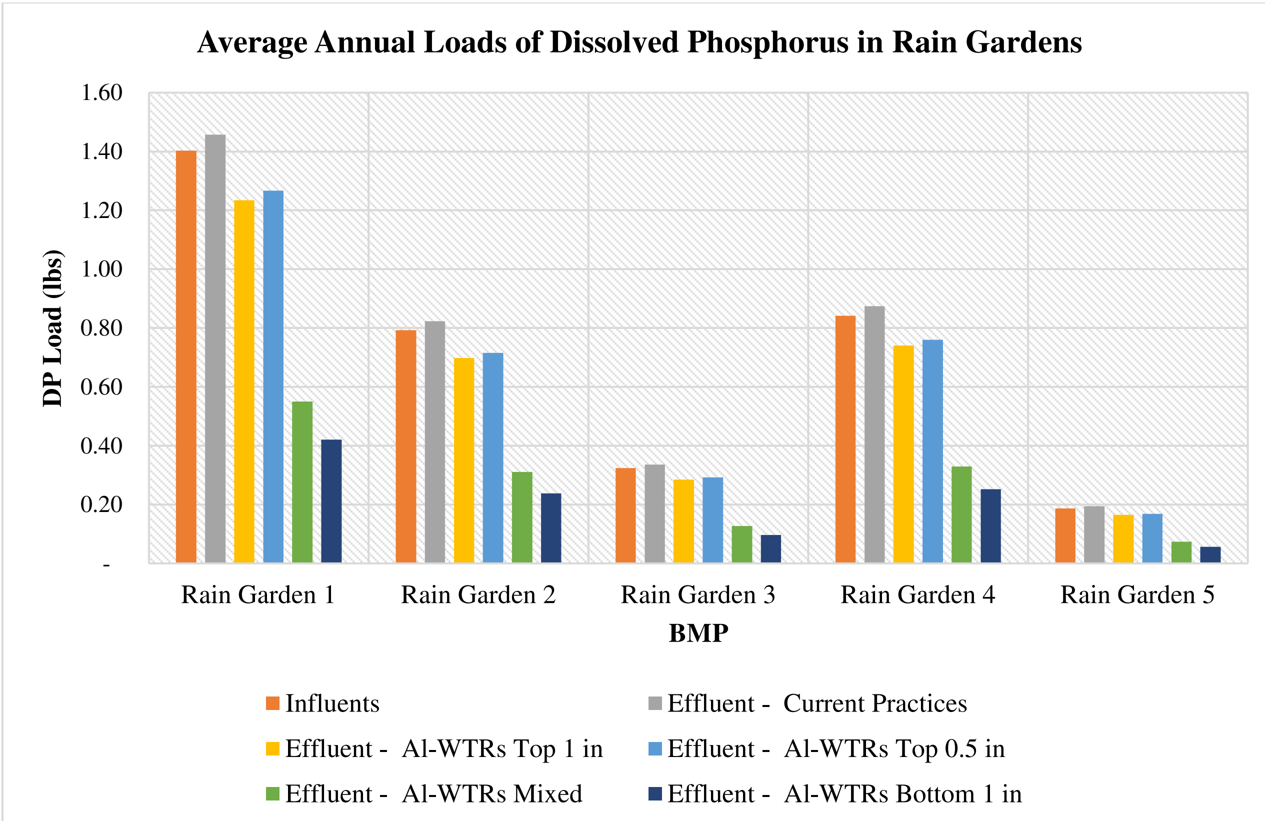


**Figure 13: Average Annual Loads of Dissolved Phosphorus in Rain Gardens**

**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.

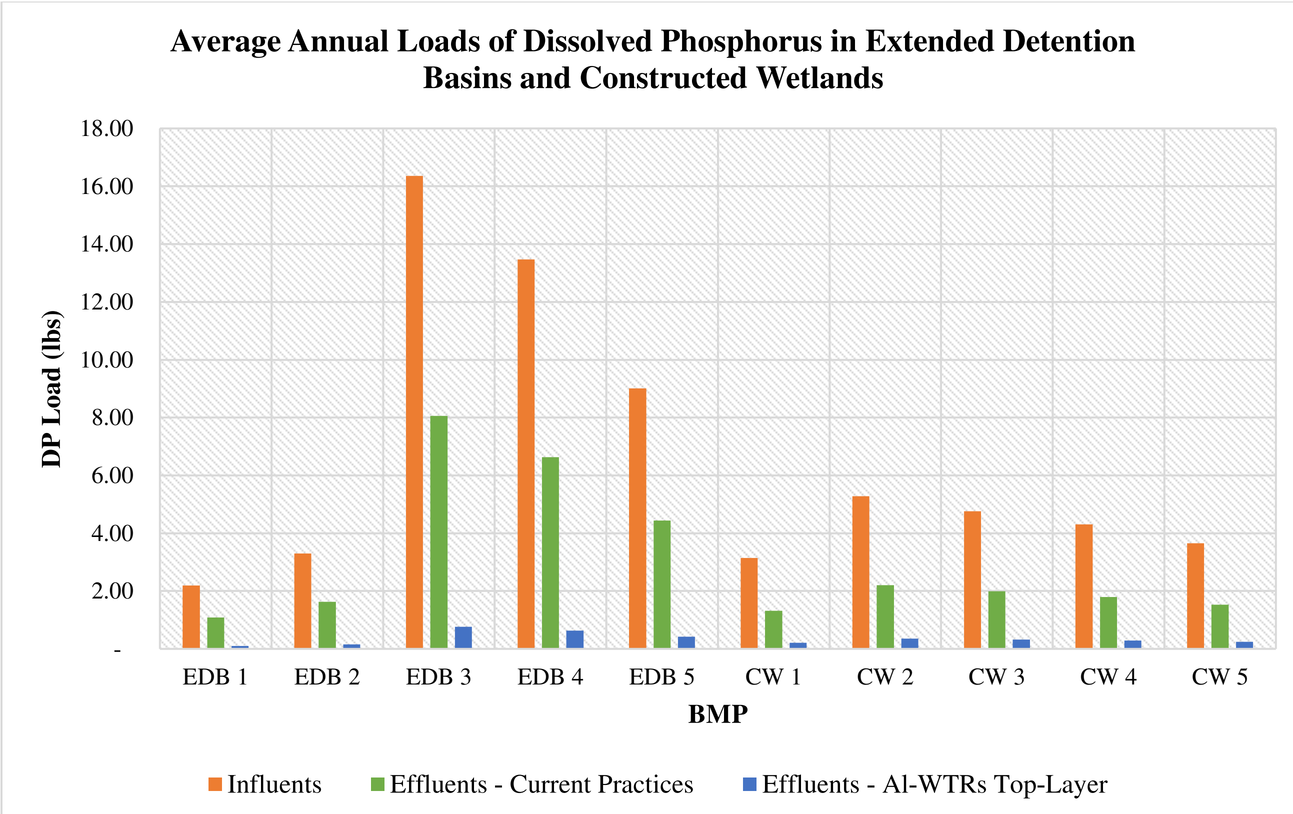


**Figure 14: Average Annual Loads of Dissolved Phosphorus in Extended Detention Basins and Constructed Wetlands**

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.

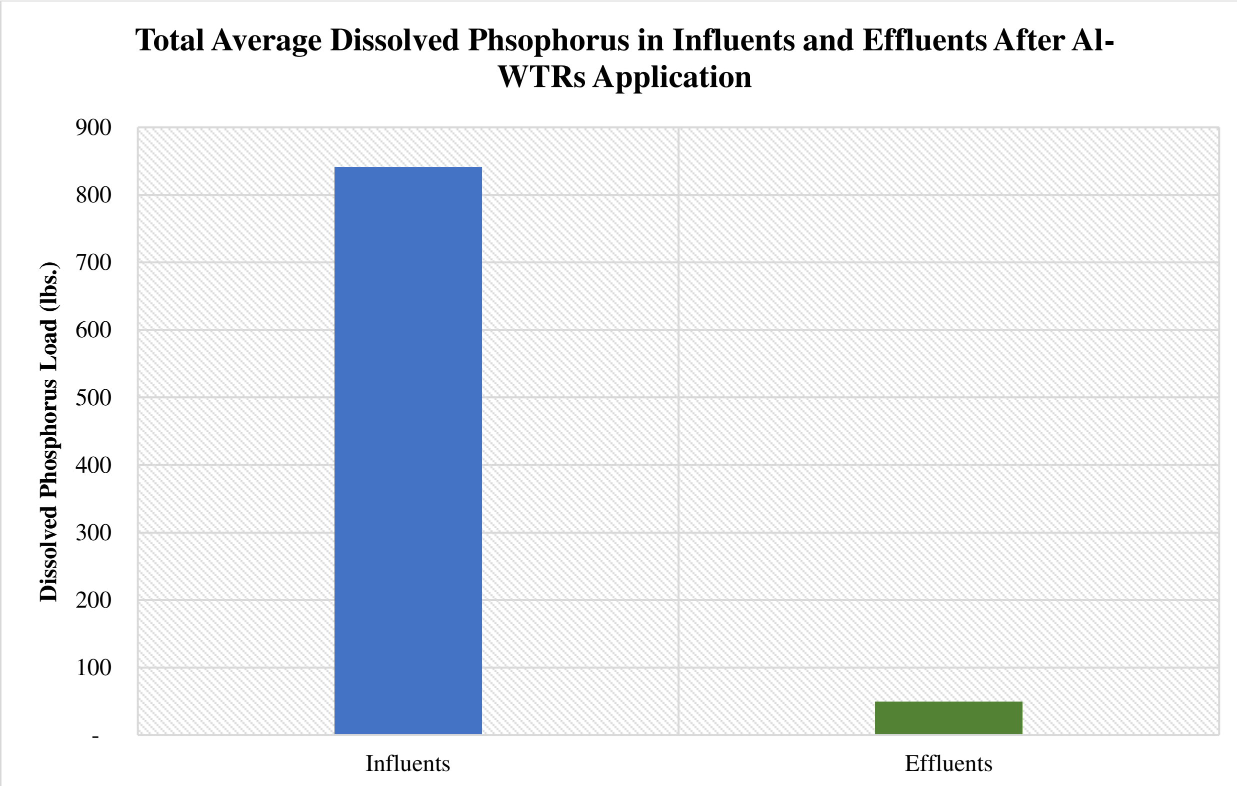


**Figure 15: Total Average Dissolved Phosphorus in Influents and Effluents After Al-WTRs Application**

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.

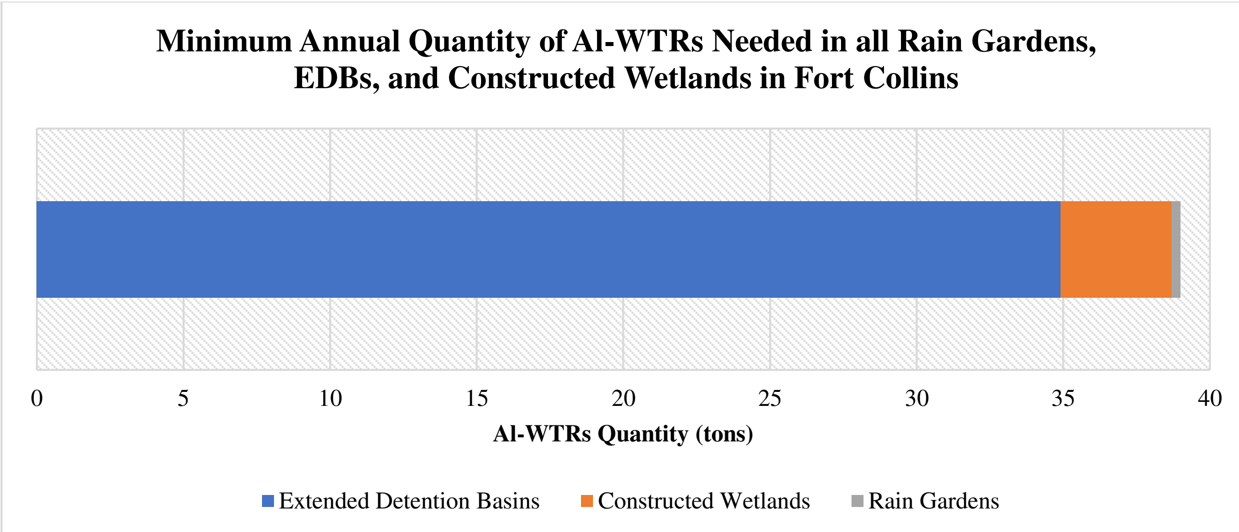


**Figure 16: Minimum Quantity of Al-WTRs Needed to Cover All Rain Gardens, EDBs, and Constructed Wetlands in Fort Collins for One Year**

**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**.

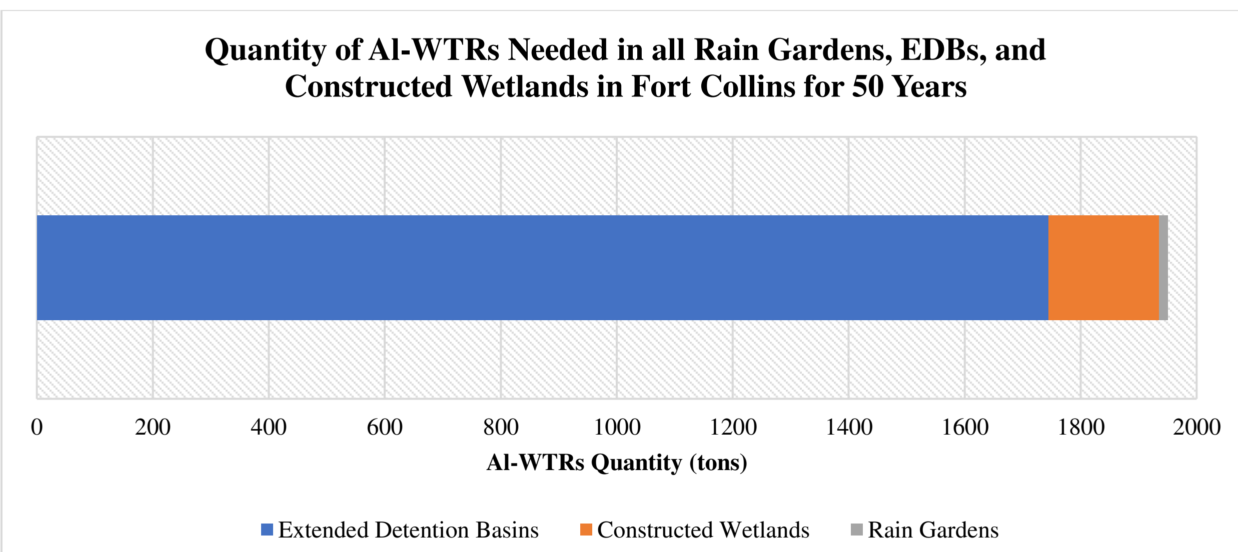


**Figure 17: Quantity of Al-WTRs Needed to Cover All Rain Gardens, EDBs, and Constructed Wetlands in Fort Collins for 50 Years**

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**.

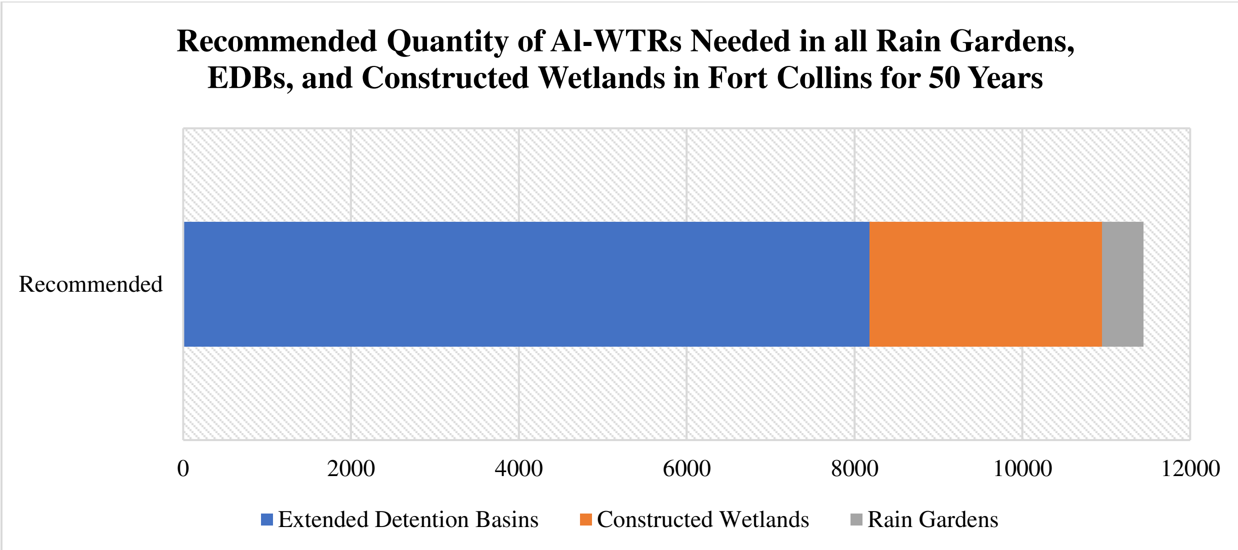


**Figure 18: Recommended Quantity of Al-WTRs Needed to Cover All Rain Gardens, EDBs, and Constructed Wetlands in Fort Collins for 50 Years**

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 |

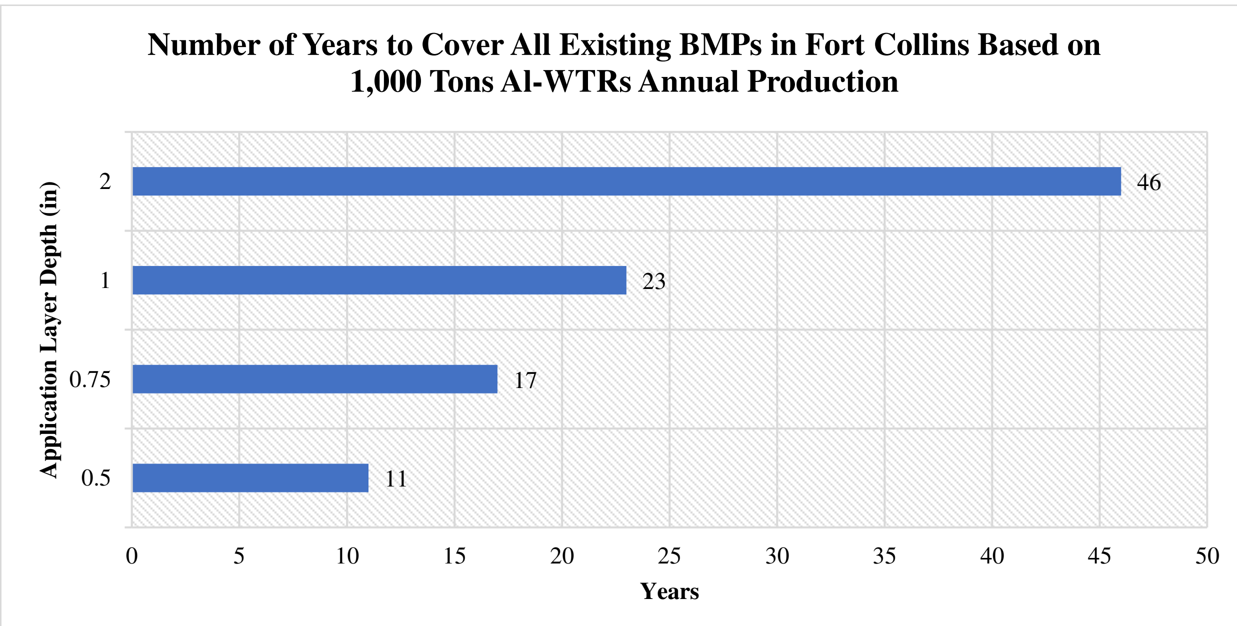


**Figure 19: Approximate Number of Years to Cover All Existing BMPs Based on the Current Production of Al-WTRs in Fort Collins**

## 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.

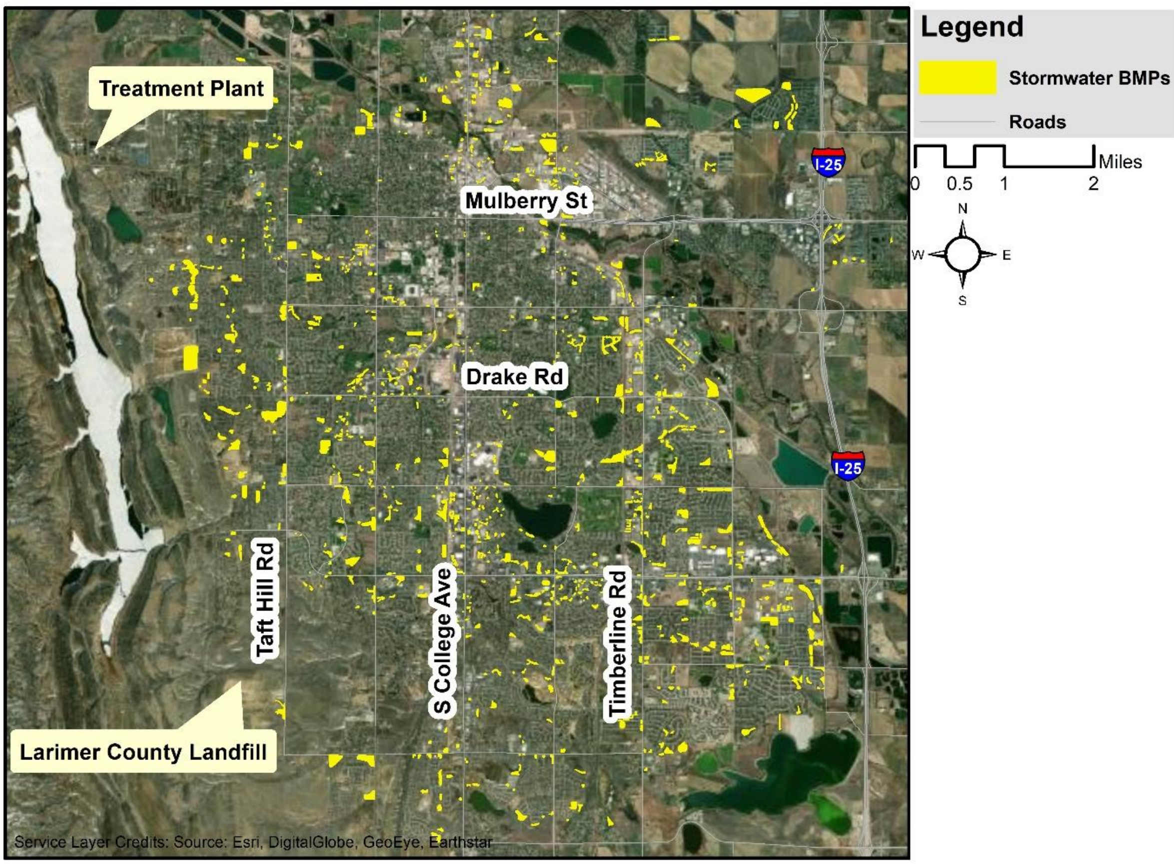


**Figure 20: Distribution of Stormwater BMPs around Fort Collins**

### 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.

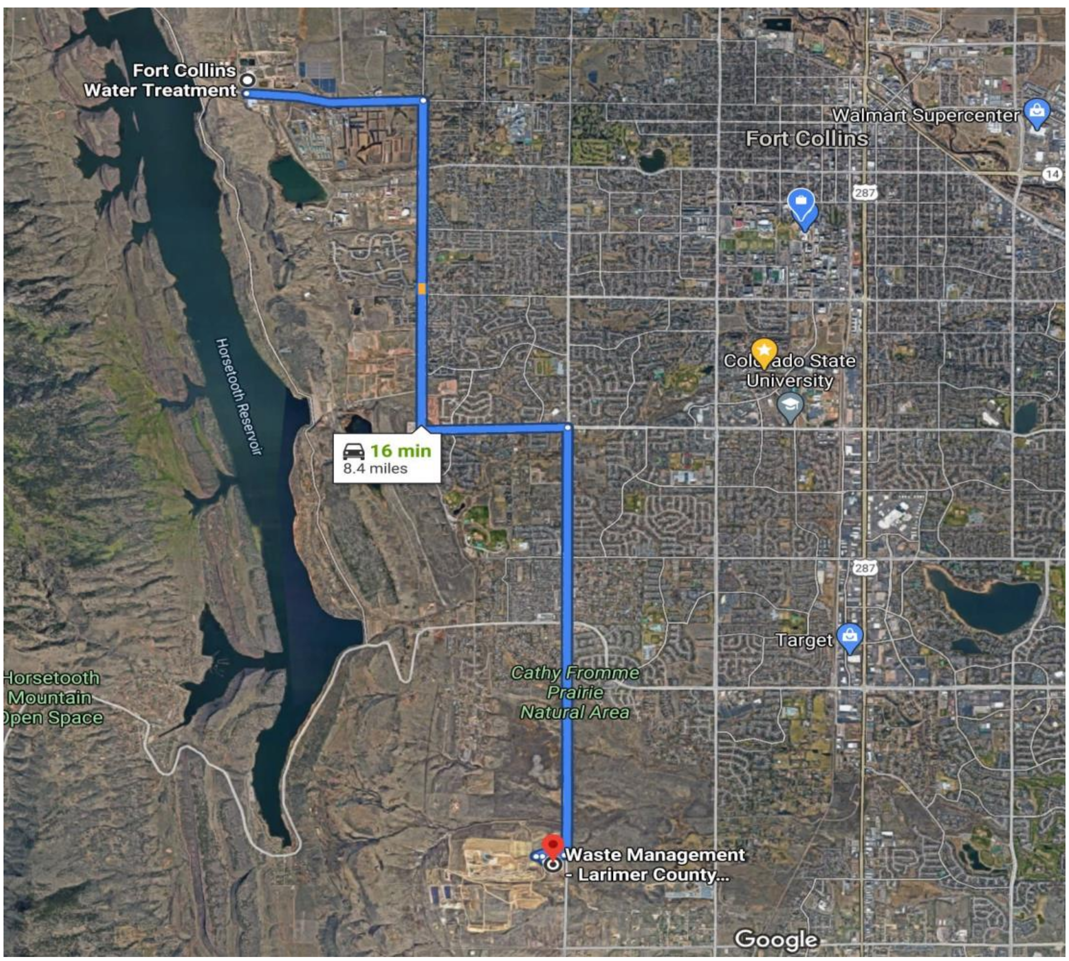


**Figure 21: Driving Distance between the Treatment Plant and the County Landfill in Fort Collins**

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<br>18₵ per truck<br>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.

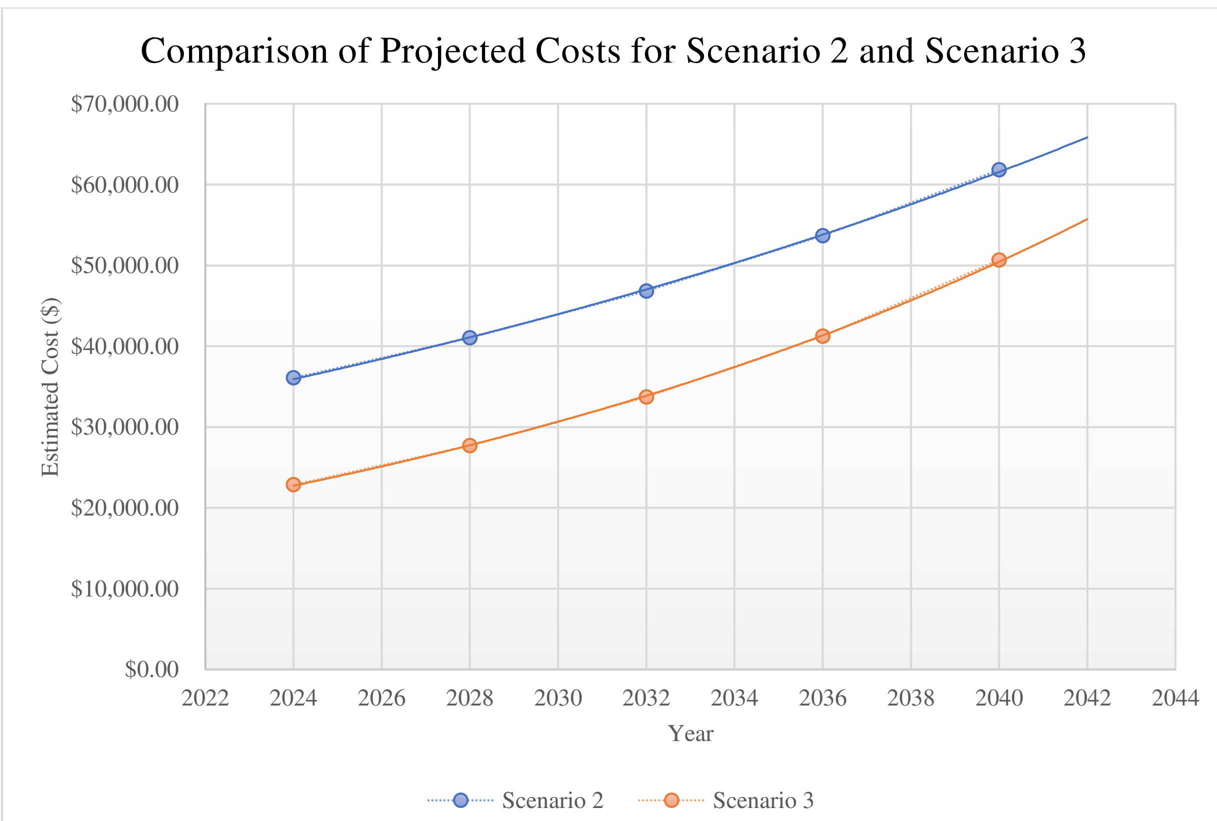


**Figure 22: Comparison of Project Costs for Scenario 2 and Scenario 3**

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

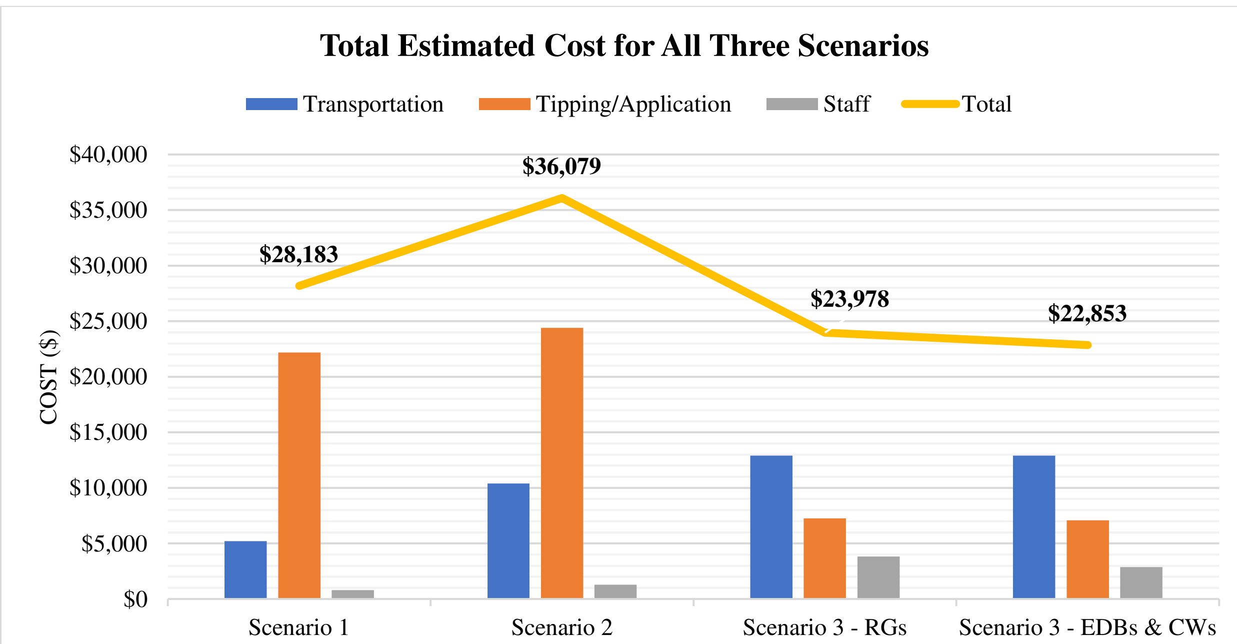


**Figure 23: Summary of Total Estimated Costs**

# 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.

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